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Alternative Treatment Technologies to Open Burning and Open Detonation of Energetic Hazardous Wastes

Final Report

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Alternative Treatment Technologies to Open Burning and Open Detonation of Energetic Hazardous Wastes

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Disclaimer

This report identifies alternative treatment technologies to the open burning and open detonation (OB/OD) of energetic hazardous wastes. Although this report summarizes information on these technologies from literature and from technology vendors, it does not evaluate the technologies or verify the data collected. Additionally, it does not substitute for CERCLA, RCRA, or other EPA regulations, nor is it a regulation itself. Thus, it does not impose legally binding requirements on EPA, States, or the regulated community, and may not apply to a particular situation based upon the circumstances. Use or mention of vendors and trade names does not constitute EPA's endorsement nor its recommendation. Errors and omissions in the information will be corrected as found and as time permits.

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Acronyms and Abbreviations

AAP	army ammunition plant
ADNTs	aminodinitrotoluene isomers
AP	ammonium perchlorate
APE	ammunition peculiar equipment
BRAC	Base Realignment and Closure
°C	degrees Celsius
CAD	cartridge actuated device
CBF	contained burn furnace
CBI	clean burning igniter
CDC	contained detonation chamber
cm	centimeter
CO2	carbon dioxide
DAVINCH	Detonation of Ammunition in a Vacuum Integrated Chamber
DDESB	Department of Defense Explosives Safety Board
demil	demilitarization
DMMs	discarded military munitions
DNTs	dinitrotoluene isomers
DoD	Department of Defense
EDS	Explosives Destruction System
EM	energetic material
EMCW	energetic material contaminated wastes
EMS	Environmental Management Support, Inc.
EPA	U.S. Environmental Protection Agency
Explosive D	ammonium picrate
°F	degrees Fahrenheit
ft	feet
FUDS	Formerly Used Defense Sites
FY	fiscal year
g	gram
HMX	1,3,5,7-octahydro-1,3,5,7-tetranitrotetrazocine
in	inch
ICM	improved conventional munitions
iSCWO	Industrial Supercritical Water Oxidation
kg	kilogram
lb	pound
LRIP	Low Rate Initial Production
MDAS	material documented as safe
MDEH	material documented as an explosive hazard
MIDAS	Munitions Items Disposition Action System
m	meter
mm	millimeter
MPPEH	material potentially presenting an explosives hazard
MTU	mobile treatment unit
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NDMA	N-nitroso-dimethylamine
NEW	net explosive weight
NOx	nitrous oxides
NPL	National Priorities List
NSWC	Naval Surface Warfare Center

OAT	operation acceptance testing
OB	open burning
OD	open detonation
PAD	propellant actuated device
PBX	polymer-bonded explosive
PDF	Portable Document Format
PEP	pyrotechnics, explosives, and propellants
PETN	pentaerythritol tetranitrate
psia	pounds per square inch absolute
psig	pounds per square inch gauge
RCRA	Resource Conservation and Recovery Act
RDT&E	DoD's Demilitarization (Demil) Enterprises' Research, Development, Test and Evaluation
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine
ROK	Republic of Korea
SDC	static detonation chamber
tetryl	2,4,6-trinitro-phenylmethylnitramine
TNT	2,4,6-trinitrotoluene
TSDF	treatment storage and disposal facility
TTU	transportable treatment unit

Introduction

For decades, open burning and open detonation (OB/OD) have been used to treat/destroy energetic hazardous wastes. “Energetic” refers to a class of materials with a high amount of stored chemical energy that can be released, such as military munitions, fireworks, and automobile airbag propellants. OB/OD is an uncontrolled treatment technology compared with enclosed alternative technologies.[1] In comparison to technologies that are capable of capturing and treating the residual byproducts prior to release, OB/OD of energetic hazardous waste occurs in the open, and the treatment byproducts are released directly into the environment (Figure 1). As a result, OB/OD-related contamination and exposure via emissions of particulates, products of incomplete combustion, or explosives chunks, and the dispersal of munitions and other waste items (kickout)[2], has raised questions on whether alternative treatment technologies are available for energetic hazardous wastes. In keeping with EPA’s commitment to monitor the progress of the ongoing development of safe alternatives to OB/OD,[3] this report presents alternative treatment technologies that have been developed, and in many cases utilized, for consideration in place of OB/OD.

Figure 1. Open Detonation Showing Uncontrolled Emissions and Kickout

Photo courtesy of Rick Stauber, Retired Army Master Sargent

[1] From EPA’s 1987 Subpart X final rule, “[i]n most cases, air emissions from open burning/open detonation cannot be controlled since it is impossible to operate these units under totally enclosed conditions” (52 FR 46957, December 10, 1987). The lack of air emission controls can be mitigated by permit conditions that lessen or monitor the impact to the surrounding environment, e.g., ensuring a high order detonation for maximized consumption of contaminants, limiting detonation size to the containment pit, identifying an exclusion zone around the detonation pit for fall out, sweeping the fallout zone for kickout after each treatment event, and routine soil and groundwater monitoring.

[2] The current practice of open detonation is much less likely to result in kickout beyond the treatment area since the wastes are usually covered with several feet of soil to reduce noise, shock, and ejected debris.

[3] Final Background Document, 40 CFR part 265, subpart P Interim Status Standards for Hazardous Waste Facilities for Thermal Treatment Processes Other Than Incineration and for Open Burning. Environmental Protection Agency, Office of Solid Waste, April 1980; p. 52. (https://nepis.epa.gov).

The purpose of this report is to identify and describe alternative treatment technologies that can reduce the reliance on OB/OD.[4] Many of the developed technologies have been tested and demonstrated to prove their capabilities in terms of the types of energetic hazardous waste they can destroy safely. Thus, this report also identifies the extent to which individual technologies have been developed, implemented, and used. It does not attempt to provide a comprehensive analysis of the technologies' efficacy for various waste streams nor does it attempt to compare their advantages and disadvantages.

EPA expects that this report will be a useful reference for permit writers reviewing applications for treatment of energetic materials, facilities that treat or propose to treat such materials, and interested community members living near OB/OD units.[5]

Scope and Report Structure

The primary purpose of this report is to identify and describe alternative treatment technologies and their developmental status. The report first reviews how energetic hazardous wastes have been treated over several decades through a synopsis of the history and regulation of OB/OD and the past and present universe of OB/OD facilities, thereby providing perspective on the relevance of alternative treatment technologies and the importance of their development and use today.

Next, the report discusses selected key points from the National Academies of Sciences, Engineering, and Medicine's (NASEM) report on "Alternatives for the Demilitarization of Conventional Munitions" [6] and provides EPA perspectives on these points. This segues into EPA's own information gathering and assessment of available alternative technologies.

The review of alternative treatment technologies conducted for this report focuses on technologies that have been used either within the U.S. or internationally[7] to treat energetic hazardous wastes and primarily includes technologies claimed to have been successfully piloted or used full-scale. A few technologies that were widely tested, but had limited success, are also included since this information may also be of benefit.

This report encompasses alternative treatment technologies as well as any recycling/reuse options, although the focus is on alternative treatment options. It does not specifically include remediation technologies for treating soil or water contaminated with energetic compounds, although some of the technologies can be used to treat contaminated media. Likewise, some technologies may be used to treat chemical munitions but are not specifically discussed in this regard. Because the Department of Defense (DoD) has developed, tested, and/or utilized many of the available alternatives for demilitarization of military munitions and explosives, much of the information in this report is devoted to the application of these alternative technologies to treat waste military munitions and explosives; however, these technology options may also be used

[4] Complete elimination of OB/OD is unlikely given that there are unstable munitions that may not be safe to handle or transport for treatment by alternative technologies (NASEM 2019, Main Message #2, page 2).

[5] Members of the public, particularly residents living near operating OB/OD units, have expressed concern over the adverse impacts of OB/OD (Harris, 2018, Lustgarten 2017, Ross 2017, CSWAB 2016, Atkin 2015, Hilburn, 2015, Rustric 2001).

[6] NASEM 2019.

[7] Note that due to differences in design and content between some U.S. and foreign munitions or pyrotechnics, treatment results may differ between countries.

for a variety of non-military applications. Many of the technologies in this report were first conceptualized, tested, improved, and implemented through DoD's Demilitarization (Demil) Enterprises' Research, Development, Test and Evaluation (RDT&E) program and DoD's demil execution program. The RDT&E program has developed specific procedures for the identification and selection of viable alternatives to OB/OD for the treatment of certain excess, obsolete or unserviceable DoD military munitions (see Figure 2).

Figure 2. DoD Procedures for the Identification and Selection of Viable Alternatives to OB/OD

The DoD demilitarization planning process includes an optimization program that takes into account specific constraints. The main constraints include cost, capability, throughput capacity, and funding. Once the initial plan is developed, the items are researched to identify any potential safety, environmental compliance, or hazardous waste characterization concerns that might impact execution. If safe alternative technologies are available, based on funding and economic feasibility, the alternative capability would be selected. OB/OD is primarily reserved for items that do not currently have a safe alternative available, for example, the 155mm and 8in propelling charges, adapter boosters, and 155mm Improved Conventional Munitions (ICM) submunitions.

DoD annually assesses the top 400 munitions in the Demil Stockpile. Where there are no alternatives (capability gaps), DoD prioritizes its research into alternatives by tonnage (most tonnage to least).

To aid in the reader's understanding of the alternative technologies that would be suitable for specific wastes, the report identifies the various kinds of energetic hazardous wastes and the forms or configurations (e.g., thick-case munitions, thin-case munitions, bulk explosives/propellants, or potentially explosive contaminated material) they may exist in. The report then describes the treatment steps based on the configuration. Each treatment step (e.g., case opening, material removal, material destruction, and decontamination) is correlated to a technology designed for that treatment step. The individual technologies are listed according to their step in the treatment process and include an operational description, along with their development and use status. This information is also presented in a tabular format in Appendix D for quick reference and ease of comparison of technologies. Appendix D further includes: technology vendor, scale at which the technology has been developed, portability, MIDAS codes of wastes treated, whether the technology requires pre- or post-treatment, output/emissions output, DoD Explosives Safety Board approval, and location(s) of deployment.

It is important to note that general information is provided for the listed technologies and thus, their viability must be determined on a site-specific basis due to the many variables involved when considering a treatment technology (e.g., the type of the material being treated, the quantity of energetics or net explosive weights (NEW) to be treated, and the stability of the energetic material). While this report provides information helpful in decision making, caution is still advised in the selection process as safety is paramount. As such, knowledge about the wastes being treated is essential.

OB/OD Regulatory Background

The treatment, storage, and disposal of hazardous wastes are governed by regulations developed by EPA under the authority of the Resource Conservation and Recovery Act (RCRA). Among the regulations EPA proposed in 1978 was a ban on the open burning of all hazardous wastes (43 Federal Register (FR) 5900, December 18, 1978). EPA received public comments, including from DoD and the private sector, indicating a lack of safe alternatives to the use of OB/OD to treat most energetic hazardous wastes (45 FR 33217, May 19, 1980).[8] In response, when the first of these regulations was finalized in May 1980, EPA provided in 40 CFR 265.382 (for interim status units), that the "open burning of hazardous waste is prohibited except for the open burning and detonation of waste explosives. Waste explosives include waste that has the potential to detonate and bulk military propellants which cannot safely be disposed of through other modes of treatment."[9] This variance, allowing for the OB/OD of energetic hazardous wastes only, was promulgated at a time when safe alternatives did not exist for many energetics. The variance allowed treatment by OB/OD only during the interim status period and only until additional viable technologies could be developed.[10]

In 1987, EPA finalized permitting standards for a catchall category of waste management units, including OB/OD units, that were not already covered in the regulations (40 CFR part 264, subpart X – Miscellaneous Units [52 FR 46946, December 10, 1987]). Unlike the other RCRA unit-specific regulations, miscellaneous units permitted under Subpart X are subject to general performance standards rather than technical performance standards since a single set of technical standards may not be suitable for the diverse types of miscellaneous units. As a result, owners and operators applying for Subpart X permits must ensure compliance of the unit with environmental performance standards. To demonstrate the unit is protective of human health and the environment, the permit application must provide detailed information on the unit's location, design, construction, operation, maintenance, monitoring, responses to releases, and closure, to prevent and control releases into the groundwater, surface water, surface soil and the subsurface environment, wetlands, and air. This requires the owner or operator to assess the potential environmental impacts of the units' unique design features and to demonstrate that operation of the unit will be protective of human health and the environment (52 FR 46951). These design and operational features then become permit conditions. For example, the resulting permit conditions for OB/OD units may include: limitations on types and quantities of wastes that may be open burned or detonated; establishment of safety buffer zones; implementation of controls over the use of lands adjacent to the permitted facility (e.g., through ownership or zoning); restrictions on hours of operation, specification of weather conditions, establishment of maximum allowable wind speed; requirements to use platforms, liners, pans, cages, or trenches with cover; and requirements to monitor the soil and groundwater. This comprehensive evaluation and the resulting permit conditions will provide assurance that the permitted miscellaneous unit poses minimal environmental threat (see 52 FR 46952 and 40 CFR 264.601). Note that, the final rule for miscellaneous units did not provide any regulatory language that removed or superseded the interim status variance and only stated in the final rule preamble that "when upgrading existing units or permitting new units, the applicable

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[8] See also: Final Background Document, 40 CFR part 265, subpart P Interim Status Standards for Hazardous Waste Facilities for Thermal Treatment Processes Other Than Incineration and for Open Burning. Environmental Protection Agency, Office of Solid Waste, April 1980. (https://nepis.epa.gov)

[9] Waste explosives are also referred to as energetic material (EM) wastes, EM contaminated wastes (EMCW), and energetic hazardous wastes..

[10] The final background document for the Subpart P interim status standards states, "the Agency has decided to allow open burning and detonation of waste explosives during the interim status period…the Agency will be monitoring the progress of the ongoing development of safe alternatives, and may propose additional regulations…" (See pp. 51-52, Final Background Document, 40 CFR part 265, subpart P Interim Status Standards for Hazardous Waste Facilities for Thermal Treatment Processes Other Than Incineration and for Open Burning. EPA Office of Solid Waste, April 1980.)

portions of Part 265 Subpart P standards…will be incorporated during issuance of Subpart X permits" (52 FR 46952, December 10, 1987).[11]

Because OB/OD is considered treatment rather than disposal under RCRA, facilities are required by statute and regulation to clean close when operations cease.[12] This requirement means removing all remaining waste, decontaminating all equipment, and cleaning up all remaining contaminants (including particulate fallout and kickout from detonations) above threshold action levels. Given the number of OB/OD units that have now closed, EPA is currently evaluating OB/OD site assessment and cleanup/closure procedures. For more information on closure and requirements, see 40 CFR part 264 subpart G for permitted units and part 265 subpart G for interim status units.

OB/OD Universe

There are approximately 225 treatment storage or disposal facilities (TSDFs) that have or had OB/OD units in the U.S. according to records in EPA's RCRAInfo database.[13] This number represents the cumulative total of OB/OD facilities that have operated under RCRA since the 1980 standards for owners and operators of TSDFs were finalized. Many of these 225 TSDFs have more than one OB/OD unit. Most of these OB/OD units started operating before the RCRA interim status and permit regulations were issued. Some of these units are small (e.g., a 55-gal drum used to burn university chemical lab energetics) and some process tons of energetics each month (e.g., some of the DoD demilitarization units). Of the 225 TSDFs, 60 facilities were still operating (under either interim status or a permit) as of November 28, 2018. These 60 OB/OD facilities are operated by both the private sector and public sector. The private sector operates 19 facilities and the public sector operates 41 facilities between DoD (36 facilities) and other government agencies (5 facilities).

DoD's demilitarization program, which is required to reduce the stockpile of excess, obsolete, and unserviceable munitions, is the main user, by weight, of OB/OD. "Use of OB/OD as a demilitarization treatment method has declined from an estimated 80 percent…in the mid-1980s to an average of about 30 percent in recent years"[14]. In fiscal years (FY) 2016 and 2017, DoD demilitarized over 10,000 tons of bulk propellant and propellant charges by open burning; over 34,000 tons of cartridges, projectiles, submunitions, mines, fuzes, and other items by open detonation; and about 650 tons of missiles by open burning or static firing (McFassel, 2017).[15]

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[11] EPA did not discuss the variance status in the 1987 final rule preamble nor address it in regulation. The presumption is that the variance continues to apply only when there are no other safe alternatives.

[12] See 52 FR 46952, December 10, 1987, and 40 CFR 265.381.

[13] Data retrieved November 28, 2018, identified 225 TSDFs as having Subpart X process type X01 with names indicative of OB and/or OD activity. Totals do not include OB/OD facilities that are/were operating under emergency permits, protective filer status, or conducting activities not requiring a permit.

[14] NASEM 2019.

[15] Data on percent by weight of waste treated by the private sector is currently not available due to the format of the Biennial Report (https://www.epa.gov/hwgenerators/biennial-hazardous-waste-report). Until recently, this reporting system did not have a management method code option specific to OB/OD. This capability has since been added for the 2019 reporting cycle. However, until data becomes available from the 2019 reporting cycle, the best source of this information is via RCRA permits which provide maximum daily and/or annual weight limits.

The preference for using OB/OD has been based largely on safety and minimizing risk from explosive hazard (i.e., reduced personnel exposure, and minimal handling of wastes) and the capacity to treat large quantities of diverse waste streams containing explosives. Irrespective of these considerations, a range of alternative treatment technologies that have demonstrated a capability to satisfy safety mandates are now available. These technologies are contained or closed and (typically) employ pollution controls to treat the byproducts before release.

Energetic Hazardous Wastes Treated by OB/OD

When energetic materials are determined to be wastes, they are designated as “hazardous” waste under the Resource Conservation and Recovery Act (RCRA) because they exhibit the hazardous characteristics of either ignitability or reactivity, or both.[16] Energetic hazardous wastes treated by OB/OD encompass many types of energetic materials (i.e., propellants, explosives, and pyrotechnics [PEP]) contained in conventional military munitions and other devices, such as marine, roadside, and signal flares, consumer and commercial fireworks, hobby rocket propellants, and auto air bag gas generators.

Although DoD has increased both its use of resource recovery and reuse and contained technologies, it still relies on OB/OD to demilitarize significant portions of its demil stockpile. DoD’s demil stockpile includes excess, obsolete, and unserviceable munitions (e.g., missiles, bombs, mortars, artillery rounds, and bulk energetic materials) which are stored at its ammunition depots, plants, and arsenals, such as McAlester Ammunition Plant in Oklahoma and Crane Army Ammunition Activity in Indiana. DoD is transitioning to insensitive munitions as these items are more stable and thus, safer for storage and transportation; the treatment technologies summarized in this report do not address insensitive munitions even though these munitions will require a treatment solution in the future when they become part of the energetic hazardous waste stream.

As of July 2017, DoD estimates it has 441,811 tons of munitions in its demil stockpile (McFassel, 2017). The energetic materials DoD produces and uses in the greatest quantities are secondary explosives (e.g., 2,4,6-trinitrotoluene (TNT), ammonium picrate (Explosive D)[17], hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), 1,3,5,7-octahydro-1,3,5,7-tetranitrotetrazocine (HMX), and 2,4,6-trinitro-phenylmethylnitramine (tetryl)). Other DoD energetic hazardous wastes requiring treatment include propellant compounds such as ammonium perchlorate, nitroglycerine, and dinitrotoluene isomers (DNTs), which may contain plasticizers and stabilizers; and other oxidizers and metal nitrates in pyrotechnics.

Also commonly treated by OB/OD are byproducts from activities occurring in munitions filling or manufacturing facilities (e.g., Radford Army Ammunition Plant in Virginia[18] and Holston Army Ammunition Plant in Tennessee) and research and development facilities (e.g., Picatinny Arsenal in New Jersey, Naval Support Facility Indian Head in Maryland, and Dugway Proving Grounds in Utah).

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[16] See 40 CFR 261.20.

[17] The accepted DOD practice for demilitarization of Explosive D containing rounds is not OB/OD, but rather a chemical conversion process that produces a resalable commercial product. This closed chemical process is located at Crane Army Ammunition Activity, IN, and has been in production for over 20 years.

[18] Radford also has a contained incinerator for some of its energetic hazardous wastes.

Several private companies also treat energetic hazardous wastes using OB/OD. These wastes can be received from a variety of sources offsite or generated onsite from their manufacturing or research and development activities. Similar to DoD, they treat primary and secondary explosives, propellant compounds, oxidizers, metal nitrates, and explosives-contaminated materials. For example, Alliant Techsystems Operations in Minnesota manufactures and treats onsite: explosives, propellants, pyrotechnics, munitions, and contaminated materials.[19] Clean Harbors in Louisiana accepts wastes from offsite and treats munitions, propellants, high explosives, warheads, shaped charges, rocket motors, and nitro-related compounds, in addition to non-military items such as undeployed air bags, and fireworks.[20] Private companies account for approximately one-third of the 60 facilities with operating OB/OD units with permits or interim status.[21]

Availability of Alternative Treatment Technologies

In January 2019, in response to a 2017 Congressional mandate, the NASEM issued the report "Alternatives for the Demilitarization of Conventional Munitions".[22] As NASEM was researching alternative technologies and developing its report, EPA was also developing its own alternative technology report and was in a good position to contribute to the NASEM report. Specifically, EPA provided testimony and a preliminary list of alternative technologies to NASEM for consideration. In turn, this EPA report references NASEM's report for more detailed descriptions of the technologies. Although the NASEM report addresses OB/OD alternative technologies for treating the demilitarization stockpile wastes at seven sites,[23] the alternative technologies generally apply to other energetic wastes as well.[24] The following sections highlight key findings of the NASEM report, note areas in which EPA believes additional research would promote further understanding, and describes EPA's research efforts on available alternative technologies.

2019 National Academies of Sciences, Engineering, and Medicine Report

The NASEM report makes several key findings in support of implementing alternatives to OB/OD such as:

1. "Viable alternative technologies exist within the demilitarization enterprise, either stand-alone or as part of a treatment train, for almost all munitions currently being treated within the DoD conventional munitions demilitarization stockpile via OB/OD."[25] The report identifies a number of energetic wastes being open burned, open detonated, or static fired (a form of OB) for which viable alternatives exist.[26]

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[19] https://www.pca.state.mn.us/sites/default/files/Permit%20Application%20-%20MND081138604%20-%202017.pdf.

[20] https://www.epa.gov/sites/production/files/2015-08/documents/clean-harbors-la.pdf.

[21] Based on the data retrieved from RCRAInfo on November 28, 2018.

[22] NASEM 2019.

[23] Demilitarization stockpile wastes refers to conventional ammunition awaiting demilitarization and disposal because it is excess, obsolete, or unserviceable. There are seven stockpile sites dedicated to demilitarization of this waste; however, there are a number of OB/OD operations at facilities that do not treat munitions in the stockpile. Summary, page 1 and The Committee's Approach, page 9, NASEM 2019.

[24] NASEM 2019; p. 7, footnote 4.

[25] NASEM 2019; p. 2, Main Messages.

[26] NASEM 2019; Tables 7.1-7.7.

2. "There are no significant technical, safety, or regulatory barriers to the full-scale deployment of alternative technologies for the demilitarization of the vast majority of the conventional waste munitions, bulk energetics, and associated wastes."[27]

3. "There is only one barrier to the full-scale deployment of alternative technologies in lieu of OB/OD – namely, funding."[28]

4. "Each of the alternative technologies that the committee evaluated…would have lower emissions and less of an environmental and public health impact, would be monitorable, and would likely be more acceptable to the public" than OB/OD.[29]

EPA offers the following observations or reactions in regard to particular areas which the NASEM report does not fully address or where it states information that deserves further explanation.

1. NASEM mentioned that alternative technology facilities will likely be less expensive than OB/OD to close and clean up since repeated OB/OD operations will continue to contaminate the surrounding environment and will require extensive mitigation during closure, particularly if groundwater is contaminated.[30] In contrast, "alternative technologies' cleanup costs would normally be associated only with nonenvironmental media (e.g., equipment and buildings)…"[31]

   Although the report acknowledged the cost difference between OB/OD and alternative technologies as a measure of environmental contamination at closure, it did not evaluate the total life-cycle cost (LCC)[32] of OB/OD. NASEM acknowledges, "due to the lack of complete information on costs, the committee was not able to conduct an LCC" analysis. It notes that "cost evaluation of any demilitarization technology also needs to include closure costs. Equipment and sites will have to be decontaminated after closure. Given the much larger land area affected by OB/OD operations, and lack of containment, their closure costs are expected to be highest. Closure costs are usually not considered in the cost of demilitarization activities but need to be considered in an overall cost comparison. A[n] LCC analysis is required if a true cost comparison of alternative technologies to OB/OD is to be made."[33]

   NASEM did not analyze in detail an issue that EPA considers to be a chief concern related to OB/OD, which is the potential for significant soil and groundwater contamination, and the resulting cleanup obligations. Acknowledgment of the need to factor in cleanup obligations associated with a treatment technology is essential from EPA's perspective. The full LCCs of OB/OD should account for site investigation activities, corrective action, cleanup, closure, and post-closure care, including land use and institutional controls, which can, depending on

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[27] NASEM 2019; p. 4, Finding 9-1.

[28] NASEM 2019; p. 3, Main Messages.

[29] NASEM 2019; p. 4, Finding 8-1.

[30] NASEM 2019; pp. 1-2, Summary.

[31] NASEM 2019; p. 11, Introduction.

[32] Life cycle costs include capital (startup), operational, environmental monitoring, and closure costs. (NASEM 2019; p. 89, Comparative Assessment of Demilitarization Technologies).

[33] NASEM 2019; p. 68, Cost.

site-specific factors, substantially increase the total LCCs of OB/OD in comparison to the total LCCs of alternatives.

EPA notes that achieving comparability between the LCCs for OB/OD and for alternatives can be challenging due to prior activities or co-located activities at OB/OD sites. As explained earlier, there are OB/OD units that operated prior to the establishment of the 1980 RCRA regulations and permit requirements, and either continue to operate today, are undergoing closure, or have been closed. These OB/OD units are referred to as "legacy" sites. In other words, due to the lack of operational controls required by the 1980 RCRA regulations that serve to minimize contamination, these sites typically have widespread and extensive soil and groundwater contamination. An additional factor affecting the amount of contamination and cleanup associated with these legacy sites, or even non-legacy sites (i.e., OB/OD sites that have always operated under RCRA controls), is that they can be co-located with other sources of contamination, such as munitions or chemical manufacturing and military training ranges. Thus, when comparing OB/OD and alternative technology LCCs, it is necessary to account for any prior or co-located activities that may have contributed contamination for truly comparable results. Ideally, an LCC analysis would be performed for an OB/OD site that has always operated under RCRA controls (i.e., RCRA interim status regulations or RCRA permit) where the land has not been previously contaminated and compared to an alternative technology that is operating under RCRA controls where the land has not been previously contaminated.

However, this type of data for OB/OD sites is not easily obtained as NASEM noted. EPA is currently evaluating OB/OD site assessment and cleanup/closure procedures with the intent of improving those procedures. As part of this evaluation, EPA also seeks to identify contamination solely from OB/OD. To the extent possible, EPA will provide its findings with appropriate qualifications.

2. NASEM states that DoD identified some energetic wastes as having "capability gaps" in that an approved method has not yet been demonstrated for demilitarizing a munition item at either a government or contactor site. Approximately six percent of stockpile munitions makeup this capability gap and include munitions containing depleted uranium, smoke-producing munitions and riot control agents with white phosphorous and hexachloroethane (HC), projectiles containing submunitions (grenades, butterfly bomblets, cluster bombs), improved conventional munitions, and ammonium perchlorate rocket and missile motors.[34]

   It is noteworthy that the NASEM report indicates that there are alternative treatment technologies for most of these wastes that cannot be open burned or open detonated and believes that the capability gap may be less than six percent. Even if alternative technologies are available, EPA believes it relevant to also acknowledge that there are still some problematic wastes, such as shock-sensitive submunitions and unstable munitions, without safe and environmentally acceptable disposition (reuse, treatment, or destruction) solutions.

3. NASEM states that "[i]n order for a facility to receive a RCRA permit, the operation must be shown to be protective of human health and the environment - a statutory requirement of RCRA. This would lead one to believe that OB/OD can be conducted in a manner that,

[34] NASEM 2019; p. 84, Munitions Not Suitable for Demilitarization Using Either OB/OD or Alternative Technologies.

according to environmental regulatory agencies, is protective of human health and the environment."[35]

While the above statements are correct, they could be misleading and further explanation is warranted. As discussed earlier in the Regulatory Background section, EPA established its position on OB/OD of hazardous waste in 1980 by restricting treatment to waste explosives only and in situations where there were no other alternatives to safely dispose of the munitions. This position was established in response to the comments on the proposed ban on OB/OD and before safe alternatives were available. In lieu of safe alternative technologies for treating explosive waste, RCRA permits have served as an important mechanism for establishing conditions to minimize exposure during OB/OD operations and ensure cleanup of contaminants upon closure.

EPA Research on Alternative Technology Availability

Information Sources

Prior to the publication of NASEM's 2019 report, most of the information and reports documenting available alternative technologies were written in the 2000-2010 timeframe (ESTCP, ITRC, & SERDP, 2006; Wilkinson and Watt, 2006; Organization for Security and Co-operation in Europe, 2008; and Poulin, 2010). This report identifies and summarizes alternatives to the OB/OD of energetic hazardous wastes based largely on these sources, but it also has been supplemented with more recent information from DoD, EPA regions, state agencies, and the NASEM report. Appendix C contains all sources consulted for this report.

Alternative Technology Development

A key feature of this report is that it provides the scale at which technologies have been developed and successfully applied by the primary user of alternative technologies, DoD.[36] This information is intended to give the reader a sense of which technologies have been successfully used in full-scale[37] demil applications versus those technologies that are promising but have limitations that make them amenable for smaller or different treatment applications, or require more research and testing to be successful for full-scale applications. Note that the DoD terminology for successful full-scale application in the demil environment is "successfully demonstrated in a sustainable, production-ready, demil execution environment." According to DoD, for a given technology, the capability has been shown that it can be successfully operated in a production environment for extended periods without significant failures or unreasonable support costs to keep it operational. Technologies that have poor availability, reliability, maintainability, affordability, and supportability are not sustainable systems from an overall Life Cycle Logistics point of view and are therefore, not considered to be viable production-ready capability solutions (Clift, 2019). Thus, a technology may be developed to full-scale application, but may not be considered sustainable from a treatment perspective in a demil environment where large quantities of waste munitions are treated. In other words, the technology may be full scale for smaller or different treatment applications such as manufacturing and RDT&E wastes

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[35] NASEM 2019; p. vii, Preface.

[36] As stated in the Scope, because DoD has developed, tested, and/or utilized many of the available alternative technologies, much of the information in this report is devoted to the use of the technologies to treat military explosives and munition. This report does not reflect the extent to which the private sector has successfully used these technologies, nor the wastes for which they have been used.

[37] Full-scale is defined in the Glossary, however, for convenience means: technologies that have reached the final design and construction stages and are operating or have operated in the past. Full-scale is the result of incorporating outcomes at the bench and pilot scale to optimize the final design.

or decontamination of explosives-contaminated scrap metal, pipes, and equipment, but not for treatment of large quantities of waste munitions. Most importantly, every technology has its own site-specific requirements and thus, what works for one site or application may not work for another, independent of the scale at which it has been used successfully by DoD in the demil environment.

Treatment Considerations

Again, the applicability of any technology is dependent upon many site-specific or case-specific variables. These include the configuration of the waste material to be treated, the quantity or the NEW, size, portability of the energetic hazardous waste, and the maturity of the technology for a given application. Thus, even though there are many alternative treatment technologies available today, some energetic hazardous wastes (e.g., certain large caliber munitions and missiles) cannot be treated with these technologies. As such, for DoD and possibly others, OB/OD will remain as the only option for certain energetic hazardous wastes until additional viable alternatives are developed or existing technologies are modified or improved upon. In cases where OB/OD remains the only viable option for certain types of munitions or other explosive waste streams, there are a number of regulatory requirements that have been and continue to be implemented to minimize the release, distribution, and impact of emissions from OB/OD.

As discussed earlier, safety is cited as a primary reason for using OB/OD. For DoD, among the many factors in choosing an alternative technology in place of OB/OD, is whether the technology meets safety mandates. DoD's Explosives Safety Board (DDESB) is responsible for determining whether a technology meets safety mandates for site-specific or munition-specific applications. The DDESB reviews demilitarization systems to validate that personal protection criteria are met, or that a system is effective in processing "Material Potentially Presenting an Explosives Hazard" (MPPEH) to "Material Documented as Safe" (MDAS) (Chiapello, 2017). Once the DDESB approves a system, it may be used (within the constraints of the DDESB's approval) by DoD at any location (King, 2015). Approval of a technology does not constitute a blanket authority to use the technology, but once a technology is approved, the full approval process need not be repeated to use that system. Additional locations where the system will be used will require a separate explosives safety quantity distance site plan. (Chiapello, 2017). Note, these evaluations do not consider economic feasibility or environmental consequences, such as the adequacy of emissions controls.

To date, eight alternative technologies have been approved by the DDESB, most of which are included in EPA's matrix.[38] Although the DDESB's list of approved technologies is specific to DoD and does not apply to other Federal agencies or private companies' ability to select and use alternative technologies, this information can potentially aid others in selecting an alternative technology from a safety standpoint. If a technology does not appear on this list, it does not necessarily mean that it is not safe for use; only that the DDESB has not evaluated or not approved it for a demilitarization application. The eight technologies, along with their locations of deployment, are listed separately at the end of the Alternative Technologies section.

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[38] One of the eight technologies have been applied only to treatment of chemical warfare materials and chemical munitions, and one other technology is no longer in use. Thus, they are not included in EPA's discussion and matrix of technologies.

Overview of EPA Alternative Treatment Technology Findings

Based on the research described earlier, EPA found that there is a wide range of available alternative treatment technologies that can be, and have been used successfully, in place of OB/OD. Furthermore, several technologies have been issued RCRA permits.[39] Each alternative technology found through EPA's research efforts, along with accompanying descriptions, is described in this section, as well as summarized in matrix format in Appendix D.

EPA Perspective on Alternative Treatment Technologies

The information in this report, as well as NASEM's, show that safe alternatives exist and are being used to divert energetic hazardous wastes away from OB/OD. Nevertheless, OB/OD is still being used despite the availability of suitable and safe alternatives, in both the public and private sectors. Therefore, the information in this report should be useful to the regulated community in exploring alternatives to OB/OD. Likewise, it should be useful to regulators in engaging in conversation with facilities on moving toward enclosed technologies for the treatment of energetic hazardous waste, with a focus on protection of human health and the environment over the long term. Moving forward, EPA plans to develop additional guidance on how these findings can be applied when considering treatment technologies for energetic hazardous waste, for example, in the permitting process. As stated before, EPA understands that there will continue to be a need for OB/OD when safe alternatives do not exist, but at the same time, seeks to promote the development, testing, and use of alternative technologies that are capable of safely treating munitions and other explosive waste in a manner that reduces the potential for exposure and environmental contamination, as well as keeping cleanup and closure obligations to a minimum.

Energetic Hazardous Waste Configurations

When evaluating potential alternative treatment technology options for use in place of OB/OD, key considerations include what the waste is and what form it is in. As discussed earlier, energetic hazardous wastes encompass many different types of materials and exist in many forms or configurations. Treating munitions and energetics with alternative technologies may be a multi-step process, depending on the starting material and its configuration (see Figure 3). In describing the munitions and energetics for treatment purposes, this report divides them into four general categories: thick-case munitions, thin-case munitions (depending on the relative thickness of the metal case enclosing the energetic materials), bulk explosives or propellants, and potentially explosive-contaminated materials.

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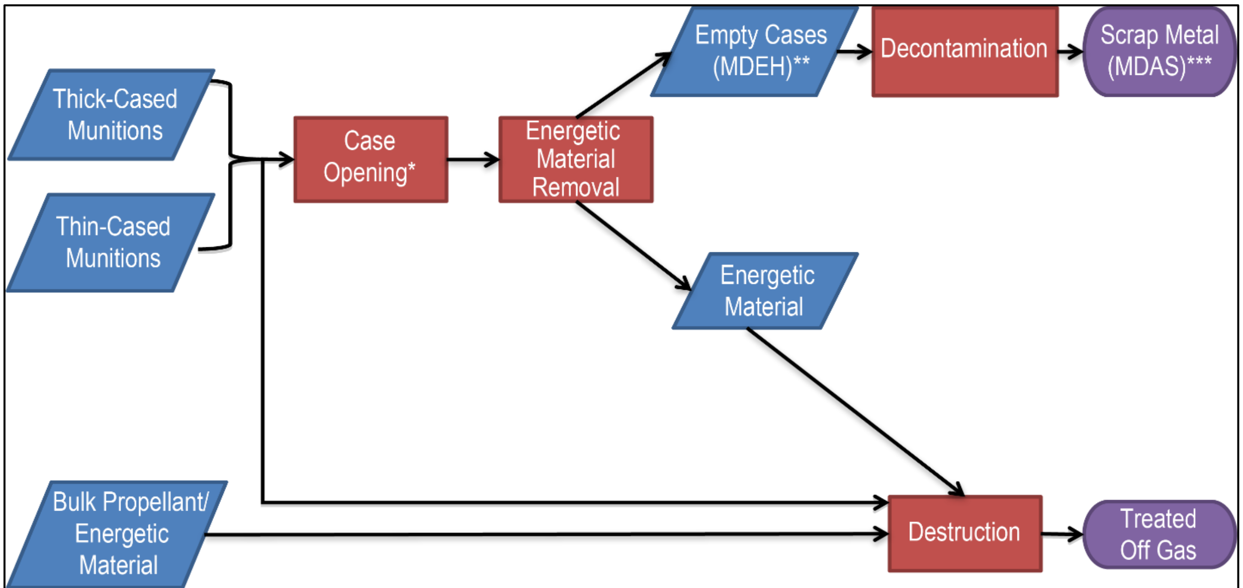
[39] The majority of RCRA permits that have been issued for alternative technologies are to DoD facilities (NASEM 2019, Table 6.1, page 73); however, the private sector holds roughly four RCRA alternative technology permits. In addition, some alternative technologies have successfully treated energetic hazardous waste through remedial or Superfund actions that do not require a RCRA permit, such as the contained burn chamber used at Camp Minden, LA.

Figure 3. Munitions Treatment Process



* Case Opening includes fluid jet cutting, robot reverse assembly, and cryofracturing.
** Removal of energetic material leaves the case decontaminated to a MDEH (material documented as an explosive hazard) for potential use at DOD installations.
*** Further decontamination of the empty case to a MDAS level (material documented as safe) readies the case for release to the public without restriction and the potential for scrap metal recycling.

Thick-Case Munitions: For the purpose of this report, thick-case munitions refer to items such as bombs, bomblets, warheads, rocket motors, large and medium projectiles, grenades, mines, sectioned munitions, and missiles. They may contain ~227 g (0.5 lb) to more than 45 kg (100 lb) of energetic material per item. In addition to the hazards from the confined energetic materials, the metal case may create additional hazards and damage in a detonation. Thick metal cases are typical in warheads and projectiles, and if detonated in the open, significant quantities of both small and large fragments are produced. These fragments can have high velocities and travel large distances.

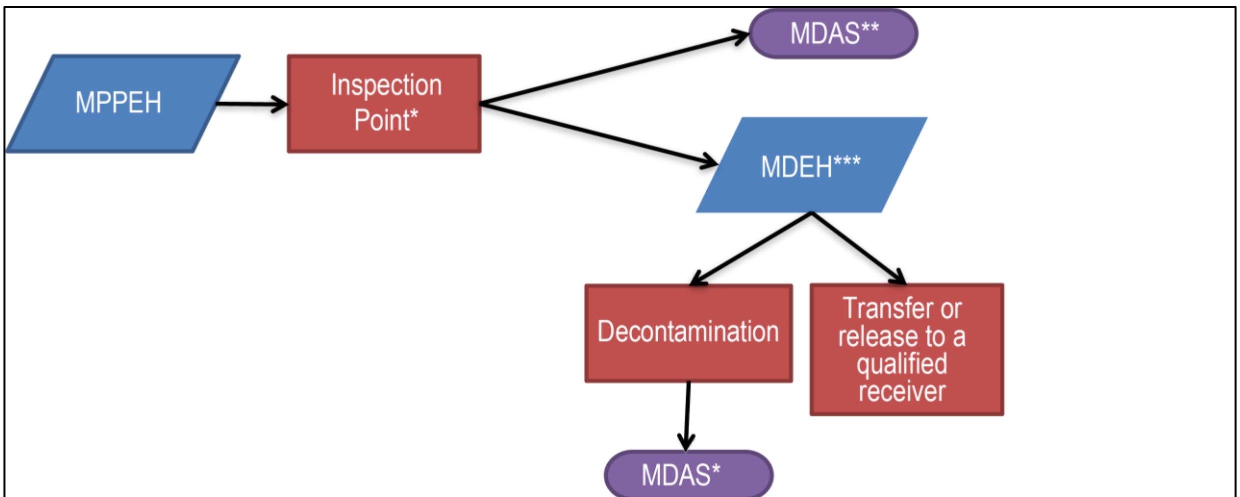
Thin-Case Munitions: Thin-case munitions refer to items such as small-caliber ammunition, ranging from .22 caliber through .50 caliber (12.7mm), medium caliber munitions (14mm through 40mm direct-fire cartridges), cartridge-actuated devices, propellant-actuated devices, exploding bolts, fuzes, bomblets, booster pellets, detonators, igniters, leads, and numerous other small munitions. They contain approximately 227 g (0.5 lb) or less of energetic material in each item. In addition to the hazards of the confined energetic materials, the metal cases may create small amounts of metal fragmentation and blast overpressure during a detonation.

Bulk Explosives/Propellants: Bulk explosives and propellants include “unconfined” energetic materials (e.g., grains of propellant).

Potentially Explosive-Contaminated Materials: Other wastes associated with explosives and munitions manufacturing, testing, and use—such as rags, gloves, and packaging material (e.g., wood crates, cardboard boxes, and shipping and storage containers)—must be assessed to determine whether they pose an explosive hazard and therefore are a "reactive" hazardous waste requiring treatment.

DoD uses the term "Material Potentially Presenting an Explosives Hazard" (MPPEH), which is material owned or controlled by DoD that, before determination of its explosives safety status, potentially contains explosives or munitions (e.g., munitions containers and packaging material; munitions debris remaining after munitions use, demilitarization, or disposal; and range-related debris) or potentially contains a high enough concentration of explosives that the material presents an explosive hazard (e.g., equipment, drainage systems, holding tanks, piping, or ventilation ducts that were associated with munitions production, demilitarization, or disposal operations). Likewise, DoD uses the term "Material Documented as an Explosive Hazard" (MDEH) for material owned or controlled by DoD that has been determined to present an explosive hazard. MPPEH and MDEH materials must be treated to achieve levels that meet "Material Documented as Safe" (MDAS) before release. The inspection and treatment process for MPPEH is outlined in Figure 4.

Figure 4. Inspection and Treatment Process for Material Potentially Presenting an Explosive Hazard (MPPEH)



* Before its transfer within the DoD or release from DoD control, personnel certified by a responsible authority as technically qualified to act as signatories in determining the material's explosive safety status must document, in writing, that the material's characterization as safe (MDAS) or explosively hazardous (MDEH).

** Documented as not presenting an explosive hazard and consequently safe for unrestricted transfer or release. Material that has been documented as safe is no longer considered MPPEH provided the chain of custody remains intact (DDESB, 2019)

*** The explosive hazard of the material is known or suspected and is documented, and consequently the MDEH is transferable or releasable only to a qualified receiver (DDESB, 2019).

Technologies

The following sections summarize the treatment technologies that have been developed, including how they work, and available information on their development and use status. The technology summaries are organized according to the steps above in Figure 3:

- **Case Opening** technologies for thin and thick-cased munitions.
- **Energetic Material Removal** technologies for thin and thick-cased munitions.

- **Energetic Material Destruction** technologies for bulk energetic or material recovered from thin and thick-cased munitions.
- **Decontamination** technologies for empty cases.

The technologies are further summarized in Appendix D, which presents information in a matrix format for easier comparison. The technology matrices, which also are organized according to the steps in Figure 3, summarize technology information, such as sites at which a technology has been tested or used; the highest scale at which it has been used (bench-, pilot-, or full-scale); the portability of the technology; whether it treats thin-cased munitions, thick-cased munitions, or bulk explosives; and the outputs of the process. Readers are recommended to consult the NASEM report for detailed information on the technologies, including throughput, safety, and cost. Additional resources to consult are listed by technology type in Appendix C. (For electronic copy users, control-click on [Additional Resources] next to the technology name to jump directly to Appendix C. Then control-click to jump back.)

Note that the technology descriptions in this section provide available information and are not evaluated from an environmental standpoint. Any technology that is selected for treatment of energetic hazardous wastes would be subject to applicable environmental regulations and permits. Generally, permitting would encompass identification of potential emissions and releases and subject the unit to specific design, control, and operating parameters. Several technologies have been permitted to operate[40] and so it is possible to obtain general information regarding potential regulatory and permit requirements via the state permit agency and technology vendor. Lastly, the technology descriptions below are general in nature. In other words, many technologies can be customized based on the user's treatment needs and environmental regulatory requirements.

Case Opening

For some treatment options used during demilitarization, the munition's body (projectile) must first be separated from the cartridge case. Thin cartridge cases may be simply pulled apart to access the propellant content. However, for ICMs that contain sub-munitions, the projectile must be opened using other methods to safely access the sub-munition housed inside the projectile's body. This can require reverse engineering the production process to open the projectile's body. The processes and forces required to access a projectile often involve high risk and, like many munitions' demilitarization processes, are conducted remotely. Some munitions may be disassembled only to a point at which it is no longer safe to disassemble further; for deteriorated or damaged munitions, disassembly may not be a viable option.

The following case opening technologies have been identified.

Reverse Assembly [Additional Resources]

Mechanical equipment is used to disassemble munitions, typically in reverse order of assembly used in production, to separate the component parts for reclamation and reuse. Reverse assembly processes are primarily used to open cluster munitions to access the submunitions. This procedure is often done remotely to protect the operator. Reverse assembly can be automated or in some cases, performed manually, but at greater risk to workers. There are a wide variety of process techniques, many of which have been successfully demonstrated in a sustainable, production-ready, demil execution environment.

[40] NASEM 2019, Table 6.1, page 73.

Fluid Jet Cutting [Additional Resources]

In fluid jet cutting (Figure 5), a high-pressure water jet cuts the munition to allow access to its fill. The water can be mixed with a sharp-edged abrasive such as garnet sand that is entrained at the nozzle or premixed prior to use in the water jet. Fluid jet cutting can be used to cut the munition into segments to reduce the NEW; the water also serves to desensitize the explosivity of the fill during cutting. Fluid jet cutting, also referred to as waterjet and slurry jet cutting in the NASEM report, has been widely used in the demil enterprise for many years. It is an effective means for cutting and accessing explosive fills, but it creates an energetic hazardous waste that must be further treated. Fluid jet cutting has been successfully demonstrated in a sustainable, production-ready, demil execution environment on a wide variety of munition items.

Figure 5. Fluid Jet Cutting

Photo courtesy of John Hutten and J.C. King, DoD

Cryofracturing [Additional Resources]

Liquid nitrogen or carbon dioxide is used to freeze certain munition bodies (e.g., submunitions, Adam Mines, grenades) below their embrittlement temperature. The munitions are then placed in a hydraulic press and fractured to expose the energetic material. Cryofracturing is an effective means for accessing energetics (i.e., the explosive fill). However, because an occasional, unintentional detonation may occur when force is applied to the frozen munitions, the process must be designed and managed to operate safely and effectively. Generally, the cryofracture process is conducted remotely and behind blast walls to reduce operator exposure. Controlling fugitive emissions that may be released during unintentional detonations also may be an issue; however, most contained systems are designed to control such emissions. Cryofracturing has been successfully demonstrated in a sustainable, production-ready demil execution environment on specific munitions. According to the NASEM report, as of fiscal year 2017, two demil RDT&E funded projects are evaluating the expansion of cryogenic processing to additional types of munitions. DoD's demil enterprise confirms that one project is utilizing cryofracture for mines at McAlester

Army Ammunition Plant while the second project involves removal of sensitive submunitions from artillery rounds at Crane Army Ammunition Activity.

Femtosecond Laser Cutting or Laser Machining [Additional Resources]

Ultra-short laser pulses are used to cut or ablate munitions (i.e., remove metal from the body) without transferring heat to the explosives inside the case. As such, there is a low risk of an unintentional detonation or fire. This technology only has been demonstrated at the pilot scale due to the protracted processing times required to cut a cased munition. According to DoD's demil enterprise, femtosecond laser cutting has not been successfully demonstrated to date in a sustainable, production-ready, demil execution environment.

Band Saws [Additional Resources]

Mechanical cutting, typically performed with a band saw, is used to cut thick munition bodies (e.g., projectiles) using a remotely operated, hydraulically powered band saw cooled by water or a cooling liquid. In some cases, the band saw may be submerged in water or soaked in a liquid cooling medium. The use of band saws has been successful, but like water jet cutting, their use produces contaminated wastewater that must be further managed and treated. In addition, due to the influence of heat, shock, and friction produced during the process, the operator must use safety precautions. Band saws have been successfully demonstrated in a sustainable, production-ready demil execution environment on a wide variety of munition items.

Figure 6. Segments of Bomb Cut by Underwater Band Saw

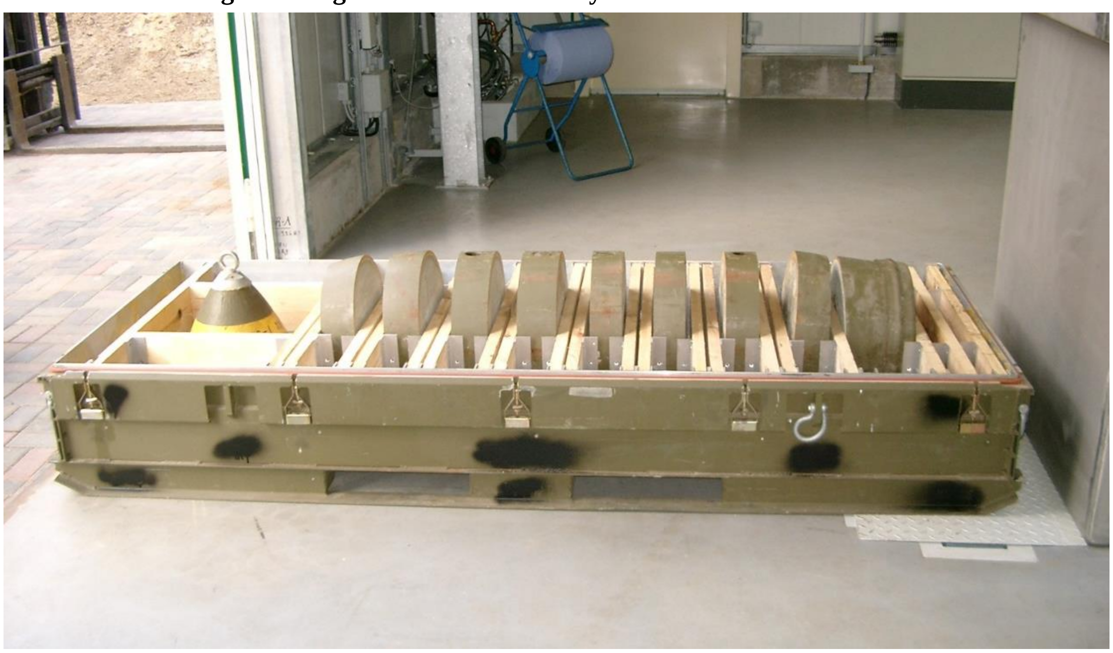


Photo courtesy of Harley Heaton, Dynasafe U.S.

Energetic Material Removal

Once a munition case is opened, the energetic material can be removed. In some cases, the recovered material can be reused. Otherwise, the material must be destroyed using technologies in the next section.

The following technologies have been identified for energetic material removal.

Autoclave Meltout [Additional Resources]

Some explosives containing TNT (e.g., cast TNT and Composition "B" (TNT/RDX)) have low melting points (~ 80°C). These types of explosives may be melted using steam that causes the explosive fill to flow out of the munition's body.

A pressurized vessel is used to heat water to the boiling point, which cannot exceed 121°C (249.5°F), creating steam to melt the cast explosive fill (Figure 7). (A cast explosive is one that was melted and poured inside the projectile's body.) The melted explosive collects in a melt kettle, is poured onto a flaker belt or into a mold, allowed to cool, and is recovered for reuse (e.g., for processing and use in other munitions, or for use as donor material required for the destruction of excess, obsolete, or unserviceable munitions). The sealing surfaces of the autoclave must have uniform clamping surfaces and seal with 0-ring gaskets to prevent water infiltration.

An autoclave applies the steam to the exterior of the munition only, thereby minimizing wastewater. For larger munitions, this process may be very slow, and a steam lance similar to a water jet can be used inside the munition to improve speed at the expense of greater wastewater production. Autoclave meltout has been successfully demonstrated in a sustainable, production-ready demil execution environment on specific munition items and continues to be viable for recovering meltable explosives.

Figure 7. Autoclave Meltout

Photo courtesy of John Hutten and J.C. King, DoD

Induction Heating Meltout [Additional Resources]

Induction heat around 149°C +/-3.9°C (300°F +/-25°F) is applied to a munition's case to melt the cast explosive for recovery or treatment. This method has been tested in the demil enterprise, but never successfully transitioned to production due to its propensity for creating "hot spots" in the metal casings that could potentially result in flash fires/explosions. According to DoD's demil enterprise, induction heating meltout has not been successfully demonstrated to date in a sustainable, production-ready demil execution environment.

Washout

- Washout with Water Jet [Additional Resources] – A water jet uses high-pressure (55,000-60,000 psig) water to remove energetic material from a case. It has been used on a variety of munitions from composite propellant rocket motors to small high explosive-filled projectiles. The energetic-contaminated water must be treated. Water jet washout has been successfully demonstrated in a sustainable, production-ready demil execution environment on a wide variety of munition items.
- Washout with Liquid Nitrogen (Cryogenic Washout) [Additional Resources] – High-pressure jets have also used liquid nitrogen to remove energetic materials from a case. It is a dry process that embrittles and fractures the energetic material. This technology was tested in the early 1990s through Army RDT&E, but never transitioned to production due to sustainment (maintenance) issues. According to DoD's demil enterprise, washout with liquid nitrogen has not been successfully demonstrated to date in a sustainable, production-ready demil execution environment.
- Washout (Blastout) with Carbon Dioxide [Additional Resources] – Removal of energetic material using high-velocity carbon dioxide (CO_2) particles has also been tested. A centrifuge accelerates pelletized carbon dioxide particles to 427 m/s (1,400 ft/s) to blast out the remaining explosive from cases. The process was tested in the early 1990s through Army RDT&E, but never transitioned to production due to sustainment (maintenance) issues. According to DoD's demil enterprise, washout with carbon dioxide has not been successfully demonstrated to date in a sustainable, production-ready demil execution environment.

Dry Ice Blasting [Additional Resources]

Cryogenic (dry ice) cleaning is an automated robotic cryogenic cleaning system for removing contaminants from the surface of old armaments and munitions. Cryogenic cleaning fires a jet of solid CO_2 particles at supersonic velocity onto the area to be cleaned (Figure 8). The force is sufficient to remove contaminants with minimal surface abrasion. When the dry ice pellets penetrate the contaminant and hit the substrate, friction slows them down and they begin to warm up. As the pellets warm up, they sublimate rapidly. The expansion forces the contaminant, which is no longer solidly bonded, to be removed from the substrate. DoD's demil enterprise indicates that although dry ice blasting is an effective method for removing surface contaminants, it is not an activity typically performed.

Figure 8. Dry Ice Blasting

Photo courtesy of John Hutten and J.C. King, DoD

Ultrasonic Separation or Sonication [Additional Resources]

Ultrasonic waves are used in a fluid (alcohol or ketones for PBX) in which munitions are immersed. When high-intensity ultrasound is applied to a liquid medium adjacent to a solid material, the stress produced by acoustic cavitation in the liquid fragments the material. The stress (or pressure) produced by the cavitation of the liquid is a function of the properties of the liquid. Ultrasonic separation has been considered for explosives mixed with plasticizers with a very high melting point that cannot be melted out using methods discussed previously.

During DoD's investigation of this process for potential use, an accidental detonation of a 5-inch Navy gun projectile with Comp A-3 filler occurred, damaging the large-scale testing plant. As a result, DoD deemed the process unsafe and ended its investigation. The NASEM report indicates that although the process has been successful in the degradation of RDX, the low throughput diminishes its applicability to demilitarization. According to DoD's demil enterprise, ultrasonic separation has not been successfully demonstrated to date in a sustainable, production-ready demil execution environment.

Energetic Material Destruction

The technologies used to destroy energetic materials can be classified in three general categories: contained or closed detonation, thermal destruction, and chemical destruction. These technologies can address bulk explosives or propellants, propellants removed from cartridge cases or the explosive removed from munitions, as well as certain munitions without prior opening and removal of the explosive fills.

Closed Detonation

Closed (or contained) detonation uses strategically placed donor charges to trigger the detonation of certain munitions within a detonation chamber. The thick-metal chamber walls contain the effects (pressure, fragmentation, and noise) of the detonation and emissions are captured for treatment by filter elements that reduce and eliminate hazardous offgases and other toxic byproducts of the detonation. The maximum treatment load depends on the size and design of the chamber and the configuration and NEW of the munitions. Closed detonation chambers may be mobile systems or stationary/fixed industrial systems.

Closed detonation is a proven technology. However, because these technologies operate using a batch waste feed process that requires cooldown, cleanout, and resetting time between batches, the throughput, or rate that items can be demilitarized, may be very low. In addition, batch sizes are limited by the NEW, including the donor charges that are often of an equal NEW to the waste. Equipment sustainment issues have been reported at Crane Army Ammunition Activity due to damage to the chamber from repeated detonations over time, which is not uncommon with these systems. A solution for minimizing damage is to insert a replaceable metal band or metal rods in the chamber, which serve to absorb the fragments.

The following are examples of closed detonation technologies.

- Controlled Detonation Chamber (CDC) [Additional Resources]
  The CDC (Figure 9), formerly known as the Donovan blast chamber prior to purchase and use by the U.S. Army and others, uses donor explosives (e.g., linear shape charges, wraps) to implode the munitions being treated. The NEW of the munitions being

destroyed determines the donor charge needed. The CDC is available as either a stationary or transportable system designed for movement to multiple locations.

Figure 9. Controlled Detonation Chamber

Photo courtesy of John Hutten and J.C. King, DoD

Individual chambers are rated according to the NEW that can be detonated in them. Munitions are encased with a donor explosive (e.g., pentaerythritol tetranitrate [PETN] sheet, granular explosives, slurry explosive, or preformed RDX donor) before being loaded into a large, double-walled steel chamber along with bags of water for thermal control and steam generation. The floor of the chamber is covered with pea gravel, which absorbs some of the blast energy. The system is sealed and the donor charge and munitions are detonated. The detonation's fireball consumes the explosive fill and most of the offgases. In certain systems, some offgases are released to the atmosphere, while other systems direct offgases to an expansion chamber that moderates the pressure wave from the detonation, and the offgases are subsequently filtered to remove acids and particulate matter and passed through a catalytic oxidizer before release.

CDC's can treat a variety of small- and medium- caliber munitions, but the types of munitions that a CDC can treat are limited to specific munitions per the DDESB approval for DoD sites. The largest projectile that the Models T-30 and T-60 CDCs can treat is 155 mm, and both models are limited to 18.1 kg (40 lb) NEW. The transportable T-25 Model is limited to 7.57 kg (16.7 lb) NEW; it can treat mortars as large as 10.7cm (4.2in) and rockets as large as 11.4cm (4.5-in). The transportable T-10 is generally limited to 4.54 kg (10 lbs) NEW and can treat up to an 81 mm mortar. Certain DDESB-approved additions to the T-10 allow it to treat up to 5.9 kg (13 lb) NEW. The throughput of the CDC can be limited by NEW and slow batch process times (cooling, cleanout, and refurbishing/resetting time between detonations). The NEW of the donor charge needed can equal the NEW of the waste, limiting batch size and throughput. This process has been successfully demonstrated in a sustainable, production-ready demil execution environment on specific munitions.

- Static Detonation Chamber (SDC) [Additional Resources]
  Made by Dynasafe of Sweden, the SDC combines thermal destruction with detonation. Munitions are fed into the contained chamber through a gastight automated loading system and electrically heated above the auto-initiation temperature of known explosives and propellants (about 500°C) until the explosives deflagrate (burn) or detonate (Figure 10). The SDC does not require donor charges or opening of the munition case. Propellants and uncased high explosives will deflagrate; while cased explosives can detonate. A thermal oxidizer operates at temperatures between 850°C and 1100°C to destroy organics in the offgases. The resulting metal scrap meets MDAS criteria (i.e., is safe for release for commercial recycling).

  Dynasafe reports several sizes of SDCs, each with different NEWs for propellants, uncased (or unconfined) munitions, and cased munitions. The largest unit, the SDC 2000, which is DDESB approved, has listed NEWs of 11 kg for propellants, 8.5 kg for uncased, and 4.5 kg for cased.

  The DoD demil enterprise has several ongoing studies to assess the capacity and sustainability of Dynasafe's SDC for demil. A recent commercial demil contract uses SDCs as the primary means of demil. The performance of these SDC units is being monitored and assessed to determine the possibility for wider use of the technology. The SDC has been successfully demonstrated in a sustainable, production-ready, demil execution environment on specific munitions.

Figure 10. Static Detonation Chamber

Photo courtesy of Harley Heaton, Dynasafe

- Detonation of Ammunition in a Vacuum Integrated Chamber (DAVINCH) [Additional Resources]
  Made by Kobe Steel in Japan, the DAVINCH employs a detonation chamber (Figure 11) in which medium or large munitions suspended from the chamber ceiling are surrounded by donor charges. Air is evacuated from the chamber. The munitions are destroyed when donor charges are electronically detonated, shattering the case and destroying the energetic materials. The DAVINCH model numbers, which range from the mobile DAVINCH Lite 24 to the DV-65, correspond to the NEWs of the munition and its donor charge in kilograms. For example, the NEW of a DV-50 is 50 kg (110 lb).

  Offgas treatment depends on the munitions being detonated. Some models have combustion chambers while others are equipped with cold plasma oxidizers, which may be preferred when destroying chemical agents, to treat the offgases generated in the detonation chamber. For units equipped with cold plasma oxidizers, offgases are filtered to remove particulate matter. An external supply of oxygen is used to pump the offgases into the cold plasma oxidizer to oxidize carbon monoxide and hydrogen gas. Condensate water is recovered from the exhaust gas. The exhaust gas may then be scrubbed or filtered through HEPA filters and activated carbon prior to release to the atmosphere. The DAVINCH has been successfully demonstrated in a sustainable, production-ready demil execution environment on specific munitions.

Figure 11. DAVINCH

Photo courtesy of John Hutten and J.C. King, DoD

Thermal Destruction

Thermal destruction technologies provide for the closed burning or incineration of energetic materials so that hazardous offgases can be captured and treated by filtration and scrubbing to meet regulatory requirements. Munitions and non-munitions (e.g., explosives contaminated packaging materials) are heated directly or indirectly to their auto-initiation temperatures, triggering deflagration. Thermal destruction is typically conducted in blast and fragmentation-proof chambers, which will absorb high-order detonations that can potentially occur when heat is applied to energetic materials. Thick-case munitions are cut or opened (vented) prior to thermal treatment to facilitate deflagration. Thermal treatment can also decontaminate casing materials and allow for the safe transfer of demilitarized scrap metal for commercial recycling. Considerations for use include: (1) the thermal sensitivity of the munitions or material being destroyed, (2) whether case opening is required to access explosives, and (3) the NEW of the energetic materials.

The following are examples of technologies for thermal destruction.

- Contained Burn [Additional Resources]
  In contained burns, the energetic material is placed onto a remotely controlled loading system for either batch or semi-continuous treatment in the thermal treatment chamber (Figure 12). The chamber is sealed, and the material is ignited remotely by the operator. The products of combustion are contained within the chamber. A valve meters the exhaust gases through a pollution control system before release to the atmosphere. The chamber is then purged with fresh air for the next contained burn cycle.

  An example of this technology is the contained burn furnace (CBF) installed by El Dorado Engineering (EDE) at Camp Minden in Louisiana that treated over 6,803 metric tons (15 million lbs) of M6 propellant. The CBF has successfully demonstrated an ability to destroy M6 bulk propellant in a sustainable, production-ready, demil execution environment. DoD anticipates that the CBF is capable of destroying other bulk propellants, however, additional testing and some modification to the pollution abatement system would be required.

  Another example is the large-scale unit that the Environmental Chemical Corporation (ECC) installed at Letterkenny Army Depot in Pennsylvania, to thermally treat ammonium perchlorate (AP)-based rocket motors. The unit is currently undergoing Operational Acceptance Testing (OAT). This testing has successfully demonstrated a viable closed-loop, environmentally acceptable solution for the demilitarization of AP-based rocket motors. Low Rate Initial Production (LRIP)-is slated to commence later this year with transition to full-rate demil production by early 2020.

Figure 12. Contained Burn Furnace

Photo courtesy of John Hutten and J.C. King, DoD

- Rotary Kiln [Additional Resources]
  The cast steel retort sections of the rotary kiln have an internal helix that moves certain munitions forward and isolates successive feeds from propagating explosions. The rotary kiln is sealed and is equipped with a discharge system, an afterburner to ensure complete combustion of energetic material, an air pollution control system, and an automated control system. One example, the U.S. Army's APE-1236 rotary kiln (Deactivation Furnace), has a thick-walled primary combustion chamber that can withstand small detonations. The closed rotary kiln process developed by the Army has been used for nearly 30 years in demil execution. Other rotary kilns have been developed by Dynasafe, El Dorado, General Dynamics, and Timberline Environmental. Rotary kilns have been successfully demonstrated in a sustainable, production-ready demil execution environment on a wide variety of munition items.

- Decineration™ and Rotary Furnace [Additional Resources]
  Decineration™ is a technology patented by U.S. Demil, LLC. The non-incinerative process occurs at ambient pressure and carefully controlled moderate temperatures (predetermined for each item to be processed) of approximately 204°C - 371°C (400°F - 700°F) to prevent detonation or volatilization of energetic materials. Use of an externally heated rotary furnace prevents contact between the electric heating source and munitions components. Solid energetic materials (e.g., nitrocellulose, nitramines and nitrate esters) are decomposed into short-chain, light hydrocarbon gases, including methane, butane, and propane, measured as total organic vapors (TOVs). Air sampling during production runs also measured trace amounts of dioxins (in the range of 0.18 ppb), furans, polycyclic aromatic hydrocarbons, and semivolatile organic compounds. The gases are extracted for treatment in an emissions abatement system, typically comprising a wet scrubber and catalytic converter. Carbon dioxide, nitrogen, and water vapor are released to the atmosphere. Metal components are discharged from the furnace via a conveyor, meet MDAS criteria as safe, and are recyclable. This Decineration™ technology has undergone testing via the demil RDT&E program, culminating in being demonstrated at pilot scale at Tooele Army Depot in Utah. According to DoD's demil enterprise, the Decineration™ technology has been proven to work in its final form and under expected conditions. Funding continues to be requested to demonstrate Technology Readiness Level (TRL) 9, after which it would be ready for utilization at full scale in a production-ready demil execution environment.

Chemical Destruction

Chemical destruction technologies convert bulk energetic materials to less toxic or benign byproducts. In most cases, bulk energetics first must be removed from cased munitions prior to treatment by chemical destruction.

The following are examples of technologies for chemical destruction.

- Alkaline Hydrolysis [Additional Resources]
  Alkaline hydrolysis uses a concentrated base solution at elevated temperatures (90°-150°C) to break down explosives and propellants into non-energetic, water-soluble materials that can be directly disposed of or treated further using biodegradation. The process occurs in a reaction chamber, where materials are immersed in a base solution. The system typically consists of an energetic feed system, a tank farm storing the base solution and hydrolysate produced during the process, a hydrolysis reactor, and an air pollution control system. An alkaline solution is deposited into the reactor containing the

energetic materials. Process water is introduced, and heating occurs. The solution is vigorously agitated to completely hydrolyze the energetic materials.

The reaction produces hydrolysate and offgases, which are treated in the air pollution control system before their release. The hydrolysate must be disposed of as hazardous waste due to its high pH or treated further to reduce the pH and render it non-hazardous. The NASEM report did not review alkaline hydrolysis, suggesting that it is not well developed for munitions applications. However, alkaline hydrolysis was successfully used full scale at United Technologies Corporation in San Jose, California, to treat Class 1.1 and Class 1.3 propellants, at the pilot-scale level at Los Alamos National Laboratory to treat HMX and nitrocellulose, and the pilot-scale level to treat Composition B4 at Holston Army Ammunition Plant, Tennessee.

- General Atomics Neutralization/Alkaline Hydrolysis[41] [Additional Resources]
  General Atomics' neutralization technology is a type of alkaline hydrolysis that involves submerging the cased munitions in a tank of sodium hydroxide and water solution. The basic solution dissolves the case to expose the bulk energetics. The solution hydrolyzes the exposed energetic material, neutralizing it and decomposing it to hydrolysate byproducts. The hydrolysates can be fed into General Atomics' industrial supercritical water oxidation (iSCWO) units (see next section) for further treatment. As noted above, alternative technologies involving the addition of liquids for treatment generate large amounts of secondary hazardous wastes that must be disposed or further treated by other processes.

  Alkaline hydrolysis is a closed disposal process that has been in production at Tooele Army Depot, Utah, for many years to treat a wide range of Cartridge Actuated Devices (CAD) and Propellant Actuated Devices (PAD) with aluminum bodies. The system is inactive due to lack of inventory of aluminum bodied CADs and PADs but is available for future use. The iSCWO neutralization technology was added to treat secondary waste streams resulting from the base hydrolysis process but eventually was not used due to lack of capacity and reliability issues, and offsite treatment methods were found to be more cost effective. This process has been successfully demonstrated in a sustainable, production-ready demil execution environment on specific munition items.

- Industrial Supercritical Water Oxidation (iSCWO) [Additional Resources]
  Supercritical water oxidation destroys energetics by mixing them with water and subjecting the mixture to temperatures and pressures above its thermodynamic critical point (374°C and 3,206 pounds per square inch absolute [psia]). General Atomics' iSCWO technology exposes bulk energetics or energetic hydrolysates to very high temperature and pressure, breaking them down into gases (oxygen-depleted, carbon dioxide-enriched air, water vapor, and nitrogen oxide), water, and sodium salts. Reactions take place in a vertically oriented reactor vessel, where the slurried material is fed at the top of the vessel and travels downward towards the exit. Gases are filtered and water can be recycled and reused by the plant in the destruction process. iSCWO operates at 650°C and 3,400 psia to oxidize energetic hazardous wastes.

  Feed containing phosphorous or halogens, which produce acids, may be neutralized by adding sodium hydroxide. General Atomics' neutralization technology decomposes bulk

[41] Note that the NASEM report classifies this technology as stationary base hydrolysis oxidation.

energetics in a sodium hydroxide and water solution, which results in hydrolysate byproducts. iSCWO can be used to treat any organic material that is able to be processed as a water slurry.

The iSCWO treatment reactor (Figure 13) is lined with titanium to protect against the corrosiveness of the mixture. The longevity of the liners and associated cost of replacement will depend on the corrosiveness of the input. Fixed and portable units are available.

The iSCWO technology has been tested and used in the demil enterprise for many years. Most recently, it was used to demilitarize waste streams produced from other closed demilitarization processes operating in the Republic of Korea (ROK) in support of demil execution of U.S. stocks still in storage in the ROK. The process was successfully tested, demonstrated, installed and supported for over five years in the ROK by Army personnel. Currently, there are three operating iSCWO units at Blue Grass Chemical Agent Destruction Pilot Plant in Kentucky. While iSCWO has been successfully tested and used, it has not yet been widely implemented at the production level because it continues to experience frequent downtime and maintenance. This process has been successfully demonstrated in a sustainable, production-ready demil execution environment on specific energetic residues and waste streams but is still being evaluated for treatment of bulk energetic materials.

Figure 13. Industrial Supercritical Water Oxidation

Photo courtesy of John Hutten and J.C. King, DoD

- MuniRem® [Additional Resources]
  MuniRem Environmental produces MuniRem®, a sulfur-based reductant that can be applied in solution or powder form to degrade bulk explosives (e.g., HMX, RDX, TNT, DNTs, ADNTs, nitrobenzenes, N-nitroso-dimethylamine (NDMA), nitrocellulose, nitroglycerin, PBX, PETN) and residual explosives in different materials. MuniRem® is formulated based on the target material and mixed with the bulk explosives in a custom-built neutralization reactor. MuniRem Environmental describes the treatment process as "neutralization," which renders compounds inert by eliminating the explosive hazard; additional reagent is added to achieve complete destruction.

Wastewater from the treatment process may be polished in a reactive column and subsequently reused or discharged to a municipal sewer system. Wastewater from the treatment of bulk nitrocellulose propellants may be treated either through: (1) biodegradation to denitrify nitrate and nitrite; or (2) by adding phosphoric acid, which converts it to a nitrogen/phosphorous/potassium-rich chemical fertilizer. Treatment of explosives with MuniRem® potentially yields nitrogen gas, nitrogen dioxide, carbon dioxide, formate, and acetate.

MuniRem® has been tested and applied to demilitarization of bulk energetics and for treating explosives-contaminated materials (e.g., production scrap and pipes). MuniRem® has been successfully applied to treatment of underwater discarded military munitions (DMMs) (170 items) containing black powder and nonenergetic components (i.e., oxidizer, fuel, and binding gent) to support salvaging of the CSS Georgia. With respect to bulk energetics, according to DoD's demil enterprise, the process does not treat these materials effectively and efficiently and has not been successfully demonstrated to date in a sustainable production-ready demil execution environment.

- Actodemil [Additional Resources]
  ARCTECH's Actodemil® is hydrolysis with a highly alkalized organic water-soluble salt of a humic acid (ActoHAX™). The solution is heated, and propellants and explosives are gradually added (without grinding or size reduction) to the preheated ActoHAX™. The solution is transferred to another vessel reactor fitted with a mixer for neutralization and oxidation. Phosphoric acid is added to lower the pH to near neutral or to what is desired based on the intended end use of the product. The reactor vessel is closed at the top, and any NOx gas produced is swept from the headspace and directed to a wet scrubber vessel containing ActoHAX™ reagent. The spent scrubber reagent is mixed with end use product so that no liquid waste is generated. The method has been tested for the U.S. Army to destroy single-, double-, and triple-base propellants and is also applicable to explosive materials such as nitrocellulose, HMX, RDX, nitroglycerin, and other nitrate ester-type materials. The liquid byproduct of this reaction is then turned into a humic-rich organic fertilizer.

  According to DoD's demil enterprise, the Actodemil process was tested over many years in the Army Demil RDT&E program, but has not been used in a sustainable, production-ready demil execution environment.

Decontamination

Fragments of metal casing remaining following treatment may contain residues of energetics. In order to be sent to a commercial recycling facility, metal must be decontaminated to achieve levels that meet MDAS criteria. (Some thermal treatment approaches mentioned above are capable of processing explosives-contaminated materials, including MDEH, to MDAS without additional steps.)

The following examples of decontamination technologies are grouped into either Thermal Decontamination or Chemical Decontamination technologies.

Thermal Decontamination

- Hot Gas Decontamination [Additional Resources]
  Developed by the U.S. Army Environmental Center, hot gas decontamination is conducted in a sealed, insulated vessel where heated air raises the temperature of the

scrap material contaminated with explosives or propellants for a specified period of time. Operating temperature and exposure time are site-specific, but typically, the decontamination process holds a steady temperature of 260°C to 316°C (500°F to 600°F) for one hour. The heat volatilizes contaminants, which are then destroyed in an afterburner. The treated metal meets MDAS criteria. Portable units that can be brought to the site are available. Hot gas decontamination has been successfully demonstrated in a sustainable, production-ready demil execution environment for a wide variety of munition items containing explosive residues only.

- Flashing Furnace [Additional Resources]
  A flashing furnace uses a direct flame to heat contaminated scrap to 316°C (600°F) for typically 45-90 minutes, depending on load size and type. Offgases are treated with a cyclone dust collector and baghouse. Flashing furnaces thermally decontaminate materials to MDAS. Portable units that can be brought to the site are available. According to DoD's demil enterprise, flashing furnaces have been successfully demonstrated in a sustainable, production-ready demil execution environment for a wide variety of munition items containing explosive residues only.

- Decineration™ [Additional Resources]
  Decineration™ is a technology patented by U.S. Demil, LLC (see discussion above under Thermal Destruction technologies) that uses an externally heated furnace (Figure 14) to decontaminate the scrap metal output to MDAS. Emissions are treated with a wet scrubber and catalytic converter; carbon dioxide, nitrogen, and water vapor are released. According to DoD's demil enterprise, the Decineration™ technology has been proven to work in its final form and under expected conditions. Funding continues to be requested to demonstrate Technology Readiness Level (TRL) 9, after which it would be ready for utilization at full scale in a production-ready demil execution environment.

Figure 14. Decineration/Rotary Furnace

Photo courtesy of John Hutten and J.C. King, DoD

- Car Bottom Furnace [Additional Resources]
  A car bottom furnace is an incinerator that consists of a fixed refractory-lined furnace and a "car" that is normally rail-mounted for loading energetic materials into the furnace. The car facilitates batch processing of large loads that would be difficult or dangerous to load directly into the furnace. Exhaust gases are pulled from the unit and cleaned in air pollution control systems. These furnaces are typically used for removing residual energetics and not as a primary demilitarization method. According to DoD's demil enterprise, the car bottom furnace has been successfully demonstrated in a sustainable, production-ready demil execution environment for a wide variety of munition items containing explosive residues only.

Chemical Decontamination

- MuniRem® [Additional Resources]
  MuniRem Environmental's MuniRem® (described above under Chemical Destruction technologies) has been used to effectively decontaminate explosives-contaminated scrap metal. It can be used to decontaminate bomb casings, scrap metal, and projectile fragments from which bulk explosives were removed and treated. Larger bomb casings may be sprayed with solution, or additional MuniRem® can be added to the neutralization reactor to achieve complete destruction. The contaminated surfaces are soaked in high-strength solution (>15%) and allowed to react for 30 minutes to four hours. The Army considers it to be an effective chemical process for treating energetic residues, lightly contaminated materials, and metal surfaces contaminated with energetics.

  MuniRem® has also been applied by DoD and commercial explosive manufacturers to decontaminate equipment, pipes, and building fixtures (e.g. Iowa AAP, McAlester Army Depot, Lake City AAP, Indian Head, former Louisiana AAP; and internationally (Israel, Taiwan, South Africa, and Australia). MuniRem® is also currently being used under a DoD demilitarization contract to decontaminate scrap metal (with EXPAL USA).

- Actodemil® [Additional Resources]
  ARCHTECH's Actodemil® process (described above under Chemical Destruction technologies) also can be used to decontaminate scrap materials and other equipment contaminated with explosives. A wet scrubber treats ammonia and nitrogen oxide offgases. The treated residues can be used as fertilizer. According to DoD's demil enterprise, Actodemil® has not been successfully demonstrated to date in a sustainable, production-ready demil execution environment.

DDESB Approved Technologies

As mentioned earlier, a list of technologies approved from a safety standpoint by the DDESB is provided here for reference. If a particular technology is not in this list, it does not necessarily mean it is not safe for use.

The DDESB's current list[42] includes the following eight technologies (parenthetical references are to sites where use has been approved):

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[42] The 2015 list of eight DDESB-approved technologies was confirmed as current by Mr. M. Luke Robertson (DDESB) in an email to EMS dated July 26, 2017. The only update to the list was an approval to a modification for

- Hot gas decontamination facility (Hawthorne Army Depot, NV).
- Industrial waste processor and Caffee Road Thermal Decontamination Area (Naval Surface Warfare Center, Indian Head Explosive Ordnance Disposal Technology Division, Indian Head, MD).
- Transportable controlled detonation chamber – Models T-25, T-30, and T-60 (Massachusetts Military Reservation, MA; Spring Valley FUDS, Washington, DC; Pier 90/91 FUDS, Seattle, WA).
- Ammunition peculiar equipment-1236 rotary kiln incinerator (Crane Army Ammunition Activity, IN; Tooele Army Depot, UT; McAlester Army Ammunition Plant, OK; and Hawthorne Army Depot, NV).
- Static Detonation Chamber 1200 (Anniston Army Depot, AL).
- Kobe Steel – Vacuum Integrated Chamber - DAVINCH™ DV-60.[43]
- Explosives Destruction System (EDS) Various Phase 1 and Phase 2 units for the onsite treatment of recovered chemical warfare materials and treatment of certain rejected stockpiled chemical munitions. The Organisation for the Prohibition of Chemical Weapons recognizes EDS as a mobile destruction system. The EDS has been used at: Camp Sibert, AL; Pine Bluff Arsenal, AR; Spring Valley Formerly Used Defense Site, Washington, DC; Dover Air Force Base, DE; Rocky Mountain Arsenal, CO; and Bluegrass Army Depot, KY.
- Tactical Missile Demilitarization (Letterkenny Army Depot, PA).[44]

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[43] Approved for experimental testing using simulants.

[44] Tactical Missile Demilitarization is the former name for the Ammonium Perchlorate Rocket Motor Destruction (ARMD) Facility. The DDESB approval for the ARMD facility applies to the rocket motor preparation building, the rocket motor segmenting building (using water cooled band saw), and the thermal treatment building (with contained burn furnace).

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APPENDIX A: Glossary

bench-scale – Refers to technologies tested only in a laboratory.

cast explosive – An explosive that was melted, poured, and solidified inside the projectile's body.

deflagration – A process in which a small amount of explosive material in an unconfined state suddenly ignites when subjected to a flame, spark, shock, friction, or high temperatures. (The Chemistry of Explosives, The Royal Society of Chemistry, 2004.)

demilitarization – The act of eliminating the functional capabilities and inherent military design features from DoD personal property. Methods and degree range from removal and destruction of critical features to total destruction by cutting, crushing, shredding, melting, burning, etc. DEMIL is required to prevent property from being used for its originally intended purpose and to prevent the release of inherent design information that could be used against the United States. DEMIL applies to DoD personal property in both serviceable and unserviceable condition. (DoD, 2011)

energetic hazardous wastes – Energetic hazardous wastes exhibit the characteristics of either ignitability or reactivity, or both. They encompass items containing energetic materials (i.e., propellants, explosives, and pyrotechnics) such as excess, obsolete, or unserviceable military munitions and ammunition used in law enforcement, flares, fireworks, rockets, and automobile air bag gas generators that are determined to be wastes.

energetic materials – Are a class of material with high amount of stored chemical energy that can be released. (https://en.wikipedia.org/wiki/Energetic_material)

full-scale – Refers to technologies deployed onsite to treat energetic hazardous wastes. Full-scale technologies have reached the final design and construction stages and are operating or have operated in the past. Full-scale is the result of incorporating outcomes at the bench and pilot scale to optimize the final design.

hazardous waste – Hazardous waste is a waste with properties that make it dangerous or capable of having a harmful effect on human health or the environment. Hazardous waste is defined in RCRA §1004(5) and codified at 40 CFR 261.3.

improved conventional munitions – Munitions characterized by the delivery of two or more antipersonnel or antimaterial and/or antiarmor submunitions by a warhead or projectile.

insensitive munitions – Munitions that will not react to unintentional stimuli, such as fast or slow heating or bullet or fragment impact, in such a way as to cause catastrophic collateral damage that impairs warfighting capability. (https://www.dsiac.org/resources/journals/dsiac/summer-2014-volume-1-number-1/insensitive-munitions-where-are-we-now)

kickout – Whole or partial munitions or still-active energetics that are ejected from the site of a disposal burn or detonation and that still represent a potential explosive or reactive hazard.[45]

material documented as safe (MDAS) – MPPEH that has been assessed and documented as not presenting an explosive hazard and for which the chain of custody has been established and maintained. This material is no longer considered to be MPPEH and may be released to the public without restriction. (DoD, 2015)

material documented as an explosive hazard (MDEH) – MPPEH that cannot be documented as MDAS, that has been assessed and documented as to the maximum explosive hazards the material is known or suspected to present, and for which the chain of custody has been established and maintained. This material is no longer considered to be MPPEH. (DoD, 2015)

material potentially presenting an explosive hazard (MPPEH) – Material owned or controlled by the DoD that, before determination of its explosives safety status, potentially contains explosives or munitions (e.g., munitions containers and packaging material; munitions debris remaining after munitions use, demilitarization, or disposal; and range-related debris) or potentially contains a high enough concentration of explosives that the material presents an explosive hazard (e.g., equipment, drainage systems, holding tanks, piping, or ventilation ducts that were associated with munitions production, demilitarization, or disposal operations). This material may be released only to a qualified receiver Excluded from MPPEH are military munitions and military munitions-related materials as well as non-munitions-related material, such as rebar. (DoD, 2011)

munition – A complete device charged with explosives; propellants; pyrotechnics; initiating composition; or chemical, biological, radiological, or nuclear material for use in operations including demolitions. (DoD, 2018)

net explosive weight (NEW) – The actual weight in pounds of explosive mixtures or compounds, including the trinitrotoluene equivalent of energetic material that is used in determination of explosive limits and explosive quantity data arcs. (DoD, 2018)

pilot-scale – Refers to technologies that have been scaled up for application onsite (typically at the eventual place where full-scale will be built or operated) to demonstrate feasibility. Pilot-scale testing may also have evaluated time, cost, and ways to improve system design prior to full-scale implementation.

primary explosive – is an explosive that is extremely sensitive to stimuli such as impact, friction, heat, static electricity, or electromagnetic radiation. A relatively small amount of energy is required for initiation. (https://en.wikipedia.org/wiki/Explosive#Primary_explosive)

reactive waste – EPA considers wastes hazardous due to the reactivity characteristic if the waste may be unstable under normal conditions, may react with water, may give off toxic gases and may be capable of detonation or explosion under normal conditions or when heated. Waste explosives are a hazardous waste under 40 CFR 261.23 Characteristic of reactivity**,** paragraphs (a) (6), (7), and (8).

[45] NASEM 2019.

secondary explosive – is less sensitive than a primary explosive and requires substantially more energy to be initiated. Because they are less sensitive, they are usable in a wider variety of applications and are safer to handle and store. Secondary explosives are used in larger quantities in an explosive train and are usually initiated by a smaller quantity of a primary explosive. (https://en.wikipedia.org/wiki/Explosive#Secondary_explosive)

sustainable production-ready demil execution environment – For a given technology, the capability has been shown that it can be successfully operated in a production environment for extended periods without significant failures or unreasonable support costs to keep it operational.

thick-case munitions – Items such as bombs, bomblets, warheads, rocket motors, large and medium projectiles, grenades, mines, sectioned munitions, and missiles.

thin-case munitions – Items such as small-caliber ammunition, ranging from 0.22 to 0.50 (.22 cartridges through Cal .50 (12.7mm), medium caliber munitions (14mm thru 40mm direct fire cartridges), cartridge-actuated devices, propellant-actuated devices, exploding bolts, fuzes, bomblets, booster pellets, detonators, igniters, and leads.

throughput – The rate that munitions or energetic materials can be demilitarized by a technology.

waste explosives – Waste that has the potential to detonate and bulk military propellants that cannot safely be disposed of through other modes of treatment (40 CFR 265.382). See also, reactive waste at 40 CFR 261.21.

APPENDIX B: MIDAS Family Code Definitions[46]

DoD's Defense Ammunition Center developed the Munitions Items Disposition Action System (MIDAS) to identify different families of ammunition defined by two-letter codes. The codes are used to identify ammunition groupings for planning and assessing technology applications, such as for demilitarization of munitions. For any current assessments, the latest MIDAS codes and information would need to be used. MIDAS is not a publicly accessible system.

MIDAS Family	Definition
CD	Munitions containing dyes as a primary disposal requirement. Also bulk dye materials.
CH	Munitions containing hexachloroethane (HC) as the primary fill. Also bulk HC.
CP	Includes a variety of ammunition types that contain white phosphorus (WP), or elasticized white phosphorus (PWP) as primary fillers. Items may also contain a high explosive, bursting charge, and/or propellant charge as well.
CR	Usually referred to as riot control agents or munitions. Includes a variety of items that contain lacrimatory or irritating agents. Common fillers are tear gas, mace, or pepper gas. Common abbreviations for irritating agents are typically shown in the item nomenclature as CS, CN, or CR.
CS	Munitions whose primary purpose is to produce smoke. This family does not include smoke-producing munitions that use white or red phosphorus, which are assigned to family CP, and those munitions containing HC, which are in family CH. This family also does not include munitions of a primarily pyrotechnic nature, such as those used for illumination or smoke and illumination, or signal kits, flares, and most simulators, which are included in family FP.
DU	Includes all ammunition items using depleted uranium as the primary material for the projectiles/penetrators. These items are typically kinetic energy projectile penetrators that may also have incendiary or tracer devices associated.
FI	Incendiary ammunition or devices that produce intense heat for destroying equipment or documents. Primary fillers are thermite, thermate, triethylaluminum, potassium perchlorate, or TPA.
FP	Pyrotechnics/Illumination/Non-Frag/Tracers. Includes a variety of ammunition types used for illumination, marking, spotting, signaling, simulating, or tracing. Typical items are ground, aircraft, or marine illumination signal stars, photoflash cartridges, personnel distress kits, and air/ground burst simulators. Does not include items whose primary purpose is to screen, which are assigned to family

[46] Source: Defense Ammunition Center Technology Directorate Demil Capabilities Matrix, released by James Q. Wheeler, Director, Defense ammunition Center and Larry Nortunen, Associate Director for Technology. September 16, 2005.

	CS. Does not include tracer and incendiary rounds from 20mm through 40 mm, which are assigned to families PDLA, PDLB, or PDLC.
HA	HE components/devices. Includes all high explosive detonators, boosters, or bursting charges that are not configured within an ammunition item. Typically hazard class/division 1.1 or 1.2 components or munitions that do not fit any other family.
HB	HE Bombs. Includes high explosive filled bombs. Items are typically air dropped, and fillers are usually tritonal, TNT, HBX, or H-6 explosives.
HC	HE Cartridges. Includes complete artillery or navy gun ammunition with a high explosive projectile and a propelling charge. Examples are 90mm, 105mm, 3"/50 Cal, 81mm, 30mm fuzed or unfuzed cartridges and fuzed 20mm cartridges.
HD	High Explosive "D". Includes all ammunition, regardless of type, that contains Explosive "D" as the primary filler. Explosive "D" is also known as ammonium picrate or Yellow "D".
HE	Bulk High Explosives. Includes all bulk high explosives such as TNT, Composition A, Composition B, Composition C-4, PBX, and RDX.
HG	HE Grenades. Includes hand or rifle grenades that contain high explosive fillers. Does not include 40mm grenades in family HC.
HH	HE Depth Charges and Underwater Munitions. Includes all high explosive filled marine depth charges and underwater mines and also the separate warheads for these depth charges and underwater mines.
HI	HE ICM/CBU & Submunitions. Includes a variety of improved and conventional munition types containing submunitions. Items may be airdropped cluster bomb units, projectiles, or warheads containing submunitions such as anti-tank mines, anti-personnel/material grenades or bomb loaded units (BLU's).
HM	Missiles and Rockets.
HP	HE Projectiles and Warheads. Includes all projectiles, warheads, mortars, or similar items that do not have a cartridge case, propellant, or rocket motor associated, and that contain a high explosive filler.
HR	HE Rockets. Includes complete rounds of rocket ammunition containing warhead, fuze and rocket motor. Note that a live rocket motor with an inert warhead would be considered a member of family PDR. This family does not include rockets with practice warheads designed to provide a flash and smoke signature. These types of rockets are in family FPR.
HT	Torpedoes, complete.
HX	Demolition Materials. Includes all demolition materials such as cratering charges, shaped charges, flexible sheet explosives, and miscellaneous standard or non-standard items, which could be used as donor material for open detonation of

other munitions items. It also includes demolition initiation items such as blasting caps, time fuze, detonation cord, etc. Typically, the initiation items will not be used for their intended purposes because they are in the demil account due to defects.

HZ	HE Land Mines. Includes all high explosive filled land mines emplaced by hand or dispersing devices, and includes the dispersing devices when the mines and the devices constitute end items. The family also includes scatterable mines when they are packed separately from the dispersing unit (e.g., a dispenser, projectile body, or other system).
I	Inert. Includes all ammunition without any explosive or reactive material or fillers. Items in this family are typically classified as Dummy or Blind Loaded ammunition used primarily for training. In general, all munitions items that are inert but that require demilitarization before being placed in the hands of the public (e.g., sold through the DRMS) are placed in this family.
LR	Large Rocket Motor. Includes solid propellant ICBM, SLBM, or space launch booster motors. Does not include those motors that are associated with tactical rocket or missile systems. Does not include anti-ballistic missile systems designed to defend against theater ballistic missiles. E202 include strategic anti-ballistic missile systems (such as Safeguard).
N	No Family. Includes a variety of ammunition and components that cannot be identified as to filler or characteristics because of incomplete supply data.
PB	Bulk Propellants. Includes all propellants in bulk form that are not assembled or configured to an ammunition item. Material is normally packaged in drums or metal lined wooden containers. Does not include black powder, which is assigned to family HE.
PC	Propellant Charges and Increments. Includes packaged propelling charges and propellant increments.
PD	Propellant Munitions/Components. Includes a variety of ammunition types such as rocket motors, some ejection seat components such as catapults or canopy thrusters, ammunition of 20mm or larger with inert (except may include tracers or incendiary mixes) or flechette projectiles, et. (Flechette projectiles containing dyes are in family CD.) Typically hazard class/division 1.3 and 1.4 items.
SA	Small Caliber Ammunition. Includes small caliber ammunition through .50 caliber.
SC	Miscellaneous and Incinerable Munitions and Components. Includes munitions and components typically assigned to hazard class/division 1.3 and 1.4 and which do not fit into any other families. Physical dimensions and weights of items in this family vary widely. Many of the items are relatively small and may be demilitarized in deactivation furnaces or other incineration methods. Typical items include small egress system components such as det cord assemblies, initiators, actuators, etc. Also included are impulse cartridges, squibs, and delay elements. At the other end of the scale, there are many items of large physical dimensions and weights. Typical items include assemblies containing small

quantities of energetic materials, components that are primarily electronic but that contain small squibs or initiators, guidance kits, engine starter cartridges, etc.

SF Fuzes. Includes all types of fuzes related to munitions. Examples include artillery ammunition/Navy gun fuzes, rocket fuzes, or grenade fuzes packaged separately from the munitions.

APPENDIX C: Compendium of Resources

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APPENDIX D: Technology Matrices

Case Opening

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	MIDAS Codes[47]	Facilities Applied[48]	Output
Case Opening								
Reverse Assembly								
U.S. Department of the Army/Linear Munitions Disassembly	N	Full	Fixed	Y	Y	CH,CP,CR,CS,HA,HB,HC, HD,HG,HH,HI,HM,HP,HR HT,HZ,PD,SF	Pueblo Chemical Agent Destruction Pilot Plant (CO); Anniston Chemical Demilitarization Facility (AL) to remove mustard from projectiles and mortars.	Energetic materials and casing/containment vessels
Pull Apart Machines e.g., APE 2271 APE 1001M2/M3	N	Full	Fixed	Y	Y	CDC, CHC, CPC, CRC, CSC, DUM, DUS, FPC, HCC, HCL, HCP, HCPS,HCS, HDC, PDLC, PDLD, PDLE, PDLF	APE 1001: McAlester Army Ammunition Plant (OK) used in 2016 to pull projectiles from cartridge cases; Tooele Army Depot (UT) not in use yet for 20 & 30mm; and Hawthorne Army Depot (NV). APE 2271: Crane Army Ammunition Activity (IN) (not yet operational) and Tooele Army Depot (UT) for 20mm.	Projectiles, propellant, and primed cartridge cases

[47] MIDAS codes (Appendix B) were assigned to items identified as having been tested, treated or potentially treatable, based on available references and/or discussions with vendors. The viability of treatment must be determined on a site-specific basis, however, due to the many variables involved (e.g., the configuration of the material being treated, the quantity of energetics or NEW to be treated, and the necessary portability).

[48] These facilities were noted in literature as having used the technology in a pilot test or at full scale (currently or in the past). Inclusion does not necessarily denote success. The EPA, state, or facility personnel contacted to confirm information on usage are acknowledged at the end of Appendix D.

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	MIDAS Codes[47]	Facilities Applied[48]	Output
Case Opening								
Fluid Jet Cutting with Abrasive Particles								
Applied New Technologies AG/ Water-Abrasive-Suspension Cutting System (Germany)	N	Full	Semi-Portable	N	Y	HB,HC,HD,HG,HH,HI,HP, HR,HZ	No sites were identified at the time this report was written.	Energetic materials and casing/containment vessels, wastewater
Gradient Technology/Water Jet Cutting	N	Full	Portable	Y	Y	CS,FP,HB,HC,HD,HG,HH, HI,HM,HP,HR,HT,HZ,LR, SF	Sectioned UXO at Naval Surface Warfare Center (NSWC) Indian Head (MD); UXO at NSWC White Oak (MD); tested for MLRS rocket motor sectioning at Redstone Arsenal (AL); and to remove Explosive D from stockpiled projectiles at NSWC Crane (IN)	Energetic materials and casing/containment vessels, wastewater
Cryofracturing								
General Atomics/Cryofracture Systems (transportable and fixed)	N	Full	Portable/ Semi-Portable	Y	N	HA,HC,HD,HG, HI, HZ, SF	Munitions Cryofracture Tests at Dugway Proving Ground (UT), Tooele Army Depot (UT, and Yuma Proving Ground (AZ). Crushes ADAM mines at McAlester AAP (OK); Planned removal of sensitive submunitions from artillery rounds at Crane AAP (IN).	Energetic materials and casing/containment vessels. Emissions in case of unintentional detonation.

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	MIDAS Codes[47]	Facilities Applied[48]	Output
Case Opening								
Femtosecond Laser Cutting								
U.S. Photonics, Inc./ Femtosecond laser cutting	N	Pilot	Fixed	Y	Y	HB,HC,HD,HH,HI,HM,HP, HR,HT,HZ,LR	Past research conducted at Lawrence Livermore National Laboratories	Energetic materials and casing/containment vessels, carbon and benign gases.
Underwater Band Saw								
Dynasafe Demil Systems AB/Underwater Band Saw UWS-500	N	Full	Semi-Portable	Y	Y	HB,HC,HD,HM,HP,HR,LR, PD	No sites were identified at the time this report was written.	Cutting debris, explosive fill, filter elements; cooling liquid containing heavy particles and shavings
Dynasafe Demil Systems AB/ Underwater Band Saw UWS-3X	N	Full	Semi-Portable	Y	Y	HB,HC,HD,HG,HM,HP, HR,HZ,PD	No sites were identified at the time this report was written.	Energetic materials and casing/containment vessels

Energetic Material Removal

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[49]	Facilities Applied[50]	Output	Pre-Treatment	Post-Treatment
Energetic Material Removal											
Meltout											
U.S. Army/Ammunition Peculiar Equipment (APE) Autoclave Meltout System	N	Full	Fixed	N	Y	N	HB,HC,HH,HP	Used at Naval Surface Warfare Center (NSWC) Crane Div. (IN) in early 2000s to remove Tritonal from 750lb bombs; Hawthorne Army Ammunition Plant, (NV) to remove TNT from munitions	Scrap metal, pink water. Energetics for reclamation.	Y	Y
El Dorado Engineering/ Demilitarization by Inductive Heating Meltout (DIHMEs)	N	Pilot	Semi-Portable	N	Y	N	HP	Tested at NSCW Crane Div. (IN) in 2007; Subsequently tested at Hawthorne Army Depot (NV) but did not have satisfactory proveout.	Scrap metal, energetic material.	Y	Y

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[50] These facilities were noted in literature as having used the technology in a pilot test or at full scale (currently or in the past). Inclusion does not necessarily denote success. The EPA, state, or facility personnel contacted to confirm information on usage are acknowledged at the end of Appendix D.

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[49]	Facilities Applied[50]	Output	Pre-Treatment	Post-Treatment
Energetic Material Removal											
Washout											
Washout Water Jet	N	Full	Semi-Portable	Y	Y	N	HB,HC,HD, HG,HH,HI, HM,HP,HT,HZ	In the late 1990s, used to remove and reclaim PBX-based energetics from munitions at NSWC, Crane Division	Scrap metal, energetic material, wastewater, which can be reused in process	Y	Y
Washout Liquid Nitrogen (Cryogenic Washout)	N	Bench	Fixed	N	Y	N	HB,HC,HD,HP, HRLR	Experimental	Scrap metal, energetic material.	Y	N
Washout (Blastout) Carbon Dioxide	N	Prototype	Fixed	N	Y	N	HB,HC,HD,HH, HP	Crane Army Ammunition Activity, (IN) See information for Dry Ice Blasting	Scrap metal, energetic material, CO2 gas released to atmosphere	Y	Y
Dry Ice Blasting											
Automation Technologies Ltd (England)/Cryogenic (dry ice) cleaning blasting booth	N	Prototype	Fixed	N	N	Y	HB, HC, HD, HP, HZ	Constructed in 1990s for R&D at Crane Army Ammunition Activity, (IN), but it was not effective.	Scrap metal, energetic material, CO2 gas released to the atmosphere.	Y	Y
Ultrasonic Separation											
TPL, Inc./Ultrasonic Separation	N	Pilot	Fixed	N	Y	N	HC,HP,HZ	Pilot tested at Picatinny Arsenal (NJ) for cast-loaded explosives (med. and large caliber). Test ended due to explosion of undetermined cause.	Scrap metal (empty shell casings), energetic material, waste fluid.	N	Y

Energetic Material Destruction

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Closed Detonation											
U.S. Army/Mobile Controlled Detonation Chambers (Models T-30, and T-60)	Y	Full	Portable	Y	Y	Y	CH,CP,CR,CS, FI,FP,HA,HC, HD,HE,HG,HP HZ,PB,PCSA,S C,SF	T-30 and T-60 units are brought to Spring Valley (Washington, DC), as needed	Scrap metal, treated offgas, potentially contaminated pea gravel.	N	Y
U.S. Army/Mobile Controlled Detonation Chambers (T-10) and (T-25)	Y (T-25)	Full	Portable	Y	Y	N	CH,CP,CR,CS, FI,FP,HA,HC,H D,HEHP,HX, HZ,PB,PC,SA, SC,SF	T-10: Used in 2005 at Fort Hunter Liggett (CA); Mare Island (CA); Naval Weapons Station Seal Beach/Fallbrook Detachment (CA); and Camp Roberts (CA). Several deployments at Massachusetts Military Reservation.	Scrap metal, treated offgas, potentially contaminated pea gravel.	N	Y

[51] MIDAS codes (Appendix B) were assigned to items identified as having been tested, treated or potentially treatable, based on available references and/or discussions with vendors. The viability of treatment must be determined on a site-specific basis, however, due to the many variables involved (e.g., the configuration of the material being treated, the quantity of energetics or NEW to be treated, and the necessary portability).

[52] These facilities were noted in literature as having used the technology in a pilot test or at full scale (currently or in the past). Inclusion does not necessarily denote success. The EPA, state, or facility personnel contacted to confirm information on usage are acknowledged at the end of Appendix D.

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Closed Detonation (continued)											
U.S. Army/Stationary Controlled Detonation Chambers (Models D-100 and D-200)	N	Full	Fixed	N	Y	N	CD,CH,CR,CS HC,HI,HP,LR, PD,SF	D-100: Limited use at Blue Grass Army Depot (KY) due to throughput, but recent treatability studies suggest increased use in future; Milan Army Ammunition Plant (TN) (decommissioned); Naval Surface Warfare Center Crane Division, Pilot tested, but did not operate as intended.	MDAS scrap metal, pea potentially contaminated pea gravel, lead-containing filter dust and soot.	N	N
Dynasafe (Sweden)/Mobile Ammunition Disposal Plant (MEA)	N	Full	Semi-Portable	Y	Y	N	HA,HC,HD, HG,HZ,SA,SF	No sites were identified at the time this report was written.	MDAS scrap metal, treated offgas, baghouse filter dust and ashes for disposal.	Y	N
Dynasafe/Munitions Destruction System (MDS)	N	Full	Fixed	Y	N	Y	HA,HC, FP, SA,SF	MDS is one component of the M77 Grenade Thermal Treatment Closed Disposal Process (TTCDP) at Anniston Army Depot. Grenades are removed from warheads and processed at the TTCDP.	Scrap metal, offgas.	Y	Y

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Closed Detonation (continued)											
Dynasafe (Sweden)/Static detonation chamber (SDC-1200) (SDC-1000)	Y (SDC-1200, Anniston Army Depot, AL)	Full	Permanent/ Semi-Portable	Y	Y	Y	CH,CP,CR,CS, FI,FP,HA,HC, HD,HE,HG,HI, HP,HX,HZ,PB, PC, SA,SC,SF	SDC-1200 at Anniston Army Depot (AL) (previously processed chemical munitions and currently processing conventional explosives); Blue Grass Army Depot (KY) for demil of H-mustard projectiles and future demil of conventional weapons; and Pueblo Chemical Depot (CO) (3 units in permitting process)	MDAS scrap metal, treated offgas, baghouse filter dust and ashes for disposal.	N	N
Dynasafe (Sweden)/Static detonation chamber (SDC-2000) (SDC-1500)	N	Full	Fixed	Y	Y	Y	FP,HA,HC,HD, HE,HG,HI,HP, HZ,PC,PD,SA, SC,SF,CH,OP, CR,CS	SDC-1500 is planned but not yet permitted nor constructed at Blue Grass Army Depot (for conventional munitions)	MDAS scrap metal, treated offgas, baghouse filter dust and ashes for disposal.	N	N
Dynasafe (Sweden)/Model D-100 (mobile disposal system)	N	Full	Portable	Y	N	Y	SA, SC	Local police departments across the United States	Scrap metal, treated offgas.	N	Y

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Kobe Steel (Japan)/Vacuum Integrated Chamber (DAVINCH™)	Y	Full	Semi-Portable	Y	Y	N	HB,HC,HD,HH HP,PD,SC	Poelkapelle, Belgium (conventional); Deseret Chemical Depot (UT) (installed, but never reached testing phase)	Water from oxidized hydrogen, offgas, scrap metal.	Y	Y
Kobe Steel (Japan)/DAVINCH Lite 24	N	Pilot	Portable	Y	Y	N	CH,CP,CR,CS, HA,HC,HD,HP HR,HZ,SC	No sites were identified at the time this report was written.	Offgas, scrap metal.	Y	Y
Closed Detonation (continued)											
TWB Designs/MACS (Mobile Ammunition Combustion System) and EMACS (Environmental Mobile Ammunition Combustion System)	N	Full	Portable	Y	N	N	SA	No large-scale applications identified. News story on use for destroying ammunition by a police department.	Expended brass cartridge cases, loose bullets, offgas.	N	N
OZM (Czech Republic)/Horizontal Detonation Chambers (Models: KV-0.2, KV-2, KV-5, RADUGA, KVG-8, KVG-16)	N	Full	Fixed	Y	N	Y	HC,CH,CS,FP HA,HE,PB,PC SA, SC, SF	No sites were identified at the time this report was written.	Ash residue, offgas, scrap metal.	N	Y

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Thermal Destruction											
Contained Burn											
El Dorado Engineering/Contained Burn Furnace (CBF)	N	Full	Fixed	Y	N	Y	HE,HI,HZ,PB, PD,SA	Component of the Ammonium Perchlorate Rocket Motor Destruction Facility at Letterkenny Army Depot, PA. Large-scale turnkey for emergency removal action at Camp Minden, LA. Demonstration at China Lake, CA.	Treated offgas. Non-hazardous particulate matter from exhaust is drummed offsite disposal. Non-hazardous neutralized brine and alumina solids. Potentially scrap metal.	N	N
Timberline Environmental Services/Bullet Buster Small Arms Munitions Demil/recycle (Thermo Deflagration unit)	N	Full	Portable	Y	N	N	SA,FP	Department of Defense Joint Munitions Command	Residue metals, treated offgas. MDAS bullets and casings can be disposed of or recycled.	N	N

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Thermal Destruction (continued)											
Rotary Kiln											
Timberline Environmental Services/Magilla Ordnance Thermo Deflagration Unit	N	Prototype	Semi-Portable	Y	N	N	HI,SA,SC,SF	U.S. Army-U.S. Navy-U.S. Air Force-USACE (Various U.S. contractors at BRAC and FUDS installations)	Scrap metal, treated offgas.	Y	Y
El Dorado Engineering/Rotary Kiln Explosive Waste Incinerator	N	Full	Semi-Portable	Y	Y	Y	FP,HA,HE,HG, PB,PC,PD,SA, SC,SF	Installed 24 explosive waste incinerators and/or pollution control systems within the U.S.	Scrap metal, treated offgas, filter dust.	Y	Y
General Dynamics Ordnance and Tactical Systems (OTS)/Rotary Kiln Incinerator	N	Full	Fixed	Y	N	Y	HA,HE,HG,HI, PB,PC,SC,SF	Commercial demilitarization facility in Carthage, MO (conventional munitions and Takata airbags)	Scrap metal, sodium salts from reaction of soda ash with sulfur oxides and hydrochloric acid in offgas treatment, and particulates from offgas treatment.	Y	Y

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Thermal Destruction (continued)											
Rotary Kiln (continued)											
Dynasafe/Tunnel Furnace	N	Full	Fixed	Y	Y	Y	PB,HE,SA,SC	No sites were identified at the time this report was written.	Scrap metal, treated offgas, waste ash, dry waste stream from the pollution abatement system, 0.2 lbs of salt per pound of treated ammonium perchlorate.	Y	Y
U.S. Army/Ammunition Peculiar Equipment (APE)-1236 Rotary Kiln (Deactivation Furnace)	Y (Crane Army Ammunition Activity, IN; Tooele Army Depot, UT; McAlester Army Ammunition Plant, OK; and Hawthorne Army Depot, NV)	Full	Fixed	Y	Y	Y	FP,HA,HE,PB, PC,SA,SC	McAlester Army Ammunition Plant (OK) destroys energetics from ADAM mines that are opened using cryofracture; Tooele Army Depot (UT); Crane Army Ammunition Activity (IN) APE-2210: Hawthorne Army Depot (NV)	Scrap metal, offgas.	Y	Y
Decineration/Rotary Furnace											
U.S. Demil, LLC/Decineration™	N	Full	Fixed	Y	N	N	HX,PB,PC,PD, SA,SC,SF	State of Indiana - Field Tested; Tooele Army Depot (Previously used for conventional small arms. No longer in use.)	MDAS scrap metal, CO2, nitrogen, and water vapor emissions. Recovered particulates/ash.	Y	N

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Chemical Destruction											
Alkaline (Base) Hydrolysis	N	Full	Fixed	N	N	Y	HE,PB,PC,SC	Full scale for rocket propellant at United Technologies (San Jose, CA); Pilot scale at Holston Army Ammunition Plant (TN) and Los Alamos National Laboratory (NM)	Treated offgases, soluble inorganic and organic salts, insoluble polymeric and metallic materials.	N	Y
General Atomics Electromagnetic Systems/ Neutralization/Alkaline Hydrolysis	N	Full	Fixed	N	N	Y	CR,HD,HE,PB	Blue Grass Army Depot (KY) demil of GB and VX nerve agents scheduled to begin 2020 and 2022, respectively; Tooele Army Depot (UT) destruction of CADs and PADs ceased operation in 2016 due to dwindling waste stream; Newport Chemical Depot (IN) pilot tested for VX nerve agent.	CO2, salts, H20, filtered offgas.	Y	Y

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Chemical Destruction (continued)											
General Atomics Electromagnetic Systems/Industrial Supercritical Water Oxidation (iSCWO)	N	Full	Fixed	N	N	Y	HX,PB	Blue Grass Army Depot (KY) demil of GB and VX nerve agents scheduled to begin 2020 and 2022, respectively; Dugway Proving Grounds (UT) (chemical munitions); Newport Chemical Depot (IN) pilot tested for VX nerve agent. U.S. DoD is funding testing of iSCWO for treatment of tear gas and ammonium.	Large quantities of waste water. Offgas containing low nitrogen oxide (NOx), sulfur oxide (SOx), and total organic carbon (TOC).	Y	N
MuniRem Environmental, LLC/MuniRem®	N	Pilot	Portable	N	N	Y	HD,HE,PD	Bench/pilot scale: Army Laboratory, Vicksburg, MS; Indiana Army Ammunition Plant, IN (nitrocellulose propellant); Naval Support Facility, Indian Head, MD Used to washout and neutralize bulk explosives (H-6) from abandoned on melter/flaker equipment at Camp Minden, LA	Nitrogen gas, carbon dioxide, sulfate, nitrogen dioxide, formate, acetate. Wastewater can be reused or discharged to municipal sewer. Possible sludge in post-treatment (via biodegradation) of wastewater resulting from treatment of bulk nitrocellulose.	Y	Y

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[51]	Facilities Applied[52]	Output	Pre-Treatment	Post-Treatment
Energetic Material Destruction											
Chemical Destruction (continued)											
ARCTECH/Actodemil Non-Thermal Humic Acid Catalyzed Hydrolysis-Neutralization Technology	N	Full	Semi-Portable	N	N	Y	HD,HE,PD	Demonstration/prove-out tests on propellants at: Hawthorne Army Depot (NV): McAlester Army Ammunition Plant (OK); Radford Army Ammunition Plant (VA) (Fertilizer not used due to high levels of heavy metals); Dyno Nobel, Hercules Corp, Naval EOD Technology Division (MD).	Large quantities of effluent, Actodemil liquid product for land application or offsite disposal, and offgas. The spent scrubber reagent is mixed with end use product so that no liquid waste is generated.	Y	N

Decontamination

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[53]	Facilities Applied[54]	Output	Pre-Treatment	Post-Treatment
Decontamination											
Thermal Decontamination											
Hot Gas Decontamination											
U.S. Army Environmental Center/Hot Gas Decontamination System	Y (Hawthorne Army Depot, NV)	Full	Portable	Y	N	Y		Hawthorne Army Depot (NV); Alabama Army Ammunition Plant (AL)	MDAS scrap metal, treated offgas.	Y	N
Flashing Furnace											
El Dorado Engineering/Transportable Flashing Furnace	N	Full	Portable	Y	Y	N	HA,HC,SA, SC,SF	Ravenna Army Ammunition Plant (OH); Eglin AFB (FL); Utah Test & Training range for target range tracers, misc. UXO and scrap; Anniston Army Depot (AL); China Lake Naval Air Weapons Station (CA); Vieques Island (PR); Kaho'olawe Island (HI); Letterkenny Army Depot (PA); unit brought in on a temporary basis to destroy dismantled fuze units at the Talon Manufacturing Company (WV)	MDAS scrap metal, offgas	Y	N

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[54] These facilities were noted in literature as having used the technology in a pilot test or at full scale (currently or in the past). Inclusion does not necessarily denote success. The EPA, state, or facility personnel contacted to confirm information on usage are acknowledged at the end of Appendix D.

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[53]	Facilities Applied[54]	Output	Pre-Treatment	Post-Treatment
Decontamination											
Flashing Furnace (continued)											
L&L Special Furnace/Industrial Waste Processor	Y (U.S. Naval Weapons Station, Indian Head, MD)	Full	Fixed	Y	Y	N		Naval Weapons Station Indian Head, MD	MDAS scrap metal, filter dust, treated offgas.	Y	N
U.S. Army/Metal Parts Flashing Furnace (APE 2048)	N	Full	Semi-Portable	Y	Y	N		Tooele Army Depot (UT) (small arms brass processing); Blue Grass Army Depot (KY) (remove explosive residue from metal parts)	MDAS scrap metal, offgas.	Y	Y
Decineration											
U.S. Demil, LLC/Decineration™	N	Full	Fixed	Y	Y	N		500 lb/hr pilot plant at Tooele Army Depot (UT)	MDAS scrap metal, treated offgas	N	N
Car Bottom Furnace											
General Dynamics Ordnance and Tactical Systems (OTS)/Car Bottom Furnace	N	Full	Fixed	Y	N	Y	HA,HC,PB,PC,PD	Commercial demilitarization facility in Carthage, MO (conventional munitions and Takata airbags)	MDAS scrap metal, sodium salts from reaction of soda ash with sulfur oxides and hydrochloric acid in offgas treatment, and particulate wastes from offgas treatment.	Y	N

Vendor/Technology	DDESB Approved	Scale	Portability	Thin-case	Thick-case	Bulk Explosives/ Propellant	MIDAS Codes[53]	Facilities Applied[54]	Output	Pre-Treatment	Post-Treatment
Decontamination											
Chemical Decontamination											
MuniRem®											
MuniRem Environmental, LLC/MuniRem®	N	Full	Portable	Y	Y	N	HD,HE,PD	Lake City Army Ammunition Plant (AAP), MO to decontaminate building that was demolished; Applied at Camp Minden, LA, to decontaminate equipment and building following explosion of a storage magazine containing clean burning igniter (CBI). Treatment removed explosive risks on the surfaces of the magazine doors and floors.	Alkyl effluent, MDAS scrap metal, nitrogen, carbon dioxide, sulfate, nitrogen dioxide, formate, and acetate.	Y	Y
Actodemil®											
ARCTECH/Actodemil Non-Thermal Humic Acid Catalyzed Hydrolysis-Neutralization Technology	N	Full	Fixed	Y	Y	N	HD,HE,PD	McAlester Army Ammo Plant (prototype unit); Research and development for propellants at Crane Army Ammunition Activity (IN) in the 1990s. Used to decontaminate equipment and buildings at Iowa AAP.	MDAS scrap metal, fertilizer for land application, treated offgas	Y	N

Facilities Applied Acknowledgements
The following people provided input on the facilities listed in the Facilities Applied column of the Appendix D Technologies Matrices:

- Blue Grass Army Depot: Dale Burton, Kentucky Department of Environmental Quality
- Camp Minden: Karen Price and Robert Thomas, Louisiana Department of Environmental Quality
- Commercial demil facility: Nathan Kraus, Missouri Department of Natural Resources
- Crane AAA: Paula Bansch and Jeff Workman, Indiana Department of Environmental Quality, and Doug Johnson, Crane AAA
- Deseret Chemical Depot: Jesse Newland, EPA Region 8
- Dugway Proving Grounds: Jesse Newland, EPA Region 8
- Hawthorne Army Depot: Mike Leigh, Nevada Department of Environmental Protection
- Hill Air Force Base: Jesse Newland, EPA Region 8
- Holston AAP: Terri Crosby-Vega, EPA Region 4, and Travis Blake and Jerry Swinea, Tennessee Department of Environmental Conservation
- Iowa AAP: Ruby Crysler, EPA Region 7
- Kaho'olawe Island: Amanda Cruz, EPA Region 9, Noa Klein and Paul Kalaiwaa, Hawaii Department of Health
- Lake City AAP: Rich Nussbaum, Missouri Department of Natural Resources
- Letterkenny Army Depot: Linda Houseal, Pennsylvania Department of Environmental Protection
- Lone Star AAP: Anna Lleras, Texas Commission on Environmental Quality
- McAlester AAP: Jon Fields and Zachary Paden, Oklahoma Department of Environmental Quality
- Milan AAP: Terri Crosby-Vega, EPA Region 4, and Jerry Swinea, Tennessee Department of Environmental Conservation
- Naval Weapon Station Seal Beach: Stephen Niou, California Department of Toxic Substances Control
- Picatinny Arsenal, Jennifer Meyers, New Jersey Department of Environmental Protection
- Pueblo Chemical Depot: Deb Anderson, Colorado Department of Public Health and Environment
- Radford AAP: Ashby Scott, Virginal Department of Environmental Quality
- Santa Susana Field Laboratory: Sam Coe and Paul Carpenter California Department of Toxic Substances Control
- Schofield Barracks: Amanda Cruz, EPA Region 9, Noa Klein and Paul Kalaiwaa, Hawaii Department of Health
- Spring Valley Superfund site: Rachel Mirro, EPA Region 3
- Talon Manufacturing: Rachel Mirro, EPA Region 3
- Tooele Army Depot: Jesse Newland, EPA Region 8
- United Technologies: Sam Coe, California Department of Toxic Substances Control
- Yuma Proving Ground: Anthony Leverock, Arizona Department of Environmental Quality