BIOREMEDIATION OF EXPLOSIVES-CONTAMINATED SOILS: A STATUS REVIEW

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ABSTRACT

The investigation of past operational and disposal practices at federal facilities and formerly used defense sites (FUDS) has dramatically increased in the past several years. The manufacture; load, assembly and pack (LAP); demilitarization; washout operations; and open burn/open detonation (OB/OD) of ordnance and explosives has resulted in contamination of soils with munitions residues. The primary constituents are nitroaromatic and nitramine organic compounds and heavy metals. A number of sites have soil contamination remaining where waste disposal practices were discontinued 20 to 50 years ago.

In conjunction with site investigations, biological treatment studies have been undertaken to evaluate the potential for full scale remediation of organic contaminants. This paper evaluates the results of 15 bioremediation treatability studies conducted at eight sites for explosives-contaminated soils, and discusses the full scale remedial implementation status. Five types of biological treatment processes have been evaluated: (1) composting, (2) anaerobic bioslurry, (3) aerobic bioslurry, (4) white rot fungus treatment and (5) landfarming. Representative bench and pilot scale studies were conducted using site-specific munitions residues to determine the ability to meet preliminary remediation goals (PRGs) or cleanup levels, and to identify issues related to scale-up of the technologies.

Composting has been selected as the full scale remedial action treatment remedy at two National Priority List (NPL) sites: (1) Umatilla Army Depot Activity, Hermiston, Oregon, for 14,800 tons of soil contaminated with TNT (2,4,6-trinitrotoluene), RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) and HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine), and (2) U.S. Naval Submarine Base, Bangor, Washington, for 2,200 tons of TNT-contaminated soils. Pilot scale composting treatability studies have demonstrated the ability to achieve risk-based cleanup levels of 30 to 33 parts per million (ppm) for TNT and 9 to 30 ppm for RDX after 40 days of treatment, with a destruction and removal efficiency (DRE) of greater than 99.0%. Feasibility Study (FS) estimates of treatment costs range from \$206 to \$766 per ton for quantities of 1,200 to 30,000 tons—40% to 50% less than on-site incineration. In the past, all NPL sites with explosives contamination have used incineration as the selected treatment technology. Actual costs for biotreatment will be refined during full scale remediation.

KEY WORDS

explosives, munitions, ordnance, bioremediation, biological treatment

BACKGROUND

The investigation of past disposal practices at federal facilities and formerly used defense sites (FUDS) has dramatically increased in the past several years. The manufacture; load, assembly and pack (LAP); demilitarization; washout operations; and open burn/open detonation (OB/OD) of ordnance and explosives have resulted in soils contaminated with munitions residues. In conjunction with site investigations, biological treatment studies have been undertaken to evaluate the potential for full scale remediation. This paper evaluates the results of 15 bioremediation treatability studies conducted at eight sites for explosives-contaminated soils and the full scale remedial implementation status.

WASTE STREAMS

The primary constituents of waste streams from explosives operations that result in soil contamination are nitroaromatics and nitramines including:

Acronym	Compound Name
TNT	2,4,6-trinitrotoluene
RDX	Hexahydro-1,3,5-trinitro-1,3,5-triazine
HMX	Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
Tetryl	Methyl-2,4,6-trinitrophenylnitramine
Picric Acid	2,4,6-trinitrophenol
PETN	Pentaerythritol tetranitrate
TATB	Triaminotrinitrobenzene

The most frequently occurring impurities and degradation products from these include:

Acronym	Compound Name
2,4-DNT	2,4-dinitrotoluene
2,6-DNT	2,6-dinitrotoluene
2A-4,6-DNT	2-amino-4,6-dinitrotoluene
4A-2,6-DNT	4-amino-2,6-dinitrotoluene
TNB	1,3,5-trinitrobenzene
DNB	1,3-dinitrobenzene
NB	Nitrobenzene
Picramic Acid	2-amino-4,6-dinitrophenol

ANALYTICAL CHEMISTRY METHODS

The preferred laboratory analytical method for explosives analysis in soil and water is EPA SW-846 Method 8330, Nitroaromatics and Nitramines by High Performance Liquid Chromatography (HPLC). The use of HPLC for munitions residue analysis is a well developed procedure capable of detecting most explosives and degradation compounds of interest. HPLC does not destroy the more thermally unstable compounds, such as RDX and tetryl, that may occur during use of gas chromatography (GC) methods. Gas chromatography/mass spectrometer (GC-MS) and gas chromatography/electron capture device (GC-ECD) methods may have published detection limits that are lower than HPLC, but their results tend to exhibit poor repeatability and are more erratic on low level analysis of field soil and ground water sample matrices [1].

Recently developments in field screening methods for TNT and RDX provide a valuable tool for guiding site characterization and optimization of laboratory analysis [2, 3]. Two colorimeteric methods for TNT (SW-846 Method 8515) and RDX (SW-846 Method 8510) exist, and four enzyme immunoassay (EIA) methods for TNT (SW-846 Method 4050) and one for RDX (SW-846 Method 4051) are commercially available. The optimum method for use at a particular site is based on the specific objectives for the field investigation and a number of other factors. Field screening methods are particularly useful due to the heterogeneous nature of explosives in soil and the uneven waste disposal history at many sites, such as open-burn/open-detonation (OB/OD) practices [4, 5]. Application of field screening methods to biological treatment residues has been limited and may be subject to matrix interferences.

RISK ASSESSMENT

The most immediate and profound risk from explosives is that of potential reactivity. Explosives exist in soils and sediments as small crystals to large chunks. Applying the correct initiating source to one of these crystals will cause a detonation. The amount of damage caused is in direct proportion to the size of the crystal. The presence or absence of water has minimal effect on the reactivity of the soil [6]. A two test protocol has been developed and tested to determine the relationship between explosives-contaminated soil content and reactivity. The Zero Gap test and the Deflagration to Detonation Transition (DDT) indicate that soils with 12% or less total explosives concentration will not propagate a detonation or explode when heated under confinement [7]. U.S. EPA Region 10, the Oregon Department of Environmental Quality (DEQ), and U.S. Army Environmental Center (AEC) have used these results for determining the characteristic hazardous waste status of explosives-contaminated soil as a reactive waste under RCRA. The basis for the RCRA characteristic hazardous waste status is the assumed explosive reactivity of the soils if subjected to a strong initiating force or if heated under confinement (40 CFR 261.23). These results apply to explosives such as TNT, RDX, HMX, DNT, TNB and DNB, and do not apply to initiating compounds, such as lead azide, lead styphenate or mercury fulminate.

A baseline risk assessment is conducted to assess the potential human health and environmental impacts associated with soil contamination. The primary exposure pathways evaluated for explosives-contamin-ated surface soils are dust inhalation, soil ingestion and dermal absorption. Reasonable Maximum Exposure (RME) concentrations are based on the 95% upper confidence interval (UCI) on the arithmetic mean of soil sampling data. The land use scenarios quantitatively evaluated may include industrial and residential use, utilizing EPA standard default exposure parameters [8].

Toxicity values for explosives may be obtained from the EPA Integrated Risk Information System (IRIS) and Health Effects Summary Tables (HEAST) for carcinogenic Slope Factors (SF) and non-carcinogenic Reference Dose (RfD). EPA classifies the data regarding carcinogenicity according to weight-of-evidence classification. Group B (probable human) carcinogens such as 2,4-DNT and 2,6-DNT utilize carcinogenic slope factors. Group C (possible human) carcinogens, such as TNT and RDX, are evaluated for carcinogenic and non-carcinogenic risks, utilizing both SFs and RfDs. Group D (non-classifiable) carcinogens, such as HMX and TNB are evaluated using non-carcinogenic RfDs only. The carcinogenic risk and non-carcinogenic Hazard Index (HI) calculated for various land use scenarios indicate the need for cleanup actions, based on Superfund National Contingency Plan (NCP) criteria and EPA policy guidance [9, 10].

ENVIRONMENTAL FATE AND TRANSPORT

Under ambient environmental conditions, explosives are highly persistent in surface soils and ground water, exhibiting a resistance to naturally-occurring volatilization or biodegradation. A number of sites have high levels of soil and ground water contamination where waste disposal practices were discontinued 20 to 50 years ago. Where biodegradation does occur, monoamino-dinitrotoluenes (2A-4,6-DNT and 4A-2,6-DNT) and diamino-nitrotoluenes (2,4-DA-6-NT and 2,6-DA-4-NT) are the most commonly identified intermediates of TNT [11]. Biodegradation beyond these intermediates is not completely understood, but suggested pathways have been developed by Kaplan and Kaplan for aerobic degradation and by

Funk for anaerobic degradation of TNT [12, 13].

Biological treatment processes have been shown to both create and degrade amino-DNT compounds. Abiotic processes may also result in the formation of amino-DNT compounds. Photodegradation of TNT to TNB occurs in the presence of sunlight and water, with TNB being generally resistant to further degradation. Site characterization studies indicate that TNT is the least mobile of the explosives, and RDX is the most mobile. A number of previous laboratory scale treatability studies indicate the potential to biologically degrade explosives. Biodegradation of explosives is considered to be most favorable under co-metabolic conditions [11]. Biodegradation of TNT, RDX and HMX has been observed under both aerobic and anaerobic conditions, although the rate of degradation varies depending upon the specific contaminant. Laboratory biodegradation studies have been performed on both spiked soil samples and site-specific munitions residues. Studies conducted on site-specific munitions residues are preferred because they exhibit different desorption characteristics than spiked soil samples, and they are more representative of field operating conditions. This paper examines the results of representative bench and pilot scale treatability studies conducted on aged munitions residues.

TREATMENT PROCESSES

Five types of biological treatment systems have been evaluated for explosives contaminated soils: (1) composting, (2) anaerobic bioslurry, (3) aerobic bioslurry, (4) white rot fungus treatment and (5) landfarming. Composting is a variation of solid-phase biological treatment. The composting process can treat highly contaminated soil by adding a bulking agent (straw, bark, sawdust, wood chips) and organic amendments (manures, fruit and vegetable processing wastes) to the soil. The soil/amendment mixture is formed into piles and aerated (natural convection or forced air) in a contained system or by mechanically turning the pile. Bulking agents are added to the compost to improve texture, workability and aeration; carbon and nitrogen additives provide a source of metabolic heat. The composting environment is characterized by elevated temperatures (> 30ºC), plentiful nutrients, high moisture levels (> 50%), sufficient oxygen and a neutral pH. Waste decomposition occurs at higher temperatures resulting from increased biological activity within the treatment bed. One potential disadvantage of composting is the increased volume of treated material due to the addition of bulking agents. Irrigation techniques can optimize moisture and nutrient control, and an enclosed system can achieve air emissions control. During slurry phase biological treatment, excavated soils or sludges are mixed with water in a tank or lagoon to create a slurry, which is then mechanically agitated. The procedure adds appropriate nutrients and controls the levels of oxygen, pH and temperature. A potential advantage of slurry phase treatment over solid phase treatment is the high degree of mixing and the effective contact between contaminated soils and nutrients. Following treatment in the reactor, the soil must be separated from the slurry by gravity settling and/or mechanical dewatering for redisposal. The water from the slurry may be recycled and/or treated and disposed. Slurry phase systems tend to have the highest capital and operating costs as compared to other biological treatment systems. White rot fungus treatment is similar to other forms of solid phase treatment, with the addition of a fungal inoculant. Bulking agents such as wood chip or corn cobs and nutrients specific for growth of fungal populations may be added to optimize treatment conditions. Landfarming places contaminated soil in a thin layer (typically 12 to 18 inches deep) in a lined treatment bed. Generally nutrients such as nitrogen and phosphorus are added. The bed is usually lined with clay or plastic liners, furnished with irrigation, drainage and soil-water monitoring systems, and surrounded by a berm. This process is one of the older and more widely used biological treatment technologies for waste treatment. Landfarming is relatively simple and inexpensive to implement, but has a lower level of process control compared to other forms of biological treatment. Landfarming is also relatively land intensive due to the thin layer of soil required for aerobic treatment.

Explosives treatment processes use two general approaches to bioremediation—biostimulation and bioaugmentation. Biostimulation relies on altering external conditions such as temperature, mixing, nutrients, pH, soil loading rates and oxygen transfer to favorable conditions for growth of native microbial populations. Bioaugmentation relies on these same factors to a lesser extent, and also relies on the use of additional inoculants to increase the performance of the system. Inoculants usually employ cultures taken from other sites known to contain explosives-degrading microbial or fungal populations.

Composting and aerobic bioslurry systems for explosives-contaminated soils generally use the biostimulation approach. Inoculation of these systems has not substantially increased the overall efficiency of the treatment process [14-16]. Anaerobic bioslurry, white rot fungus treatment and landfarming have generally used the bioaugmentation approach. Some overlap occurs

Treatment Technology/Site	Chemical	Quantity	Initial/Final Concentration (mg/kg)	DRE (%)	Treatment Time (days)
Composting					
Bangor, WA[17]		1 kg			
Site A	TNT		2200/22	99.0	
Site D	TNT		193/0.5	99.7	
Site F	TNT		73/<0.2	>99.7	
	Mean		**822/8**	**99.5**	**60**
Anaerobic Bioslurry					
WSOW, MO[25]	TNT	20 gm	**2000/7**	**99.5**	**25**
Bangor, WA[17]		20 L			
Site D	TNT		154/16	89.6	
Site F	TNT		125/1	99.2	
	Mean		**140/9**	**94.4**	**80**
Aerobic Bioslurry					
Hastings, NE[15]		5 L			
	TNT		18572/ND	>99.9	
	2A-4,6-DNT		282/346	-22.7	
	Mean		**9427/173**	**38.6**	**77**
Mead, NE[22]		Unknown			
	TNT		1730/901	47.9	
	RDX		539/433	19.7	
	HMX		80/79	1.3	
	Mean		**783/471**	**23.0**	**16**
White Rot Fungus Treatment					
Bangor, WA[20]	TNT	2.5 kg	**1844/1087**	**41.1**	**120**

Table 1. Bench scale treatability studies.

in the presence or absence of inoculants in aerobic and anaerobic bioslurry treatment systems [17-22].

MINERALIZATION/ TOXICOLOGY

With an incomplete understanding of the complete TNT biodegradation pathway, laboratory and bench scale treatability studies have employed the use of radiolabeled (^{14}C) TNT to establish mass balances for the extent of mineralization. Results of radiolabeled studies indicate 5% to 30% mineralization in compost residues, 15% to 23% in aerobic bioslurry reactors, and up to

Treatment Technology/Site	Chemical	Quantity (cu yds)	Initial/Final Conc. (mg/kg)	DRE (%)	Treatment Time (days)
Composting					
LAAP, LA[11]					
Static Piles (36% Soil, Sawdust/Straw/Manure Mix)					
Mesophilic	TNT	14	2970/1075	63.8	
(35ºC)	RDX		1825/1897	-3.9	
	HMX		256/276	-7.8	
	Mean		**1684/1083**	**17.3**	**33**
Thermophilic	TNT	14	2970/469	84.2	
(50ºC)	RDX		1825/1707	6.5	
	HMX		256/307	-19.9	
	Mean		**1683/828**	**23.6**	**33**
Static Piles (3% Soil, Alfalfa/Straw/Manure/Horse Fee Mix)					
Mesophilic	TNT	14	11187/50	99.6	
(35ºC)	RDX		4630/242	94.8	
	HMX		643/84	86.8	
	Mean		**5487/125**	**93.7**	**153**
Thermophilic	TNT	14	11840/3	99.9	
(35ºC)	RDX		5293/45	99.1	
	HMX		739/26	96.5	
	Mean		**5957/25**	**98.5**	**153**
Umatilla, OR[14]					
Thermophilic (50ºC)					
Static Piles	TNT	3	4984/200	95.9	
(10% Soil, Mix A)	RDX		1008/542	46.2	
	HMX		180/12	21.3	
	Mean		**2057/295**	**54.5**	**90**
MAIV	TNT	3	3452/90	97.4	
(10% Soil, Mix A)	RDX		1011/104	89.7	
	HMX		169/120	28.8	
	Mean		**1544/105**	**72.0**	**44**
MAIV	TNT	3	3126/5	99.8	
(10% Soil, Mix B)	RDX		574/3	99.3	
	HMX		119/6	94.9	
	Mean		**1273/5**	**98.0**	**44**
MAIV	TNT	3	5208/14	99.7	
(25% Soil, Mix C)	RDX		597/18	97.0	
	HMX		161/51	68.0	
	Mean		**1989/28**	**98.6**	**44**
Hercules, CA[21]					
Mulch Box	TNT	1	1965/574	75.8	
	2,6-DNT		2351/186	92.1	
	2,4-DNT		1942/233	88.0	
	Mean		**2086/298**	**85.3**	**235**

MAIV - Mechanically Agitated In-Vessel Reactor

Table 2. Pilot scale treatability studies (continued in next table).

80% mineralization in mixed anaerobic/aerobic treatment system sludges [23-25]. The use of radiolabeled TNT in pilot scale treatability studies is generally prohibitive due to the administrative and safety requirements for handling and analysis of the large quantities of radioactive material that would be required. It is also doubtful whether spiked, radiolabeled TNT samples can be considered truly representative of aged munitions residues in soil.

An alternative approach to mineralization studies is to employ the use of toxicity and

Treatment Technology/Site	Chemical	Quantity (cu yds)	Initial/Final Conc. (mg/kg)	DRE (%)	Treatment Time (days)
Umatilla, OR[27, 42]					
Windrows (Thermophilic, Mixed, 30% Soil, Mix C)					
Forced Aeration	TNT	30	1869/4	99.8	
	RDX		1069/8	99.3	
	HMX		175/47	73.1	
	Mean		**1038/20**	**90.7**	**40**
Unaerated	TNT	30	1574/4	99.7	
	RDX		944/2	99.8	
	HMX		159/5	96.9	
	Mean		**892/4**	**98.8**	**40**
Windrows (Full Scale Treatment Trials)					
	TNT	411	296/2.3	99.2	
	RDX		290/1.2	99.6	
	HMX		26.9/11.0	59.1	
	Mean		**204/4.8**	**86.0**	**30**
Bangor, WA[43]					
Windrows		30			
Site D	TNT		**146/41**	**71.9**	**60**
Site F	TNT		636/1.0	99.8	
	RDX		48/<1.0	97.9	
	HMX		37/1.5	95.9	
	Mean		**204/1.2**	**97.9**	**60**
Anaerobic Bioslurry					
WSOW, MO[18]	TNT	18	**1500/44**	**97.1**	**150**
Bangor, WA[43]		10			
Site D	TNT		**535/75**	**86.0**	**60**
Site F	TNT		199/22	88.9	
	RDX		22/<1.0	95.5	
	HMX		30/7.7	74.3	
	Mean		**83.6/10.2**	**86.2**	**60**
Aerobic Bioslurry					
JAAP, IL[19]	TNT	400 (gal)	3000/20	99.3	70
	TNT		3000/35	98.8	35
	Mean		**3000/28**	**99.1**	**53**
Landfarming					
Hercules, CA[21]					
Cultured Bacteria	TNT	1	1189/1140	4.1	
	2,6-DNT		1517/915	39.7	
	2,4-DNT		1409/664	52.9	
	Mean		**1372/906**	**32.2**	**235**

Table 2 (cont.). Pilot scale treatability studies.

leachability tests to evaluate bioremediation treatment residues. The advantage of this approach is that it can be conducted on pilot scale studies and can be used to evaluate the environmental effects of multiple explosives, intermediate compounds, final degradation products and interactions with soil humic materials in the same treatment process. This approach is also consistent with the Superfund National Contingency Plan (NCP) objectives of evaluating the toxicity, mobility and volume reduction effects of innovative treatment technologies. Toxicity tests that have been used for explosives bioremediation treatment residues include: (1) Microtox (2) Ames assays for mutagenicity, (3) aquatic toxicology tests on soil leachates, (4) oral rat feeding studies and (5) earthworm toxicity tests. Toxicology and leachability tests were performed on pilot scale compost residues from the Umatilla Army Depot Activity to evaluate toxicity and mobility effects compared to untreated soils. Toxicity results showed 87% to 92% reduction of leachate toxicity to Ceriodaphnia dubia, and 99.3% to 99.6% reduction in mutagenicity for Ames assays using strains TA-98 and TA-100. A brief oral rat feeding study did not produce mortality from consumption of compost residues. Leachable concentrations for TNT, RDX and HMX were reduced by greater than 99.6%, 98.6% and 97.3%, respectively, using the EPA Synthetic Precipitation Leach Procedure (SPLP) (SW-846 Method 1312) [14, 26, 27]. Toxicology tests are currently being performed on treatment residues from the anaerobic bioslurry pilot scale test conducted at the Weldon Springs Ordnance Works, Missouri, NPL site as part of the EPA Superfund Innovative Technology Evaluation (SITE) Program. An Innovative Technology Evaluation Report will be available in 1995 [28]. Planned toxicology tests for the Joliet Army Ammunition Plant (JAAP) pilot scale demonstration of aerobic slurry-based treatment will be similar to those conducted at the Umatilla site.

RESULTS/CONCLUSIONS

The results of bench scale treatability studies are shown in Table 1, and pilot scale studies are shown in Table 2. The waste disposal history and site characterization at explosives-contaminated sites indicate that munitions residues in soils are extremely heterogeneous. The variability in

Technology (Site)	DRE (%)	Treatment Time (days)	Toxicity/ Mobility Reduction (%)	Post-Treatment Volume (%)	Projected Treatment Costs ($/ton)
Composting (Umatilla)	99.7	40	87-99.6/>99.6	+ 50% - 100%	206-766*
Anaerobic Bioslurry (WSOW)	97.1	150	Ongoing	Slight + (dewatered)	200-600**
Aerobic Bioslurry (Joliet)	99.1	35-70	Ongoing	Slight + (dewatered)	Unknown
White Rot Fungus (Bangor)	41.1	120	Unknown	+ 60%	Unknown
Landfarming (Hercules)	4.1	235	Unknown	Unknown	Unknown

* = Feasibility study estimate.
** = Vendor estimate.

Table 3. Summary of pilot/field scale TNT biotreatment parameters.

soil concentration is often attributed to analytical error, but is usually representative of site conditions. The heterogeneous nature of explosives in soils presents a challenge for adequately designing and assessing the performance of biological treatment systems. Bench scale treatability studies cannot adequately address variability in soil concentrations and material handling issues related to full scale remediation. Due to these factors, process control is a major component in optimizing the performance of biological treatment technologies for explosives-contaminated soils, and it strongly supports the use of ex-situ treatment technologies. In-situ biological technologies for explosives have many inherent difficulties due to: (1) heterogeneous concentrations in soil, (2) extremely low volatility, (3) unfavorable soil/water partitioning, particularly for TNT, (4) co-metabolic degradation is optimum, (5) an increase in the mobility of parent explosives and intermediate compounds during biological treatment, and the (6) strong influence of mixing on treatment performance. Initial results also indicate that soils from open burn/open detonation (OB/OD) sites may have more tightly bound residues than wastewater lagoons or spill sites. OB/OD sites may require more intensive mixing and materials handling procedures and longer treatment times during full scale remediation.

Composting, aerobic bioslurry and anaerobic bioslurry treatment have shown the greatest destruction and removal efficiencies and meet or approach preliminary remediation goals (PRGs) for site cleanup. These processes are also the most highly engineered systems with the greatest level of process control. At the current state of development, white rot fungus treatment and landfarming have been substantially unable to meet PRGs, show low or moderate treatment performance, and appear to be nutrient and/or bioavailability limited. In addition, white rot fungus exhibits toxicity inhibition at moderate and high concentrations of TNT, and competition from native microbial populations [14, 20, 29, 30]. Table 3 provides a summary of representative biotreatment parameters for pilot/field scale studies of TNT degradation for each of the five processes. Composting is the most fully optimized treatment system to date, followed by anaerobic bioslurry, aerobic bioslurry, landfarming and white rot fungus treatment. In general, two pilot scale treatability studies have been required to fully optimize a particular treatment process. The results indicate the following optimization parameters for biological treatment processes: temperature, mixing, nutrient selection, pH, soil loading rate, oxygen transfer and inoculant addition.

RECOMMENDATIONS

Five primary criteria are suggested for evaluating bioremediation as the full-scale treatment alternative for explosives-contam-inated soil. Table 4 indicates how

Technology	Pilot Scale Tested?	Meets Cleanup Levels?	Nutrient/ Bioavailability Limited?	Inoculation Required?	Sensitive to Soil Type?
Composting	Yes	Yes	No	No	No
Anaerobic Bioslurry	Yes	Yes	No	Maybe	Yes
Aerobic Bioslurry	Yes	Yes	No	Maybe	Unknown
White Rot Fungus	No	No	Yes	Yes	Unknown
Landfarming	Yes	No	Yes	Yes	Unknown

Table 4. Explosives-contaminated soils bioremediation remedy selection considerations.

each of the explosives bioremediation treatment processes meet these criteria: (1) Has a pilot scale treatability study been completed? This addresses optimization parameters, materials handling, and refines analytical variability, reaction kinetics, treatment times and unit costs. (2) Does the pilot scale study meet preliminary remediation goals (PRGs) or cleanup levels? The pilot scale study should clearly demonstrate the ability to achieve PRGs or cleanup levels. Extrapolation of data should not be used, since many explosives biotreatment studies do not demonstrate predictable degradation rates such as linear or first-order decay. The range of treatment cleanup criteria established in Records of Decision (RODs) for seven facilities with explosives-contaminated soils in five EPA Regions [31-33, 41] are shown in Table 5. Based on these criteria, PRGs of 30 ppm for TNT, 50 ppm for RDX, and 5 ppm for 2,4-DNT and 2,6-DNT are suggested. (3) Do the treatability studies (bench and pilot scale) suggest nutrient and/or bioavailability limitations? If there are substantial differences in the performance of the system between the bench and pilot scale treatability studies, the problem should be evaluated. Operating parameters which were controlled during bench scale may have been different under field conditions. These parameters should be resolved before proceeding to full scale. (4) Does inoculation increase the performance of the system or is it required to meet the cleanup levels? If inoculation is required, then acclimation of the inoculant to field conditions becomes critical to success of the treatment system. Inoculation may also affect whether the technology is proprietary and requires an agreement or license to implement. (5) Is the process sensitive to soil type? Biotreatment systems may perform differently on different soil types. If the treatment technology has not been tested on soils similar to the site under consideration, a treatability study should be conducted to verify performance. Unlike incineration, bioremediation is always a site-specific remedy.

Chemical	Treatment Criteria (mg/kg)
TNT	1 to 33
RDX	1 to 52
HMX	1 to 3722
Tetryl	1 to 112
2,4-DNT	0.42 to 5
2,6-DNT	0.40 to 5
TNB	1 to 15
DNB	1 to 7.4
NB	1 to 37

Sites	EPA Region
AAAP - Alabama Army Ammunition Plant, AL	4
SADA - Savanna Army Depot Activity, IL	5
LAAP - Louisiana Army Ammunition Plant, LA	6
CAAP - Cornhusker Army Ammunition Plant, NE	7
WSOW - Weldon Springs Ordnance Works, MO	7
UMDA - Umatilla Army Depot Activity, OR	10
BANGOR - Naval Submarine Base Bangor, WA	10

Table 5. Summary of explosives cleanup levels.

REMEDY SELECTION

Based on the results of the treatability studies and a number of other factors, composting was selected as the full scale remedial action treatment remedy at two National Priority List (NPL) sites: (1) Umatilla Army Depot Activity, Hermiston, Oregon, for 14,800 tons of TNT-, RDX- and HMX-contaminated soils, and (2) the U.S. Naval Submarine Base, Bangor, Washington, for 2,200 tons of TNT-contaminated soils [31, 32]. The pilot scale composting treatability studies demonstrated the ability to achieve site specific risk-based cleanup levels of 30 to 33 ppm for TNT and 9 to 30 ppm for RDX after 40 days of treatment, with a destruction and removal efficiency (DRE) of greater than 99.0%. Feasibility Study (FS) estimates indicate projected treatment costs of $206 to $766 per ton for quantities of 1,200 to 30,000 tons—40% to 50% less than on-site incineration [34, 35]. The composting process mixes organic amendments, such as manure, wood chips, alfalfa and vegetable processing wastes with contaminated soil. The process utilizes native aerobic thermophilic microorganisms and requires no inoculation. Amendments serve as a source of carbon and nitrogen for thermophiles, which degrade explosives under co-metabolic conditions. Optimization process parameters that affect composting performance are shown in Table 6 [11, 14, 17, 27]. The composting process is suitable for soils and sludges. Rocks and debris can be crushed or shredded and treated with soils. The process does not appear to be particularly sensitive to soil type. Umatilla soils are sands/gravel and SUBASE Bangor soils are loams and glacial till. Additionally, composting produces no emissions of explosives into the air, no leachate, and does not require dewatering upon completion of treatment. Compost residues will support growth of vegetation after treatment, unlike incinerator ash or soils treated by solidification/stabilization.

Process Parameter	Range Tested	DRE Change (%)	Optimal Condition	Comments
Temperature	30-60ºC	7	50-55ºC	Thermophilic conditions superior
Mixing	Static piles, MAIV, windrows	18	Windrows	Mixed systems treat faster and to lower levels
Amendment Selection	Mix A, B, C	25	Mix C	Probably the most critical parameter, looking for "energetically viable" nutrients, also effects the formation of intermediate compounds
Soil Loading Rate	3%-40%	42	30%	Up to 30% soil loading is effective
Oxygen Transfer	<1%-20%	8	Unknown	The minimum interstitial O_2 required is unknown
pH	4.7-9.4	Unknown	Not Controlled	Ambient Parameter

MAIV - Mechanically agitated in-vessel reactor.

Mix A - Potato waste (35%), sawdust (30%), chicken manure (20%), apple pomace (15%) (by volume).

Mix B - Horse manure/straw (50%), alfalfa (22%), sawdust (22%), potato waste (17%), apple pomace (6%) (by volume).

Mix C - Cow manure (33%), alfalfa (22%), sawdust (22%), potato waste (17%), apple pomace (6%) (by volume).

Table 6. Optimization parameters for explosives composting.

REMEDIAL DESIGN/REMEDIAL ACTION (RD/RA)

Since a majority of explosives-contaminated sites are federal facilities or formerly used defense sites (FUDS), a discussion of government contracting procedures for Remedial Design/Remedial Action (RD/RA) is appropriate. The pilot scale treatability test may serve as a 30% Remedial Design (RD) and should be included as government-furnished information in the Remedial Action (RA) solicitation/contract documents to provide independent verification that the selected biotreatment system is capable of achieving the cleanup levels required for the site. The Remedial Design (RD) should also focus on developing performance specifications so that a Request for Proposals (RFP) or pre-placed Remedial Action contract can be bid and awarded. An RFP or pre-placed RA contract will allow the site's technical evaluation team to clearly evaluate the contractor's capability to perform in accordance with the solicitation requirements prior to implementation of the full scale treatment system.

If proprietary biotreatment processes are proposed, sole source contracting or procurement may be required to obtain the services of the treatment vendor. Sole source procurement under government contracting procedures requires extensive justification and, in many cases, may not be possible if there are other processes or contractors that can meet the government's minimum performance specifications. Contracting officers should also clearly evaluate what procedures are in place should the contractor's treatment system fail to meet the cleanup criteria established for the site. Full scale treatment trials, similar in function to incineration test burns, should be performed before beginning full scale operations. Value engineering (VE) sessions may be of limited usefulness where there is no previous full scale treatment experience, except for materials handling processes [36]. The RD should include an explosives safety hazards analysis by a competent explosives safety expert. All contaminated soils handling and treatment equipment should be evaluated to identify any concerns or equipment modifications required for full scale materials handling operations. Unexploded ordnance (UXO) may also be present at disposal sites and presents a serious safety concern. UXOs must be located and removed or deactivated before excavation work begins.

Umatilla Army Depot and Naval Submarine Base Bangor are currently involved in Remedial Design (RD) of composting bioremediation treatment systems [37]. Umatilla has completed excavation and stockpiled 14,800 tons of soil for treatment. The Seattle District Corp of Engineers (COE), EPA Region 10, Oregon DEQ and the U.S. Army Environmental Center are reviewing the Remedial Action Management Plan (RAMP) for full scale treatment operations [38]. Full scale treatment trials are scheduled to begin in mid-1995. SUBASE Bangor has completed pilot scale treatment trials which began in late 1994. The results of the treatability study and development of the Remedial Design will be reviewed by the U.S. Navy, EPA Region 10 and the Washington Department of Ecology [39]. Both the Umatilla and Bangor sites utilize an asphalt liner and temporary building to house the biotreatment system [40]. Consistent with the Superfund National Contingency Plan (NCP) objectives, biological treatment of explosives-contaminated soils provides the opportunity to implement effective innovative treatment technologies at a lower cost than incineration. In the past, incineration has been used as the selected treatment technology at all NPL sites with explosives-contaminated soil. Actual costs for biological treatment will be refined during full scale remediation.

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