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# Evaluation of Processes for Remediating Explosives- Contaminated Debris

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Contract No. DAAL03-91-C-0034  
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Scientific Services Program

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May 1994

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SFIM-REC-TSD  
Aberdeen Proving Ground, MD 21010-5401

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**Final Report**

**EVALUATION OF PROCESSES  
FOR  
REMIEDIATING EXPLOSIVES-CONTAMINATED DEBRIS**

**Prepared for**

**U.S. ARMY ENVIRONMENTAL CENTER (USAEC)  
SFIM-AEC-TSD  
Aberdeen Proving Ground, MD 21010-5401**

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## Executive Summary

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This study identified, described, and evaluated technologies to facilitate remediation of oversize explosives-contaminated debris. During composting of explosives-contaminated soil at military installations, such debris interferes with the operation of the flail-type windrow equipment used to turn and aerate the composting soil. The study examined size reduction and return of the crushed debris to the compost pile and removal of the contaminants from the debris followed by disposal of the cleaned debris. If the debris is to be returned to the compost pile, the particle size must be less than ½-inch diameter. For removal, the explosives contaminants level must be reduced to below 30 mg/kg.

The technologies evaluated were (1) thermal/hot-gas decontamination; (2) composting debris crushed to less than ½-inch diameter; (3) enhanced soil washing with surfactants or other solubility enhancers; and (4) chemical degradation. Literature reports indicated that chemical degradation was impractical for explosives-contaminated solids. This technology was not evaluated in detail. For the first three technologies, the evaluation considered effectiveness, implementability, and cost. Thermal decontamination is the most expensive of the technologies. Size reduction through crushing does not generate further waste requiring treatment, as does enhanced soil washing.

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## Acronyms and Abbreviations

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<b>COE</b>	<b>U.S. Army Corps of Engineers</b>
<b>DAVE</b>	<b>Desorption and Vaporization Extraction</b>
<b>2,4-DNT</b>	<b>2,4-dinitrotoluene</b>
<b>HMX</b>	<b>High Melting Explosive (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine)</b>
<b>LT<sup>3</sup></b>	<b>Low Temperature Thermal Treatment</b>
<b>LTTA</b>	<b>Low Temperature Thermal Aeration</b>
<b>PCB</b>	<b>polychlorinated biphenyl</b>
<b>RCRA</b>	<b>Resource Conservation and Recovery Act</b>
<b>RDX</b>	<b>Royal Demolition Explosive (hexahydro-1,3,5-trinitro-1,3,5-triazine)</b>
<b>SVOC</b>	<b>semivolatile organic compound</b>
<b>TNB</b>	<b>trinitrobenzene</b>
<b>TNT</b>	<b>2,4,6-trinitrotoluene</b>
<b>USAEC</b>	<b>U.S. Army Environmental Center</b>
<b>USATHAMA</b>	<b>U.S. Army Toxic and Hazardous Materials Agency</b>
<b>U.S. EPA</b>	<b>U.S. Environmental Protection Agency</b>
<b>UV</b>	<b>ultraviolet</b>
<b>VOC</b>	<b>volatile organic compound</b>

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## 1.0 Introduction

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The purpose of this study was to identify, describe, and evaluate technologies to facilitate remediation of explosives-contaminated debris. Soil contaminated with explosives is encountered at numerous military installations. Typical remediation consists of excavation followed by incineration, a highly effective although relatively high-cost technology. The U.S. Army Environmental Center (USAEC) has recently sponsored bench- and pilot-scale treatability studies demonstrating the effectiveness of explosives degradation via composting. Composting is an innovative technology for this application and has the potential for providing effective treatment at a moderate cost.

During composting, the contaminated soil must be periodically turned with flail-type windrow equipment to provide aeration. The rock debris in the contaminated soil decreases the operating efficiency of the equipment used to turn and aerate the soil. The rocks are thrown by the turning equipment, causing them to be potentially damaging projectiles.

The study examined two general methods to process the contaminated debris: (1) size reduction and return of the crushed debris to the compost pile or (2) removal of the contaminants from the debris followed by disposal of the cleaned debris. The cleanup goals for these two end points differ. If the debris is to be returned to the compost pile, the physical form (particle size) must be altered to be consistent with operation of flail-type composting equipment. The target particle size to allow return to the compost pile is less than ½-inch diameter. For contaminant removal options, the cleanup goal is to reduce the explosives contaminants level to below 30 mg/kg.

Four technologies for removal of explosives from contaminated debris were evaluated:

- Thermal/hot-gas decontamination (see Section 3.2)
- Composting debris crushed to less than ½-inch diameter (see Section 3.3)
- Enhanced soil washing with surfactants or other solubility enhancers (see Section 3.4)
- Chemical degradation (see Section 3.5)

The evaluations of the first three technologies considered effectiveness, implementability, and costs. Literature reports indicate that chemical degradation is not expected to be efficiently implementable for treatment of explosives-contaminated debris. Chemical degradation was not evaluated in detail.

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## 2.0 Typical Wastes Treated

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The identification, quantification, and characterization of the contaminants present at a site form the logical and necessary basis to study the applicability of a treatment technology. Characteristics influencing selection of remedial options for explosives-contaminated debris include:

- **Contaminant Type.** Typical military explosives include TNT, RDX, HMX, TNB, and 2,4-DNT.
- **Form of the Contaminated Matrix.** The contaminated matrix is rocks and similar debris with a particle size over ½-inch diameter.
- **Quantity of Debris Requiring Remediation.** The quantity of explosives-contaminated debris is in the range of 2,000 to 25,000 tons. The debris is assumed to be 20% of the total weight of the soil being composted.
- **Water Solubility.** The explosives considered as potential contaminants have low water solubility, typically less than 200 mg/L.
- **Solubility in Organic Fluids.** The explosives considered as potential contaminants are soluble in many organic solvents.
- **Ignitability and Reactivity.** The Army Environmental Center (AEC) has established a guideline that soils containing more than 10% energetic material by weight should be considered explosive during handling and transportation. Most soils and sludges containing less than 10% energetic material will pass AEC criteria for nonreactivity (U.S. EPA, 1993a, EPA/625/R-93/013). The technology evaluation for treatment of explosives-contaminated debris assumes that the concentration of energetic material in the soil with debris is below the AEC reactivity threshold and does not exhibit RCRA ignitability or reactivity characteristics.

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## 3.0 Technology Descriptions

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### 3.1 Pretreatment

All treatment technologies require an initial step to separate the debris from the soil prior to further processing. Physical screening by size can be used to separate debris from the soil. Screening through parallel grizzly bars and/or coarse mesh screens is effective, easily implemented, and inexpensive. To prepare for pretreatment, the soil with debris is picked up from the composting area by a 1- to 5-cubic-yard front-end loader and moved to an integrated two-stage screening plant. The screening plant will be a portable integral unit such as a Read Screen-All model RD 25, RD 40, RD 90, or equivalent. Typically, a unit will be leased, moved to the site, and set up to process the soil.

At the plant, the soil with debris is off-loaded onto the high end of a grizzly bar separator. Debris larger than 2 inches in diameter rolls over the bars, and the smaller material falls through. The slope of the grizzly bars is field-adjustable to allow effective separation. Debris smaller than 2 inches in diameter drops through the bars onto a vibratory screen. The screen separates debris larger than  $\frac{1}{4}$  inch in diameter from the soil. The debris larger than  $\frac{1}{4}$  inch in diameter exits the top of the screen to the same pile as the 2-inch and larger debris. The soil passes through the screen. The same loader will take the screened soil back to the composting area. A conveyor will move the oversize debris for subsequent treatment.

The costs for the screening operation at 5 and 20 tons per hour (tph) processing rate are indicated in Table 3-1. For the base case, 10,000 of soil is screened producing 2,000 tons of debris. The estimated cost of screening is \$68,750 with the 5 tph throughput unit or \$47,500 with the 20 tph throughput unit. For the large-volume case, 125,000 tons of soil is screened producing 25,000 tons of debris. The estimated cost is \$570,750 with the 20 tph unit.

**TABLE 3-1. COSTS FOR DEBRIS SEPARATION**

<b>Cost Element</b>	<b>5 Tons per Hour Processing Rate</b>	<b>20 Tons per Hour Processing Rate</b>
Mobilization/Demobilization	\$1,750	\$2,000
Equipment Leasing	\$5.20/ton	\$3.75/ton
Labor Cost	\$1.50/ton	\$0.80/ton
Total Variable Cost	\$6.70/ton	\$4.55/ton

### **3.2 Technology 1 — Thermal/Hot-Gas Decontamination**

A variety of thermal treatment technologies can be applied to remediate organic contaminants in solid matrices. The common methodology in each of the thermal treatment techniques is to apply elevated temperatures to oxidize, pyrolyze, or volatilize combustible pollutants. The main products from the combustion processes are carbon dioxide and water. Nitrogen in the air and any halogens, phosphorus, and sulfur in the waste typically are converted to acidic vapors.

A variety of thermal treatment systems are available. Treatment can be accomplished on site with mobile treatment equipment or in an on-site facility, or off site at a centralized plant.

Thermal treatment is an effective and implementable option, but one which is relatively high in cost. For example, incineration of PCB-contaminated wastes could range from \$280 to \$1,000/ton (U.S. EPA, 1993b). The cost per ton would be even higher when the volume to be treated is small due to the high fixed cost of thermal treatment equipment (COE, 1992). This evaluation of thermal/hot-gas decontamination of the debris assumes on-site treatment with transportable modular equipment.

Thermal treatment may use either direct or indirect heating. Direct heating uses direct contact with combustion gas or heat carrier gas to heat the contaminated media. Indirect heating inputs heat by contacting the debris with a heated wall, screw impeller, or other device. The device is in turn heated by an external source, such as a heat transfer fluid (e.g., hot oil or hot gas) or a radiant heat source.

Thermal treatment units cannot process an unlimited range of particle sizes in the feed material. Units using indirect heating require the presence of smaller particles to provide sufficient

contact surface with the heated wall. Fluidized bed or rotary kiln units require a reasonably narrow particle size range to control particle residence time in the heat zone. All units are unable to process large chunks due to the potential for mechanical damage to the equipment from impact. The maximum allowed particle size depends on the unit but typically ranges from 1.5 to 2 inches in diameter. The explosives-contaminated debris will require some sorting and conditioning prior to being fed to thermal treatment equipment.

Thermal processing can be accomplished by incineration of the debris at high temperature ( $> 1,000^{\circ}\text{F}$ ) or by thermal desorption/decomposition at lower temperatures ( $< 320$  to  $900^{\circ}\text{F}$ ). High-temperature incineration systems process the waste at high temperature and then pass the combustion off-gas through an afterburner and final off-gas cleaning devices (e.g., filters, carbon absorbers, and/or scrubbers) to ensure as complete as possible destruction and control of contaminants. Transportable incineration units are available from several vendors (Woodyard, 1990). The types of equipment available for the high-temperature incineration step include rotary kiln, infrared conveyor, circulating bed combustor, infrared incinerator, and fluidized-bed incinerator. A range of sizes of transportable incinerators are available from 1.5 million BTU/hr ( $\sim 0.3$  tph) to 82 million BTU/hr ( $\sim 20$  tph). The setup time for the smaller units is 1 to 7 days. Larger units require a setup time of 2 to 8 weeks. Due to the longer setup time, the larger units are economical only when volumes of more than about 15,000 tons are to be processed (U.S. EPA, 1991, EPA/540/2-91/004).

Incineration of hazardous organic contaminants in a soil matrix is a mature, commercially available technology. High-temperature destruction of explosives has been demonstrated. Mobile high-temperature incineration equipment is available in a wide range of sizes. The size of equipment can be selected depending on the amount of material to be processed. Therefore, this approach is both effective and implementable.

Although high-temperature thermal treatment has proven effective, the cost for process implementation historically has been high (MacKinnon et al., 1994). As a result, this study focuses on evaluation of low-temperature treatment technologies for the explosives-contaminated debris.

The low-temperature systems heat the contaminated material to increase the rate of contaminant volatilization and cause the organics to partition to the vapor phase. The general sequence of steps for low-temperature thermal treatment is shown in Figure 3-1. For explosives contaminants, the removal mechanism will be a combination of decomposition and volatilization. The organic-laden off-gas stream is collected and processed. Low-temperature systems have been demonstrated for remediation of soil contaminated with a variety of volatile and semivolatile organic compounds

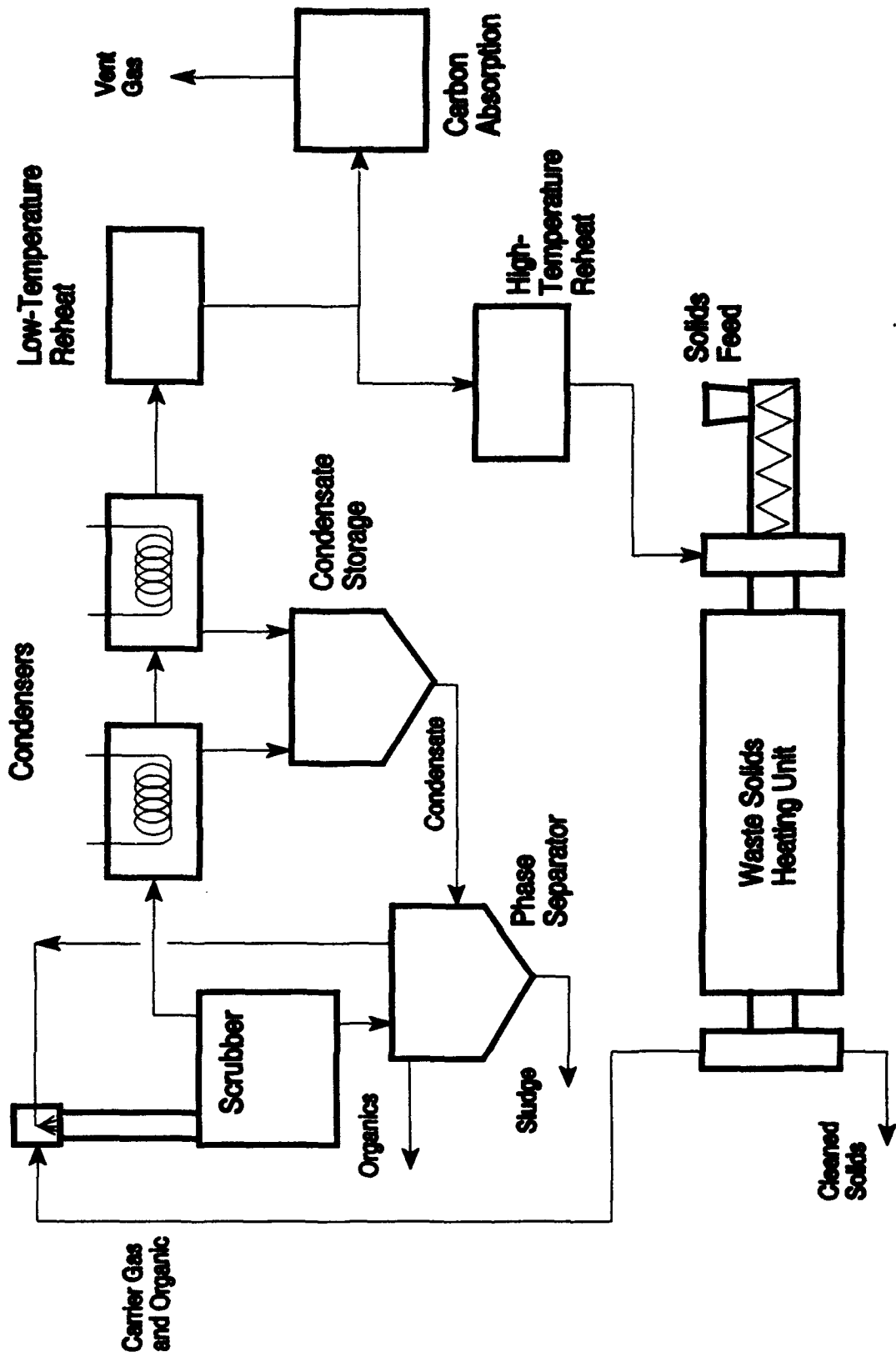


Figure 3-1. Low-temperature thermal treatment process concept.

including PCBs, anthracene, and pentachlorophenol (U.S. EPA, 1991, EPA/540/2-91/008). The systems have not been demonstrated for remediation of explosives-contaminated soil.

The designs of the low-temperature treatment systems include the Desorption and Vaporization Extraction (DAVE) system, the Low Temperature Thermal Treatment (LT<sup>3</sup>) system, the X\*TRAX system (Just and Stockwell, 1993), Low Temperature Thermal Aeration (LTTA) (U.S. EPA, 1993c, EPA/542/N-93/007), and the Seaview Thermal Systems HT-6 (Horne and Jan, 1994).

In the DAVE system, wastes are heated to between 320°F and 340°F in a fluidized bed. Thermal input is provided by fluidizing the contaminated solid with gas heated to between 1,000 and 1,500°F. The fluidizing gas contains about 1% to 2% oxygen. The hot gas vaporizes water and organic contaminants in the waste. Off-gas is passed through a cyclone separator and baghouse (to remove particulates) and then a scrubber, a countercurrent washer, a chill/reheat unit, and the adsorption steps to remove organic vapors. Condensed liquids are treated by a centrifuge with pressure filter for particulate removal and by carbon filtration for organic removal.

The LT<sup>3</sup> system mixes and heats the contaminated soil with a hot oil-filled screw processor to a temperature of about 400°F. The off-gas is passed through a baghouse and a condenser. The gas exiting the condenser is treated by an afterburner. An oil/water separator treats the condensate to produce a concentrated organic contaminant stream and an aqueous stream. The aqueous stream is cleaned by carbon adsorption.

The X\*TRAX process uses an externally fired rotary kiln. The processing temperature typically is 750°F to 850°F (maximum 900°F). An inert nitrogen carrier gas passes through the kiln to collect water vapor and volatilized organics. The kiln off-gas is scrubbed with water to remove particulate and cool the gas stream. The scrubbed off-gas then passes through primary and secondary condensers. Most of the cleaned carrier gas is recycled to the kiln. The discharged portion is cleaned by carbon adsorption. The scrubber liquid and liquid from the two condenser stages is collected and passed through a phase separator. Light organics are skimmed from the top and a sludge containing solids, water, and organics is continuously withdrawn from the bottom. The cleaned water from the phase separator is recycled to the off-gas scrubber (Ayen and Swanstrom, 1991).

The LTTA process desorbs organic contaminants by heating soils up to 800°F in a materials dryer. The main components of the process include (U.S. EPA, 1993c, EPA/542/N-93/007):

- a materials dryer
- a pug mill
- two cyclonic separators
- a baghouse
- a wet Venturi scrubber
- a liquid-phase granular activated carbon column
- two vapor-phase granular activated carbon beds.

The Seaview Thermal Systems HT-6 uses a closed-loop treatment system with a nitrogen atmosphere. Contaminated debris is introduced into the processing where it is electrically heated in two stages. The first stage removes moisture at lower temperature. The second-stage temperature is selected based on the contaminants and matrix but can be as high as 2,200°F. Organics are removed from the nitrogen by condensation and water scrubbing for recovery or treatment. The nitrogen is recycled to the heating unit (Horne and Jan, 1994).

The low-temperature desorption processes are best suited for removal of organics from sand, gravel, or rock fractions. The high sorption capacity of clay or humus decreases partitioning of organics to the vapor phase, making these materials difficult to process. The debris considered in this study will have little or no clay or humus.

High-temperature thermal treatment will mineralize the explosives contaminants to form mainly CO<sub>2</sub> and H<sub>2</sub>O. The fate of the explosives contaminants is not as clear in the lower temperature thermal desorption case. Low-temperature thermal treatment involves some decomposition, but volatilization is the main removal mechanism. As discussed above, all of the low-temperature systems provide for methods to capture the volatilized organics from the off-gas. Residuals from the off-gas treatment may be organic liquid and/or spent carbon sorbents. These residuals will require further treatment or disposal. The low-temperature techniques provide good protection of human health and the environment by either destroying the contaminants or concentrating them in a controlled manner for further processing.

Low-temperature treatment uses complex equipment operating at elevated temperatures. Equipment operation involves hazards, but the nature and level of risk are consistent with normal industrial practice. Good design and operating procedures can reduce the hazard levels. The organic concentrate collected by thermal desorption may be sufficiently rich in energetic material to require handling as an energetic material and/or a RCRA ignitable or reactive waste.

Low-temperature thermal treatment equipment is in commercial operation and could be readily obtained from any of several vendors. There is a mechanistic basis to believe that the systems

could treat the explosives-contaminated debris. However, low-temperature thermal desorption has not been demonstrated for remediation of explosives contaminants. The required treatment temperatures or residence time may be too high for economical operation. Low-temperature treatment units could be transported to the site as trailer-mounted or modular units on standard highway transport trucks with a maximum gross vehicle weight of 80,000 pounds.

Thermal treatment is a capital-intensive operation using complex, expensive equipment. The costs can be controlled to some degree by selecting the size of the processing equipment relative to the amount of material to be treated at the site. A smaller system will have a lower throughput but will have lower setup costs and lower use rate costs. Even for an optimum match of process throughput and the resulting fixed setup cost, both the fixed and variable treatment costs will be high per unit of waste treated.

The cost for setup and trial run for a low-temperature thermal treatment system depends on the system selected as well as site- and waste-material-specific conditions. The Weston LT<sup>3</sup> system costs about \$300,000 for installation and has an operating cost of about \$100 to \$150 per ton. The fixed cost for the X\*TRAX process was \$834,000 in 1989. The cost for feed sorting and conditioning is assumed to be included in the above thermal treatment costs.

The average cost for thermal treatment of a unit of waste is sensitive to the quantity treated due to the high fixed costs. The estimated cost ranges for low-temperature thermal treatment, based on the total amount of waste to be treated, are shown in Table 3-2.

Using the midpoint of the range for the operating costs at a very small site gives an estimated unit cost for thermal treatment of \$1,000 per ton. The midpoint of the range for a medium-sized site gives an estimated unit cost for thermal treatment of \$400.

The estimated cost of screening, crushing, and thermal treating for the base case of 2,000 tons of debris is \$2,048,000 (\$47,500 for screening and \$2,000,000 for thermal treatment). The estimated cost for the large-volume case of 25,000 tons is \$10,571,000 (\$570,750 for screening, and \$10,000,000 for thermal treatment).

Incineration systems historically have received very poor acceptance from the public. The low-temperature treatment systems are likely to be viewed as a variation on the incineration process.

**TABLE 3-2. APPROXIMATE UNIT COST RANGE FOR THERMAL TREATMENT OF VARIOUS QUANTITIES OF WASTE MATERIALS**

<b>Site Size Designation</b>	<b>Total Waste Material Treated (Tons)</b>	<b>Approximate Unit Treatment Cost Range (\$/Ton)</b>
Very small	<5,000	500 to 1,500
Small	5,000 to 15,000	300 to 900
Medium	15,000 to 30,000	200 to 600
Large	>30,000	100 to 400

### **3.3 Technology 2 — Composting Debris Crushed to Less Than ½-inch Diameter**

Much contaminated debris is incompatible with flail-type windrow aeration equipment used for composting due to its large size. Physical size reduction is an effective option for preparing the debris for compatibility with the windrow equipment. Crushing is a standard method to reduce the particle size of rock materials. The size-reduced debris would be returned to the composting system to reduce the explosives concentrations to the remedial action objective levels. The crushing process will use mechanical size reduction equipment to crush the large debris.

Three types of commercially available crushing/grinding equipment potentially are applicable to reducing the size of the explosives-contaminated debris:

- Toothed-roll crushers for coarse crushing
- Jaw crushers for initial crushing of hard or large materials
- Hammermills to produce controlled particle size and achieve the highest ratio of particle size reduction.

Battelle personnel contacted manufacturers and vendors of these types of crushers to determine the applicability of the equipment types to the specific requirements for the explosives-contaminated debris. Toothed-roll crushers would be unable to achieve the required size reduction. This type of equipment was not recommended by the manufacturers and/or vendors.

Jaw crushers can achieve the required ¼-inch size. However, reduction from 3 inches (maximum) to less than ¼ inch in one pass is near the maximum size reduction ratio possible with a jaw crusher. The use of two jaw crushers in a row would give more reliable operation and generally is the accepted approach for achieving the size reduction required. However, two crushers in series would increase both the capital cost and the system complexity.

Hammermills are capable of reducing 3-inch-diameter rock to less than ¼-inch-diameter in a single step. Hammermill designs typically include an outlet screen that controls the size of particles leaving the crusher. Hammermills are available in standard sizes to meet the relatively low throughput required and are shipped within reasonable delivery times from a variety of vendors. The hammermill was selected as the preferred type of rock crusher for explosives-contaminated rock debris.

The overall processing steps for the hammermill rock crushing operation are shown in Figure 3-2. As discussed in Section 3.1, the soil will be screened to separate the rock debris and the smaller soil fractions. A belt conveyor will move the oversize fraction from the screening area to the crusher. The rock will be rinsed before crushing and will be sprayed during crushing to reduce dust generation. A second conveyor will transfer the crushed rock from the mill back to the composting area.

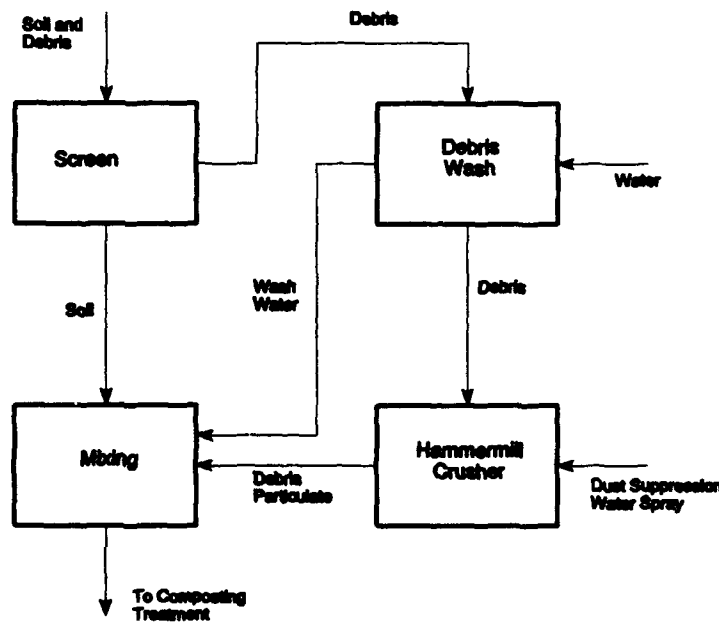


Figure 3-2. Hammermill crushing process concept.

The input flow of rinsewater is estimated at 2 gpm. The water will not require separate discharge. Some rinsewater will return to the compost pile along with the crushed rock. Any rinse runoff from the pre-rinse will contain, at most, low concentrations of explosives. The water can be added to the compost pile as part of the normal water addition.

The crushing process provides excellent protection of human health and the environment. The explosives-contaminated debris will be processed and returned to the composting pile to allow degradation of the contaminants.

Composting will treat contaminants to concentrations of 30 mg/kg or below. The composting process converts the contaminants to CO<sub>2</sub>, H<sub>2</sub>O, and biomass. The crushed debris will be returned to the compost pile for continued treatment of the contaminants, thus providing excellent long-term effectiveness. The rinsewater runoff from the pre-rinse will be added to the compost pile as part of the normal water addition.

Crushing uses complex rotating equipment. Equipment operation involves hazards, but the nature and level of risk are consistent with normal industrial practice. Good design and operating procedures can reduce the hazard levels. Due to the low concentrations of explosives on the debris and the intended prewetting of the debris, the crushing operation is not expected to present an explosion hazard.

Crushing can be performed with commercially available equipment. Implementability is excellent for the crushing process.

Based on vendor budget estimates, a hammermill sufficient to process 5 to 10 tons per hour of explosives-contaminated rock debris would cost \$10,000 to \$15,000 to purchase and install. The purchase and installation costs of conveyors and a crusher feed hopper are estimated at \$7,000. The crusher throughput will depend on the hardness of the rock. The crusher operating cost is estimated to range from \$5 to \$10 per ton. The crushed rock will then need further on-site treatment by composting. The assumed marginal cost for labor and material to compost additional units of explosives-contaminated debris is estimated to be \$30 to \$90 per ton.

Using the midpoint of the ranges, the estimated fixed cost for the crushing option is \$19,500. Due to the low capital cost of the crusher, only one size crushing unit was considered for the cost estimate. The midpoint estimate for the operating cost is \$67.50 (\$7.50 + \$60) per ton.

The estimated cost of screening, crushing, and composting for the base case of 2,000 tons of debris is \$202,000 (i.e., \$47,500 for screening, \$34,500 for crushing, and \$120,000 for compost-

ing). The estimated cost for the large-volume case of 25,000 tons is \$2,278,000 (i.e., \$570,750 for screening, \$207,000 for crushing, and \$1,500,000 for composting).

Crushing will allow the debris to be returned to the compost pile for destruction of the organic contaminants. Composting is generally accepted as preferable to more conventional methods such as incineration for wastes where composting will provide cost-effective cleanup. The crushing operation will have minimal effect on the off-site population or the environment. Crushing is expected to have excellent general acceptance.

### **3.4 Technology 3 — Enhanced Soil Washing with Surfactants or Other Solubility Enhancers**

Soil washing treatment methods involve contacting the debris with an aqueous washing fluid to dissolve the explosives contaminants. The aqueous washing fluid and contained contaminants are then separated from the debris by physical methods. For efficient soil washing, a method must be available to regenerate the washing fluid. If the washing fluid cannot be regenerated, the water use and volume of waste residuals produced would be excessive.

Researchers at Roy F. Weston performed treatability studies of washing explosives-contaminated debris with water and surfactants (Roy F. Weston, 1993). Due to the low water solubility of the explosives, washing with water alone did not remove the contaminants to the 30 mg/kg level. However, washing with a surfactant was able to decrease concentrations to below the 30 mg/kg level.

Experience with soil washing systems indicates that spent surfactant along with the contained organics can be removed from the washing solution by froth flotation. The cleaned water can be recycled to wash more debris. Surfactant-enhanced soil washing should be effective for removing explosives contaminants from the debris.

Soil washing has been selected as a remedy for soils contaminated with semivolatile organic compounds (SVOCs) or volatile organic compounds (VOCs) at more than 10 Superfund sites (U.S. EPA, 1992, EPA/542-R-92-011). Some SVOC contaminants of concern at these Superfund sites with properties similar to the explosives contaminants include dinitrotoluene, dioxins, creosote, *bis*(2-ethylhexyl) phthalate, and dimethylphenol. Surfactant washing systems for remediation of soil contaminated with SVOCs are available from a variety of vendors (U.S. EPA, 1993d, EPA/542/R-93/001). Soil washing should be implementable for the explosives-contaminated debris.

The reported costs of soil washing range from \$50 to \$300 per ton (U.S. EPA, 1993d, EPA/542/R-93/001). The large-particle-size debris considered in this study is the easiest fraction to process by soil washing, reducing processing costs. Soil washing systems generally have high mobilization and capital costs. Lower costs resulting from system simplicity will be offset by high fixed costs when small volumes are processed.

Soil washing is effective and implementable but requires several processing steps to contact the solids with a washing fluid, separate the debris from the fluid, and regenerate the washing fluid. The sequence of steps for the soil washing process is illustrated in Figure 3-3. The oversize debris from the screening operation is processed by attrition scrubbing with an aqueous surfactant solution. The combination of surface abrasion and surfactant washing removes the explosives contaminants along with some sand and fine particulate.

The scrubbed oversize particles exit the attrition scrub to a traveling screen. A clean water spray rinse removes residual surfactant solution from the scrubbed oversize debris. The scrubbed oversize debris can be returned to the original excavation or can be stored for later recombination with the composted soil. The rinse solution is recycled to the attrition scrubber.

Scrubbing solution exiting the attrition scrubber will contain surfactant, explosives contaminants, sand, and fine particulate. Additional processing is needed to recycle the water and reduce the residual volume requiring disposal. The first step in processing the scrubbing solution is to settle the sand in a clarifier. The clarifier overflow is an aqueous suspension of explosives, surfactant, and fine particulate. The overflow is fed to a froth flotation tank where air bubble injection causes the explosives and surfactant emulsion along with fine solids to float to the water surface. The resulting surface froth is collected as a sludge and transferred for off-site disposal. Water from the flotation unit is recycled to the attrition scrubber.

A wet sand slurry exits the bottom of the clarifier to a traveling belt vacuum filter. The first portion of the filter removes any excess water. The last portion of the filter provides a spray rinse to remove residual surfactant solution from the sand. The recovered sand can be returned to the original excavation or can be stored for latter recombination with the composted soil. The recovered wash solution and rinsewater are recycled to the attrition scrubber.

The soil washing circuit is designed to fully recycle water. Water exiting the system in the cleaned rock and sand and in the contaminated sludge is made up by rinsewater additions. At the end of the debris cleaning process, solution remaining in the equipment is disposed of by treatment in an on-site water treatment plant, if available, or by disposal off site.

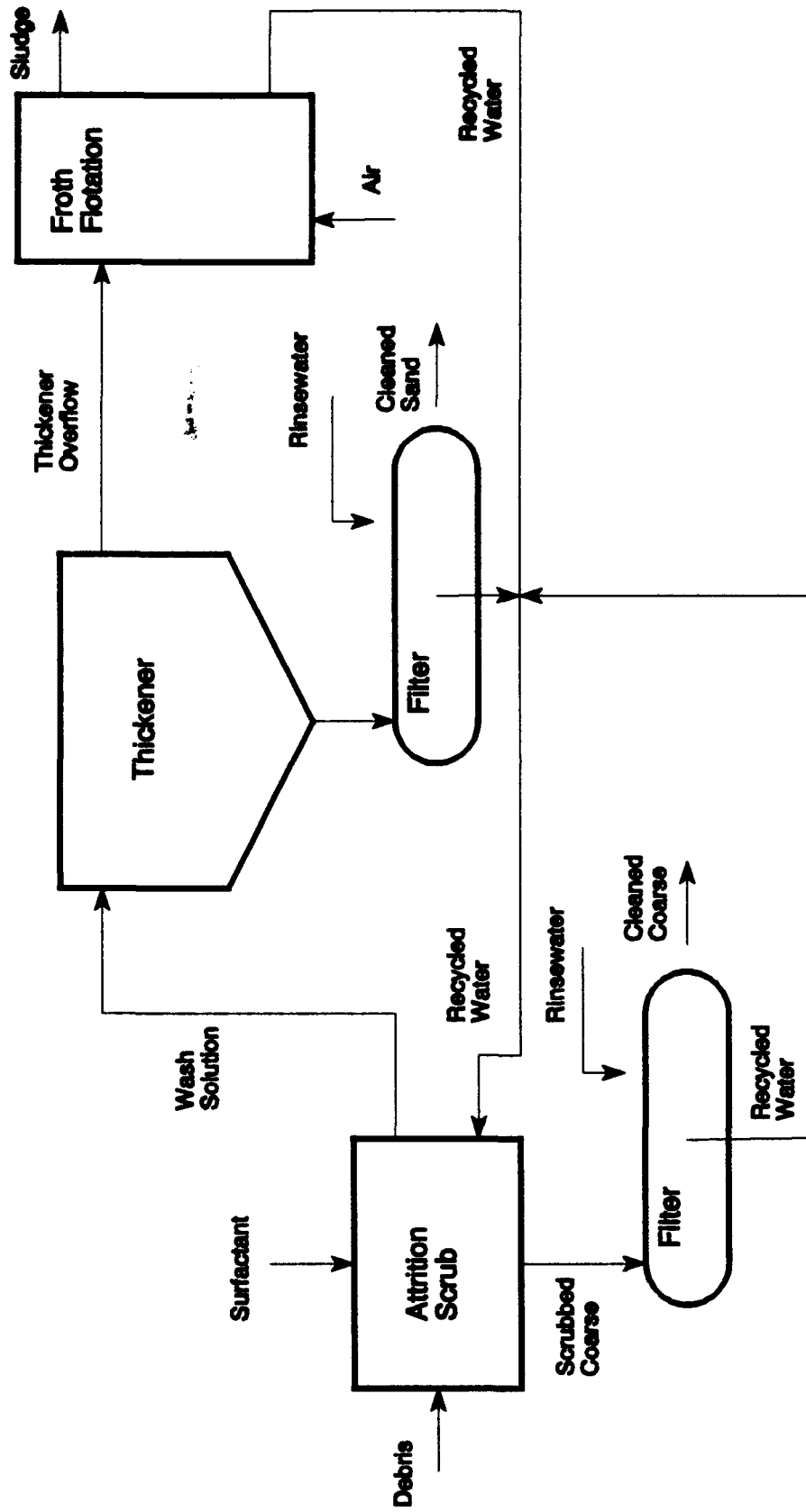


Figure 3-3. Soil washing process concept.

Soil washing transfers the explosives contaminants from the debris into a much smaller volume of sludge residual. The sludge will require further treatment or disposal. Soil washing provides fair protection of human health and the environment by concentrating contaminants in a controlled manner for further processing but does not reduce the quantity of contaminants.

Soil washing uses complex rotating equipment. Equipment operation involves hazards, but the nature and level of risk are consistent with risk in normal industrial practice. Good design and operating procedures can reduce the hazard levels. The organic concentrate collected in the froth flotation unit may be sufficiently rich in energetic material to require handling as an energetic material and/or a RCRA ignitable or reactive waste.

Surfactant soil washing is a well-established technology for removing SVOCs from soil. The oversize rock debris considered in this study is the easiest soil fraction to clean by soil washing techniques.

Soil washing processing costs can vary depending on the system complexity, amount of material processed, and the residuals management requirements. The costs may be competitive, particularly if the amount of material processed is large and low-cost options are available for treatment of the residuals. Cost estimates for this evaluation were developed for 5 tons per day and 20 tons per day of throughput based on the basic soil washing circuit shown in Figure 3-3. The estimated cost factors for soil washing of explosives-contaminated debris are shown in Table 3-3.

**TABLE 3-3. ESTIMATES OF SOIL WASHING COST FACTORS**

<b>Cost Element</b>	<b>Costs for 5 Tons per Day Soil Washing System</b>	<b>Costs for 20 Tons per Day Soil Washing System</b>
Installed equipment (\$)	280,000	700,000
Labor (\$/ton)	35.00	15.00
Chemicals (\$/ton)	30.00	30.00
Utilities (\$/ton)	4.00	4.00
Maintenance (\$/ton)	15.00	8.00
Process testing (\$/ton)	25.00	15.00
Disposal of residues (\$/ton)	50.00	50.00
<b>Total variable cost (\$/ton)</b>	<b>159.00</b>	<b>122.00</b>

The estimated cost of screening, crushing, and soil washing for the base case of 2,000 tons of debris is \$645,500 (\$47,500 for screening and \$598,000 for soil washing). The estimated cost for the large-volume case of 25,000 tons is \$4,321,000 (\$570,750 for screening, and \$3,750,000 for soil washing).

Soil washing is generally accepted as preferable to more conventional methods such as incineration for wastes where soil washing will provide cost-effective cleanup. The soil washing operation will have minimal effect on the off-site population or environment. However, soil washing produces a small volume of residual requiring further treatment or disposal.

### 3.5 Technology 4 — Chemical Degradation

Chemical treatment methods involve the use of alkaline hydrolysis, oxidizing, and/or reducing agents to convert organic compounds to less hazardous forms. Ultraviolet (UV) photochemical oxidation is one method that has been used to oxidize explosive and propellant contaminants. Commonly, hydrogen peroxide ( $H_2O_2$ ) (refs. 1-3 as cited by Ho, 1986) or ozone ( $O_3$ ) (refs. 4-6 as cited by Ho, 1986) is the oxidizing agent, which is used in conjunction with a high-powered UV light source to produce hydroxyl radicals ( $\cdot OH$ ). The hydroxyl radicals destroy the organic contaminant molecules by converting them ultimately to carbon dioxide, water, nitric acid, and other benign species. Studies have shown that complete oxidation is possible in pure systems, but that the photochemical and chemical pathways are not fully understood (Ho, 1986). Commercial processes such as from Solarchem Environmental Systems (Las Vegas, Nevada and Markham, Ontario, Canada) are available (Notarfonzo and McPhee, 1993). In addition, Fenton's reagent, a combination of hydrogen peroxide and a ferrous salt, has been shown to induce an effective reaction mechanism in 2,4-dinitrotoluene (Mohanty and Wei, 1993). In studies conducted by USATHAMA (IT, 1987), neither oxidation nor reduction was successful. The explosives contaminants resist oxidative degradation. Chemical reduction resulted in the formation of hazardous compounds.

Partial, or selective, reduction of 2,4-dinitrotoluene has been obtained under controlled, mild reducing conditions using metal/organic acid systems (Ono and Kitazawa, 1983). Using nickel powder and maleic acid in acetic acid and heating under reflux for 2 hours, after which the contents were basified by sodium hydroxide with continued refluxing, produced 4-methyl-3-nitroaniline as the reduction product (Ono and Kitazawa, 1983). Other systems of heavy metal/acetic acid or hydrochloric acid have resulted in 2,4-dinitrotoluene being reduced to 2-methyl-5-nitroaniline. For

example, the systems of iron/acetic acid and stannous chloride/hydrochloric acid have been used (refs. 3, 10-13 as cited by Ono and Kitazawa, 1983).

Chemical treatment of explosive and propellant wastes has been accomplished by alkaline hydrolysis. In alkaline hydrolysis a strong base is used to react with nitroaromatic contaminants in aqueous solutions. In the course of this reaction, hydroxide ion ( $\text{OH}^-$ ) displaces nitro groups ( $-\text{NO}_2$ ), which results in the formation of aqueous nitrite ( $\text{NO}_2^-$ ) or nitrate species ( $\text{NO}_3^-$ ). A study of glyceryl nitrate esters indicated that hydrolysis may eliminate alpha or beta hydrogen atoms from parent contaminant molecules and break carbon-carbon bonds, resulting in simple by-products (ref. 17 as cited by Garg et al., 1991). This study reports the hydrolysis products of glyceryl trinitrate with calcium hydroxide to be nitrate and nitrite (56%), hydroxide (15%), oxalate (6.3%), and formate and unidentified products (22.7%) (ref. 17 as cited by Garg et al., 1991).

Another study reports formation of nitrate and nitrite ions by alkaline hydrolysis of nitro compounds (ref. 18 as cited by Garg et al., 1991). Based on these findings, Garg et al. (1991) infer that alkaline hydrolysis probably can occur in other types of aromatic and nonaromatic nitro compounds. For example, citing research into the breakdown of the nitrocellulose polymer structure (ref. 19 as cited by Garg et al., 1991), Garg et al. (1991) discuss how alkaline hydrolysis could be used to chemically degrade nitrocellulose. In this proposed process, aqueous ammonium hydroxide is added to a water slurry of contaminated material. Within the reactor the working concentration of ammonium hydroxide is 10%. The residence time in the reactor is about 8 hours. The temperature in the reactor is controlled to the optimum level. After processing, the sediment mixture is returned to a lagoon for biological degradation of any remaining ammonia and organic carbon material. A neutralization step, requiring an acid, may be necessary to eliminate residual alkalinity.

The main drawbacks to treatment of nitrocellulose by alkaline hydrolysis are

- the reaction may not go to completion
- a residue of ammonia (or other strong base) is left in the soil
- the biodegradability of the remaining organic carbon materials is uncertain.

Data (refs. 18, 19 as cited by Garg et al., 1991) indicate that the rate and extent of chemical degradation of nitrocellulose by alkaline hydrolysis depend on concentrations of the nitrocellulose and the base. When processing of a contaminated sludge takes place in a slurry, residual nitrocellulose could be reduced to less than 1% in appropriate mixtures. However, processing of nitrocellulose in

contaminated soils could be less effective due to adsorption, particulate size, and porosity factors. However, neither pilot-scale nor full-scale data are available to confirm the performance of alkaline hydrolysis in sludge, much less in soils. Adsorption data for 2,4- and 2,6-dinitrotoluene, TNT, RDX, and HMX in two Mississippi and Texas soils are given in EPA/600/2-89/011 (U.S. EPA, 1989).

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