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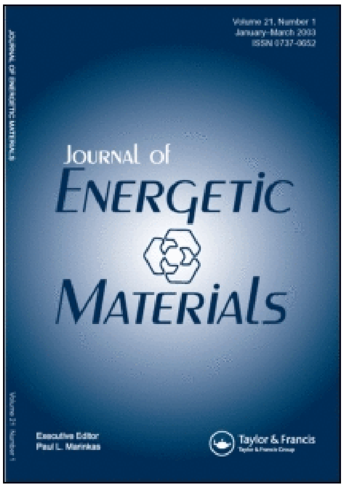

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Composting of energetic materials

Agamemnon D. Koutsospyros[a]
[a] Dept. of Civil and Environmental Engineering, University of New Haven,

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COMPOSTING OF ENERGETIC MATERIALS

Agamemnon D. Koutsospyros, Ph.D
Dept. of Civil and Environmental Engineering
University of New Haven

ABSTRACT

Composting has been used for centuries for stabilization of organic residues and production of a humus-like end product traditionally used as a soil conditioner. The process may be successfully adopted for the treatment of solid organic matrices contaminated with various hazardous wastes including energetic materials. Composting methods and their application for treatment of energetic materials are reviewed along with design methodologies. The design and operation of composting facilities for treatment of energetic materials must be based on thermodynamic, kinetic, public health and aesthetic principles. A generalized design methodològy is presented. Composting treatability studies are necessary for derivation of thermodynamic and kinetic data. Concerns related to production and fate of metabolites require a careful study and should be always addressed. Ultimate disposal of composted energetic materials must be studied extensively.

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INTRODUCTION

Overview

Composting is a stabilization method applicable to a wide array of solid-phase waste matrices with sufficient organic content including agricultural residues, municipal solid waste, wastewater residual slurries, contaminated soils and sediments. The process has been known and practiced by agricultural communities for centuries all over the world as a means of decomposition of organic residues and production of a humus-like end product that may be beneficially reused as a soil conditioner/fertilizer. As the fertilizing value and crop productivity of composts are inferior to those of artificially produced chemical fertilizers, composting became obsolete at the beginning of 20th century. The interest in the process was revived after World War II and more recently (in the seventies) because of environmental concerns of fertilizers, and other disposal practices (i.e. landfilling, incineration), as an inexpensive alternative solid waste and wastewater solids disposal method.

The first composting facilities in the USA were built and operated in the early 1970's. As of 1991 there were 150 operational facilities, with an additional 115 projects in various stages of planning and development. Many of these facilities are still threatened with financial difficulties mainly due to lack of market for their end product and concerns over the fate of heavy metals present in certain wastewater residuals. In other countries composting is quite popular. For example, it is estimated that in the Netherlands 25% of the organic wastes produced are converted to compost[1].

Applications of composting in the area of hazardous waste treatment have been known since the late 60's. First attempts included successful composting of pesticides diazinon, parathion, DDT and dieldrin[2]. Subsequently, the method has been applied with varying degree of success to wastes including coal tar[3], petroleum refinery sludges[4], incecticides[2,5], ethylene glycol[6], wood treatment chemicals[6], explosives[7] etc.. In the 80's composting received attention as a potential alternative for hazardous waste treatment and disposal[8-10]. The primary reasons for the revived interest in composting and its application on industrial and hazardous wastes are inherent disadvantages of other competing practices (i.e. excessive land requirements of land farming, high capital/operational costs and air pollution concerns of incineration, increased regulation and shortage of landfills, etc.), low cost, as well as the appeal of natural processes (such as composting) to environmental activists and the public in general.

Use of composting for treatment of explosives and propellants was first introduced in the early 80's primarily as a result of increased regulation that banned previous disposal practices such as open pit burning and lagooning[7]. Geopolitical changes and arms reduction in mid and late 80's created a severe demand for demilitarization practices including decontamination of military facilities. Composting was assessed as a potential inexpensive technology for treatment of explosive contaminated soils in laboratory[7,11] and field[12] studies. The present work attempts to present the principles of the composting process, explore its applicability for treatment of hazardous wastes in general, and summarize research and application findings in the area of explosive decontamination in particular.

Definition of Composting

Composting is a process in which organic material present in a self-insulated solid matrix undergoes microbially mediated degradation resulting in production of terminal oxidation products (CO_2 and H_2O) and/or other intermediates accompanied by simultaneous heat release. Under such conditions, the generated heat accumulates causing a temperature ascent acting as a dynamic selector favoring thermophilic organisms. Eventual depletion of the available substrate is demonstrated by a temperature descend. Process temperature varies within the pasteurization range of 50 to 70 °C where enteric pathogenic organisms are destroyed. Although both types of metabolism, aerobic and anaerobic, are possible, aerobic metabolism is preferred for most applications mainly because aerobic metabolic transformations:

- proceed at higher rates
- liberate higher amounts of heat
- achieve higher operating temperatures resulting in a more effective pathogen destruction

- minimize the potential for odors

However, for complex waste matrices containing contaminants resistant to aerobic degradation and prone to anaerobic metabolism, interposing an anaerobic cycle[5] may be beneficial for the system.

For waste matrices such as agricultural residues, municipal solid waste and wastewater residuals rich in putrescible material and low in conservative pollutants, the final product can be a relatively stable, nuisance-free, humus-like material known as compost. The presence of nutrients and relatively stable organic matter in compost can be beneficial as a soil conditioner particularly for soils with excessive amounts of sand and clay. Potential benefits to unbalanced soil systems include[13]:

- improved water retention and content for sandy soils
- enhanced aggregation
- increased aeration, permeability and water infiltration for clay soils
- greater root depth
- enhanced microbial population
- reduction surface crusting

It should be noted that persistent organics such as those frequently encountered in certain hazardous wastes, pathogens, and heavy metals impose severe restrictions on use of composts for agricultural purposes. However, in many situations land application of finished hazardous wastes composts is the most frequently practiced method of ultimate disposal.

Although composting of hazardous wastes shares many of the fundamental underlying mechanisms with composting of municipal wastes, the process also differs in many respects. Most hazardous wastes do not contain sufficient organic matter for sustainable composting and an external carbon source (often termed thermal source or amendment) must be supplied.

Care should also be exercised in the selection of bulking agents. Bulking agents are normally inert reusable materials that provide the necessary structural integrity for semi-solid wastes, provide insulation minimizing heat losses, increase void spaces thus allowing air circulation. In addition to these general characteristics, bulking agents used in hazardous wastes applications should not be made of highly adsorptive material in order to minimize abiotic losses. Also in some situations it may be desirable to minimize use of bulking agents as that increases the volume of the waste that is classified as hazardous. Practices that can minimize the use of bulking agents for insulation purposes include installation of concrete pads with aeration pipes and form-fitting covers of fiberglass or other suitable insulating, air-permeable material. Selection criteria and general characteristics of thermal sources and bulking agents are shown in Table 1.

Composting process modifications are classified into two major categories namely unconfined (windrow, aerated static pile) and confined processes (composting reactors).

TABLE 1: Desirable Characteristics of Thermal Sources and Bulking Agents

Component	Characteristics
Amendment (Thermal Source)	• It should be a readily degradable substance • It should be readily available and at low cost • For hazardous waste it should not represent a preferential carbon source impeding degradation of the target compound(s) • In certain conditions it should act as a co-metabolite
Bulking Agent	• It should provide structural integrity to the composting mixture • Easily separable, reusable, and preferably inert material • It should provide insulation when used as a pile bottom or cover • It must increase the porosity of the composting mixture to facilitate air circulation • For certain hazardous waste applications use of bulking agents may not be desirable

FUNDAMENTALS OF COMPOSTING

Process Chemistry and Microbiology

Composting is a complex phenomenon involving microbial oxidation of organic matter into various oxidation by-products. Assuming that organic material originally and finally present are represented by $C_aH_bO_cN_d$ and $C_wH_xO_yN_z$ respectively, the following oxidation reaction can be used for estimating the oxygen requirements:

$$C_aH_bO_cN_d + 0.5(ny + 2s + r - c)O_2 \Rightarrow$$
$$nC_wH_xO_yN_z + sCO_2 + rH_2O + (d - nx)NH_3 \qquad (1)$$

where $r = 0.5[b - nx - 3(d - nx)]$

$s = a - nw$

If complete conversion of the organic material is accomplished the following reaction can be used to estimate the amount of oxygen required:

$$C_aH_bO_cN_d + \left(\frac{4a + b - 2c - 3d}{4}\right)O_2 \Rightarrow aCO_2 + \left(\frac{b - 3d}{2}\right)H_2O + dNH_3 \qquad (2)$$

If ammonia is to be oxidized to nitrate, the amount of oxygen required is given by:

$$NH_3 + \frac{3}{2}O_2 \rightarrow NO_2^- + H^+ + H_2O \qquad (3)$$

$$NO_2^- + \frac{1}{2}O_2 \rightarrow NO_3^- \qquad (4)$$

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O \quad \text{(overall)} \qquad (5)$$

From the microbiological standpoint, three major categories of organisms have been implicated bacteria. actinomycetes, and fungi. The exact roles and interrelationship of these microbial species are not fully understood. Literature suggests that bacteria are responsible for decomposing the major fraction of the organic material present. Depending on the prevailing temperature bacteria are thought responsible for the degradation of carbohydrates and proteins in the mesophilic range. In addition to these compounds degradation of lipids and fats is accomplished under thermophilic conditions[1].

The role of actinomycetes is not fully known. Early studies[14] suggest that this group is capable of degradation of a wide range of compounds including sugars, starches, lignin, proteins, organic acids, hemicellulose, but not cellulose. A more recent study[15] indicates that under thermophilic conditions actinomycetes play an important role in cellulose degradation.

Similarly to the two other groups, fungi may also be present at both the mesophilic and thermophilic temperature range. Fungi are responsible for degradation of cellulose and other complex carbon sources[16]. In another study in composts enriched with white rot fungus (Phanaerochaete Chrysosporium) degradation of TNT was shown[17]. Since both groups, actinomycetes and fungi, are obligate aerobic organisms their occurrence is observed in oxygen rich locations commonly at surface layers of compost piles.

Thermodynamic Considerations

Biological oxidation of organics accompanied by simultaneous heat release is the driving force for three important and desirable aspects of composting namely waste stabilization, temperature elevation and moisture evaporation. Application of thermodynamic principles coupled with mass balance equations involving the various compost mixture components namely waste, amendment, bulking agent, and recycle can be used to derive design criteria for self-sustaining composting systems. Based on such analysis for wastewater residuals Haug[18] defined ratio W and the mass of recycled composted material X_m as following:

$$W = \frac{\text{Mass of Water in the Initial Compost Mixture}}{\text{Mass of Organics Degraded under Composting Conditions}} \qquad (6)$$

$$W = \frac{\sum_{i=1}^{i=l} X_i(1 - S_i)}{\sum_{i=1}^{i=l} X_i S_i V_i K_i} \qquad (7)$$

$$X_l = \frac{\sum_{i=1}^{i=k} X_i(S_m - S_i)}{S_l - S_m} \qquad (8)$$

where X = component wet mass, kg/d

S = component fractional solids content

V = component fractional organic matter content

K = component fractional degradable organic matter content

i = subscript denoting waste

j = subscript denoting amendment

k = subscript denoting bulking agent

l = subscript denoting recycled composted material

m = subscript denoting initial composting mixture

Accordingly for such systems self-sustaining composting takes place for $W \leq 10$. A similar analysis may also be applicable to waste matrices other than sludge.

Factors Affecting Composting

Several factors affect the design and performance of composting systems. Each of these factors must be considered carefully in order to meet the requirements of each system. The most important factors include mixing, particle size, aeration. moisture content, pH, temperature and carbon-to-nitrogen ratio.

Table 2 summarizes the various factors and outlines their relative significance to the process of composting.

TABLE 2: Factors affecting the composting process

Factor	Comment
Carbon-Nitrogen Ratio	- 25:1< C/N < 35:1
Organic Content	- Composting mixture should have an organic content greater than 50%
Air Requirements	- Aerobic conditions should be maintained throughout the pile. - Minimum oxygen content 5%.
Moisture Content	- < 60% for unconfined processes - < 65% for confined processes
pH	- Optimum pH range for bacteria: 6.0-7.5 - Optimum pH range for fungi: 5.5-8.0
Temperature	- Optimum temperature range: 55 - 65 °C
Particle Size	- Small uniform particles are easier to degrade. - Compost mixture components must be well blended
Mixing	- Compost must be mixed frequently to prevent, drying, caking and air channeling

ENERGETIC MATERIALS

Overview

Energetic materials are substances characterized by extremely rapid decomposition, release of high amounts of energy and subsequent development of high pressure. Although the invention of black powder dates as far back in history as the 10th century, the development of energetic materials has surged during the last 200 years. It is of interest to note that one of the primary components of black powder potassium nitrate (saltpetre) was originally extracted from compost piles. Composting was used as the source of synthesis back then, composting is sought as means of destruction of energetic materials today.

Numerous compounds are used for their explosive properties in civilian and military applications. Most of these are nitric esters of a wide variety of organic compounds including glycerin, glycol, mono- and poly- hydroxylic alcohols (straight-, branched-chain and cyclic), cellulose, sugar and polysaccharides. Other explosives include nitro-derivatives of lignin and abietic acid, esters and salts of oxy-acids of chlorine, and salts of nitric acid[19].

As expected physical properties, chemical, and biochemical characteristics of energetic materials vary widely depending on their chemical structure. Table 3 presents a summary of physical characteristics for selected energetic materials most commonly found in contaminated soils and sediments at U. S. Army munitions facilities. The structural formulae of selected explosives of concern are depicted on Figure 1.

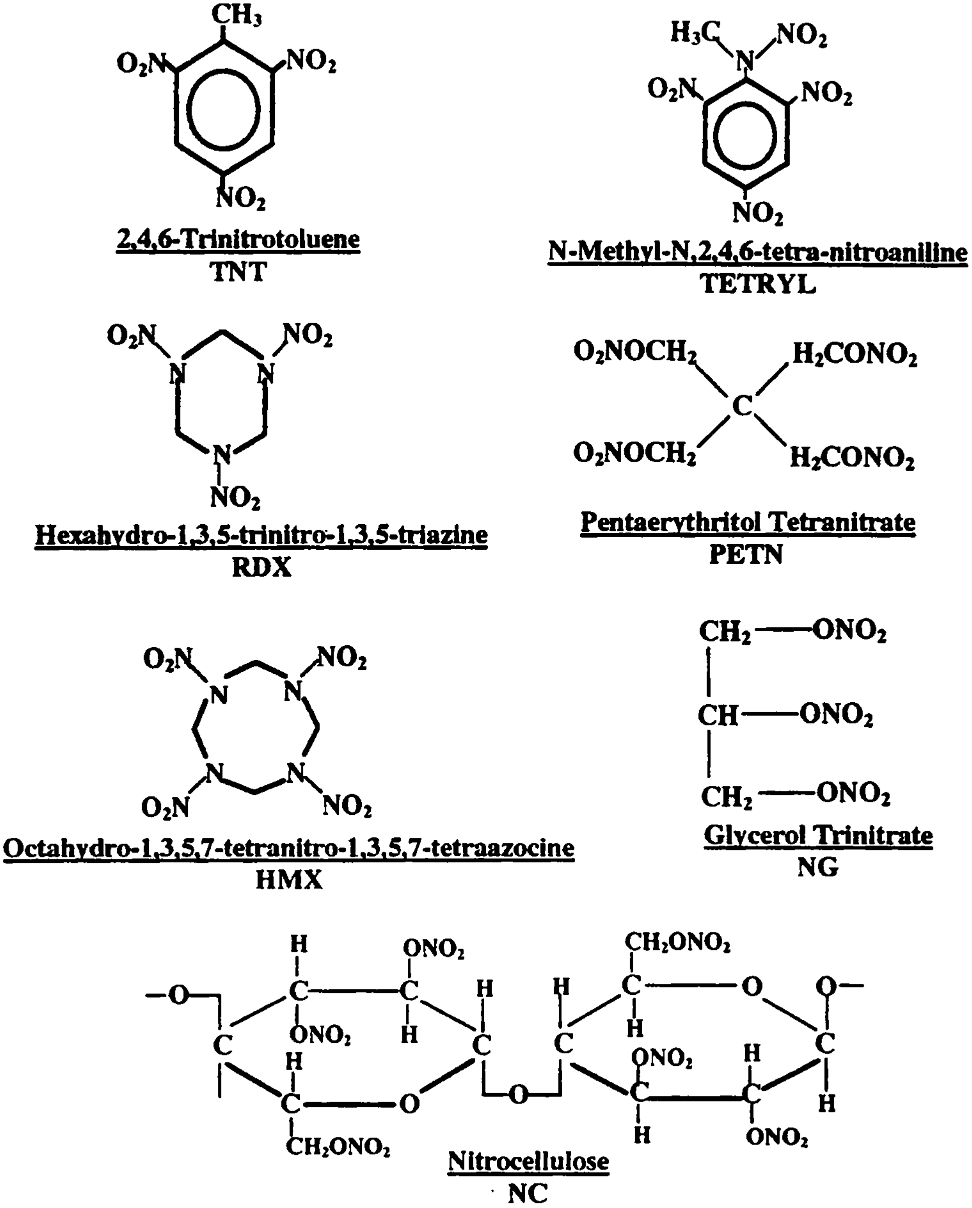
Biodegradability of Explosives in Microbial Systems Other than Composting

A brief overview of previous research on biodegradation of explosives in microbial systems other than composting is presented following. Although such biodegradation data can be used as a guide, no inferences should be made about composting degradability. Composting degradation is handled in a separate section. Trinitrotoluene (TNT) is the principal military energetic material used for munitions and as a result it has attracted most of the research efforts over the years.

TABLE 3: Physical characteristics of selected energetic materials

Compound	Formula	Mol. Mass	M. P., °C	B. P., °C
HMX **(Octahydro-1,3,5,7 tetranitro-1,3,5,7-tetraazocine)**	$C_4H_8N_8O_8$	296.60	276	-
RDX **(Hexahydro-1,2,5 trinitro-1,3,5-triazine)**	$C_3H_6N_6O_6$	222.12	205	-
PETN **(Pentaerythritol-tetranitrate)**	$C_5H_8N_4O_{12}$	316.14	140	200
TNT **(2,4,6-Trinitrotoluene)**	$C_7H_5N_3O_6$	227.13	82	240
Tetryl **(N-methyl-N,2,4,6 tetranitroaniline)**	$C_7H_5N_5O_8$	287.15	131	187
NG **(Nitroglycerin)**	$C_3H_5N_3O_9$	227.09	13	~180
NC **(Nitrocellulose)**	Variable	Variable	617	-

Biodegradation of TNT by phenol acclimated bacteria has been reported since 1963[20]. Studies conducted in the 70's suggested that TNT could be used as a sole carbon source by microorganisms[21]. Other researchers indicated that TNT transformation by sewage effluent, soil or pond water organisms proceeds through co-metabolism in the presence of yeast extract or domestic waste[22,23]. The vast majority of studies performed on TNT biodegradation in various waste matrices including ^{14}C-labeled TNT rule out microbial transformation of the compound via



2,4,6-Trinitrotoluene
TNT

N-Methyl-N,2,4,6-tetra-nitroaniline
TETRYL

Hexahydro-1,3,5-trinitro-1,3,5-triazine
RDX

Pentaerythritol Tetranitrate
PETN

Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine
HMX

Glycerol Trinitrate
NG

Nitrocellulose
NC

FIGURE 1: Chemical Structure of Explosives of Concern

ring cleavage to complete mineralization products (CO_2 + H_2O). The suggested pathway proceeds via a stepwise reduction of the nitro-groups to yield a variety of amino- and hydroxylamino- and azoxy- compounds[24].

Nitrocellulose based "powders" are used extensively as gun and missile propellants and tube munitions. NC also has a wide variety of applications in materials such as pharmaceuticals, adhesives, and varnishes. Early studies suggest that NC is not readily susceptible to direct microbial attack. However it has been postulated that metabolic end products of other substrates in presence of NC may affect adversely its stability[19]. A number of studies reviewed by Duran[25] suggest that pretreatment by acid or alkali hydrolysis can liberate nitrates which could subsequently be utilized by denitrifying cultures. Brodman and Devine[26] have shown that *Aspergillus fumigatus* can enhance hydrolysis of NC in a nitrogen deficient medium with a supplementary carbon source. Anaerobic biotransformation of NC in the presence of cellulose or acetate in conventional and two-phase anaerobic reactors has been demonstrated[25]. Use of enzyme inducers (lactose, cellobiose, cellulose) in conventional anaerobic digestion experiments led to minimal amounts of NC degradation[27].

1,3,5-traza-1,3,5-trinitrocyclohexane (RDX) is also used widely as an explosive. RDX reportedly resists aerobic degradation. In a soil enrichment study RDX reduction was observed however no conclusive evidence of degradation was presented[22]. In the presence of supplementary carbon sources under low redox potential conditions (Eh = -200 to -400 mV), continuous denitrifying cultures observed in municipal wastewater can easily degrade RDX with no accumulation of intermediates[28]. In the same study small amount of mono-, di-nitroso derivatives and trace amounts of hydrazines were observed.

Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine (HMX) is an explosive produced independently or as a by-product during RDX production. Green[29] reported partial degradation of HMX by aquatic cultures. Several studies in various reactor settings including activated sludge, sequencing batch reactor and rotating biocontactors (RBC) presented by Williams[12] indicate similar findings.

COMPOSTING OF ENERGETIC MATERIALS

Biodegradation of Energetics in Laboratory Composting Systems

Biodegradation pathways of energetic compounds by composting microflora generally proceeds in similar ways as in other environments. However, as it will be shown following in certain cases notable differences have been reported. Degradability information on selected energetics is given in Table 4.

It appears that with the exception of TNT, for which most laboratory composting studies are in good agreement, composting of all other compounds appears to differ from research findings from other microbial ecosystems. For example, RDX and HMX which are not considered degradable under aerobic conditions in aquatic systems appear to be fairly degradable in composting

Compound	Pathway	Metabolites	Conditions	Comments	Ref.
TNT	Denitration, no ring cleavage	Amino-, hydroxyl-amino compounds	• Laboratory • Hay horse feed, sludge, wood chips • Soil, corn cobs, fungal innoculum	• 80-98% TNT removal in 6-8weeks • No metabolites after 3 weeks • 53% TNT removal in 3.5 weeks (fungi runs)	7, 11, 21, 30 17
RDX	Ring cleavage	• Not detected • 40-55% $^{14}CO_2$ recovery	• Laboratory ^{14}C-RDX • Hay horse feed, sewage sludge	• 70-75% RDX removal in 6-8 weeks	7, 11
HMX	Possible cleavage	• Not sought • 31% $^{14}CO_2$ recovery	• Laboratory ^{14}C-RDX, pilot-scale • Hay horse feed • sludge, manure	• 48 % HMX reduction in 7 weeks(sewage-lab) • 78% HMX reduction in 8 weeks (manure-lab) • 81% HMX reduction in 8 weeks (manure-pilot)	7
PETN	Mineralization	• 50% CO_2 recovery • ^{14}C-metabolites not identified, lost by volatilization or degradation	• Laboratory ^{14}C-PETN, pilot-scale • horsefeed, alfalfa hay, horse manure 1:2:2	• 88% PETN reduction in 6 weeks (lab study) • Initial PETN mass of 17 g reduced to ND limits in 12days (pilot)	31
NC	N/A	N/A	• Laboratory • Hay horse feed • Sludge, wood chips	• 99.6% avg. NC removal in 3 weeks (horse feed) • 94.5% avg. NC removal in 3 weeks (sludge	32

TABLE 4: Biodegradation Data of Selected Explosives from Laboratory Studies

systems. Similar conclusions can be drawn for NC. Although these discrepancies have been noted by some researchers, no serious attempts have been made for their justification. Credible explanations that can be based on the robust nature of the composting process include:

- presence of diverse microbial communities
- alternation of mesophilic and thermophilic conditions and the subsequent shifts in microbial populations
- long periods of treatment for gradual adaptation of microorganisms
- localization and alternation of aerobic/anaerobic cycles

The discussion above does not in any way intend to discount the importance of the experience gained in aquatic suspensions or any other systems. In fact such information is necessary and should serve as the starting point of every serious research project. However, composting treatability bench and pilot scale should be conducted for compounds or waste matrices that no prior composting experience exists.

Composting of Explosives-Field Studies

Although considerable experience have been gained on composting of other matrices such as wastewater residuals and municipal solid waste, the design and operation of composting units still remains empirical at large. A limited number of field studies have been performed in the area of energetic materials. Most of these studies are based on previous experience, bench and pilot scale composting treatability studies. Table 5 presents a summary of design and operational data for selected field studies on energetic materials.

The results of the "first generation" of full-scale studies indicate the composting technologies can be used successfully for remedial treatment of waste matrices contaminated with energetic materials. Contaminants such as NC, RDX, and HMX persistent to degradation in other microbial environments show encouraging results. It should however be noted that due to possible formation of intermediates ultimate disposal of composting residues should be studied further.

Another area of needed improvement includes a generalized design procedure based on a scientific and rational rather than empirical approach. In that view a design protocol will be presented in a following section.

Cost Considerations

Due to the limited number of full-scale studies insufficient cost data are available in the literature. Capital costs of composting facilities include land, site development, construction, and equipment. Operation and maintenance costs include labor, energy, bulking agent costs, amendment costs, materials and supplies. To these ultimate disposal costs may be, if necessary, added.

An economic feasibility study on composting of NC fines, conducted by McGill[34] compared the aerated static pile modification to three in-vessel systems, (Metcalf & Eddy, Fairfield, Ebara). Results of this study for a facility processing

Parameter	LAAP[12]	BAAP[32,33]	BAAP[32,33]	RAAP[34]
Waste Matrix [Target Compound(s)]	Lagoon Sediment [TNT, RDX, HMX, Tetryl]	Contaminated Soil [NC fines]	Contaminated Soil [NC fines]	Slurried NC Fines [NC fines]
Process Modification	Static Pile	Static Pile	Static Pile	Static Pile
Pile Volume	39 cubic. yards	78 cubic yards	78 cubic yards	90 cubic yards
Pile Height	N/A	3 feet	3 feet	4.5 feet
Bulking Agent	Straw	None	Pine Wood shavings	Wheat straw
Amendment	Alfalfa hay & horse feed, fertilizer, manure	Alfalfa, horse feed, seed compost	Sewage sludge, manure	Recycled compost, sawdust
Waste/Additives Ratio	36% (v), 79%(m)	2-3%(v), 19%(m)	11.8-19.3%(v) 22.2-32.5%(m)	50% (v)
Air Supply	Vacuum	Vacuum	Vacuum	Vacuum
Moisture Content	400 gal added initially	Not Reported	Not Reported	Not Reported
Temperature	55 °C	55 °C	55 °C	55 °C
Target Compound Reduction	99% of total explosive concentration	98.0% of NC concentration	96.4% of NC concentration	Not Reported
Treatment Time	22 weeks	10 weeks	4 weeks	6 weeks

TABLE 5: Design and Operational from Full-Scale Composting of Energetic Materials

6,000 lb. of waste per day are given in Table 6. For the sake of comparison, operating costs for incineration of NC fines is estimated at $2,000 dry ton NC.

TABLE 6: Cost Comparison for Composting of NC Fines (capacity = 6000 lb/d)

Process	**Capital Cost, Millions**	**Operating Cost $1,000's**	**Operating Cost $/Ton NC (dry)**
Static Pile	7.8	498	455
Metcalf & Eddy	12.2	849	772
Fairfield	8.3	780	712
Ebara	7.6	516	471

PROCESS DESIGN

Process Selection

Selection of composting as a possible treatment method for energetics and other hazardous waste matrices is based on sound reasons including[35]:

- competing alternatives such as incineration, landfilling, landfarming, bioslurry treatment are more difficult to implement
- composting is often less costly than other alternatives
- composting enjoys has a more favorable status for funding by regulatory agencies
- as a natural treatment system the process has a positive image among environmental activists, public interest groups and the public in general.

The composting process must minimally satisfy the thermodynamic and kinetic constraints imposed. As long as such constraints are satisfied all three process modifications can be equally desirable. Other factors that can affect the selection of a specific composting technology include technical, economic, public health, and aesthetic factors.

Technical factors that must be addressed include: 1) waste characterization and quantity 2) materials balance and characteristics of the composting mix 3) aeration aspects including operational mode (positive or negative), blower time cycling, mixing, and moisture content 4) detention time and process staging based on kinetic considerations 5) operating temperature (mesophilic or thermophilic) 6) area requirements accounting for pre- and post- and treatment operations, storage of supplementary materials and finished compost, runoff and leachate collection, access roads, access roads and other support areas, 7) topography, 8) meteorology including ambient temperature conditions, precipitation, prevailing winds 8) equipment requirements including mixing, turning, screening, materials handling, monitoring, and sampling, 9) off-gas treatment, 10) leachate treatment

Public health and aesthetic factors that should be considered include: 1) sitting including proximity to populated areas, and groundwater table, 2) appearance, and 3) employee safety.

The aerated static pile and in-vessel composting are the composting methods of preference in hazardous waste applications.

Process Design

Satisfaction of thermodynamic constraints can be accomplished by empirical means, based on previous experience and treatability studies. Haug's procedure consisting of equations 6-8 presented earlier can also be used for determination of W, amount of recycled compost, amendment and thermal source.

Similarly, determination of aeration needs can be based on treatability data. Design equations derived recently[36] for soil piles of semi-circular cross-section can be applicable for the static pile method. Application of these equations presupposes knowledge of the compost mixture characteristics and can be used in conjunction with Haug's equations. Accordingly the overall aeration requirements can be calculated as:

$$Q_t = \frac{MV \cdot OD \cdot (V_t \cdot C_o \cdot \rho_c)}{V_O \cdot MW \cdot E \cdot t} \qquad (9)$$

where Q_t = overall air flow, L/d

MV = 22.4 L O_2 at STP

OD = oxygen demand determined from treatability studies, 2.5-3.5 g O_2/g organics

V_t = volume of compost mixture, m^3

C_o = concentration of organics in the compost mixture, g/Kg

ρ_c = compost mixture density, Kg/m^3

V_O = O_2 fraction in air = 0.2

MW = Molecular mass of O_2 = 32 g/mole

E = efficiency of O_2 utilization, assumed or determined, decimal fraction

t = treatment time.

Assuming N_p is the number of piles, the air flow per pipe, Q_p is:

$$Q_p = \frac{Q_t}{N_p} \tag{10}$$

The air flow per unit pipe length L, q_o is:

$$q_o = \frac{Q_p}{L} = \frac{Q_t}{N_p \cdot L} \tag{11}$$

Assuming that the pile is equipped with N perforated pipes the specific air flow per pipe, $q_{o/pipe}$ is given by:

$$q_{o/pipe} = \frac{q_o}{N} = \frac{Q_t}{L \cdot N_p \cdot N} \tag{12}$$

The required vacuum at the collection header is given by:

$$P_w = \frac{\mu \cdot q_{o/pipe}}{\pi \cdot k} \ln\left(\frac{R}{R_w}\right) = \frac{\mu}{\pi \cdot k} \cdot \frac{Q_t}{L \cdot N_p \cdot N} \cdot \ln\left(\frac{R}{R_w}\right) \tag{13}$$

where μ = air viscosity = 1.8×10^{-5} kg/m/s

k = compost mixture permeability, cm^2

R = pile radius, m

R_w = pipe radius, m

Area requirements, A can be calculated from equation:

$$A = L \cdot \left[2N_p \cdot R + \left(N_p - 1\right) \cdot D\right] \tag{14}$$

where D = minimum distance between piles, m.

The design and scale-up of composting systems for treatment of hazardous waste matrices such as energetic materials can be based on experience gained from composting of other wastes (i.e. wastewater residuals, solid wastes etc.), literature and laboratory data. Pertinent design information may also be derived from carefully designed and executed laboratory bench-.and pilot-scale studies. A design methodology for composting of hazardous wastes is outlined in the form of a protocol presented in Figure 2.

CONCLUSIONS

Composting can be used effectively for the treatment of hazardous waste matrices such as soils and sediments contaminated with energetic materials. The process can compete favorably with other technologies including bioslurry treatment, incineration and landfilling. Treatability studies on bench and pilot scale basis are necessary for derivation of important design information including metabolites, treatment time, aeration requirements, type of bulking and thermal source materials. Although a limited number of field applications are in operation up to date, the economics of composting systems appear to compare favorably to other competing processes. Ultimate disposal of finished composts of hazardous materials needs to be further studied because of justifiable concerns related to production of undesirable metabolites.

PHASE I - PRELIMINARY EVALUATION

Sampling of contaminated material

1. **Initial sample characterization**
    - Soil/sediment properties
    - Target contaminant identification and concentrations
    - Microbial characterization [organism enumeration, identification, isolation of target contaminant(s) degraders]

2. **Literature review**
    - Contaminant(s) biodegradation pathways (aerobic, anaerobic)
    - Metabolic, co-metabolic considerations
    - Presence of metabolites
    - Microbial populations involved

3. **Laboratory biodegradation studies (if literature is not available)**
    - Selection of microbial cultures (aerobic, anaerobic)
    - Addition of co-metabolites
    - Test tube/shaker flask studies
    - Biodegradation rates of targeted contaminants
    - Toxicity/inhibition
    - Identification/biodegradability of metabolites

PHASE II - BENCH-SCALE COMPOSTING

1. **Design of laboratory composting experiments**
    - Selection of thermal sources and bulking agents and nutrients
    - Materials balance and characteristics of composting mix (equations 6-8)
    - Theoretical oxygen requirements (equations 1-5)
    - Process selection (static pile, in-vessel)
    - Design of laboratory composting unit
    - Experimental protocol
    - Monitoring and analytical testing methods
    - Scheduling of activities

FIGURE 2: Design protocol for composting of energetic and other hazardous materials

2. Operation of bench-scale composting unit

- Oxygen uptake rate, optimal C/N ratio
- Temperature and moisture profile
- Biokinetic data, identification of metabolites (production, biodegradation)
- Comparison of various thermal sources/bulking agents
- Process efficiency
- Characterization and toxicity of final compost

PHASE III - PILOT SCALE EXPERIMENTS

1. Design of pilot-scale unit

- Site selection
- Pre- and post-treatment area requirements
- Equipment requirements
- Unit sizing (static pile: equations 9-14; in-vessel: use manufacturer's specifications)
- Construction of pilot-scale units
- Experimental protocol, monitoring and analytical testing requirements
- Scheduling of activities

2. Operation of pilot-scale units

- Compost mixture characterization
- Aeration requirements (blower cycling)
- C/N ratio
- Temperature and moisture profile
- Process efficiency and treatment time
- Characterization and toxicity of final compost
- Post-treatment requirements

3. Parameter estimation for scale-up and full implementation

4. Cost analysis

PHASE IV - FIELD IMPLEMENTATION

FIGURE 2: continued

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