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Special Report 89-38

December 1989

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US Army Corps of Engineers

Cold Regions Research & Engineering Laboratory

AD-A219 352

Low-temperature effects on systems for composting of explosives-contaminated soils

Part 1: Literature review

Olufemi A. Ayorinde and Charles M. Reynolds

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1B. RESTRICTIVE MARKINGS
Unclassified	

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
Special Report 89-38	

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION
U.S. Army Cold Regions Research and Engineering Laboratory	CECRL	U.S. Army Toxic and Hazardous Materials Agency

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
72 Lyme Road Hanover, N.H. 03755-1290	Aberdeen Proving Ground, Maryland 21010

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
		A1-8-F2511-91-48

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Low-Temperature Effects on Systems for Composting of Explosives-Contaminated Soils
Part 1: Literature Review

12. PERSONAL AUTHOR(S)
Ayorinde, Olufemi A. and Reynolds, Charles M.

13a. TYPE OF REPORT	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) December 1989	15. PAGE COUNT 21

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Cold regions engineering Explosives-contaminated soils
			Composting Soil decontamination
			hazardous materials Waste disposal management (k7)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report reviews literature on the influence of major parameters on composting, with emphasis on temperature and explosives. Heat energy is produced by composting as a result of the microbial conversion of chemical energy to thermal energy. Hence, heat production and transfer, the influence of engineering design on compost pile temperatures, and the control and measurement of compost pile temperatures are also examined. In addition, the report includes a general discussion on composting, fundamental composting principles, available types of composting systems, applications of composting technology, and the established parameters influencing composting under various environmental conditions that may be applicable to cold regions treatment of hazardous waste.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Olufemi A. Ayorinde	603-646-4100	CECRL-RC

DD FORM 1473, 84 MAR   83 APR edition may be used until exhausted.   SECURITY CLASSIFICATION OF THIS PAGE
All other editions are obsolete.

PREFACE

Accession For		
NTIS GRA&I		☒
DTIC TAB		☐
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Justification		
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Distribution/		
Availability Codes		
Dist	Avail and/or Special	
A-1		

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Low Temperature Effects on Systems for Composting of Explosives-Contaminated Soils
Part 1: Literature Review

OLUFEMI A. AYORINDE AND CHARLES M. REYNOLDS

INTRODUCTION

The manufacture, use, and disposal of organic-based explosives at military bases and U. S. Army ammunition plants have resulted in soils and sediments contaminated with explosives residue. These compounds include 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), N-methyl-N,2,4,6-tetranitroaniline (tetryl), nitrocellulose and other compounds. Composting is being studied as a means to decontaminate explosives-contaminated soils and may have the potential to be a cost effective, environmentally safe, and readily implemented biorestoration technology. Requirements for using composting technology in a wide range of environmental conditions include increased knowledge of the extent of environmental influences on explosives-composting processes, an understanding of methods to control or mediate these influences, and the ability to successfully apply this knowledge on a practical scale. Sites having explosives-contaminated soils occur over a wide range of latitudes, and temperature has been shown to have an effect on microbially mediated processes involved in composting explosives-contaminated soils (Isbister et al. 1982, Doyle et al. 1986). Both the effect of temperature on the composting process and the methods to manipulate temperature to advantageously influence the ongoing composting processes require more study.

The purpose of this report is to review available literature on the influence of cold temperatures on composting with emphasis on composting explosives, the influence of engineering design on compost pile temperatures, and the control and measurement of compost pile temperatures. In addition, the report includes a general discussion on composting, composting fundamental principles, available types of composting systems, applications of composting technology, and the established parameters influencing composting under various environmental conditions that may be applicable to low temperature composting.

DEFINITION OF COMPOSTING

A review of the literature indicates that there is no universal definition of composting. In a broad sense, Haug (1980) defines composting as the biological decomposition and stabilization of organic substrates under conditions that allow development of thermophilic temperatures greater than 40°C as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmental effects. Thus, composting is a form of waste stabilization, but one that requires special conditions of moisture and aeration to produce thermophilic temperatures.

According to Williams et al. (1988), composting is a biological treatment process in which soil and sediment are mixed with bulking agents and carbon sources to enhance microbial metabolism in degrading and stabilizing soil contaminants. Organic materials are biodegraded by microorganisms, resulting in the production of organic and/or inorganic by-products and energy in the form of heat. When applied to waste control or used for contaminant destruction and detoxification in soils, composting is a combination of biological and engineering processes.

The process of composting is readily classified into two broad categories. Aerobic composting, the decomposition of organic substrates in the presence of oxygen, is usually achieved by supply-ing air through ventilation. The main products of aerobic metabolism are microbial biomass, carbon dioxide, water and heat. Conversely, anaerobic composting is the biological decomposition in the absence of oxygen and yields the metabolic end products of methane, carbon dioxide and organic acids. In general, anaerobic composting releases significantly less energy per unit weight of organic material decomposed compared to aerobic composting, and anaerobic composting has a higher odor potential (Haug 1980).

Finstein et al. (1986b) differentiates between product-oriented composting, such as that used for producing a beneficial soil amendment, and treatment-oriented composting, such as that used as a component in an overall treatment plan. More-over, the authors clearly stress that the two composting uses have different goals. It is reasonable to question whether the two composting goals require different or similar process design and controls.

In municipal waste composting systems, the goal is to provide municipal waste decomposition in a manner that is cost-effective, odor-free, and environmentally sound (Finstein et al. 1986b, Epstein et al. 1976). Because aerobic composting surpasses anaerobic composting in meeting these goals, the preponderance of municipal waste composting research has centered on increasing the rate of the composting process. That is, faster aerobic composting rates are synonymous with achieving the desired goal of better cost efficiency.

In developing composting systems to treat toxic and hazardous wastes, a new goal, different from the two described by Finstein et al. (1986b), is distinguished. The goal of toxic and hazardous composting is to detoxify or render harmless the waste being composted. In such composting systems, the hazardous waste compound may lack the organic substrates necessary to initiate spontaneous composting, and suitable organic substrates must be added. Although the goal in municipal waste composting is equivalent to maximizing the rate of organic substrate decomposition, the same may not be true for hazardous waste composting, in which the relationships among decontamination of different hazardous wastes and the decomposition rates of added organic substrates have not been clearly defined.

BIODEGRADATION/ BIOTRANSFORMATION PROCESSES

The term "biodegradation" is often inappropriately used to describe the microbial transformation of compounds (Atlas and Bartha 1987). Frequently the result of biotransformation of anthropogenic compounds is a synthesis of more complex products (Brooks 1974, Sjoblad and Bollag 1981, Wood 1971). Such products have been shown to result from composting explosives (Kaplan and Kaplan 1982b, McCormick et al. 1975). For clarity, this review will use the term "biodegradation" to mean complete or ultimate degradation of a substrate to carbon dioxide and inorganic mineral forms, such as ammonium. For other microbially mediated processes that do not culminate in such complete oxidation, the term "biotransformation" will be used. Notably, a series of biotransformations may be required to eventually yield biodegradation.

Biotransformation describes the transformation of a substrate to another compound or compounds. All biotransformation products may not be completely identified. They may be either more toxic than the original compound composted, nontoxic, or subject to further biotransformations or biodegradation under favorable environmental conditions (Atlas and Bartha 1987). Moreover, different environmental conditions may favor formation of one or several products resulting in minimal formation of others (Atlas and Bartha 1987, McCormick et al. 1975). For poorly defined processes, biotransformation rates are much more readily measured than biodegradation rates. In general, monitoring biotransformation requires measuring only the disappearance or loss of the starting substrate. Confirming biodegradation requires monitoring $^{14}CO_2$ evolution from ^{14}C-labeled contaminants. If ^{14}C-labeled contaminants are not available, separation and analysis of a suite of possible by-products, some of which may be unknown or have no proven analytical methodologies, is required. Much of the research on composting explosives in soils has determined only the disappearance of the starting substrate, and is therefore a measure of biotransformation rather than biodegradation.

Knowledge of the reactivity, toxicity, and stability of these transformation products is incomplete, although laboratory incubations involving ^{14}C-labeled compounds have indicated that biodegradation accounts for only a slight portion of all biotransformation processes that occur during

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explosives composting (Isbister et al. 1982). There is also evidence that the biotransformation of explosives is a process of co-metabolism (Osmon and Klausmeier 1972). This fact reinforces the view that the microbial activity in the pile is primarily associated with processes other than explosives metabolism. Furthermore, it implies that, by better controlling these governing processes and understanding their relationship with reactions involving explosives and their metabolites, it may be possible to develop methods to advantageously influence the processes leading to complete and effective bioremediation of explosives.

PARAMETERS AFFECTING COMPOSTING

A number of studies in the literature (Finstein et al. 1986a,b 1987a,b,c; Haug 1980, 1986a,b,c; Cathcart et al. 1986; Bhoyar et al. 1979) have addressed the importance of environmental conditions and parameters affecting composting. The parameters that consistently have been found to significantly impact the efficiency of the composting process include temperature, moisture content, chemical and biological characteristics, availability of substrates, substrate concentration and ratio of concentrations, inorganic and organic nutrients, heat production and retention characteristics of the compost, and the partial pressure of oxygen within the compost material (Finstein et al. 1986b). However, to date, no research information or data are found in the literature on the sustained effect of a cold climate on composting.

The majority of published research has been concentrated on the composting of municipal and industrial solid wastes, with relatively few studies on composting hazardous/toxic wastes. Although it may not be appropriate to directly transfer all the conditions used in municipal or industrial waste composting to systems designed for hazardous waste composting, a great deal of knowledge can be obtained from previous research information on composting municipal and industrial solid wastes.

Temperature
Among the interrelated factors influencing composting processes, temperature is perhaps the most significant. The temperature within a composting system is a function of the accumulation of heat generated metabolically, and simultaneously the temperature is a determinant of metabolic activity. Hence temperature is both a cause and an effect in terms of the heat output in a self-heating ecosystem of compost and governs the self-limiting conditions for microbial activity (MacGregor et al. 1981). The interaction between heat output and temperature is therefore the centerpiece of rational control of the composting system (Haug 1980, Finstein et al. 1986a,b; Williams et al. 1988; Bhoyar and Bhide 1982). Almost all the referenced studies on the temperature effect were conducted in high mesophilic to thermophilic (35°–55°C) temperature ranges.

There is a scarcity of information on the effect of low temperature on compost operation and performance. No published data are available to help establish the low temperature level at which composting microbial activity would cease. It is generally acknowledged by researchers that a low starting temperature (cold start) tends to prolong the start-up stage. Mosher and Anderson (1977) reported that, at an ambient temperature of 9° to 17°C, it took 2 to 6 days for a compost of sludge wood chip mixture to reach 55°C, while at –17° to 0°C, it took 7 to 18 days. It appears that minimal starting ventilation was used to speed the temperate ascent to more biologically favorable levels. The authors claimed that a compost material initially at 0°C reached thermophilic temperature in 4½ days; however, there was no quantitative evidence offered to support this claim. Nevertheless, it appears that marginally effective composting can spontaneously occur at low temperatures if necessary oxygen and water are present, and the compost mass is sufficient to retain heat.

Studies have generally concluded that thermophilic conditions ranging from approximately 40°–60°C are desirable for composting (Finstein et al. 1986a,b; Sikora and Sowers 1985). These conclusions are generally based on studies of municipal wastes in which decomposition was determined by CO_2 evolution or substrate mass reduction. In such a system, thermophilic conditions are desirable for both rapid decomposition and pathogen destruction. Although thermophilic conditions up to approximately 60°C generally result in faster microbial metabolic rates than those under mesophilic conditions (Finstein et al. 1986a,b), there is evidence that microbial diversity may be reduced as conditions become increasingly thermophilic (Strom 1985). Owing to the natural predominance of mesophilic conditions and microbial specificity for substrates, reduction in microbial diversity may result in less complete oxidation and reduced net biodegradation of complex substrates.

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Among several composting studies that have focused on explosives, few have been conducted at temperatures lower than thermophilic. This is understandable considering the natural tendency of a compost pile to reach a thermophilic regime, the desirable faster metabolic rates that result, and the realization that the considerable volume of published research has been primarily aimed at composting municipal waste. Kaplan and Kaplan (1982a) compared the mesophilic-biotransformation products of TNT (McCormick et al. 1975) to those resulting from thermophilic incubation conditions (Kaplan and Kaplan 1982b) and found them to be similar.

Method for quantifying temperature during composting

For any system, open or closed, the first law of thermodynamics (also known as the law of conservation of energy) prevails and helps to establish "energy balance" in the system. Hence, in a composting system, there is an "energy balance" given as

$$\text{Net amount of energy} = \text{Net increase in stored energy of system added to system}$$

Thermodynamically, energy can be added to the *system or taken from it by means of heat and work* for both open and closed systems. However, in the case of an open system, there is an additional mechanism for increasing or decreasing the stored energy of the system. When mass enters a system, *the stored energy of the system is increased by the* stored energy of the entering mass. On the other hand, the stored energy of a system is decreased by the stored energy of mass leaving the system. Distinguishing the transfer of stored energy of mass crossing the system boundary from heat and work, the system "energy balance" can be expressed as:

Net amount energy added to system as + heat and all forms of work	Stored energy of mass entering system	–	Stored energy of mass leaving system	=	Net increase in stored energy of system.

When there is no transfer of mass across the boundary of a system, the net increase in the system's stored energy is only due to the net amount of energy added to the system as heat and work. This is shown schematically in Figure 1 where heat flow into the system (+q) and work done by the system (+w) are classified as positive system energy, while heat flow out of the system (–q) and work on the system (–w) are considered to

be negative system energy. Expressed mathematically (Jones and Hawkins 1963), Figure 1 becomes

$$Q - W = \Delta E \qquad (1)$$

where Q = net heat flow into the system
W = net work done by the system = $\int p\,dV$
E = net change in stored or internal energy of the system
p = system pressure
V = volume of the system.

If the system is isovolumetric (i.e., maintained at constant volume), eq 1 becomes

$$Q_v = \Delta E. \qquad (2)$$

In differential form, eq 1 becomes

$$dQ = dW + dE. \qquad (3)$$

Temperature change in any system is directly related to its heat content. Hence, the heat per unit mass flowing into the system can be expressed as

$$dQ = mc\,dt \qquad (4)$$

where m is the mass, c is the temperature-dependent specific heat and dT is the change in temperature.

By integrating eq 4, if we assuming a constant specific heat, the amount of heat in the system can be estimated as

$$Q_v = mcv(\Delta T) \quad \text{(for constant-volume process, } T \text{ not large)}$$

$$Q = mcp(\Delta T) \quad \text{(for constant-pressure process, } T \text{ not large)}$$

where v and p denote conditions for constant volume and constant pressure, respectively.

Since many chemical and most biological processes operate under constant pressure, eq 3 can be expressed as

$$dQ_p = de + p\,dV \qquad (5)$$

which, after integration, becomes

$$Q_p = (E_2 + pV_1) - (E_1 + pV_1) = H_2 - H_1 = \Delta H$$

where H is the enthalpy. In addition, the temperature change during composting can be estimated under the constant pressure condition by using eq

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Figure 1. Schematic illustration of the principle of conservation of energy, also known as the first law of thermodynamics. Note the sign convention on the terms for heat and work (Jones and Hawkins 1963, Haug 1980).
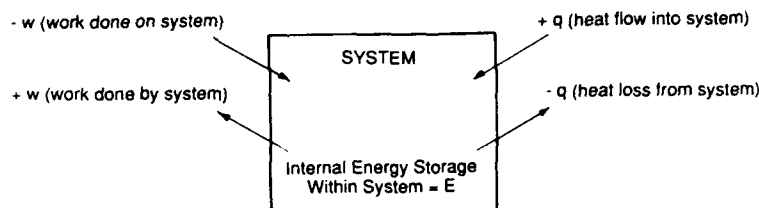
5 with the following equation:

$$\Delta T = Q_p \: / \: (mcp) \quad (\Delta T \text{ is not large}) \tag{6}$$

where c_p is the specific heat at constant pressure.

Equations 5 and 6 are not applicable for spontaneous chemical or biological reactions, which may occur in some composting processes. To quantify heat generated (and thus temperature) for spontaneous chemical reactions, the second law of thermodynamics (which states that any spontaneous change in an isolated system always occurs with an increase in entropy; i.e., the change in entropy S must always be positive for any system) is used. Since all chemical reactions have a standard free energy change, the relationship between enthalpy (H) and entropy (S) can be expressed in terms of the Gibb's free energy function (G). Hence

$$G = H - TS. \tag{7}$$

For constant pressure and temperature, eq 7 becomes

$$\Delta G = \Delta H - T\Delta S. \tag{8}$$

Table 1. Standard state enthalpy and free energy of formation at 25°C.

Substance	State	ΔH^* (kcal/mol)	ΔG^* (kcal/mol)
CH₄	gas	–17.89	–12.14
CH₃COOH	aqueous	–116.74	–95.51
C₆H₁₂O₆	aqueous		–217.02
CO₂	gas	–94.05	–94.26
CO₂	aqueous	–98.69	–92.31
H₂O	liquid	–68.32	–56.69
H₂O	gas	–57.80	–56.64
H₂S	aqueous	–9.4	–6.54
NH₄⁺	aqueous	–31.74	–19.00
SO₄²⁻	aqueous	–216.90	–177.34
H⁺ (pH 7)	aqueous		–9.67
NH₄Cl	crystal	–75.38	–48.73
Cl⁻	aqueous	–40.02	–32.35

*Compiled from data in Handbook of Chemistry and Physics (CRC Press 1970).

Standard state values for enthalpy and free energy at 25°C for various substances encountered in compost mixture and by-products are given in Table 1. Table 2 gives the values for the heats of combustion of some organic fuels (Haug 1980).

Empirical methods for estimating heats of reaction during composting

In the composting of municipal, industrial or hazardous/toxic wastes, mixtures usually comprise several organic compounds of unknown composition. Hence, it is often difficult to estimate the heats of reaction from organic wastes from standard enthalpy values, since the mixture composition is not completely known. Even if it is known, the enthalpy values would only help to define a range of probable heats of reaction. As a result, several experimental and empirical techniques have been developed to determine heat of reaction.

One experimental method for determining heating value of organic waste is by calorimetric measurements. Calorimetric measurement technique is undoubtedly the most accurate way of determining heats of reaction for organic mixtures (Haug 1980). This technique consists of either 1) an "open calorimeter" in which the heat of chemical reaction is measured at a constant pressure of one atmosphere, or 2) a "bomb calorimeter" in which reactions are conducted under constant-volume conditions. Even though the heat release in a bomb calorimeter would be different from that in a constant-pressure calorimeter, the differences are usually small for organic materials which release considerable energy on oxidation (Lee and Sears 1963).

An experimentally based empirical formula for determining the fuel values of different types of vacuum-filtered sludges was formulated by Fair et al. (1968):

$$Q = a[(100 \times P)_v \: / \: (100 - P_c) - b] \times$$

$$[(100 - P_c) \: / \: 100] \tag{9}$$

where Q = fuel value (Btu/lb dry solids)

a = 131 and b = 10 for raw and digested primary sludge

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Table 2. Heats of combustion of some organic fuels.*

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Feed	Formula	Molecular weight	ΔH_R^{0**} (cal/mol)	g COD†/ (mol)	g COD/ (g organic)	kcal/g	kcal/g COD
Carbohydrate							
Glucose	$C_6H_{12}O_6$	180	–673,000	192	1.067	3.74	3.51
Lactic acid	$CH_3CH(OH)COOH$	90	–326,000	96	1.067	3.62	3.40
Polysaccharides, e.g., starch and cellulose	$(C_6H_{10}O_5)_x$				essentially same as for glucose		
Lipid							
Palmitic acid	$CH_3(CH_2)_{14}COOH$	256	–2,398,000	736	2.87	9.37	3.26
Tripalmitin	$(CH_3(CH_2)_{14}COO)_3(C_3H_5)$	809	–7,510,000	2,320	2.87	9.28	3.24
Protein							
Glycine (Amino acid)	$CH_2(NH_2)COOH$	75	–163,000	48	0.64	2.18	3.41
Hydrocarbons							
n-Decane	$CH_3(CH_2)_8CH_3$	142	–1,610,000	496	3.49	11.34	3.25
Methane	CH_4	16	–210,000	64	4.00	13.18	3.29

* Heats of combustion were obtained from Handbook of Chemistry and Physics (CRC Press 1970), and correlated to products of combustion as $(CO_2)_g$, $(H_2O)_{aq}$ and $(NH_4^+)_{aq}$.

† Chemical oxygen demand.

** Heat of reaction.

a = 107 and b = 5 for raw waste-activated sludge

P_v = percent volatile solids in sludge

P_c = percent of inorganic conditioning chemical in sludge.

Data used to derive eq 9 were obtained from a constant-volume bomb calorimeter. Although eq 9 was developed only for municipal sludge and should not be extended to other organic wastes, this approach may be applicable to hazardous waste composting.

Spoehr and Milner (1949) presented a formula that relates the heat of combustion to the degree of reduction of organic matter. Products of combustion are assumed to be gaseous carbon dioxide (CO_2), liquid water (H_2O), and nitrogen (N_2). Thus, the degree of reduction (DR) for any organic matter is given by

$$DR = \{100 \times [2.66(C) +$$

$$7.94(H) - (O)]\} / 398.9 \tag{10}$$

where C, H and O are the percentages of carbon, hydrogen and oxygen, respectively, on an ash-free basis. The heat of combustion (Q) is given by:

$$Q(cal/g) = 127 \times DR + 400. \tag{11}$$

Corey (1969) presented the Dulong formula which is sometimes useful for estimating gross heating values for the feed composition:

$$Q(Btu/lb) = 145.5(C) +$$

$$620 \times (H - O/8) + 41(S) \tag{12}$$

where S is the percentage of sulfur.

It should be noted that eq 11 and 12 require a fairly complete laboratory analysis of the waste to accurately determine the percentages of carbon, hydrogen, oxygen and sulfur. These data may not be available routinely. A list of heat contents of dry refuse and sewage sludge samples is given in Table 3.

Reaction rates and effect of temperature

Biological, biochemical and chemical reaction rates in composting system are usually a function of temperature. Above mesophilic and within thermophilic temperature ranges, it has been shown that there is faster microbial activity leading to a rapid generation of heat (Finstein et al. 1986b). Haug (1980) noted that a convenient way of expressing the temperature effect is to determine and compare the rate of activity at one temperature to the rate at a temperature 10°C lower. The resulting ratio is known as the temperature

Table 3. Representative chemical analysis and heat content of dry refuse and sewage sludge samples (Loran 1975).

Constituent	Refuse (wt %)	Raw sludge (wt %)	Digested sludge (wt %)
Carbon	33.11	37.51	24.04
Hydrogen	4.47	5.54	3.98
Oxygen	25.36	22.56	12.03
Nitrogen	0.60	1.97	2.65
Chlorine	0.41	0.33	0.17
Sulfur	0.14	0.37	0.75
Metal	11.64		
Glass, ceramics, stone	16.23		
Volatiles @110°C		3.66	3.01
Ash	8.04	28.06	53.37
Total	100.00	100.00	100.00
Higher heating value (cal/g)	3280	3910	2570

coefficient, Q_{10}. Within certain limits, the rates of most chemical reactions approximately double for each 10°C rise in temperature (with Q_{10} approximately equal to 2.0).

The effect of temperature on chemical reactions on the rate constants for chemical reactions can be estimated using Arrhenius equation:

$$d(\ln k)\,/\,dT = E_a/RT^2 \tag{13}$$

where k = reaction rate constant
E_a = activation energy for the reaction (cal/mol)
T = absolute temperature (K)
R = as constant (cal/mol) (K)

and activation energy is defined as the amount of energy needed by a molecule to undergo a successful chemical reaction. Integrating eq 13 yields

$$\ln(k_2/k_1) = E_a(T_2 - T_1)/RT_1T_2 \tag{14}$$

In composting systems, most biological and biochemical processes operate within a limited range of temperatures. Since the product of T_1 and T_1 changes only slightly over the biological temperature range (e.g., 0 to 80°C, which is equivalent to 273 K to 353 K), E_a/RT_1T_2 can be assumed constant. Hence, eq 14 can be written as

$$\ln(k_2/k_1) = \theta(T_2 - T_1) \tag{15}$$

i.e.,

$$k_2 = k_1 \exp[\theta(T_2 - T_1)] \tag{16}$$

where θ is assumed to be reasonably constant. However, Haug (1980) indicated that θ has been found to vary considerably even over small temperature ranges. He suggested that applicable temperatures should be clearly stated for values of θ used in eq 15 and 16. For comparison, a θ of about 0.069 corresponds to a Q_{10} of 2.0.

Moisture content

In composting systems, decomposition of organic matter depends upon the presence of moisture to support microbial activity. It has been suggested that the theoretical ideal moisture content for composting would be one that approaches 100%, because under such conditions, biological decomposition would occur in the absence of any moisture limitation (Golueke 1977). Hence, maintaining a proper moisture balance is a critical factor in the design of sludge or any other organic substrate composting system. The thermodynamic balance of the composting system and the ability to aerate the compost material are greatly influenced by proper moisture content (Atchley and Clark 1979; Haug 1980; Jacobowitz and Steenhuis 1984).

Optimum gravimetric moisture content levels for composting have been reported to range from 50 to 70% (McKinley and Vestal 1985). Bakshi et al. (1987) found that 70% gravimetric moisture content provided the most suitable conditions for natural fermentation of urea-treated straw. For composting explosive-contaminated soils, Williams et al. (1988) used a range of 20 to 26% gravimetric moisture content.

Due to the heterogeneity of compost mixtures, the use of percentage water content rather than water potential is, at best, merely a gross approximation of the water characteristics of the compost system; hence it prevents comparing moisture effects from published results or transferring experimental results to other situations. The water available for microbial processes is dependent on not only the amount of water in the system but also the solution osmotic potential, the sorptive capacity, and hygroscopicity of the matrix. Consequently, at a given gravimetric moisture content, the available water can vary significantly, depending on solute concentration and the texture and quantity of soil added to a compost mixture, as well as the texture and nature of the compost bulking agents used. Despite the lack of quantitative data, it is well established that ventilation used for heat

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removal causes drying and water must be added to the compost system (Finstein et al. 1987a,b,c). Available literature does not provide sufficient data to interpolate the optimum water potential for explosives biotransformation in composting systems that consist of blends of soil and bulking agents.

Aeration

Composting is an exothermic process that increases the temperature in the system; temperature, in turn, is a determinant for microbial activity rates, thereby influencing heat output. These coupled feedback processes effectively raise compost-pile temperatures sufficiently high to inhibit the active microbial population and temporarily inhibit the composting process. To counter the heat production effect on temperatures, forced ventilation is generally employed (Macgregor et al. 1981). Ventilation promotes cooling both by convection and, to a much greater extent, by evaporation. Ventilation also serves to promote aerobic conditions, thus favoring faster aerobic metabolic pathways and rates that are associated with aerobic processes. Although there is significant evidence that RDX biotransformation is an anaerobic process (McCormick et al. 1981), there is a general agreement that aerobic conditions should be favored in the composting pile (Finstein et al. 1987a,b,c; Williams et al. 1988). Ventilation and the subsequently induced evaporation dry the system to a degree that inhibits microbial activity.

Heat removal mechanisms during composting

To develop and design an effective system for large field-scale composting of explosives-contaminated soils and wastewater, heat removal and control techniques have to be used to moderate a large temperature buildup caused by heat generation during composting. According to Finstein et al. (1986b), the heat removal mechanisms that occur during composting include radiation, conduction, vaporization of water (evaporative cooling), and sensible heating (temperature increase of dry air). Hence

$$Q_{tot} = Q_{rad} + Q_{cond} + Q_{vent} \qquad (17)$$

where Q_{tot} = total heat removal
Q_{rad} = radiant removal
Q_{cond} = conductive removal
Q_{vent} = ventilative removal.

The sum of conductive and radiative heat removal

is very small compared to the ventilative heat removal, and therefore can be neglected in eq 17. Hence, the total heat removal can be equated to the ventilative heat removal. The relationship governing ventilative removal is given by

$$Q_{vent} = m(H_{out} - H_{in}) \qquad (18)$$

where Q_{vent} = rate of ventilative heat removal (energy/time)
m = dry air mass flow rate (mass dry air/time)
H_{out} = outlet air enthalpy energy/mass dry air)
H_{in} = inlet air enthalpy (energy/mass dry air).

The enthalpy of the air is a function of both its temperature and relative humidity (RH).

Effect of ventilation on composting

Ventilation, whether forced or natural, supplies oxygen required to support aerobic biological activity in composting. The stoichiometric oxygen demand will depend on chemical composition of the organic material. For municipal sludge, a value of approximately 2 g of oxygen per gram of organic material oxidized is assumed reasonable (Haug 1980, Kuter et al. 1985). Also, it has been found that, compared to natural ventilation in windrow composting systems, forced ventilation by means of blowers is the major aerating mechanism in the aerated static pile and many reactor systems.

Furthermore, the use of a blower to force air through a composting pile increases ventilative heat removal, leaving conduction to play a minor role in removing the generated heat. In addition, vacuum-induced ventilation is commonly used for odor control by venting the outlet air through a "scrubber pile" consisting of aged or stabilized old compost (Epstein et al. 1976). Two mechanisms that account for heat removal rate through ventilation, Q_{vent} (energy/time) are represented by 1) the heat removal rate through vaporization, Q_{vap} (energy/time), and 2) the heat removal rate through sensible heating of air, Q_{sens}, (energy/time). Thus

$$Q_{vent} = Q_{vap} + Q_{sens}. \qquad (19)$$

Assuming outlet air at 60°C temperature and a relative humidity (RH) of 100%, Finstein et al. (1986b) estimated that

$$Q_{vap} = 9 \times Q_{sens}. \qquad (20)$$

From eq 18 19 and 20, the vaporization heat removal rate can be estimated as

$$Q_{vap} = 0.9 \times m(H_{out} - H_{in}). \qquad (21)$$

No information was available on research that investigated the impact on compost biological activity of forced or natural ventilation of air far below the mesophilic temperature or close to freezing temperature.

Organic content and inorganic nutrients

Microbial activity of a composting system is directly influenced by the organic content and inorganic nutrients of the composting material (Finstein et al. 1987a,b,c; Haug 1980, 1986a,b,c). Cathcart et al. (1986) conducted experiments to determine the optimum value of the carbon/nitrogen ratio of material used as a nutrient for the composting of solid waste (crab scrap). The effects of different types of inoculum and mineral concentrations were found to profoundly affect the composting activity of synthetic solid waste in the thermophilic temperature range (Clark et al. 1978).

COMPOSTING SYSTEM DESIGN AND TECHNOLOGY

Almost all the existing compost design concepts were developed for composting municipal and industrial solid wastes. These types of solid wastes usually consist of wet feed substrates that are difficult to compost alone because of the high moisture content. Hence, the general schematic diagram for composting is represented as shown in Figure 2. The fundamental concepts embodied in Figure 2 underlie all composting systems and their operations; therefore they are applicable to the composting of explosives-contaminated soils, sludge or wastewater.

Classification of composting systems

Composting systems can be classified according to the reactor type and nonreactor type, solids flow mechan-

isms, bed conditions in the reactor and manner of air supply. All of the available systems have advantages and disadvantages relative to one another. The nonreactor ("open") systems consist of those that maintain an agitated solids bed and those that employ a static bed as shown in Figure 3. In the compost systems with an agitated solids bed, the compost mixture is disturbed or broken up in some manner during the compost cycle.

Reactor systems, on the other hand, are usually termed "mechanical," "enclosed" or "within-vessel" composting systems (Haug 1980). The term "mechanical" is a misnomer because most modern composting systems, including nonreactor systems, are mechanical to some extent. Figures 4–7 illustrate the different types of reactor systems. The following classification scheme, which can be used to classify any type of composting system, has been developed (Haug 1980):

I. **Nonreactor (Open) Systems**
   1. *Agitated solids bed (windrow)*
      a. Conventional
      b. Forced aeration
   2. *Static solids bed*
      a. Forced aeration (aerated static pile)
      b. Natural ventilation
II. **Vertical Flow Reactor Systems (Tower Reactor)**
   1. *Moving agitated bed*
   2. *Moving packed bed*
      a. Continuous or intermittent feed
      b. Batch feed
III. **Horizontal and Inclined Flow Reactor Systems**
   1. *Tumbling solids bed (rotating drum)*
      a. Dispersed flow
      b. Cells in series
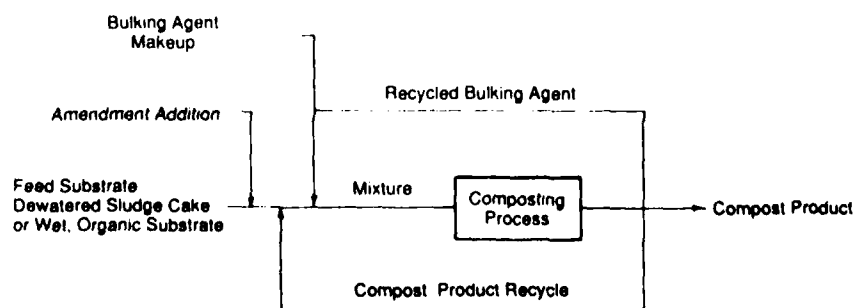   c. Completely mixed
   2. *Agitated solids bed (bin reactors).*

Figure 2. *Generalized diagram for composting showing inputs of feed substrate, compost product recycle, amendment and bulking agent (Haug 1980).*
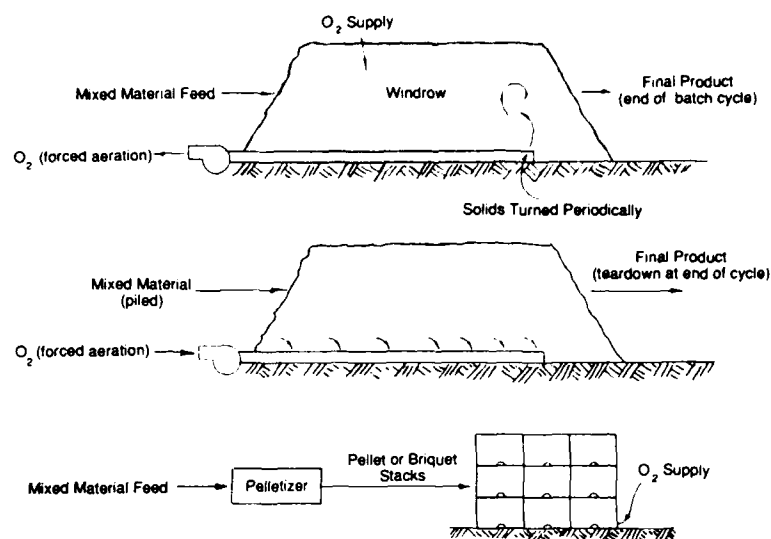
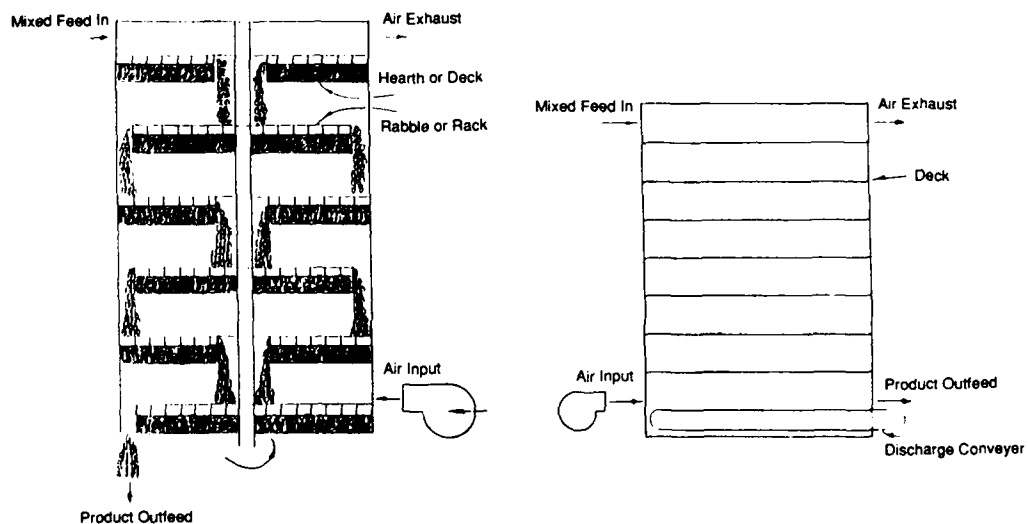**Figure 3. Nonreactor composting systems (Haug 1980).**

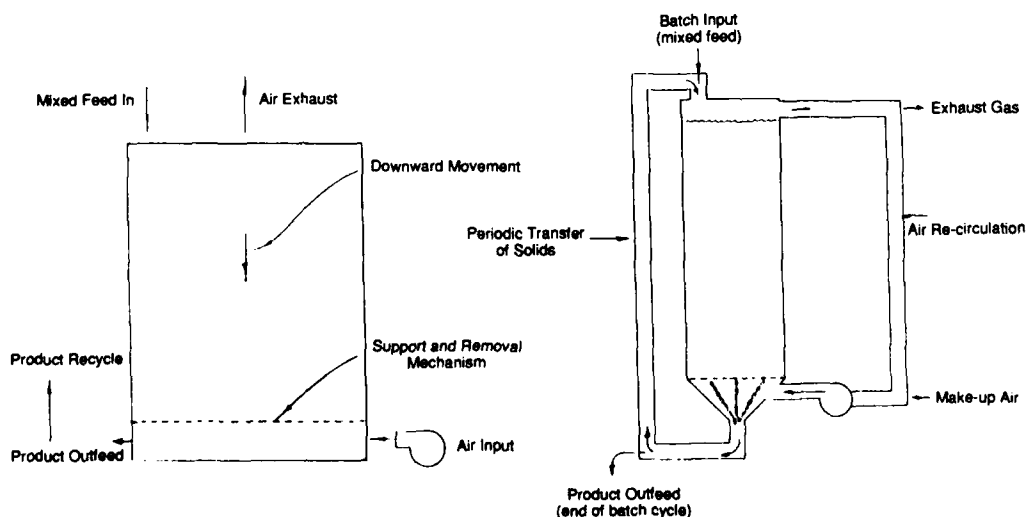**Figure 4. Vertical flow reactor systems (tower or silo reactors) (Haug 1980).**

Figure 5. Vertical flow reactor systems (tower or silo reactors) (Haug 1980).
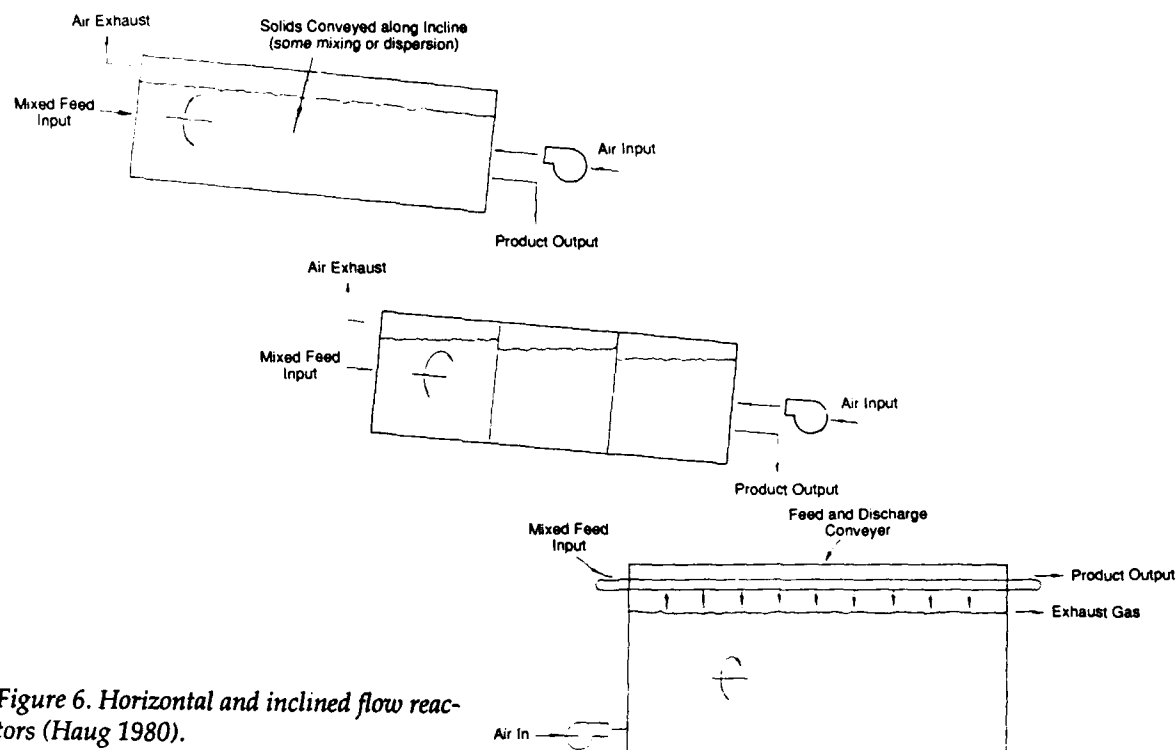
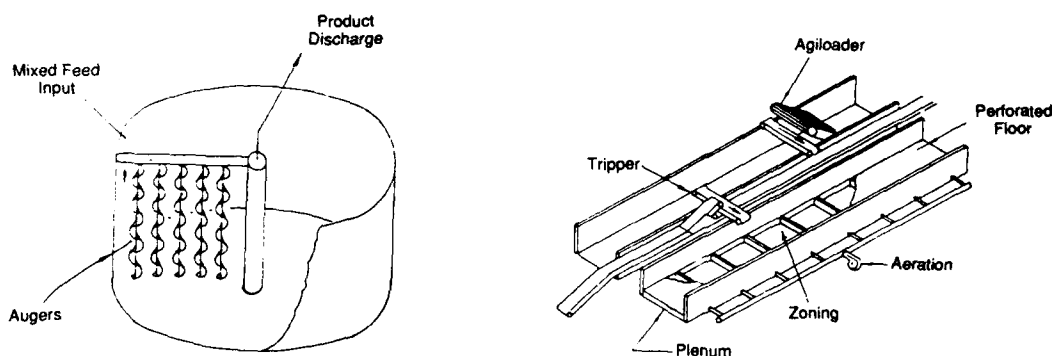Figure 6. Horizontal and inclined flow reactors (Haug 1980).

Figure 7. Horizontal and inclined flow reactors (Haug 1980).

A general comparison between various composting processes is given in Table 4.

Design of composting systems

The design of composting systems can be classified into six categories: 1) windrow composting design, 2) static pile composting design, 3) enclosed composting design, 4) in-vessel composting design, 5) bin composting design, and 6) mechanical or high rate composting (Finstein et al. 1986b 1987c). According to the above classification scheme, windrow composting, aerated static pile composting and enclosed composting are classified as "nonreactor" systems, while the in-vessel composting, the bin composting and the mechanical or high rate composting are classified as "reactor" systems.

In windrow composting, an elongated unenclosed pile is subjected to mechanical agitation by means of a turning machine (windrowing) or front-end loader. No mechanical agitation is used for the static pile composting and pile dimensions in this system are usually larger than in windrow composting. For the enclosed composting, material is sheltered, but not held in a special vessel; the processing technique is similar to the windrow or static pile systems. Bin composting is a form of in-vessel composting where material is held in a spe-

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Table 4. Comparison between various composting processes when used for sludge composting (Haug 1980).

Item	Nonreactor systems		Reactor systems	
	Windrow	Aerated pile	Forced aeration + agitation	Forced aeration No agitation
Capital costs	Generally low	Generally low in small systems; can become high in large systems	Generally high	Generally high
Operating costs	Generally low on bulking agent used	High, depending largely	Generally low	Generally low
Land requirements	High	High	Low, but can increase windrow drying is drying is required	Low, but can increase if windrow drying is required
Control of air supply	Limited unless forced aeration is used	Complete	Complete	Complete
Operational controls	Turning frequency, amendment or compost recycle addition, forced aeration rate	Air flow rate, bulking agent addition	Air flow rate, level of agitation, amendment or compost recycle addition	Air flow rate amendment or compost recycle addition
Sensitivity to dewatered cake solids	More sensitive	Less sensitive	Less sensitive	Less sensitive
Need for subsequent drying	Drying usually occurs in windrow but de-depends on climate	Drying can be achieved in pile with high air supply; windrow drying may be required	Drying can be achieved reactor; final drying in windrow or heat dryer may be required	Less drying potential from lower air flow rates; final drying in windrow or heat dryer usually required
Sensitivity to cold or wet weather	Sensitive unless in housing; demonstrated mainly in warm, dry climates	Demonstrated in cold and wet climates	Demonstrated in cold and wet climates	Demonstrated in cold and wet climates
Demonstrated on digested sludge	Yes	Yes	Yes	Yes
Demonstrated on raw sludge	Yes, but odor problems observed	Yes	Yes	Yes
Need for amendment or bulking agent	Well demonstrated using recycled compost only	All designs to date use bulking agents; pilot operations used recycled compost with digested sludge	Demonstrated using recycled compost only	Amendment addition addition along with compost ususually used
Control of odors	Depends largely on feedstock; potential large-area source	Handling of raw sludge is potentially odorous; may be large-area source	Potentially good	Potentially good
Potential operating problems	Low cake solids will increase odor potential and cause reduced temperature in windrow; susceptible to adverse weather	Mixing and screening of bulking agent can be difficult; anaerobic balls sometimes observed; wood chips can harbor opportunistic fungal pathogens	High operational flexibility should reduce composting problems; system may be mechanically complex	Potential problems of sludge compaction and channeling or short-circuiting of air supply; system may be mechanically complex

cial vessel for better control of agitation, ventilation, residence time, batch or processing mode, material handling and curing.

Because there is a potential for explosion in any system containing explosives, caution should be exercised if any of the above-noted mechanical systems is used for composting explosive-contaminated soils and wastes. It is therefore recommended that a careful and adequate design analysis should be performed when adopting any type of mechanical system for explosives-laden composting system.

A detailed description of a bin composting system design and operation for municipal solid wastes is given below, since it has been brought to the attention of the CRREL compost researchers that such a system may be considered for a potential field design operation for composting explosives-contaminated soils by U.S. Army Toxic and Hazardous Materials Agency (USATHAMA).

Bin composting design and operation

Senn (1971) reported the use of bin-type composting (horizontal flow, agitated solids bed reactor) with wet organic feed materials to compost dry dairy manure. The system was designed to provide agitation of the material during the compost cycle and a forced aeration in the floor of the bins as indicated in Figure 8. Normal aeration rates were 6.7 m³ of air/hr-m³ of the manure. Maximum static pressures were about 15 cm (water gauge). A composting time of 2 to 7 days was provided in each bin followed by a minimum 30-day period in stockpiles. Senn gave a typical temperature profile (Fig. 9) developed under optimum moisture and air flow conditions. He noted that rapid tempera-

Figure 9. Typical temperature developed during bin composting of dairy manure under conditions of constant airflow and optimum moisture (Senn 1971).

ture elevations within the first 24 hours were characteristically observed.

According to Senn (1971), the most rapid production of attractive, stable compost was found to occur at temperatures between 71° and 79°C. Even though temperatures as high as 87°C were measured, composting above 79°C produced an end-product considered undesirable due to the resulting dark color and unpleasant, "cooked" odor. Optimum gravimetric moisture content was found to be in the range of 50–56% moisture. However, the material was successfully composted if loaded at moisture contents of 45–60%. A phenomenon commonly observed during the operation that might impact the explosives-contaminated soils composting was the "packing" of material in the bins, particularly at high moisture contents. The transfer of material from bin 1 to bin 2 loosened the material, allowing increased temperature development as indicated in Figure 10. Agitation was also found to be effective in loosening the material so that higher air flow
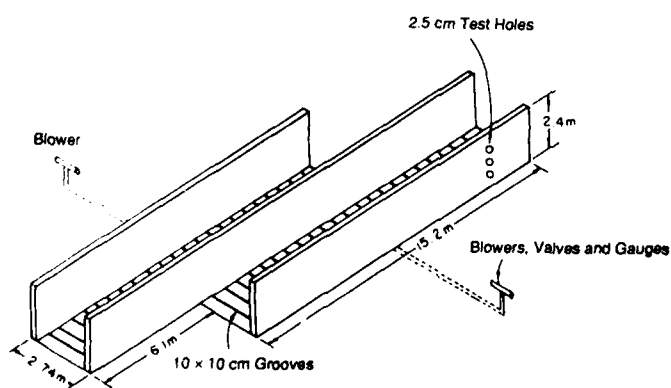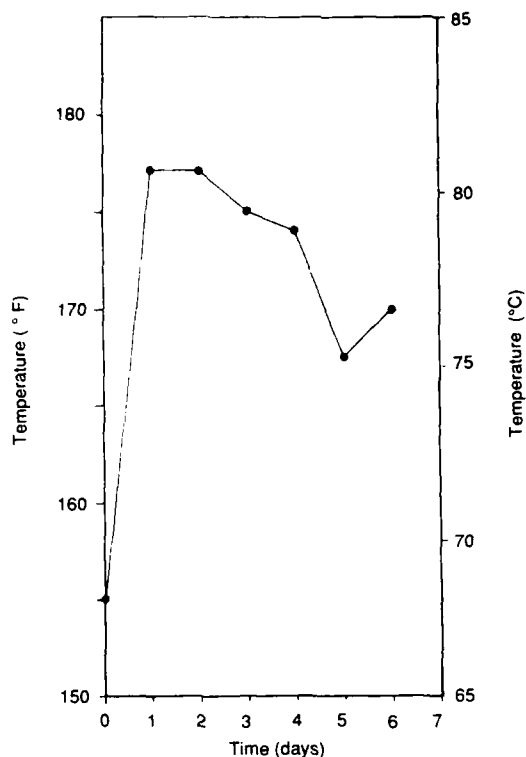

Figure 8. Aerated bins used in field composting tests on dairy manure. Bins were staggered and sized for transferring and unloading by conveyor buckets and belt of "Eagle Loader" (Senn 1971).
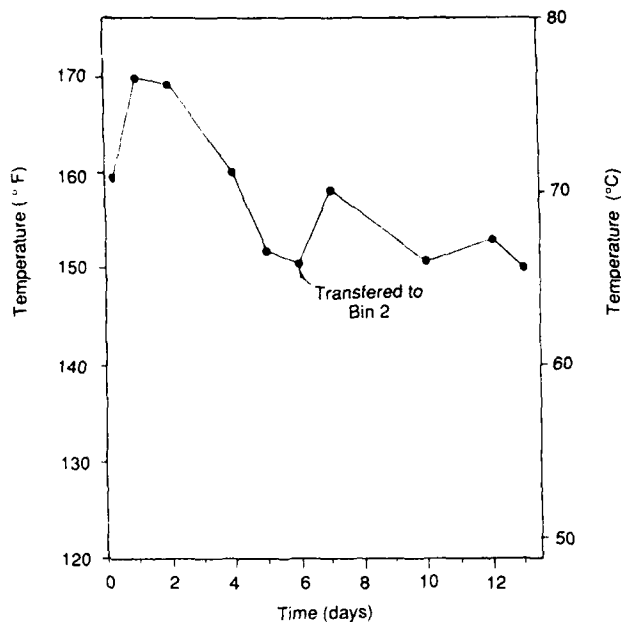
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Figure 10. Effect of agitation on the temperature profile during bin composting of dairy manure. Moisture content was 50% and air flow rate was held constant. Points to note: 1) rapid temperature rise to 70°C in six hours, 2) flow rate temperature drop is graded and can be stopped by lowering air flow rate, 3) temperature rise caused by mixing and loosening from transfer (Senn 1971).

Figure 11. Average temperatures observed during bin composting of digested sludge cake mixtures. Sludge cake was approximately 25% solids and recycled compost about 65% solids. Each data point represents an average of 17 temperature readings over the cross section of the reactor (Iacoboni et al. 1977).
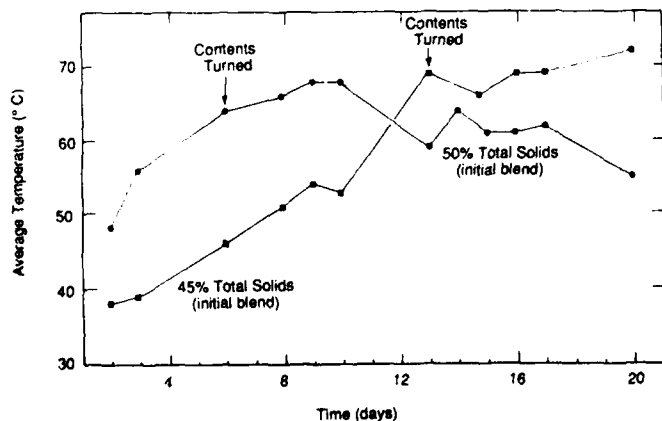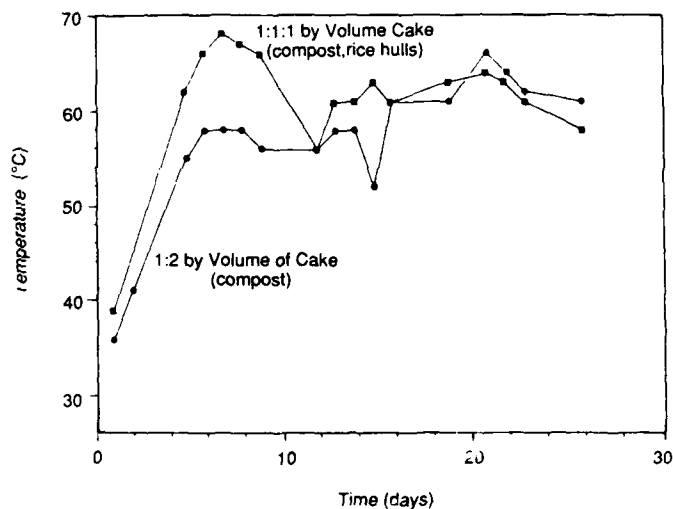
Figure 12. Effect of initial mixture solids content on the temperature profile during bin composting of digested sludge cake blended with recycled compost. Each data point represents an average of 17 temperature readings over the cross section of the reactor (LeBrun et al. 1978).

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rates could be maintained, which, in turn, resulted in a higher rate of heat removal, thus lowering the high temperature buildup to a more optimum range. As expected, it was found that low air flow rates could lead to excessively high temperatures that limited the compost biological activity.

Iacoboni et al. (1977) and LeBrun et al. (1978) provided data from the compost experiment sponsored by Los Angeles Orange County Metropolitan Authority in which dewatered municipal sludge was composted in a bin-type system with bed depths of 2.5 to 3 m (Fig. 11 and 12). As was the case with manure composting, it was observed that the initial solid content of the mixture used was important in order to achieve rapid temperature rise. The effect of the initial mixture solid content on the temperature profile is shown in Figure 12. The data showed that an initial mixture with 50% solids was considered near optimum compared with 45% solids content (LeBrun et al. 1978).

Haug (1980) discussed another bin-type composting system operated at the Minamitama Sewage Treatment Plant (MSTP), Japan, where the feed material consisting of raw sludge was conditioned with lime and ferric chloride, and then dewatered by filter press to about 35% cake solids. What is unique about the MSTP operation was that the dewatered sludge was blended with recycled compost product to achieve optimum 50% solids mixture, which was then composted for 10 days. Compost product was used for feed conditioning primarily because other additives such as "wood chips" were not consistently available. This may be relevant to a large field operation for composting explosives-contaminated soils.

PERFORMANCE EVALUATION OF COMPOSTING SYSTEMS

Most researchers concur that the evaluation of composting process performance centers on the issue of decomposition rate, with higher rates generally desirable. In other words, decomposition rate is an overriding determinant of composting process performance. Evaluation of compost product quality is also essential (Finstein et al. 1986a,b). The absence of a decomposition rate measure in composting tends to contribute to suboptimal process design and control, erratic operational performance, and odor problems.

A review of composting-process-performance evaluation by Finstein et al. (1983) indicated that tests involving organic content (volatile solids, organic carbon, chemical oxygen demand [COD],

biochemical oxygen demand [BOD], starch, and cellulose) lack sensitivity, specificity and general relevance. Tests which tend to quantify some decomposition (heat output, metabolic-water production, oxygen consumption, and carbon dioxide production) are generally inapplicable in routine field practice for industrial and municipal solid wastes. As for the composting of explosives-contaminated soils and sludges, the potential problems tend to become more difficult because of the complex nature of the biodegradation and biotransformation processes of the organic compounds that need to be decomposed.

Although the biotransformation of explosives occurs most rapidly under thermophilic conditions, there is a paucity of information on the fate of the biotransformation products and how environmental factors may influence the direction and rate of these processes. Because temperature has a profound effect on microbial diversity, kinetics, and metabolites, a system that provides for a more uniform and responsive temperature distribution might be employed to direct the composting process in a way most favorable to desired goals. From published research to date, it is clear that composting at thermophilic temperatures approaching but not exceeding approximately 65°C results in most rapid biotransformation of explosives. What is not at all clear is how best to manipulate temperatures, as well as other parameters, to best render harmless the products from the biotransformation of explosives.

Recent work by Berardesco and Finstein (1988) has clearly demonstrated that polyaromatic hydrocarbon transformation ability was present in a greater percentage of the microbial population at mesophilic temperatures than at thermophilic temperatures. In contrast to the generally accepted rational that "faster composting is better," the development of a hazardous waste composting system that enables more uniform and precise control of composting temperatures to be maintained for extended time periods may prove to have applications beyond those that are currently obvious.

CONCLUSIONS

1. A thorough review of available literature was conducted on the impact of cold climates on composting with emphasis on composting explosives, the influence of engineering design on compost pile temperatures, and the control and measurement of compost pile temperatures.

2. It was found that there is no universal defini-

tion of composting. In a broad sense, composting has been defined as the biological decomposition (involving biodegradation and biotransformation processes) of organic substrates under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmental effects.

3. The majority of published research on composting has been focused on the composting of municipal and industrial solid wastes. It is important to realize that the goals of municipal and industrial waste composting may differ from the goals of hazardous waste composting.

4. To date, no research information or data are found in the literature on the sustained effect of a cold climate on composting.

5. Although it may not be appropriate to directly transfer all the conditions used in municipal or industrial waste composting to systems designed for hazardous waste composting, a great deal of knowledge can be obtained from research information on the composting of municipal and industrial solid wastes.

6. Parameters that consistently have been found to significantly influence composting include temperature, moisture content, and chemical and biological characteristics, as well as the concentrations of the organic substrates, the concentration of available nutrients such as nitrogen and phosphorus, the ratio of available nutrients such as organic carbon and nitrogen (C/N), heat production and retention in the compost, and the partial pressure of oxygen within the compost material.

7. There is little information available on the persistence and fate of intermediate metabolites formed during composting of explosives. Because some metabolites are known to be toxic, this question needs to be resolved before composting can be used for decontaminating explosives-laden soils and sediments. Nevertheless, due to the self heating nature of the composting process, our ability to design composting systems in which optimum temperatures can be maintained, and the likelihood that some hazardous materials may be rendered harmless permanently by incubation under appropriate conditions, composting may offer an attractive decontamination method that is well suited for cold regions use.

LITERATURE CITED

Atchley, S.H. and J.B. Clark (1979) Variability of temperature, pH, and moisture in an aerobic composting process. *Applied Microbial Biology*, 41: 1040–1044.

Atlas, R. M. and R. Bartha (1987) *Microbial Ecology, Fundamentals and Applications.* Menlo Park, California: Benjamin/Cummings Publishing Co. Inc., 2nd edition.

Bakshi, M. P.S., V. K. Gupta and P. N. Langar (1987) Effect of moisture level on the chemical composition and nutritive value of fermented straw. *Biological Wastes*, 21: 283–289.

Berardesco, G. and M.S. Finstein (1988) Thermophilic and mesophilic polyaromatic hydrocarbon degrading bacteria isolated from composting material. In *Abstracts, Annual Meeting of the American Society of Microbiologists, 8–13 May, Miami, Florida.*

Bhoyar, R.V., M.S. Olaniya, A.D. Bhide (1979) Effect of temperature on mineralization of nitrogen during aerobic composting. *Indiana Journal of Environmental Health*, 21: 23–34.

Bhoyar, R.V. and A.D. Bhide (1982) Effect of temperature on cellulose degradation and cellulose activity during aerobic composting. *Journal of In-stitutional Engineering*, (India), Part EN: Environmental Engineering Division, 1: 45–49.

Brooks, G.T. (1974) *Chlorinated Insecticides.* Cleveland, Ohio: CRC Press, vol. II, p 84.

Cathcart, T.P., F.W. Wheaton, R.B. Brinsfield (1986) Optimizing variables affecting composting of blue crab scrap. *Agricultural Wastes*, 15: 269–287.

Clark, C.S., C.O. Buckingham, R. Charbonneau and R.H. Clark (1978) Laboratory scale composting: Studies. *ASCE, Journal of the Environmental Engineering Division*, 104: 47–59.

Corey, R. C., Ed. (1969) *Principles and Practices of Incineration.* New York: Wiley-Interscience.

CRC Press (1970) *Handbook of Chemistry and Physics.* Cleveland, Ohio: CRC Press, 50th edition.

Doyle, R. C., J. D. Isbister, G. L. Anspach, and J. F. Kitchens (1986) Composting explosives/organics-contaminated soils. USA Report AMXTH-TE-CR-86077 (Toxic and Hazardous Wastes Administration. U.S. Army Toxic and Hazardous Materials Agency.

Epstein, E. G.B. Wilson, W.D. Burge, D.C. Mullen and N.K. Enkiri (1976) A forced aeration system for composting wastewater sludge. *Journal of the Water Pollution Control Federation*, 48: 688–692.

Fair, G.M., J.C. Geyer and D.A. Okun (1968) *Water and Wastewater Engineering, Vol. 2, Water Purification and Wastewater Treatment and Disposal.* New York: John Wiley & Sons, Inc.

Finstein, M.S., F.C. Miller, and P.F. Strom (1983.) **Evaluation of composting process performance.** In *Proceedings, International Conference on Composting Solid Wastes and Slurries* (E.I. Stentiford, organizer). The University of Leeds, England.

Finstein, M.S., F.C. Miller, and P.F. Strom (1986a) Monitoring and evaluating composting process performance. *Journal of the Water Pollution Control Federation,.* 58: 272–278.

Finstein, M.S., F.C. Miller and P.F. Strom (1986b) Waste treatment composting as a controlled system, In *Biotechnology*, vol. 8, *Biodegradations* (H.J. Rehm and G. Reed, Ed.). VCH Verlagsgesellschaft (German Chemical Society), Wienheim, German Federal Republic, p. 363–368

Finstein, M.S., F.C. Miller, J.A. Hogan and P.F. Strom (1987a) Analysis of EPA guidance on composting sludge. Part I—Biological heat generation and temperature. *BioCycle*, 28: 20–25.

Finstein, M.S., F.C. Miller, J.A. Hogan and P.F. Strom (1987b) Analysis of EPA guidance on composting sludge. Part II—Biological process control. *BioCycle*, 28: 42–47.

Finstein, M.S., F.C. Miller, J.A. Hogan and P.F. Strom (1987c) Analysis of EPA guidance on composting sludge. Part III—Oxygen, moisture, odor, pathogens. *BioCycle*, 28: 38–44.

Golueke, C.G (1977) *Biological Reclamation of Solid Waste.* Emmaus, Pennsylvania: Rodale Press.

Haug, R.T (1980) *Composting Engineering: Principles and Practice.* Ann Arbor, Michigan: Ann Arbor Science Publishers Inc., the Butterworth Group.

Haug, R.T. (1986a) Composting process design criteria. *BioCycle*, 27: 38–40, 42–43.

Haug, R.T. (1986b) Composting process design criteria: Part II—Detention time. *BioCycle*, 27: 36–39.

Haug, R.T. (1986c) Composting process design criteria: Part III—Aeration. *BioCycle*, 27: 53–57.

Iacoboni, M., T. LeBrun and D.L. Smith (1977) Composting study. Technical Services Department, Los Angeles County Sanitation Districts, September–December.

Isbister, J. D., R. C. Doyle, and J. K. Kitchens (1982) Composting of Explosives. Report DRXTH-TE. USA Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland.

Jacobowitz, L.A. and T.S. Steenhuis (1984) Compost impact on soil moisture and temperature. *BioCycle*, 5: 56–60.

Jones, J. B. and G. A. Hawkins (1963) *Engineering Thermodynamics.* New York: John Wiley & Sons, Inc.

Kaplan, D. A. and A. M. Kaplan (1982a) Composting industrial wastes—Biochemical considerations. *Biocycle*, 23: 42–44.

Kaplan D. A. and A. M. Kaplan (1982b) Thermophilic biotransformations of 2,4,6-trinitrotoluene under simulated composting conditions. *Applied Environmental Microbiology*, 44: 757–769.

Kuter, G.A., H.A.J. Hoitink and L.A. Rossman (1985) Effects of aeration and temperature on composting of municipal sludge in a full-scale vessel system. *Journal of the Water Pollution Control Federation*, 57: 30–315.

LeBrun, T., M. Iacoboni and J. Livingston (1978) Composting study. Technical Services Department, Los Angeles County Sanitation Districts.

Lee, J.F. and F.W. Sears (1963) *Thermodynamics.* Reading, Massachusetts: Addison-Wesley Publishing Co., Inc.

Loran, B.I. (1975) Burn that sludge. *Water Wastes Engineering*, October.

MacGregor, S.T., P.C. Miller, K.M. Psarianos and M.S. Finstein (1981) Composting process control based on interaction between microbial heat output and temperature. 43: 132–1330.

McCormick, N. G., F. E. Feeherby, and H. S. Levinson (1975) Microbial transformations of 2,4,6-trinitrotoluene and other nitroaromatic compounds. *Applied Environmental Microbiology*, 31: 949–958.

McCormick, N. G., J. H. Cornell, and A. M. Kaplan (1981) Biodegradation of Hexahydro-1,3,5-trinitro-1,3,5-triazine. *Applied Environmental Microbiology*, 42: 817–823.

McKinley, V.L. and J.R. Vestal (1985) Physical and chemical correlates of microbial activity and biomass in composting municipal sewage sludge. *Applied Environmental Microbiology*, 47: 1395–1403.

Mosher, D. and R.K. Anderson (1977) Composting sewage sludge by high-rate suction aeration techniques: B. The process as conducted at Bangor, Maine, and some guides of general applicability. Report SW-614d, U.S. Environmental Protection Agency, Washington, D.C.

Osmon, J. L. and R. E. Klausmeier (1972) The microbial degradation of explosives. *Developments in Industrial Microbiology*, 14: 247–252.

Senn, C.L. (1971) Dairy Waste management project—Final Report. University of California Agriculture Extension Service, Public Health Foundation of Los Angeles County.

Sikora, L. J. and M. A. Sowers (1985) Effect of Temperature Control on the Composting Process.

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Journal of Environmental Quality, **14**: 434–439.

Sjoblad, R. D. and J.-M. Bollag (1981) Oxidative coupling of aromatic compounds by enzymes from soil microorganisms. In *Soil Biochemistry* (E. A. Paul and J. M. Ladd, Ed.) New York: Marcel Dekker, Inc., p. 113–153.

Spoehr, H.A. and H.W. Milner (1949) The chemical composition of chlorella; Effect of environmental conditions. *Plant Physiology*, **24**: 120.

Strom, P. F. (1985) Effect of temperature on bacterial species diversity in thermophilic solid-waste compounds. *Applied Environmental Microbiology*, **50**: 899–905.

Williams, R.T., P.S. Ziegenfuss and P.J. Marks (1988) Field demonstration—Composting of explosives-contaminated sediments at the Louisiana Army Ammunition Plant (LAAP). Final Report No. AMXTH-IR-TE-88242 under Contract No. DAAK-11-85-D-007 prepared for USA Toxic and Hazardous Wastes Administration, Aberdeen Proving Ground, Maryland by Roy F. Weston, Inc., West Chester, PA 19380.

Wood, J. M. (1971) Environmental pollution by mercury. *Advances in Environmental Science and Technology*, **2**: 39–56.