**DEPARTMENT OF THE NAVY**
CRANE DIVISION
NAVAL SURFACE WARFARE CENTER
300 HIGHWAY 361
CRANE, INDIANA 47522-5000

IN REPLY REFER TO:
5090
Ser 095/6237
9 SEP 1996
9 SEP 1996

U.S. Environmental Protection Agency, Region V
Waste, Pesticides, & Toxics Division
Waste Management Branch
Illinois, Indiana, and Michigan Section
Attn: Ms. Carol Witt-Smith (DRP-8J)
77 West Jackson Blvd.
Chicago, IL 60604

Dear Ms. Witt-Smith:

Crane Division, Naval Surface Warfare Center (NAVSURFWARCENDIV Crane) submits for review two copies of the Bench Compost Implementation Report prepared by the U.S. Army Corps of Engineers, Waterways Experiment Station as enclosure (1). Enclosure (2) is the required certification statement.

For your records and information CDR Fred R. Smith, P.E., replaced CDR L. A. Laws as the Director of Public Works (Code 09) NAVSURFWARCENDIV Crane. The address and telephone numbers are unchanged. Request you pass this change on to the appropriate divisions in Region V.

NAVSURFWARCENDIV Crane point of contact is Mr. Thomas J. Brent, Code 09510, telephone 812-854-6160.

Sincerely,

Public Works Officer
By Direction of
the Commanding

Encl:
(1) Bench Compost Implementation for NAVSURFWARCENDIV Crane
(2) Certification Statement

Copy to: (w/o encls)
ADMINISTRATIVE RECORD
COMNAVSEASYSCOM (SEA 07E)
MK (Steve Downey)
SOUTHNAVFACENGCOM, (Code 1864)

**DEPARTMENT OF THE NAVY**
CRANE DIVISION
NAVAL SURFACE WARFARE CENTER
300 HIGHWAY 361
CRANE, INDIANA 47522-5000

IN REPLY REFER TO:
5090
Ser 095/6238
9 SEP 1996

Indiana Department of Environmental Management
Defense Environmental Restoration Program
Attn: Mr. John Manley
100 North Senate Avenue
P.O. Box 6015 (Room N-1255)
Indianapolis, IN 46206-6015

Dear Mr. Manley:

Crane Division, Naval Surface Warfare Center (NAVSURFWARCENDIV Crane) submits for review a copy of the Bench Compost Implementation Report prepared by U.S. Army Corps of Engineers, Waterways Experiment Station as enclosure (1).

For your records and information CDR Fred R. Smith, P.E., replaced CDR L. A. Laws as the Director of Public Works (Code 09) NAVSURFWARCENDIV Crane. The address and telephone numbers are unchanged. Request you pass this change on to the appropriate divisions within the department.

NAVSURFWARCENDIV Crane point of contact is Mr. Thomas J. Brent, Code 09510, telephone 812-854-6160.

Sincerely,

Encl:
(1) Bench Compost Implementation Report

Copy to: (w/o encls)
ADMINISTRATIVE RECORD
MK (Steve Downey)
SOUTHNAVFACENGCOM, (Code 1864)

# Bench Compost Implementation at Naval Surface Warfare Center Crane

by Dr. Kurt T. Preston, Mr. Roy Wade
U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Dr. Kyoung S. Ro
Louisiana State University

Mr. Steve Seiden
North Carolina State University

Final Draft report
Approved for public release; distribution is unlimited

Prepared for Department of the Navy
Southern Division, Naval Facilities Engineering Command
Charleston, South Carolina

# Contents


Preface . . . . . vi

1 Introduction . . . . . 1
- Background of NSWCC . . . . . 1
- Synopsis of Former Studies . . . . . 2
- Sites History . . . . . 3
  - Ammunition Burning Ground (SWMU 03) . . . . . 3
  - Rockeye Site (SWMU 10) . . . . . 4
- Sites Contamination . . . . . 5
  - ABG Site . . . . . 5
  - Rockeye Site . . . . . 6
- Purpose . . . . . 7
- Testing Objectives . . . . . 7
- Scope of Work . . . . . 7

2 Remediation Composting Process Parameters . . . . . 9
- Physical Factors . . . . . 9
  - Porosity . . . . . 9
  - Free Air Space . . . . . 10
  - Moisture Content . . . . . 10
  - Particle Size . . . . . 11
  - Temperature . . . . . 12
  - Electroconductivity . . . . . 12
- Chemical Factors . . . . . 13
  - Contaminated Soil Loading . . . . . 13
  - Carbon to Nitrogen Ratio . . . . . 13
  - Acidity . . . . . 14
- Biological Factor . . . . . 14
  - Biodegradability and Biodegradation Rate . . . . . 14
  - Aeration . . . . . 15

3 Respirometric Study . . . . . 16
- Introduction . . . . . 16
- Materials and Methods . . . . . 17
  - Soil Samples . . . . . 17
  - Compost Mixtures . . . . . 17
  - Respirometer Procedure . . . . . 18

Physicochemical Parameters . . . . . 18
Explosive Analysis . . . . . 19
Half-life Estimations for Explosives . . . . . 20
Results and Discussion . . . . . 20
Recommended Compost Recipe . . . . . 22

4 Bench-Scale Composting Study . . . . . 23
Introduction . . . . . 23
Materials and Methods . . . . . 24
Compost Reactor System . . . . . 24
Procedures . . . . . 25
Results and Discussion . . . . . 25

5 Toxicity Experiment . . . . . 28
Introduction . . . . . 28
Material and Methods . . . . . 29
Pilot-Scale Reactor System . . . . . 29
Soil Extraction for Mutagenicity . . . . . 29
Mutatox™ . . . . . 30
Earthworm Acute Toxicity . . . . . 30
Results and Discussion . . . . . 31
Compost Temperature . . . . . 31
Respiration Rate . . . . . 31
Explosive Analysis . . . . . 32
Mutatox™ . . . . . 32
Earthworm Acute Toxicity . . . . . 33

6 Conclusions . . . . . 34
Conclusions . . . . . 34
Recommendations . . . . . 36

References . . . . . 37

## List of Figures

Figure 1. Location of NSWCC, Indiana . . . . . 41

Figure 2. Location of ammuntion burning ground and rockeye sites 41

Figure 3. Ammuntion burning ground site soil boring locations . . . . . 42

Figure 4. Rockeye site soil borings and surface sample areas locations . . 44

Figure 5. Schematic diagram of bench-scale batch compost reactor system . . . . . 44

Figure 6. Mixture 7 maximum and minimum compost core temperature profile . . . . . 46

Figure 7. Mixture 7 temperature profile of various WACS II components . . . . . 47

Figure 8. WACS II aeration times for Mixture 7 . . . . . 48

Figure 9. Physicochemical properties for Mixture 7 . . . . . 49

Figure 10. Explosive analysis results for Mixture 7 . . . . . 50

Figure 11. Schematic of Oxymax system with an adiabatic chamber . . . 51

Figure 12. Mix 1 temperature profile . . . . . 52

Figure 13. Mix 2 temperature profile . . . . . 53

Figure 14. Mix 1 maximum and minimum oxygen in exit air profile . . . 54

Figure 15. Mix 1 maximum and minimum carbon dioxide in exit air profile . . . . . 55

Figure 16. Mix 1 respiration rate during composting . . . . . 56

Figure 17. Mix 2 maximum and minimum oxygen in exit air profile . . . 57

Figure 18. Mix 2 mzximum and minimum carbon dioxide in exit air profile . . . . . 58

Figure 19. Mix 2 respiration rate during composting . . . . . 59

## List of Tables

Table 1. Physical Characteristics of Crane's Soil . . . . . 60

Table 2. Respirometric Result-Composition and Physicochemical Properties Of The Compost Mixtures . . . . . 61

Table 3. Biodegradation Kinetic Coefficients of Compost Mixtures . . . . 61

Table 4. Result Of Explosive Analysis, Half-Live Calculations, And Degradation Ranking . . . . . 62

Table 5. Compost Composition of Mixture 7 . . . . . 63

Table 6. Result of Explosives Analysis and Standard Deviation For Reactor 1 and Reactor 2 . . . . . 63

Table 7. Mutatox™ Results . . . . . 64

Table 8. Percent Mortality From The Earthworm Acute Toxicity Results . . . . . 64

Appendix A: Respirometric Raw Data

Appendix B: Bench Scale Raw Data

# Preface

The study herein was conducted as a part of the Bench Compost Implementation Study. This report was prepared at the U.S. Army Engineer Waterways Experiment Station (WES) in cooperation with the U.S. Navy, Naval Surface Warfare Center, Crane (NSWCC), Indiana and Department of the Navy, Southern Division, Naval Facilities Engineering Command (NFEC), Charleston, South Carolina. Program Manager for NFEC was Ms. Adrienne Wilson. Project Manager for NSWCC was Mr. Tom Brent. Project Managers for WES were Dr. Kurt T. Preston and Mr. Roy Wade.

The bench-scale and toxicology studies were conducted between October 1994 and July 1996 in the WES Environmental Laboratory (EL). This report was written by Dr. Kurt T. Preston and Mr. Roy Wade, Environmental Restoration Branch (ERB), Environmental Engineering Division (EED), EL, WES, Dr. Kyoung S. Ro, Louisiana State University, and Mr. Steve Seiden, North Carolina State University. Laboratory support was provided by Mr. James Davis. The toxicity study was conducted by Messrs. Michael E. Honeycutt and Victor A. McFarland and Ms. A. Susan Jarvis of EL FATES and Effects Branch.

The report was prepared under the direct supervision of Mr. Danny Averett, Chief, ERB, and under the general supervision of Mr. Norman R. Francingues, Jr., Chief, EED, and Dr. John W. Keeley, Acting Director, EL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

This report should be cited as follows:

Preston, K.T., Wade, R., Ro, K.S., and Seiden, S. (1996). "Bench Compost Implementation at Crane Naval Surface Warfare Center." Technical Report EL-96- , U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

# 1 Introduction

The production and handling of conventional munitions have resulted in the generation of explosives-contaminated soils at various military installations. The principle explosive contaminants are 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX). The Naval Surface Warfare Center, Crane (NSWCC) is one of those military installations that provide material and logistic support to the Navy's weapon systems and expendable and nonexpendable ordnance items. As the complexity of weapons increased, the facility became more involved in the technical aspects of weaponry through the development of test methods, procedures, and equipment, while the facility's basic mission remained the same.

Because of the potential for groundwater contamination, and the subsequent migration of explosives, treatment of the explosive contaminated soils at several sites at NSWCC is necessary to protect the environment and avoid costly actions in the future. Incineration and composting are demonstrated technologies for the remediation of explosives contaminated soils. However, incineration is publicly undesirable and essentially economically unfeasible for remediation of small sites. Composting was the selected technology that was evaluated for the remediation of the explosives contaminated soils at Crane. The results of the bench scale study are presented.

## Background of NSWCC

Naval Surface Warfare Center, Crane (NSWCC) is located 20 miles southwest of Bloomington, Indiana, approximately 75 miles southwest of Indianapolis and 71 miles northwest of Louisville, Kentucky (Figure 1). The NSWCC

and 71 miles northwest of Louisville, Kentucky (Figure 1). The NSWCC occupies 62,463 acres (approximately 96 square miles) of the northern portion of Martin County and small portions of neighboring Greene, Daviess, and Lawrence Counties. NSWCC provides material, technical, and logistic support to the Navy for equipment, weapon systems, and expendable and nonexpendable ordnance items. The facility was opened in 1941 as the Naval Ammunition Depot, Burns City, Indiana and renamed as the U.S. Naval Ammunition Depot Crane, Burns City, Indiana in 1943. Its mission was to serve as an inland munitions production and storage center for all types of ammunition, including pyrotechnics and illuminating projectiles. The facility was renamed as the Naval Weapons Support Center in 1975 and was changed to Naval Surface Warfare Center, Crane Division in 1991. The Department of Defense (DoD) ammunition procurement responsibility was transferred to the Army in 1977. The Army has assumed ordnance production, storage, and related responsibilities under the single service management directive. All environmental activities on the installation, including permitting activities, remain the responsibility of the Navy.

## Synopsis of Former Studies

In early 1981, a potentially hazardous substance release from the NSWCC was discovered (draft workplan, 1994). An Initial Assessment Study (IAS) for the NSWCC was begun in April 1981 and completed in May 1983 by the Naval Energy and Environmental Support Agency (NEESA). A Solid Waste Management Unit (SWMU) report submitted to the U.S. Environmental Protection Agency (USEPA) in January 1985 listed all of the hazardous waste sites identified in the IAS. The Navy decided in the summer of 1993 to implement remedial action at those SWMUs for which sufficient site assessment and characterization data were available. Bench scale testing to evaluate and design composting of explosive contaminated soils at SWMU 03 Ammunition Burning Ground (ABG) site and SWMU 10 Rockeye site were among the tasks that were assigned to the WES. In the fall of 1994, WES initiated a study of composting as a remediation method for explosive contaminated soils.

## Sites History

### Ammunition Burning Ground (SWMU 03)

The ABG is located near the eastern boundary of NSWCC (Figure 2) and consist of approximately 50 acres. The ABG lies near the head of the valley of Little Sulfur Creek. The site is approximately 2000 ft long by 1000 ft wide with the long axis oriented east-west. The ABG has been used extensively since the 1940's for the destruction of materials contaminated with explosives, rocket motors, candles, flares, solvents, red phosphorus, small detonators, and fuse materials. The largest quantities were destroyed between 1956 and 1960, when 15,000 pounds per day of smokeless powder and 48,000 pounds per day of high explosives (H-6 and Composition B) were burned. The area also is used for flashing (burning) of the residue from bombs and projectiles after they have been subjected to melt out or drill out operations removing bulk of the explosives. From 1970 to 1981, at least 10,000 major weapons were destroyed.

Solid explosives residues not in containers or bombs were formerly spread out on burning pads or in flash pits and ignited, or flashed. Flashing today is done in clay-lined steel pans. There are 29 pans currently in operation at the ABG. Bulk propellants typically are poured into burning pans to a depth of a few inches, primed and remotely initiated. An ash pile consisting of approximately 12,290 pounds of burn residue accumulated near the incinerator pit. The ash pile was removed between July 1986 and February 1987. Hazardous waste ash from the burning operations is now stored in two large roll-off boxes. The ash is stored until sent to the landfill.

Three surface impoundments (ponds) were constructed for the purpose of removing liquids from otherwise combustible sludges resulting from the blending and loading of munitions. In 1982 the impoundments were modified to include a liner and leachate collection system for each one. Each of the impoundments is approximately 40 feet in diameter. Two ponds held TNT, RDX and breakdown compounds in water from the Rockeye facility and other locations within NSWCC. The other pond held phosphorus compounds. The three ponds have been replaced by the sludge burn pads. The ponds are now

empty and scheduled for closure. Another tank holds explosives wastes contaminated with pink water. Two empty underground storage tanks (USTs), scheduled for closure, were used to store runoff and leachate from the three ponds. The USTs are near the pink water tanks.

### Rockeye Site (SWMU 10)

Rockeye site is a 40 acre tract located in the north central portion of the NSWCC (Figure 2). The Rockeye facility began operation in the mid-1950s as a press loading operation for 3-inch projectiles using Composition A-3 explosive (RDX and wax). In 1967-68, the Rockeye Facility was converted to a case-filling operation in order to produce the MK20 series anti-tank Rockeye cluster bomb. The explosive material in Rockeye bombs is Octal Compound B (RDX, HMX, TNT, and wax) high explosive. As part of the loading operation, the system generates a large volume of wastewater, primarily from bomblet and tray washdown and from melt and pour operations in Buildings 2731 and 2734. The wastewater was collected in four sumps which were periodically pumped. After pumping, the remaining residue was sent to the ABG for disposal. Prior to 1978, explosive-contaminated waters were discharged, from full sumps, directly into local surface drainage pathways. Red-colored "pink water" from washdown operations was observed in drainage way surface waters in 1977, prior to installation of a treatment facility. On the north side of the facility, the waters were released to a headwater branch of Sulfur Creek. On the south side of the facility, the waters were released to a headwater branch of Turkey Creek. TNT concentrations as high as 50 ppm were detected in surface water discharges.

In the spring of 1978, an activated carbon water treatment facility, located in Building 3044, was brought into operation to purify the wastewater for recycled usage. A scrubber system was designed and installed to remove contaminated particles in the steam-fed tray wash area. In the tray wash area, explosives contaminated trays were steam cleaned. Since the installation of the pollution abatement equipment, the release of explosive contaminated waters has declined.

## Sites Contamination

Soils at the ABG and Rockeye sites were tested for explosives, metals, and organic analytes. These compounds and elements are known to have carcinogenic, mutagenic, or other adverse effects on living organisms.

### ABG Site

The soil at ABG has elevated levels of explosives, metals, and perhaps organic analytes. Ammunition burning and thermal treatment activities at the ABG have released residues of antimony, cadmium, chromium, copper, lead, mercury, nickel, silver, zinc, aluminum, barium, magnesium, manganese, tin, sodium, and phosphorus to the soils. Soils south and east of the former ash pile (Borings 7, 9, and 12 shown on Figure 3) had particularly high concentrations of metal constituents when compared to background soils as well as when compared to soils from the other test borings. Soils from borings around the burn pads (Borings 4, 5, 6, 8, 10, and 11 shown on Figure 3) also produced soil samples with metals concentrations that were higher than those determined for the background borings but generally not as high as those reported for borings 7, 9, and 12. These inorganics are common constituents of material burned at the ABG site.

Explosives compounds were found in soils from all ABG borings except the background borings. Borings 4 and 5 had maximum total explosives concentrations exceeding 1,000 mg/kg. A TNT concentration of 1,640 mg/kg was detected in Boring 4 which was the highest explosives concentration detected in the soil samples. A RDX concentration of 1,070 mg/kg was detected in Boring 5. Explosives contamination was also detected in deeper soil samples within the borings, but not always.

Several volatile organic compounds (VOC) were found in the ABG soils. The maximum concentrations measured for the two compounds were 2.9 $\mu$g/kg TCE and 1.3 $\mu$g/kg tetrachloroethene. Semivolatile organics, pesticides, herbicides, and PCBs were either not detected or were at detection levels.

In general, the most significant ABG soil contamination can be defined by the metals and explosives compound listed earlier. Other contaminants

including, other inorganics, PAHs, VOCs, pesticides, and herbicides were present but at concentrations that were orders of magnitude lower than explosives and metal concentrations.

### Rockeye Site

Groundwater and soil contaminant release characterization studies indicate explosives contamination in several groundwater monitoring wells in the northeast drainage ways of the site and surface soils located in the central and northeast quarter of the site.

Explosive analytes were detected in soils samples collected from the borings around the sumps, in the surface drainage ways, and in the surface soil sampling (Figure 4). Soil borings are indicated in Figure 4 by numbers 1-13 and surface soil scrapes are indicated by letters A-H. Locations marked BN1-BN3 were "background north" surface soil samples. The explosives DNB, DNT, RDX, and HMX were detected. HMX was detected in more soil samples and in greater concentrations than any other explosive analytes. The maximum HMX concentration of 1,960 mg/kg was detected in one soil sample from Area G (Figure 4) and 42.7 mg/kg in the soil from Boring 12. Area E had the greatest number of explosives contaminated soil samples of any sampling area. Area H, behind Building 2734 near the center of the facility, had concentrations of TNT, RDX, and HMX of 295, 3,350, and 10,400 mg/kg, respectively. Area H is bare earth on an otherwise grassed berm, near an exhaust vent of Building 2734.

Because inorganic compounds are naturally occurring compounds at the Rockeye site, the inorganic analytical data had to be compared to established background samples. The maximum metal concentration was detected in the surface soil samples except antimony and aluminum. Additionally, the maximum concentrations of all inorganic parameters, except copper and tin, were detected in the northeast and south streams. The lack of pattern in the inorganic concentrations was not determined with certainty from the available data. There was insufficient information to link the inorganic concentrations detected in the surface drainage to the possible contaminant sources (i.e., the sumps). It is possible that inorganic contaminants were carried by the surface

drainage away from the sumps and deposited along the Rockeye perimeter. This would explain the higher metal concentration in the surface soil samples than the boring samples near the sumps.

## Purpose

The purposes of this report are to document and present the results of the respirometric, toxicity, and bench-scale composting tests performed as a part of comprehensive remediation composting study. The results of this study will assist in proper design of pilot-/field-scale remediation compost systems at Crane.

## Testing Objectives

The objective of this study was to evaluate and to select the best combination of amendments, contaminated soils, and bulking agents to be utilized in the composting technology for remediating soils contaminated with explosives TNT, HMX, and RDX. The objective of the respirometric test was to provide a general indication of biological activity within each compost mixture. The respirometry also was used as a tool for the specific screening of compost mixtures for the Crane soil. The objective of the bench-scale compost reactor test was to expend the respirometric study, evaluating the applicability of the screened compost mixtures for the degradation of explosives compounds under actual composting environments prior to the pilot-/field-scale implementation. The objective of the toxicity test assured that the humified explosives and the biotransformed products were not toxic to the environment.

## Scope of Work

The scope of work includes a survey of locally available sources of amendment and bulking agents to be used for testing on the ABG and Rockeye soils and collection of soil samples at these sites. An initial screening of 8 compost mixtures was performed to determine if any biological activity will occur using the respirometer and to select an optimum compost mixture for further evaluation. The bench scale composting test was run to further

validate the respirometric test results under actual composting environments. The acute toxicity and genotoxicity testings used earthworms and compost mixtures to characterize the toxicity reduction of the composted soils.

# 2 Remediation Composting Process Parameters

Successful design and operation of the remediation composting requires careful consideration of numerous factors affecting the process. The factors can be divided into four classes; physical, chemical, and biological. Physical factors define the structure of the compost matrix. Chemical factors consider the adequacy of substrates and the toxic effects of contaminants on the compost biomass. Biological factors define biodegradability and the biodegradation rate. Careful choice of a composting system with proper thermodynamical properties ensures the optimal thermophilic conditions.

## Physical Factors

### Porosity

Pore space is the open or void space between solid particles. The measure of pore space, generally on a percentage basis, is termed porosity. Porosity is important in compost systems for a number of reasons. The pore space provides a conduit for nutrient movement through the compost pile, space for the growth of microbial communities, and a reservoir for moisture held in the compost mixture. Free airspace (FAS) is that portion of the pore space occupied by gas and not liquid. FAS is critical for the movement of oxygen and other gases into and through the compost matrix by either diffusion, convection, or forced ventilation.

The gas/liquid ratio has a profound impact on the efficiency of the compost operations and the efficacy of the treatment process. When the pore space is completely filled with water, oxygen within the system may become limiting and would become anaerobic. Also the physical strength of the compost matrix will be undermined. Although this example is extreme, it highlights the importance of the interaction of solid particles, pore space, and the free air

space in the definition of the physical nature of the compost matrix.

### Free Air Space

FAS is the ratio of the empty pore space ($V_a$), or void volume not occupied by water, to the total volume. FAS may be managed by selection of the amendments and bulking agents. The definition of a bulking agent is a material added to a compost system to reduce bulk density and increase FAS.

Bulking agent and amendment selection are perhaps two of the most critical design decisions. The section of these will influence the nature of the compost, the efficiency of the operation, and the economics of the system. Research indicates that the optimal biological activity occurs with a FAS ranging from 0.20 to 0.35 (Haug, 1993).

### Moisture Content

Water is the principle liquid of life on earth. It is the solvent in which all known biochemical relations occur and an understanding of the role of water in compost design is of paramount importance. Beyond the role of water as a biochemical solvent, water in compost systems has an even larger multi-faced role. Water plays a key role in cooling of the compost systems. Also, moisture content influences the nutrient movement and the compost matrix structure.

As a biochemical solvent, aqueous solutions are theoretically the ideal media for biological activity. In a completely mixed aqueous system, substrate is instantly available to the microbial community in equal concentration. When nutrients are added to the system, the biomass will be very active and immediately utilize the available substrate. However, in aqueous aerobic systems, oxygen is often the limiting substrate due to its low solubility in aqueous solutions. Aqueous bacterial reactor systems generally attempt to improve oxygen transfer into solution by physical agitation or sparging of air.

Compost, a highly active aerobic system, can also suffer from oxygen limitation. As a result, proper management of the air and water within the compost pore volume is critical. In general, FAS begins to become available within the pore space in most compost systems at approximately 40% solids

(Haug, 1993; Golueke, 1991). Thus, 40% solid content is generally considered as the maximum for most compost systems without augmentation by forced aeration.

The optimal moisture content reported by previous researchers varied from 45-90% (Biddlestone et al., 1987; Haug, 1993). The reported optimal moisture content varied widely because of widely varying water absorption capacity of soil particles and composting materials used in research (Mathur, 1991). Generally, a moisture content of about 45 to 65% is used. Above this range, the pore space will be filled with water or at the vary least water tension in the pore space hinders the movements of gases between pores so that oxygen in the pore space becomes depleted. Below this range, moisture is not available to the microbial communities. The water remaining becomes associated with the solid particles due to the matrix potential arising from the capillary forces and adsorption. This water is held so tightly that it may be considered a non-liquid. Consequently, moisture may be present in the matrix, but the lack of moisture available to the microbial communities results in growth rate limitations and a loss of process efficiency.

### Particle Size

Various shredders and other mixing devices are used to break down and homogenize the compost materials into smaller and manageable sizes. Since most of the composting microbial activities occur on the surface of the substrate particles, smaller size particles, which offer larger surface area, appear to enhance the microbial reactions. However, porosity of the compost matrix will decrease with the decrease in particle size and it will hinder the movement of oxygen and water in narrow interstitial spaces between the small particles packed together tightly. Generally, particle size between 1.3 to 5 cm is used for composting to yield sufficiently large surface area, at the same time, to produce enough pore space for efficient oxygen and substrate transport (Forster and Wase, 1987). While for naturally aerated static piles and windrows a particle size of approximately 5 cm is appropriate, a particle size as small as 1.3 cm can be used for forced aeration systems.

### Temperature

As the composting microorganisms degrade organic substrates, heat is generated which raises the compost temperature to the desired thermophilic conditions. Microbial activities and chemical reactions are usually faster at higher temperatures. For municipal solid wastes (MSW), retention of heat is also necessary in order to sanitize the wastes. The retention and continual generation of heat are dependent upon the configuration, size, and insulating property of composting systems, ambient temperature, and the heat values of substrates. Although higher temperature is beneficial in many ways, the microorganisms and enzymes are inactivated and the composting process will stop beyond 70°C. Above 60°C, most mesophiles including fungi will be destroyed or inactivated and the decomposing activity is carried out mainly by actinomycetes. After readily available substrates such as starches, sugars, lipids, and proteins have been consumed, the compost temperature will fall below 60°C, and it will allow fungi and actinomycetes to attack cellulose and lignin portions of the substrates. Recently, researchers agree that 55-60°C is the optimal temperature range (Bollen, 1985; Finstein and Miller, 1985).

### Electroconductivity (EC)

Avinmelech and et.al. (1996) suggested that EC could be used as a quick stability index for compost derived from municipal solid wastes (MSW). Their stabilized compost EC values decreased approximately 50% of the initial values, which was also observed by Iannotti, et.al. (1994). EC usually decreases as compost ages due to destruction of organic volatile acids. However, Grebus, et.al. (1994) reported the opposite trend of EC for their compost made of grass clippings and yard trimmings. Their ingredients contained relatively large fraction of nitrogen and EC. The ammonium ion concentration increased with composting time. More research is required to clearly understand the relationship between EC and compost stability.

## Chemical Factors

### Contaminated Soil Loading

The economics of the remediation composting systems will be based on the amount of contaminated soil pushed through the system during a given time period. The higher the ratio of contaminated soil in a unit volume of compost given an equivalent microbial activity, the lower the overall cost of the system on a unit basis. However, this economic incentive must be carefully balanced for the possible inhibition by the contaminants on the compost microbial activities and for the decrease in compost temperature simply due to replacing organic substrates with mostly inert soil. Loading the system with an excess of inhibitory contaminant will slow microbial activities and result in an overall lengthening of composting time or may cause a total process upset. As a result, the composting process may not be able to reach or maintain a stable thermophilic state for desired reaction time due to lack of organic substrates.

### Carbon to Nitrogen Ratio (C/N)

Compost microorganisms require adequate levels of carbon (C) sources and other nutrients including nitrogen (N), phosphorous, sulfur, and other trace minerals and growth factors. Among these, C and N are usually the limiting substrates, while other elements and nutrients are abundant in composting processes. Chemical elemental analysis of soil microorganisms revealed that the cells in general contain about 50% C, 5% N, and 0.25-1% phosphorous on a dry weight basis (Alexander, 1977). Assuming about 1/2 to 2/3 of carbon is converted to carbon dioxide and the rest to cell mass, the required C/N ratio would be about 23 to 35. The optimal C/N ratios for different composting materials ranged from 20 to 35 (Haug, 1993).

If the initial C/N ratio is too high (i.e., low nitrogen level), the microorganisms pass through many life cycles to achieve a stable state (i.e., C/N of about 10). This may not be desirable for conventional MSW composting because it will slow down the substrate stabilization rate. It may however be beneficial for remediation composting because dead microorganisms themselves are organic substrates and will support endogenous activities for long periods. If the C/N ratio is too low, nitrogen will be lost as

ammonia which may reach toxic levels and raise the compost mix Ph. For a compost mix with high C/N ratio, ammonia releasing substrates such as blood, urine or urea can be added. If phosphorous and other nutrients are low as in cases of using industrial solid wastes as substrates, these components need to be supplemented in order to avoid unnecessary rate limitations.

### Acidity (pH)

The pH of the compost matrix must be near neutral (i.e., pH of 7) because most biological systems balance their cationic and anionic ions near neutrality. For all practical purposes, microbial growth is severely limited at pH values less than 3 or greater than 11. The optimum pH of composting was reported to be between 6.0 to 8.5 (Fitzpatrick, 1993). At higher pH (strongly basic), ammonium ions (nitrogen source) will be lost as ammonia, and essential elements such as calcium and magnesium may not be available to microorganisms due to precipitation as insoluble metal hydroxides or carbonates. At lower pH (strongly acidic), toxic metals, aluminum, copper, zinc, and etc., will be leached from minerals and substrates and may stop the composting process.

Overall, compost mix pH should be adjusted with co-substrates or other pH adjusting chemicals such as lime and baking soda if the initial pH falls outside the optimum range. For instance, wood wastes and sludges from pulp and paper mills may have a low pH of 5-6 and high C/N. Addition of ammonia releasing substrates such as urine or urea will neutralize the acidity and provide necessary nitrogen to microorganisms. Some depression of pH values (4.5-5.0) of compost materials stored in a closed container is not unusual due to anaerobic production of volatile fatty acids.

## Biological Factor

### Biodegradability and Biodegradation Rate

Substrate biodegradability determines the quantity of available heat and the stoichiometric oxygen demand. In literature, biodegradability of substrates varied widely, for instance, 28% for steer manure to 68% for chicken manure

(Klein, 1972) or 21.7% for newsprint to 81.9% for food wastes (Kayhanian and Tchobanoglous, 1992). Chandler, et al. (1980) reported that the lignin content was the single most important factor influencing the biodegradability.

Contrast to MSW which requires a long retention time (typically more than 90 days of composting) to achieve adequate stabilization, it may not be required nor desired for remediation of soils contaminated with explosive compounds. Most of the previous remediation composting studies indicated that less than 30 days were required to substantially degrade or transform TNT, RDX, and other explosive compounds by aerobic composting (Doyle and Isbister, 1982; USATHAMA, 1988; Garg, 1991, Pennington et al., 1995).

Respirometric analysis can be effectively used not only to estimate oxygen requirements but also the biodegradabilities and the biodegradation rates of substrates and explosive compounds. Respirometric analysis with less than a hundred grams of compost substrates can be also used to screen potentially useful compost mixtures in short time. The accumulated oxygen uptake of the compost substrates with respect to incubation time provides direct information on the oxygen requirements of the substrates at various retention times.

### Aeration

Aeration in general composting is important in two aspects; oxygen supply to aerobic microorganisms and cooling/drying of the compost by evaporation of water. For non-mechanical aeration systems, oxygen may be transported via molecular diffusion and free convection of air movement due to temperature gradients existent within compost piles. Oxygen may also be supplied by forcing air through the compost matrix, or mechanically mixing the compost intermittently to enhance the oxygen transfer. Aeration is also used to dry and subsequently cool the compost temperature through promoting evaporation of water. Approximately 10 to 30 times more aeration is required for drying of 20% solids than that for biological oxygen oxidation (Haug, 1993). Composters typically use about 1 $m^3$ air/kg VS-d.

# 3 Respirometric Study

## Introduction

Respiration is a biochemical process in which microorganisms or biomass metabolize organic materials (substrate). During aerobic respiration, the biomass mineralizes organic matter into carbon dioxide ($CO_2$) and water, as well as uses the substrate as a carbon and energy source for cell growth and maintenance. Monitoring of respiration rates in microbial populations or biomass has become a very useful tool for measuring the biodegradation of organic matter and can be applied to wastewater treatment, composting, and bioremediation. Respirometry is an analytical technique that can determine oxygen consumption in an aerobic environment. Mahendraker and Viraraghavan (1995) describes respirometry as an assessment of the oxygen uptake required by a microbial population.

Respirometry has become an important tool for environmental applications by providing biodegradation rates through microbial kinetics, the rate that microorganisms degrade different organic substrates (Flathman and Nowakowski, 1995; Carlsson, 1993; Vanrolleghem and Verstraete, 1993; Kappeler and Gujer 1992; Grady et al., 1989). This kinetic data can be used to approximate the short-term biochemical oxygen demand (SBOD) or oxygen uptake rate (OUR) of a particular sample to estimate the standard biochemical oxygen demand (BOD), typically a five day test (Spanjers et al., 1994a; Vanrolleghem and Spanjers, 1994; Jacobi and Fussa, 1993). In addition, respirometry helps to identify the toxic and inhibitory effects that organics may have on the microorganisms which might retard their performance in a biological treatment process (Boening et al., 1995; Spanjers et al, 1994b; Herricks et al, 1991).

Finally, respirometry can be used as a tool for determining plant design parameters for sizing blowers, aerators, and composting piles (Hunter et al., 1995; Brouwer et al., 1994; Arthur and Meredith, 1993; Klapwijk et al, 1993;

Watts and Garber, 1993; Rozich and Guady, 1992). Several reviews are available that discuss different techniques and applications for respirometry (Mahendraker and Viraraghavan, 1995; Arthur and Meredith, 1994). To date no significant research has been conducted on using a respirometer to provide insight on contaminated soils, in particular, soils contaminated with explosives (Mahendraker and Viraraghavan, 1995).

WES used a respirometric technique as a first step to determine the optimal compost mix for treating explosives contaminated soils. This study evaluated eight different compost mixtures for their total oxygen utilization and uptake rates as well as the degradation of TNT, HMX, RDX, 4A-DNT, and 2A-DNT.

## Materials and Methods

### Soil Samples

A 0.5 cubic yard of contaminated soil was collected during October 1994 by WES from an area near the center of the ABG burn pit (latitude 32°12.78'N and longitude 90°53.20'W). These samples locations were selected because they were near previous core sampling sites where explosive analytes were detected. Grab samples were collected to a depth of 18-in. Upon delivery at WES, the soil samples were stored at 4°C until experimentation. Physicochemical characteristics of the soil is shown in Table 1.

### Compost Mixtures

Eight different composting mixtures were evaluated and two optimal compost mixtures were selected for bench-scale composting experiment. Ingredients for these mixes are shown in Table 2. Each compost mixture, used in the initial study, contained 20% (v/v) soil, 40% (v/v) amendments, and 40% (v/v) bulking agents. The amendments were cow, pig, turkey manures and POTW sludge, while the bulking agents included recycled paper, sawdust, and alfalfa. The compost mixtures had C/N ratios of 16-93 except one C/N ratio was 414, moisture contents of 53-64%, and pH of 6.2-8.2.

### Respirometer Procedure

A BI-1000 Electrolytic Respirometer (Bioscience, Inc., Bethlehem, Pa) was used to collect oxygen utilization data. This respirometer consisted of eight 1-liter reactor bottles, a reactor module, a water bath (40°C), a temperature controller, a personal computer, and control software. Approximately 200 ml of each mix was placed into a flask. The initial amounts of TVS, TKN, TNT, RDX, HMX, 4A-DNT, and 2A-DNT in each treatment were determined by analyzing a portion of the remaining mix.

After ten days, the compost was removed from each bottle and analyzed for final amounts of each explosive, TVS, TKN, pH, and moisture content. The half-life of each mix was calculated to determine which mix most effectively removed the explosives in the soil. In addition, the final respiration data were used to estimate the amount of oxidized carbon, which was later used to determine the specific biodegradation rate (SBR) of each mix.

### Physicochemical Parameters

**Oxygen utilization.** The BI-1000 was set to record data every 30 minutes. This respirometer incorporates a potassium hydroxide trap to remove the carbon dioxide respired by the biomass, resulting in the change of the pressure inside the flask. The change in pressure is proportional to oxygen utilization. Oxygen was replaced by the electrolysis of water and was generated at 100 milligram per hour.

**Oxygen uptake rate (OUR).** The OURs were determined from the data collected by the BI-1000 respirometer. They were calculated by dividing the change in accumulated oxygen by the change of a specific time interval.

**Moisture Content.** The moisture content is determined by oven-drying the compost at 104°C for 24 hours and subtracting the final weight from the initial weight and dividing the result by the initial weight (Greenburg, 1992).

**Total volatile solid (TVS).** The TVSs are determined by placing the compost sample into a furnace at 550°C, subtracting the final weight from the initial weight, and dividing the result by the initial weight (Method 2540G Total, Fixed, and Volatile Solids and Semi-solid Samples; Greenberg et al. 1992).

**Total Kjeldhal Nitrogen (TKN).** Three to five grams of compost are mixed

together with 5 milliliter of sulfuric acid in a 250 ml polyethylene bottle. After agitating the bottle for 3 minutes, 245 ml of double-distilled water was added. Twenty milliliter of sample was digested using a BD-46 Digestor. After digestion, the TKN values were measured on a Lachat instrument using QuikChem method 10-107-06-02-D (Lachat, 1995).

**Specific Biodegradation Rate (SBR).** The SBR was calculated by dividing the grams of respired carbon as $CO_2$ by the grams of initially available carbon in dry weight and by the days of incubation. A similar method was described by Atkinson et al. (1996). The total amount of dry weight carbon can be estimated as follows:

$$Dry\ Weight\ C = (TVS/1.8) * Dry\ Weight \quad (1)$$

Haug (1993) states that percent carbon is equal to TVS divided by 1.8. The mole ratio of $O_2$ consumed to $CO_2$ generated was about 16.5/16 and this ratio was used to estimate $CO_2$ generation based on $O_2$ consumption data.

**pH.** Approximately 5 grams of compost was mixed into a slurry using 2 to 3 times the amount of DDI water. The mixture was stirred twice before measuring it with a pH meter.

**C/N Ratio.** The percent available carbon is calculated using the following equation:

$$C/N = biodegradability\ factor * (TVS/1.8) \div (TKN*10^{4}) \quad (2)$$

The biodegradability factor assumed to be 0.5 (Haug, 1993). The percent available nitrogen is the TKN value divided by 10,000.

### Explosive Analysis

Explosives were determined by SW846 Method 8330: Nitroaromatics and Nitroamines by High Performance Liquid Chromatography (HPLC) (United States Environmental Protection Agency (USEPA 1992). Samples were homogenized by stirring and extracted without drying. Chromatographic analysis was performed with a Perkin Elmer Integral 4000 HPLC using a C-18 Reverse Phase HPLC column (Supelco LC-18), 25 cm x 4.6 mm (5$\mu$m).

Extraction was performed using acetonitrile.

### Half-life Estimations for Explosives

The half-life estimations were determined by assuming the first-order equation,

$$\frac{dC}{dt} = -kC \tag{3}$$

where

$C$ = the explosive concentration (mg/kg)

$k$ = the rate constant ($days^{-1}$)

$t$ = time (days) for the concentration of any the explosives of interest within the composting mix

Equation 3 is solved for the rate constant ($k$). The half-life (days) is then estimated from equation 4.

$$t_{1/2} = \frac{0.693}{k} \tag{4}$$

## Results and Discussion

The respirometric study ran for 10 days. TVS remained constant during the 10 days of incubation. Due to relatively large sample volume required for explosive analysis, an insufficient amount of composting material was available to run final pHs and moisture contents on all the mixtures and TVS. In addition, procedural errors in TKN analysis were later discovered and consequently, the final TKN and C/N ratio values are not presented.

Table 3 shows the SBRs, the maximum $O_2$ uptake rates, and the first-order substrate biodegradation rate coefficients. The SBR for each mix was

determined from accumulated oxygen data from the respirometer. Mix 5 had the highest SBR of 0.029 $days^{-1}$ and the mix 4 had the lowest at 0.012 $d^{-1}$. If the explosive degradation rates increase with SBRs, the first choice would be the mixes 5, 6, and 7. The maximum oxygen uptake rates varied from 1.50-6.68 g $O_2$/day. Again, the mixes 5 and 7 exerted high OUR values.

The substrate degradation rate coefficients ranged from 0.013-0.034 $d^{-1}$. Haug (1993) reworked a correlation for substrate degradation rate coefficient at various temperatures for composting a mixture of garbage and dewatered, digested sludge cake as:

$$k_d = 0.00632*(1.066)^{T-20} \quad (5)$$

where

$k_d$ = rate coefficient ($d^{-1}$)

$T$ = temperature (°C).

Equation 5 using 40°C of the respirometric test temperature predicts $k_d$ of 0.023 $d^{-1}$, which is within our rate coefficient range.

The initial and final concentrations of TNT, HMX, RDX, 4A-DNT, and 2A-DNT as well as the average half-lives for each compost mix assuming a first-order decay reaction are shown in Table 4. The initial concentrations of the explosives were analyzed in triplicate; however, the final concentrations were determined from single samples due to limited amount of compost mix in the respirometer tubes. The average half-live ranges are presented in Table 4. The half-lives of TNT from this study similar to that from static tank composting of the contaminated soils at the Umatilla Depot Activity Hermiston, Oregon (i.e., 0.55-1.24 day) (USAEC 1993).

To determine the optimum mix for explosive degradation, each explosive compound was ranked from the shortest half-life to the longest. The shortest half-life was given a ranking of 1, while longest had a ranking of 8. The ranks for each compound in a mix were than added, then divided by the number of explosive compounds (5) in order to determine the average overall effective rank (Table 4) for all five explosives. Mixes 4 and 7 had the lowest overall ranking score (i.e., the fastest degradation potential of all five

explosive compounds). The rankings do not consider the toxicity effects to humans.

### Recommended Compost Recipe

Eight compost mixtures were evaluated for their substrate utilization rates and degradation rates of explosive analyte and transformation products found in the Rockeye soils. Compost mixes 4 (swine manure, recycled paper, and soil) and 7 (cow manure, alfalfa, and soil) showed the fastest degradation potential of the explosives. Although mix 7 was among the highest in terms of substrate degradation rate, mix 4 was the lowest in that category. The low substrate utilization rate of the mix 4 may not heat the compost piles due to low energy generation rate. This insufficiently heated compost poses threat to public health because of improper sanitization at low temperatures. Furthermore, compost mix 4 was a slurry mixture and appeared not to possess the structural integrity of normal compost with sufficient FAS. Therefore, compost mix 7 was recommended for subsequent bench-scale composting experiment.

Compost mixes 1 (turkey manure and sawdust) and 5 (POTW sludge and sawdust) may be effective in treating the explosives contaminated soils. Having the highest SBR, the compost temperature of the mix 5 is expected to be high enough to achieve proper sanitation and thermophilic conditions in which explosives may be degraded more effectively. The explosives degradation effectiveness rankings for the mixes 1 and 5 are 4.0 and 4.2, respectively, which is slightly below that of mixes 4 and 7.

# 4 Bench-Scale Composting Study

## Introduction

The preliminary success of the compost mix 7 from the respirometric test was furtherly evaluated under actual composting environments. A bench-scale remediation composting system which closely simulates the actual composting process was used to expand the respirometric study. The bench-scale study is expected to provide the preliminary feasibility, the fate of the contaminants, and the health risk of composted products. The pilot-scale studies can be initiated to cover the scale-up factors and the heterogeneity of field conditions, and finally successful field operations can be implemented.

The standard composting method of ASTM D5338 uses incubators in order to externally control the compost reactors at pre-defined temperatures (35°C for the first 16 days and 55°C for 28 days). With this externally pre-defined temperature control, reproducibility of data may be improved; however, many leading experts argue that it may not adequately represent the actual composting process in which self-heating is induced. A relatively high surface area to volume ratio compared to field or pilot compost piles results in high conductive and convective heat loss. The heat generated from degrading organic substrates may not be enough to raise and maintain the thermophilic compost temperatures. It has been a common perception among composting researchers and practitioners that the minimum size of a pilot compost pile must be at least 25 to 50 cubic yards in order to retain the heat (Hanif 1995).

Several researchers used feed-back temperature control and heating systems in order to minimize the heat loss and were able to maintain self-heating induced thermophilic conditions (Cook et al., 1994; Hogan et al., 1989; Magalhaes 1993). The small bench-scale remediation composting systems require much more precise design and operational parameters in order to be successful, compared to rather insensitive but more stable pilot-scale compost

piles.

The Waterways Experiment Adiabatic Composting System (WACS) II is a composting reactor with a sophisticated feed-back temperature control and heating system. Compost mix 7 was furtherly evaluated for the feasibility of treating soils contaminated with the explosives in actual composting environments using the WACS II system.

## Materials and Methods

### Compost Reactor System

The WACS II is a pseudo-adiabatic composter combined with instrumentation and automatic data collection, as shown in Figure 5. The composting reactor is a 14 liter PVC cylinder insulated to reduce conductive heat transfer. This reactor is placed into a Styrofoam box to further isolate the composter from ambient temperatures. This isolation will attempt to simulate the core of a field-scale composting pile so that heat can accumulate inside the reactor, raising the composting temperature. Temperature probes (RTDs) are inserted into the center of the composting reactor as well as against the inside and outside of the cylinder wall. A proportional-integral-derivative (PID) feedback temperature control system used the two reactor wall RTD measurements to track the temperature differences. The temperature of air in the Styrofoam box attempts to maintain at the same temperature of the inside reactor wall by passing preheated or cooled water through a radiator inside the box while a fan circulates the temperature controlled air.

Finally, preconditioned air is supplied to the reactor to maintain aerobic respiration and to reduce convective heat losses from the composting pile through the latent heat of vaporization. Air temperature is dynamically adjusted to the temperature at the core of the composting pile. Air is also humidified before entering the reactor. Aeration events occur every one in ten minutes if the composting temperature is less than 55°C or continuously if the temperature is above 55°C. Temperature readings were recorded every

two minutes as well as total elapsed time for aeration events.

**Procedures**

The ingredients for the mix 7 (40% cow manure, 40% alfalfa, and 20% soil) were measured by volume, weighed, and mixed together in a 15 gallon twin-shell mixer (Table 5). The ingredients were homogenized for at least 2 hours. Compost mix samples were collected in triplicate. Each sample was analyzed for pH, moisture content, TVS, TKN, total organic carbon (TOC), EC, and explosives. Other samples were collected on day 15 and day 35.

## Results and Discussion

Figure 6 displays the average maximum and minimum core compost temperature profile for 30 days as Y error bars. The compost reached a thermophilic temperature range within the first 24 hours and remained thermophilic for approximately 4 days. The compost achieved the maximum temperature of 55°C during days 3, 4, and 5. The compost temperature dropped to room temperature after 10 days of composting. This core compost temperature profile indicated that the WACS II system closely simulated actual field scale compost piles.

The composting temperature profiles of the core, inside wall, outside wall, and air temperatures are shown in Figure 7. The core compost temperature was slightly higher than the wall temperature, showing radial heat loss through the reactor. This ensured self-heating of the compost and no external heat input as in the real field compost piles. The air temperature maintained an approximate 10-15°C below the core temperature to allow heat removal from the system and achieve the optimal composting temperature of 55°C.

Figure 8 shows the daily aeration and cumulative aeration minutes for 35 days. Day 3 had the highest aeration of 235 minutes of air at a rate of 3.78 liters per minute. The number of aeration minutes corresponded well to the temperature profile, increasing from days 0-3, declining from days 3-5, and remaining constant to day 35. The overall accumulated air was 4,959

minutes. Air was exchanged 1,339 times throughout this run. Haug (1993) estimated that a yard waste composting pile with 80% TVS and 50% degradability would require 1,510 exchanges of air. The overall aeration for this composting run was 0.43 $m^3$/kg VS-d.

Physicochemical properties of the compost at days 0, 15, and 35 are shown in Figure 9. The moisture content decreased slightly but still maintained the optimal values, ranging from 48.2-44.9% during the 35 days of composting. The initial pH was 6.73, increased to 8.74 at day 15, and decreased to 7.78 at day 35. The values and trend of pH during composting in our study compares well with other studies (Tchobanoglous et al., 1993; Avnimelech et al., 1996).

TVS decreased from 30.0 to 21.8% on day 15, and remained constant at 21.1% to day 35. This indicated a substantial reduction in organic matter during the first 15 days of composting where thermophilic conditions prevailed (Figure 6). At the later stage of composting, when the substrate utilization rate became rather insignificant due to depletion of readily available organic carbon sources, the compost temperature dropped to room temperature, resulting in practically no change in TVS.

Total nitrogen continuously decreased throughout the study from 2,330 to 1,690 mg/kg. Several possibilities for the decrease in total nitrogen are ammonia-N loss through volatilization and leachate and nitrification resulting in the decrease in TKN values during composting. The change in compost temperature did not appear to affect the TKN loss rate since a linear decrease in TKN was observed during composting. The C/N ratio decreased from 35.8 to 30.7 on day 15, but increased to 34.7 on day 35. In general, as compost ages the C/N ratio decreases. In our case, the decrease in the carbon utilization rate with continual reduction of TKN during the later stage of composting resulted in increase in C/N ratio.

The EC decreased from 3,230 to 2,397 mmho/cm on day 15, but increase to 2,790 mmho/cm at the end of composting run. This EC pattern was similar to that of C/N ratio. EC values decrease with the increase in the age for many MSW composts due to destruction of organic volatile acids with time (Avinmelech, 1996; Hue and Liu, 1995). In addition, nitrification of ammonia may begin during the later stage of composting when the available

organic carbon was low but with adequate supply of oxygen through frequent aeration, resulting in production of electrolytes. This may explain the down (destruction of organic volatile acids in the beginning) and up (production of electrolytes at the later stage) pattern of EC.

Contrast to the respirometric study, no substantial HMX reduction occurred. The initial and final HMX concentrations were 4,817 and 4,658 mg/kg, respectively. The reason for the difference in HMX degradation between respirometry and composting runs is not clear at this time. The most significant difference observed between the two experiments is the temperature. In respirometry, the mixture was maintained at 40°C, whereas, the composting mixture heated to 55°C and cooled down to room temperature. Different microbial populations may exist for the two studies. Figure 10 exhibits significant reduction for all other explosive compounds as predicted from the respirometric study. RDX, TNT, 2A-DNT, and 4A-DNT concentrations were reduced by 99.6, 99.3, 97.0, and 94.1%, respectively. Explosives and the transformation products disappeared within the first 15 days of composting as found in other remediation studies (USAEC, 1993).

# 5 Toxicity Experiment

## Introduction

Although previous composting experiments showed heat generation and significant reduction of target contaminants, in particular RDX and TNT, it is important to determine the environmental effects of remediation via composting. To quantify hazardous effects on ecosystem, toxicological experiments was performed on the final compost mix.

Two assays were employed to evaluate the efficacy of composting in reducing the toxicity of explosive contaminated soils, the Mutatox™ assay and earthworm acute toxicity. The Mutatox™ assay is a proprietary assay that determines the mutagenic potential of sample extracts. It utilizes a dark mutant of the bacterial strain, *Photobacterium phosphoreum*, which normally bioluminesce (similar to fireflies). These dark mutants of *P. phosphoreum* revert to the wild type in the presence of mutagens. The mutation causes *P. phosphoreum* to bioluminesce, and the light produced is easily measured with a luminometer.

The earthworm acute toxicity test estimates the acute toxicity of solid wastes to the earthworm (*Eisenia sp.*) in a 14-day static test and is accepted by EPA (Greene, 1989). The responses measured include the synergistic, antagonistic, and additive effects of all the chemical, physical, and biological components that adversely affect the biochemical and physiological functions of the test animal. The test uses soil as the exposure medium because the exposure conditions closely mimic natural conditions. The test soil is serially diluted with a non-contaminated "artificial soil" in which mature earthworms are placed for 14 days. At the end of the exposure, the number of live earthworms are counted and an $LC_{50}$, the concentration which is expected to kill 50% of a test population, is calculated.

The Mutatox™ assay is a quick and easy assay that utilizes extracts of the sample. As such, the assay results are dependent on the ability to extract the

contaminants from the sample. Conversely, Mutatox™ could "overexpress" the mutagenic potential of the sample if the contaminants are not bioavailable, but are extractable. The earthworm acute toxicity assay exposes the organisms to the soil sample and therefore assesses the toxicity of only the bioavailable contaminants. The combination of the two assays works together to provide a picture of the acute and subacute (mutagenicity) toxicity of the soil in addition to the bioavailability of soil contaminants.

## Material and Methods

### Pilot-Scale Reactor System

To simulate field-scale operations, WES ran the composting mixture in a 40-liter adiabatic composter (Oxymax) developed by Columbus Instruments (Figure 11). A pilot-scale system provides enough composting material to run both toxicological and mutagenic experiments. Similarly to the WACS II system, the Oxymax composter uses a temperature control feedback system to minimize heat transfer effects. The reactor tracks temperature as well as microbial activity through an $O_2$ and $CO_2$ sensors. Filtered air is passed through the compost reactor with a known flowrate. The gas then passes through the sensors. The temperature, flowrate, $O_2$, and $CO_2$ measurements were automatically recorded every 20 minutes via a personal computer.

### Soil Extraction for Mutagenicity

Five soil samples (Rockeye soil, Mix 1 Initial, Mix 2 Initial, Mix 1 Final, and Mix 2 Final) were immediately stored at 4°C until testing. Mixes 1 and 2 are replicates from mix 7. Aliquot of the samples were oven dried overnight at 130°C for determination of wet/dry weights. Four replicate 1 gram samples of each soil sample were combined with 3 ml of pesticide grade acetonitrile in 25ml glass centrifuge tubes and sonicated for 18 hours in a sonicating water bath at 9°C. The soil extracts were centrifuged for 5 minutes at 2,000 rpm and 14°C for sedimentation of the soils. An aliquot of the extract was pipetted into an amber vial and solvent exchanged under a

stream of ultrapure nitrogen into an equal volume of spectrophotometric grade dimethyl sulfoxide (DMSO).

### Mutatox™

As per the Mutatox™ testing protocol, 10$\mu$l of each soil extract was added to 250$\mu$l of Mutatox™ medium and serially diluted over a wide range with extra media into cuvettes. A 10$\mu$l portion of bacterial reagent was pipetted into cuvettes, mixed, and incubated at 27°C for 21 hours. Phenol was used as a positive control in addition to DMSO and acetonitrile solvent controls. Each extract was measured and recorded after the incubation period using the Microbics M500 Toxicity Analyzer (Microbics Corp.). A soil extract was considered mutagenic when light levels produced were greater than two times the DMSO control for two consecutive dilutions, e.g., modified twofold rule (Chu *et al.*, 1981).

### Earthworm Acute Toxicity

Adult earthworms (*Eisenia sp.*) were purchased from Carolina Biological Supply Company (Burlington, NC) and held in moistened sphagnum peat for at least 3 weeks prior to testing on a diet of Magic Worm Food (Carolina Biological Supply Co.). The acute toxicity test was conducted according to EPA protocols (Greene, 1989). Test soil samples were diluted with artificial soil (70% industrial sand, 20% kaolin clay, and 10% sphagnum peat on a dry weight basis). The artificial soil pH was adjusted to 6.0$\pm$0.5 with calcium carbonate. The dilutions were 100, 50, 25, 12.5, 6.3, and 3.1% sample soil to artificial soil on a dry weight/dry weight basis. Aged tap water was added, if needed, to increase the percent moisture of the soil mixtures to 25%. Each soil samples were split into three replicate of 100 g of wet weight samples. The replicates were placed in 250 ml polypropylene beakers, covered with polyethylene wrap, sealed with a tight-fitting rubber band, and allowed to sit overnight.

On day 0 of the 14-day exposures, mature earthworms were removed from the peat bedding, rinsed with aged tap water, and four earthworms were placed in each beaker. The beakers were re-covered with polyethylene wrap

and held under continuous illumination at room temperature (23±2°C) for 14 days. The earthworms were not fed during exposure. At the end of the exposure period, the earthworms were removed and the number of live earthworms per beaker were recorded. Earthworms were considered dead if they did not respond to gentle probing with a blunt probe. A reference toxicant control was run simultaneously with the test soils by spiking artificial soil with 2-chloroacetamide. The calculated $LC_{50}$ for 2-chloroacetamide was compared with published data for performance validation of the tests (Edwards, 1984). The test data were found to be acceptable.

## Results and Discussion

### Compost Temperature

Figure 12 and 13 show the average daily temperature profiles for the two mixes. The Y bars show the maximum and minimum temperatures for each system. These figures show that the temperatures of both mixes did not increase to thermophilic ranges as reported in the bench-scale system within the first 24 hours. We suspected that the energy content of the compost mix was insufficient to generate the required heat to raise the temperatures in the Oxymax system. In attempt to rectify the situation, molasses was added to each reactor. Approximately three kilograms was added to each reactor during the incubation period. The molasses supplied enough energy for both reactors to reach thermophilic temperatures.

### Respiration Rate

Figures 14-16 show the average daily respiration profiles in exit air for mix 1, while Figures 17-19 profile mix 2. The Y bars show the maximum and minimum $O_2$ and $CO_2$ for each system. Both mixes show significant biological activity within the first day. Figure 14 shows that $CO_2$ increased to 9% while oxygen level reduced to 12% in Figure 15. Similarly, trends are observed in mix 2. However, it appears as if the energy released was not adequate to increase the temperature even in psydo-adiabatic reactor.

### Explosive Analysis

Table 6 shows the explosive profiles during composting of both reactors. As previously discussed, HMX concentration decreased slightly over 30 days of composting in both reactors. HMX concentration was reduced 25 and 28% for reactor 1 and 2, respectively. RDX concentration was reduced 82 and 88% for reactor 1 and 2, respectively. TNT concentration was reduced 99.9 and 99.8% for reactor 1 and 2, respectively. The TNT biotransformation products (2A- and 4A-DNT) concentrations increased initially, but later decreased to less than 100 mg/kg, except for 4A-DNT in reactor 1. Majority of the explosives concentration were significantly reduced after 15 days of composting. The explosive removal efficiency from the 14-L system (WACS II) and the 40-L system (Oxymax) was similar.

Previous researchers reported that majority of the disappeared TNT was incorporated into humic material (Pennington, et.al., 1995). The following toxicological tests will evaluate how safe and environmental-friendly the finished compost with explosive compounds binding into the humic material.

### Mutatox™

Table 7 contains Mutatox™ results. Each number represents the average degree of light output from four replicate samples. In some instances, the extract dilutions were acutely toxic to the bacteria. The values indicate the range of mutagenicity of the extract dilution series as determined by the modified two fold rule. A higher number indicates a higher degree of mutagenicity. Table 6 shows that the Rockeye soil was acutely toxic from 1:1 to 1:64 dilutions and the three lower dilutions (1:80, 1:128, and 1:160) were mutagenic. The mix 1 initial and mix 2 initial samples caused bacterial mortality, but to lesser degree than the Rockeye soil, probably due to the dilution of the Rockeye soil with the compost amendments. The degree of mutagenicity in the Rockeye soil and two initial mixes are relatively comparable.

Composting apparently reduced the bacterial acute toxicity of the extracts as shown by the lack of toxicity in the two final mixes. However, the degree of mutagenicity increased dramatically. This can probably be attributed to TNT

degradation products formed during composting.

### Earthworm Acute Toxicity

Table 8 contains earthworm acute toxicity results. Each number represents the mean percent mortality of three replicate samples. The Rockeye soil was extremely toxic, with 100% mortality at all dilutions. The Mix 1 initial and Mix 2 initial samples yielded $LC_{50}$ of 4.4% as determined by linear interpolation (Stephen, 1977). Therefore, a mixture of 4.4% of either Mix 1 Initial or Mix 2 Initial in noncontaminated soil would be expected to kill 50% of the earthworms exposed to the mixture. The decrease in toxicity can again be contributed to the dilutional effect of adding the composting amendments to the Rockeye soil.

Mix 1 final and Mix 2 final samples yielded $LC_{50}$ of 35.3% and 100%, respectively. Apparently, composting reduced the acute toxicity of the Rockeye soil to the earthworms (the higher the $LC_{50}$ value, the less toxic).

# 6 Conclusions and Recommendations

## Conclusions

The best combination of locally available amendments and bulking agents to be utilized in the composting technology for remediating the Crane's soil contaminated with explosive compounds was selected. A combination of respirometry to screen out the optimal compost mixtures was evaluated using the respirometer. The bench-scale composting with the compost mixture selected from the respirometry was used to test the effectiveness of explosive compounds removal in actual composting environments. The efficacy of the selected compost mixture was evaluated in reducing the toxicity of explosive contaminated soils by the Mutatox™ assay and earthworm acute toxicity.

Based on the results of the respirometric, bench-scale compost, and toxicity tests, the following is concluded:

*a.* The locally available amendments was cow manure, pig manure, turkey manure, and POTW sludge. The locally available bulking agents was sawdust, alfalfa, and recycled paper.

*b.* Of eight compost mixes used in the respirometric study, Mix 4 (40% pig manure, 40% recycled paper, and 20% soil) and Mix 7 (40% cow manure, 40% alfalfa, and 20% soil) were ranked the highest.

*c.* Although most effective in removing explosives from the respirometric study at 40°C, SBR and the substrate rate coefficient of Mix 4 were the lowest among the eight mixtures. This low substrate degradation rate may lead to insufficient self heat generation capability and anaerobic conditions if used in actual field compost piles. Since unsanitized and odor producing compost may be the outcome of the Mix 4, Mix 7 was selected for subsequent bench-scale compost study.

*d.* The bench-scale composting study had an overall average rate of aeration of 0.43 $m^3$ air/kg VS-d. The moisture content decreased slightly but maintained at an optimal range of 44.9 to 48.2%. The substrate degradation rate slowed down considerably during the later stage of composting resulting in the temperature drop and almost no volatile solid destruction was observed after 15 days of composting.

*e.* TKN values continuously decreased over the entire composting period. Several reasons may be volatilization loss of ammonia-N during initial composting phase and nitrification during final phase of composting. The decrease in TKN during the later stage of composting resulted in increase in C/N ratio from 30.7 on day 15 to 34.7 on day 35.

*f.* EC values followed the C/N ratio trend during composting. The volatile organic acid destruction in the beginning and the generation of nitrate at the later state may be the reasons for the decrease and increase in values.

*g.* Majority of the explosive and transformation product concentrations were reduced within the first 15 days of composting. These results paralleled that of the 10-day respirometric study except HMX. HMX was not reduced by composting, contrasting 40% reduction from the 10-days of incubation using Mix 7 during the respirometric study.

*h.* HMX concentration was reduced 25 and 28% for reactor 1 and 2, respectively. RDX concentration was reduced 82 and 88% for reactor 1 and 2, respectively. TNT concentration was reduced 99.9 and 99.8% for reactor 1 and 2, respectively. 2A- and 4A-DNT concentrations increased initially, but later decreased to less than 100 mg/kg, except for 4A-DNT in reactor 1.

*i.* The similar removal patterns of most explosive compounds from both respirometric and composting support the use of simple and short respirometric tests to screen for the best compost mixtures. However, the exception like HMX still necessitate the use of bench-scale composting in order to verify or reinstate the removal capacity of the chosen mixes under actual composting environments before implementing pilot-/field-scale composting systems.

*j.* The toxicity study showed that the Rockeye soil was extremely toxic with 100% mortality even after dilutions.

*k.* The composting process apparently reduced the acute toxicity of the Rockeye soil, however the finished compost product was still acutely toxic and cannot be considered ecologically safe. The increased mutagenic potency of the compost extracts points to the production of reactive degradation products during the composting process.

## Recommendations

Based on the results of this study, it is recommended that Mix 7 be utilized in the pilot-scale study at NSWCC sites. Mixes 1 and 5 may also be proven to be beneficial in a pilot-scale study. Additional toxicity study should be conducted to relate the remediation composting engineering design and operation to the quality of compost in terms of target chemical removal and toxicity reduction.

# References


Alexander, M. (1977). *Introduction to Soil Microbiology*. John Wiley, New York.

Arthur, R.M. and Arthur, B. (1994). Thirty Years of Respirometry. Proceedings of 49th Purdue Industrial Waste Conference, W. Lafayette, Indiana.

Arthur, R.M. and Meredith, D. (1993). On-Line Respirometry. ISA International Conference.

Avnimelech, Y. et al. (1996). "Stability Indexes for Municipal Solid Waste Compost", *Compost Science Utilization*.

Biddlestone, A.J. et al. (1987). *Environmental Biotechnology*. Chichester, UK, Ellis Horwood.

Boening, D., Hendricks, C.W., and Rossignol, A.M. (1995). "Automated Respirometer Method for Microbial Toxicity Assessment of Low-Level Zinc Contamination in Soil", *Bull. Environmental Contamination Toxicology*.

Bollen, G.J. (1985). *Composting of Agricultural and Other Wastes*. J.K.R. Gasser, ed., Elsevier Applied Science, London.

Brouwer, H., Klapwijk, A., and Keesman, K.J. (1994). "Modelling and Control of Activated Sludge Plants on the Basis of Respirometry", *Water Science Technology*.

Carlsson, B. (1993). "On-line Estimation of the Respiration Rate in an Activated Sludge Process", *Water Science Technology*.

Chandler, J.A. et al. (1980). Predicting Methane Fermentation Biodegradability. *Biotechnology Bioengineer Symposium*. No. 10

Chu, K.C., Patel, K.M., Lin, A.H., Tarone, R.E., M.S. Linhart, and V.C. Dunkel. (1981). "Evaluating statistical analyses and reproducibility of microbial mutagenicity assays", *Mutatation Research*. 85:119-132.

Cook, B.D., Bloom, P.R., and Halback, T.R. (1994). "A Method for Determining the Ultimate Fate of Synthetic Chemicals During Composting," *Compost Science and Utilization, winter*, 42.

Doyle, R.C. and Isbister, J.D. (1982). "Treatment of TNT and RDX Contaminated Soils by Composting", *Proceeding of National Conference on Management of Uncontrolled Hazardous Waste Sites*, Washington, D.C.

Edwards, C.A. (1984). Report of the second stage in development of a standardized laboratory method for assessing the toxicity of chemical substances to earthworms. European Economic Communities EUR 93600 EN 99. Brussels, Belgium.

Finstein, M.S. and Miller, M.C. (1985). *Composting of Agricultural and Other Wastes,* Gasser, J.K.R., ed., Elsevier Applied Science, London.

Fitzpatrick, G.E. (1993). "A Program for Determining Cocompost Belding Ratios", *Compost Science and Utilization,* Summer, 30.

Flathman, P.E. and D.M. Nowakowski. (1995). Electrolytic Respirometry Taps Bioremediations Potential for Site Cleanup. Environmental Solutions. Issue: May, 52.

Forster, C.F. and Wase, D.A.J. (1987). *Environmental Biotechnology.* John Wiley & Sons, New York.

Garg, R., Grasso, D., and Hoag, G. (1991). "Treatment of Explosives Contaminated Lagoon Sludge", *Hazardous Waste and Hazardous Materials,* 8 (4), 319.

Golueke, C.G. (1991). "Principles of Composting", *The Biocycle Guide to the Art and Science of Composting.* J. Waste Recycling, The JG. Press, Inc.

Grady, C.P.L, Jr., Dang, J.S., Harvey, D.M., Jobbagy, A., and Wang, X.L. (1989). "Determination of Biodegradation Kinetics through Use of Electrolytic Respirometry", *Water Science Technology.* Vol. 21.

Greenburg, A.E., Clesceri, L.S., and Eaton A.D., Joint Editorial Board. (1992). *Standard Methods for the Examination of Water and Wastewater.* American Public Health Association, Washington, DC.

Greene, J.C., Bartels, C.L., Warren-Hicks, W.J., Parkhurst, B.R., Linder, G.L., Peterson, S.A., and Miller, W.E. (1989). "Protocols for Short Term Toxicity Screening of Hazardous Waste Sites", EPA 600/3-88/029. USEPA, Corvallis, Oregon.

Guady, A.F., Jr., Rozich, A.F., Garniewski S., Moran, N.R., and Ehambaram, A. (1988). "Methodology for Utilizing Respirometric Data to Assess Biodegradation Kinetics", 42nd Purdue Industrial Waste Conference Proceedings, W. Lafayette, Indiana.

Hanif, M. (1995). "Focus on Composting", *Hazardous Technical Information Services,* May/June, 7.

Haug, R.T. (1993). *The Practical Handbook of Composting Engineering.* Lewis Publishers, Ann Arbor, MI.

Herricks, E.E., Rittmann, B.E., Grady, C.P.L. Jr., Pascoe, D., Somlyódy, L., Fleit, E., Olah, J., van der Gaag, M., van de Guchte, C., Verstraete, W., Dries, D., and Schowanek, D. (1991). "Advancements in Toxicity Testing Applied to Design and Control of Biological Processes", *Water Science Technology*, 23, 271.

Hogan, J.A., Miller, F.C., and Finstein, M.S. (1989). "Physical Modeling of the Composting Ecosystem", *Applied Environmental Microbial.* May, 1082.

Hue, N.V. and Liu, J. (1995). "Predicting Compost Stability", *Compost Science Utilization*, 3 (2), 8.

Hunter, G., Johnson T., and Carns, K. (1995). "DO Probes: Friends or Foes", Water Environment Federation. 68th Annual Conference and Exposition. Miami Beach, Florida.

Iannotti, D.A., Pang, T., Toth, B.L., Elwell, D.L., Keener, H.M., and Hoitink, H.A.J. (1993). "A Quantitative Respirometric Method for Monitoring Compost Stability", *Compost Science and Utilization. Issue: Summer, 52.*

Jacobi, T.A. and Fussa, A.D. (1993). "Low Level Process Wastewater Monitoring Using Total Oxygen Demand", ISA International Conference, 91.

Kappeler, J. and Gujer, W. (1992). "Estimation of Kinetic Parameters of Heterotrophic Biomass under Aerobic Conditions and Characterization of Wastewater for Activated Sludge Modelling", *Water Science Technology*, 25 (6), 125.

Kayhanian, M. and Tchobanoglous, G. (1992). "Computation of C/N Ratios for Various Organic Fractions", *Biocycle*, May, 33.

Klapwijk, A., Spanjers, H., and Temmink, H. (1993). "Control of Activated Sludge Plants Based on Measurements of Respiration Rates", *Water Science Technology*, Vol. 28.

Klein, S.A. (1972). "Anaerobic Digestion of Solid Waste", *Compost Science*, Jan/Feb, Cited in Haug (1993).

Magalhaes, A.M.T., Shea, P.J., Jawson, M.D., Wicklund, E.A., and Nelson, D.W. (1993). "Practical Simulation of Composting in the Laboratory", *Waste Management and Research*, 11, 143.

Mahendraker, V. and Viraraghavan, T. (1995). "Respirometry in Environmental Engineering", *Journal of Environmental Science and Health.* A30 (4), 713.

Pennington, J.C., et al. (1995). "Fate of 2,4,6-Trinitrotoluene in a Simulated Compost System", *Chemosphere*, 30 (3), 429.

Rozich, A.F. and Gaudy, A.F., Jr. (1992). "Design and Operation of Activated Sludge Processes using Respirometry", Lewis Publishers, Ann Arbor, Michigan.

Spanjers, H., Olsson G., and Klapwijk A. (1994a). "Determining Short-Term Biochemical Oxygen Demand and Respiration Rate in an Aeration Tank by Using Respirometry and Estimation", *Water Resources.*, 28 (7), 1571.

Spanjers, H., Temmink, H., and Klapwijk, A. (1994b). "Monitoring of the Maximum Respiration Rate", *Water Science Technology.*, 30 (4), 285.

Stephen, C.E. (1977). "Methods for calculating an $LC_{50}$". *Aquatic Toxicology and Hazard Evaluation ASTM STP 634*, F.L. Mayer and J.L. Hamelink, eds., American Society for Testing and Materials.

U.S. Army Environmental Center. (1993). "Windrow Composting Demonstration for Explosives Contaminated Soils at the Umatilla Depot Activity Hermiston, Oregon", Contract No. DACA31-91-D-0079, Report No. CETHA-TS-CR-93043, Aberdeen Proving Ground, MD.

U.S. Army Toxic and Hazardous Material Agency. (1988). "Field Demonstration Composting of Explosive Contaminated Sediments at Louisiana Army Ammunition Plant (LAAP) Final Report," Contract No. DAAK-11-85-D-007, Report No. AMXTH-IR-TE-88242, Aberdeen Proving Ground, MD.

U.S. Environmental Protection Agency. (1992). "Nitroaromatics and nitramines by high performance liquid chromatography," SW846 Method 8330, Office of Solid Waste and Emergency Response, Washington, DC.

Vanrolleghem, P.A. and Spanjers, H. (1994). "Comparison of Two Respirometric Principles for the Determination of Short-Term Biochemical Oxygen Demand", 49th Purdue Industrial Waste Conference Proceeding, W. Lafayette, Indiana.

Vanrolleghem, P.A. and Verstraete, W. (1993). "Simultaneous Biokinetics Characterization of Heterotrophic and Nitrifying Populations of Activated Sludge with an On-line Respirographic Biosensor", *Water Science Technology*, 28 (11-12), 377.

Watts, J.B. and Garber, W.F. (1993). "On Line Respirometry: A Powerful Tool for Activated Sludge Plant Operation and Design", *Water Science Technology*, 28 (11-12), 389.

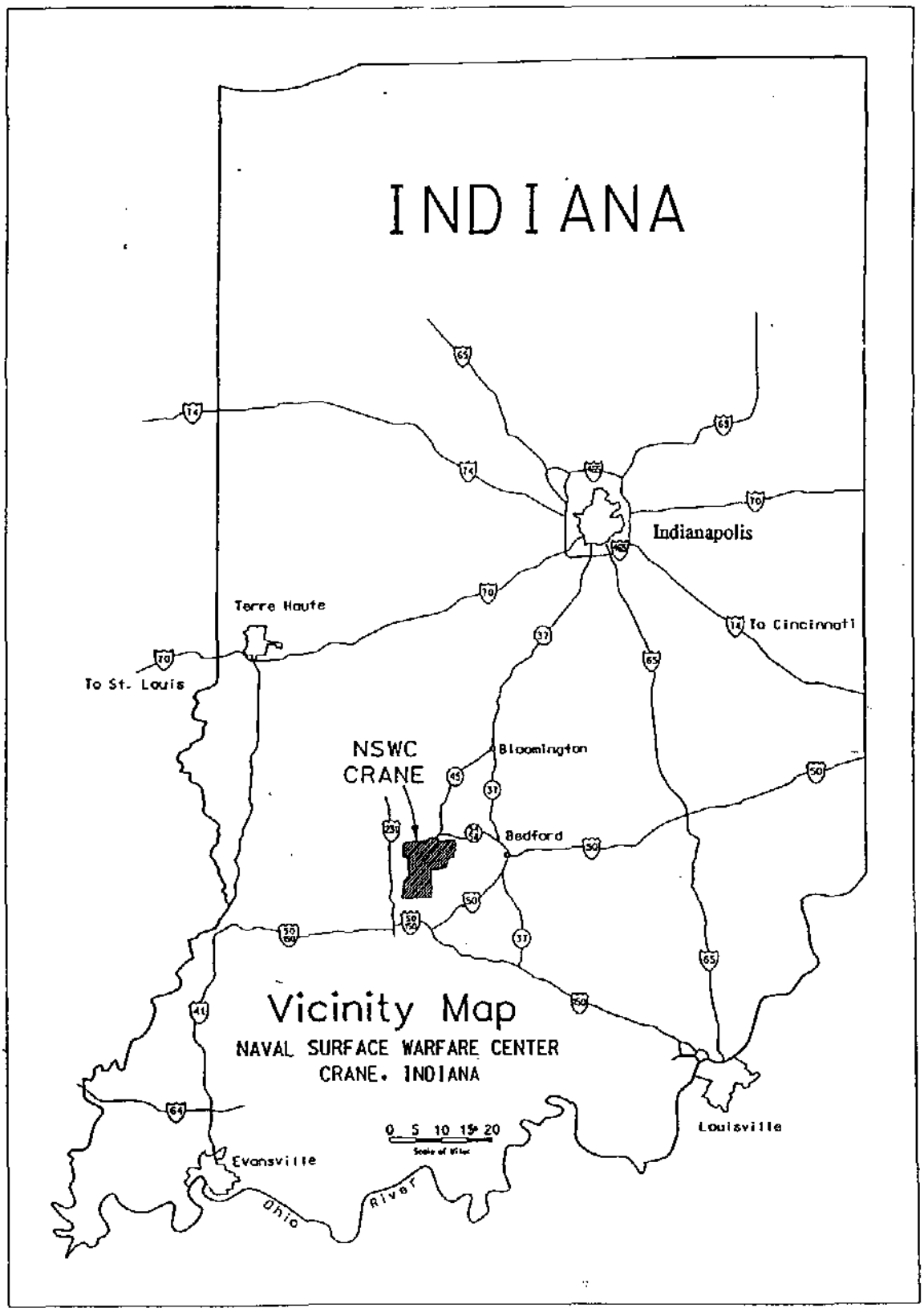


Figure 1. Location of NSWCC, Indiana

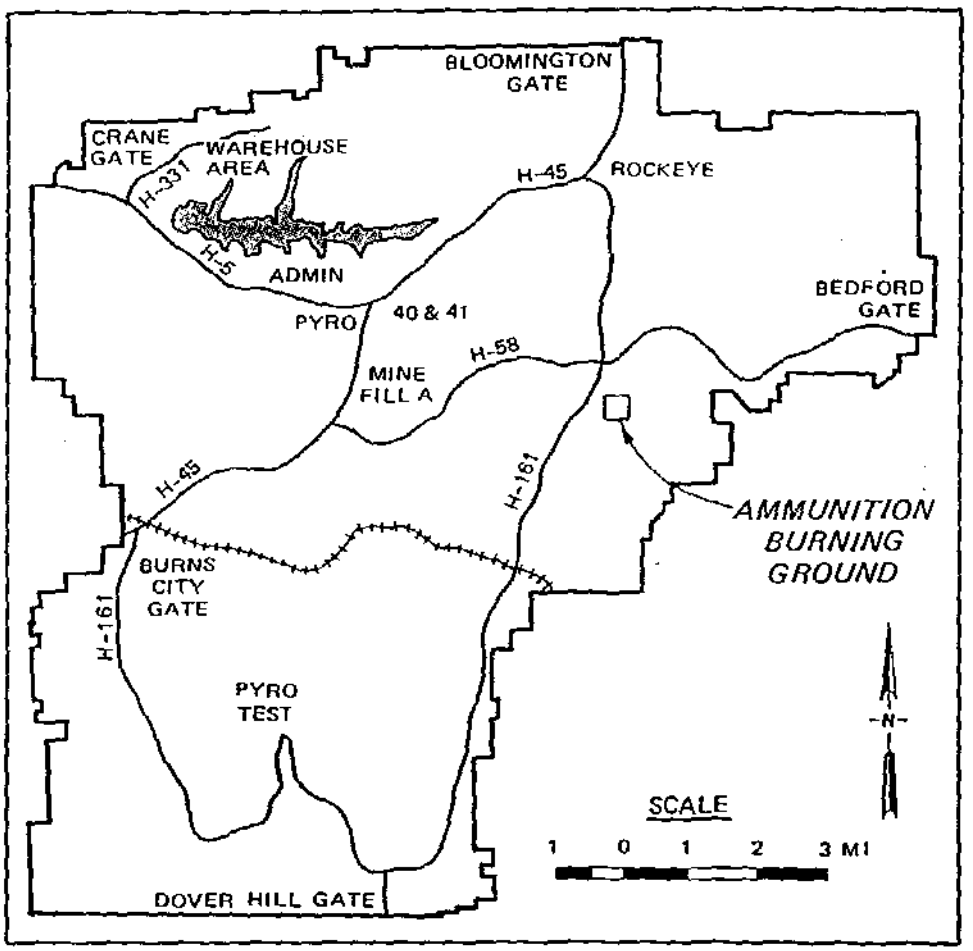


Figure 2. Location of ammuntion burning ground and rockeye sites

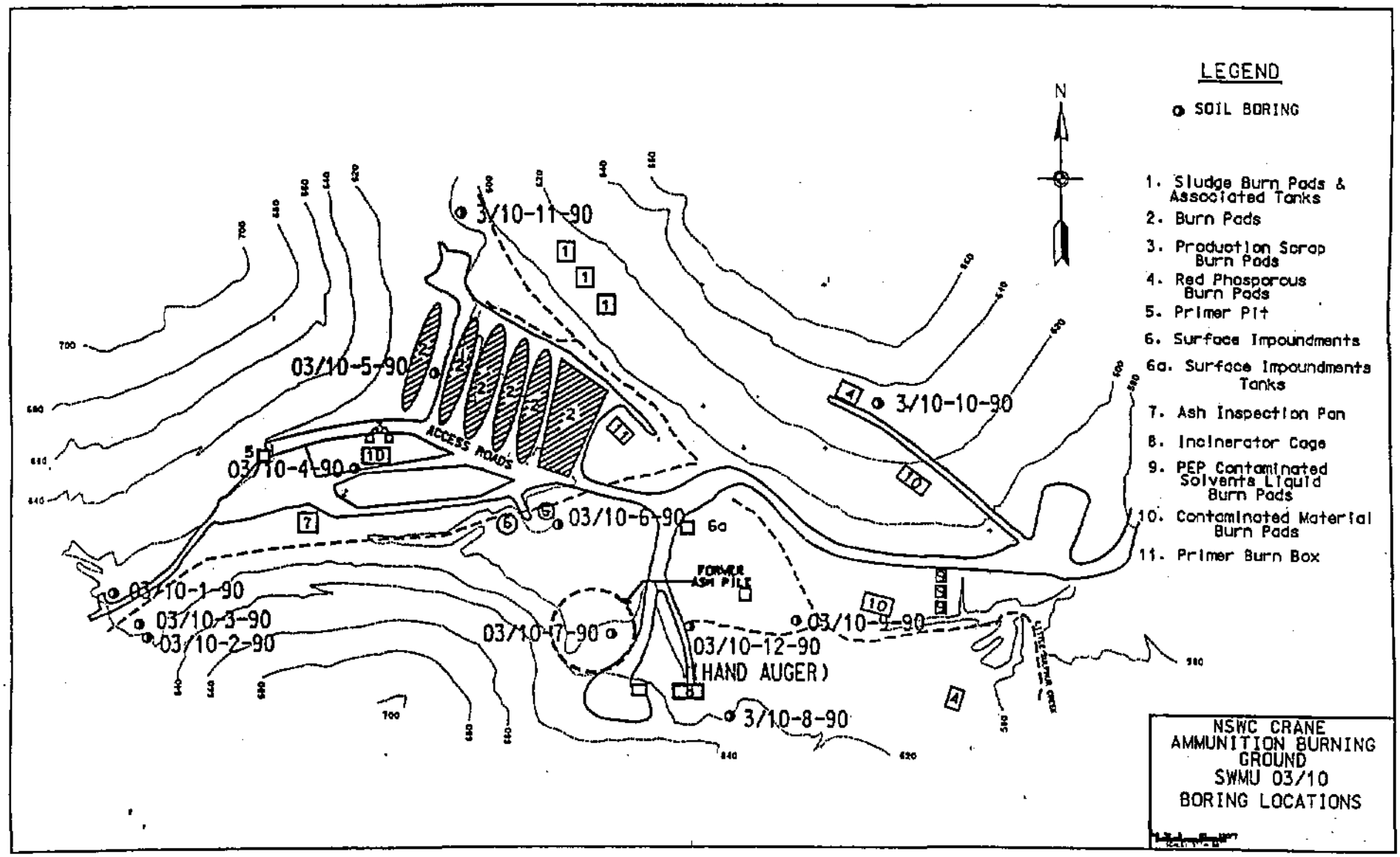


Figure 3. Ammuntion burning ground site soil boring locations.

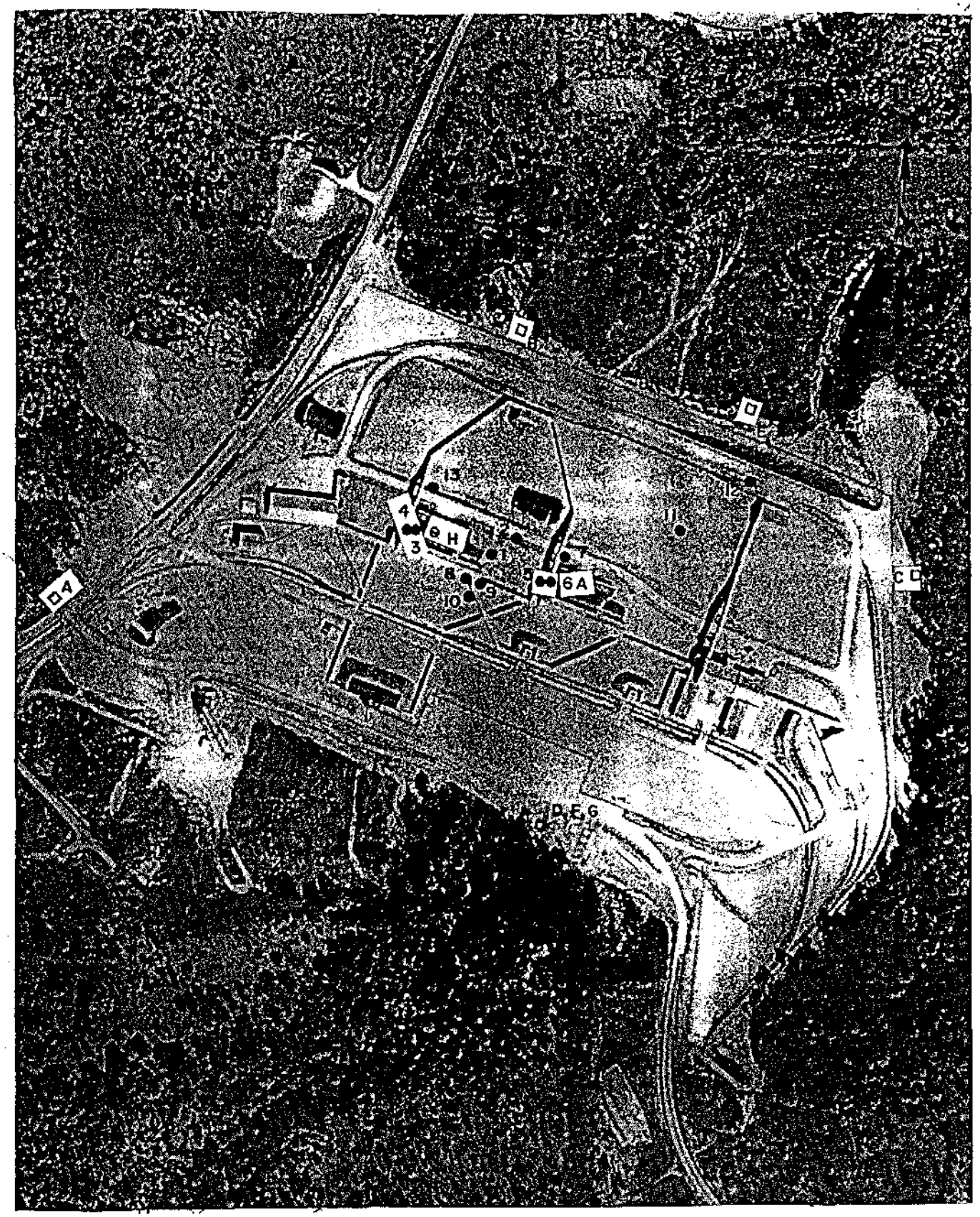


Figure 4. Rockeye site soil borings and surface sample areas locations.

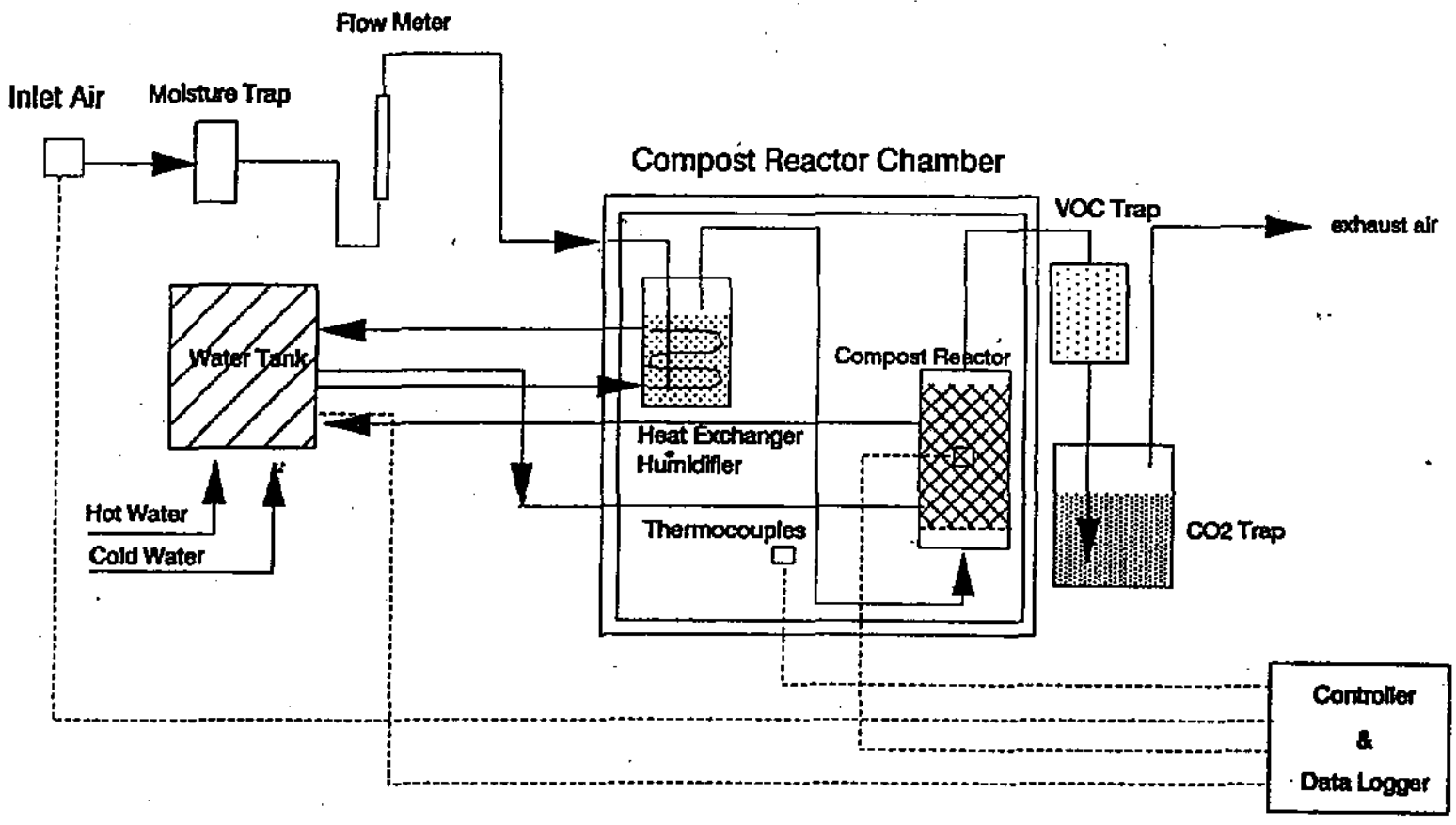


Figure 5. Schematic diagram of bench-scale batch compost reactor system.

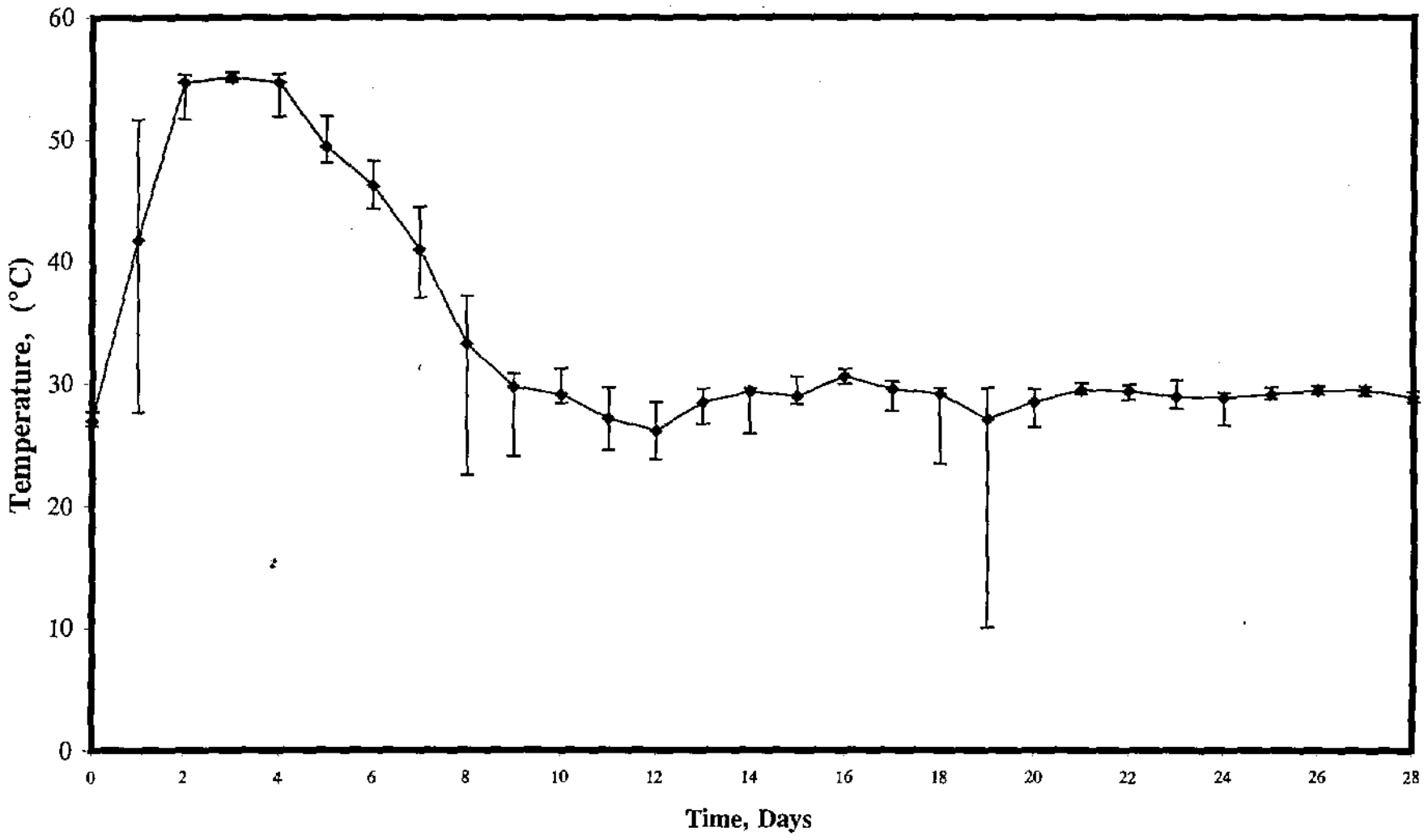


Figure 6. Mixture 7 maximum and minimum compost core temperature profile.

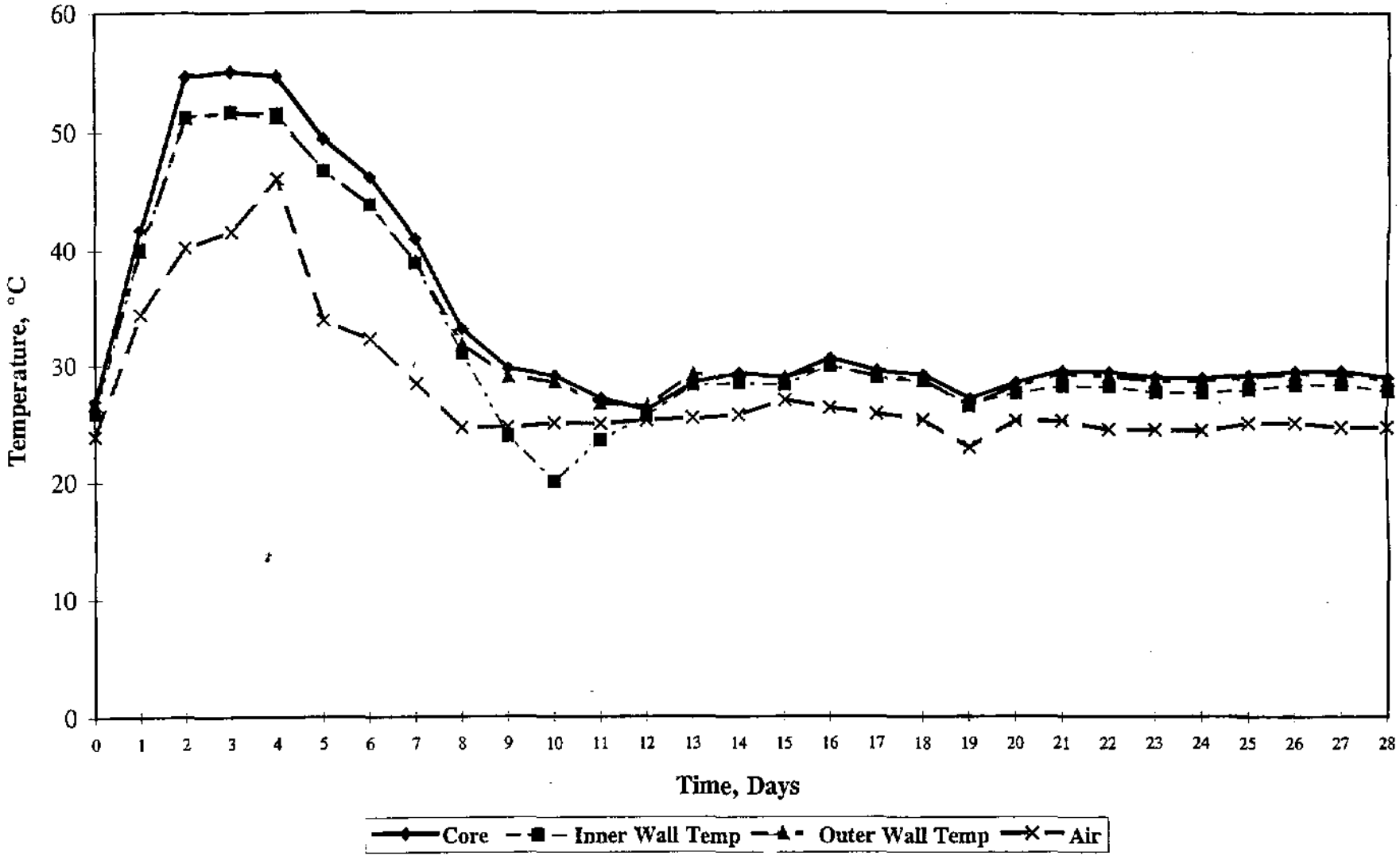


Figure 7. Mixture 7 temperature profile of various WACS II components.

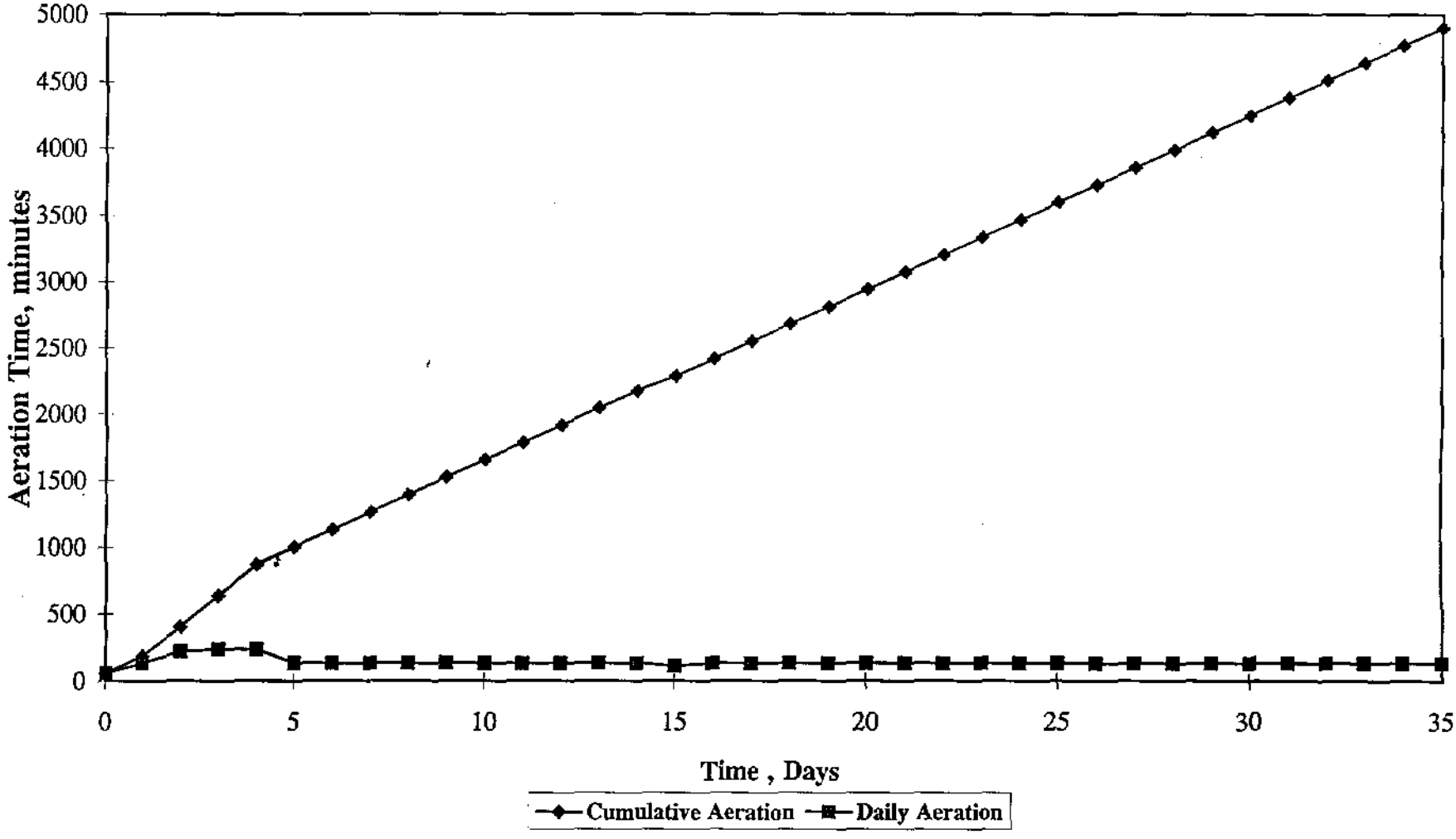


Figure 8. WACS II aeration times for Mixture 7.

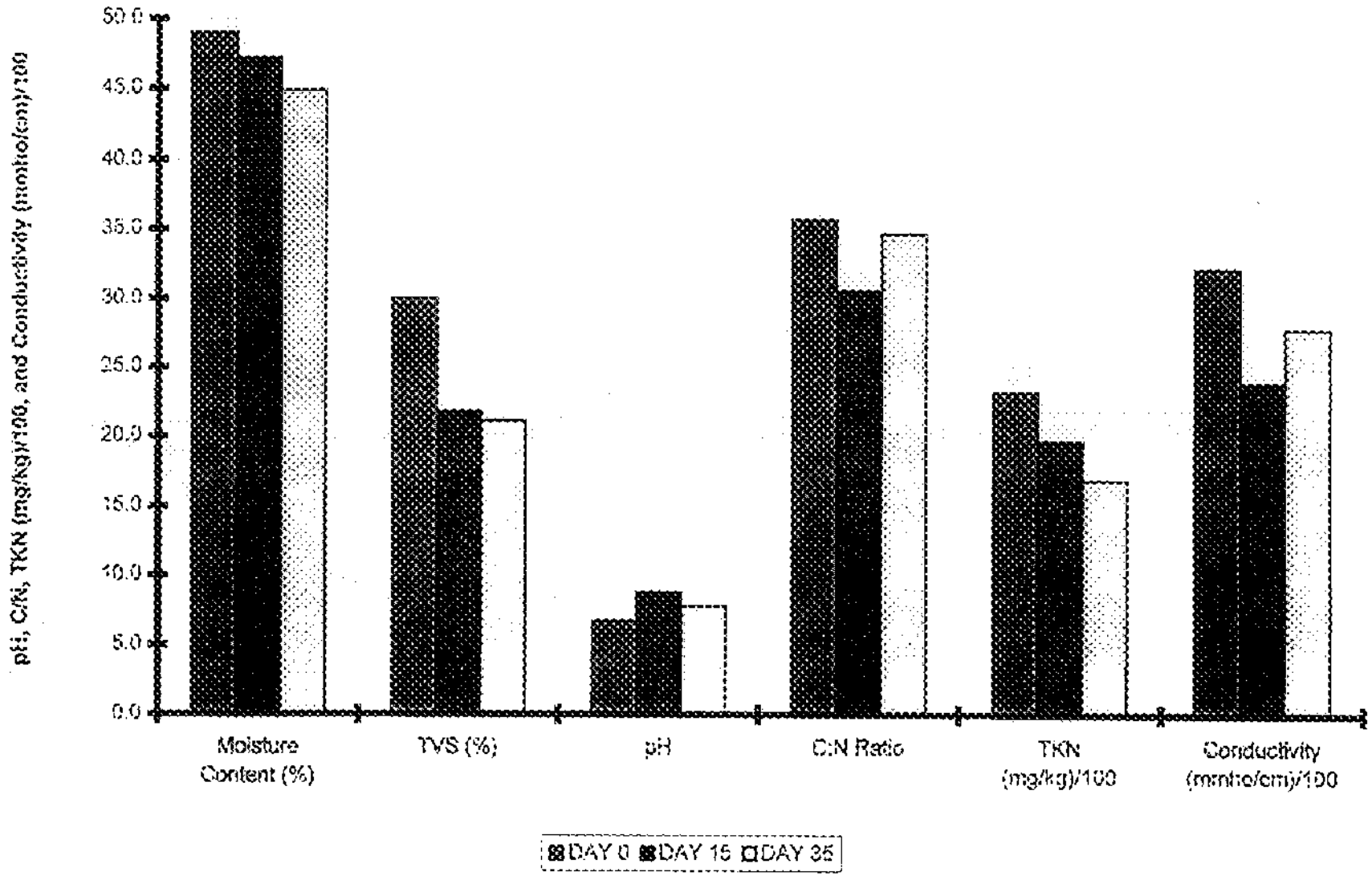


Figure 9. Physicochemical properties for Mixture 7.

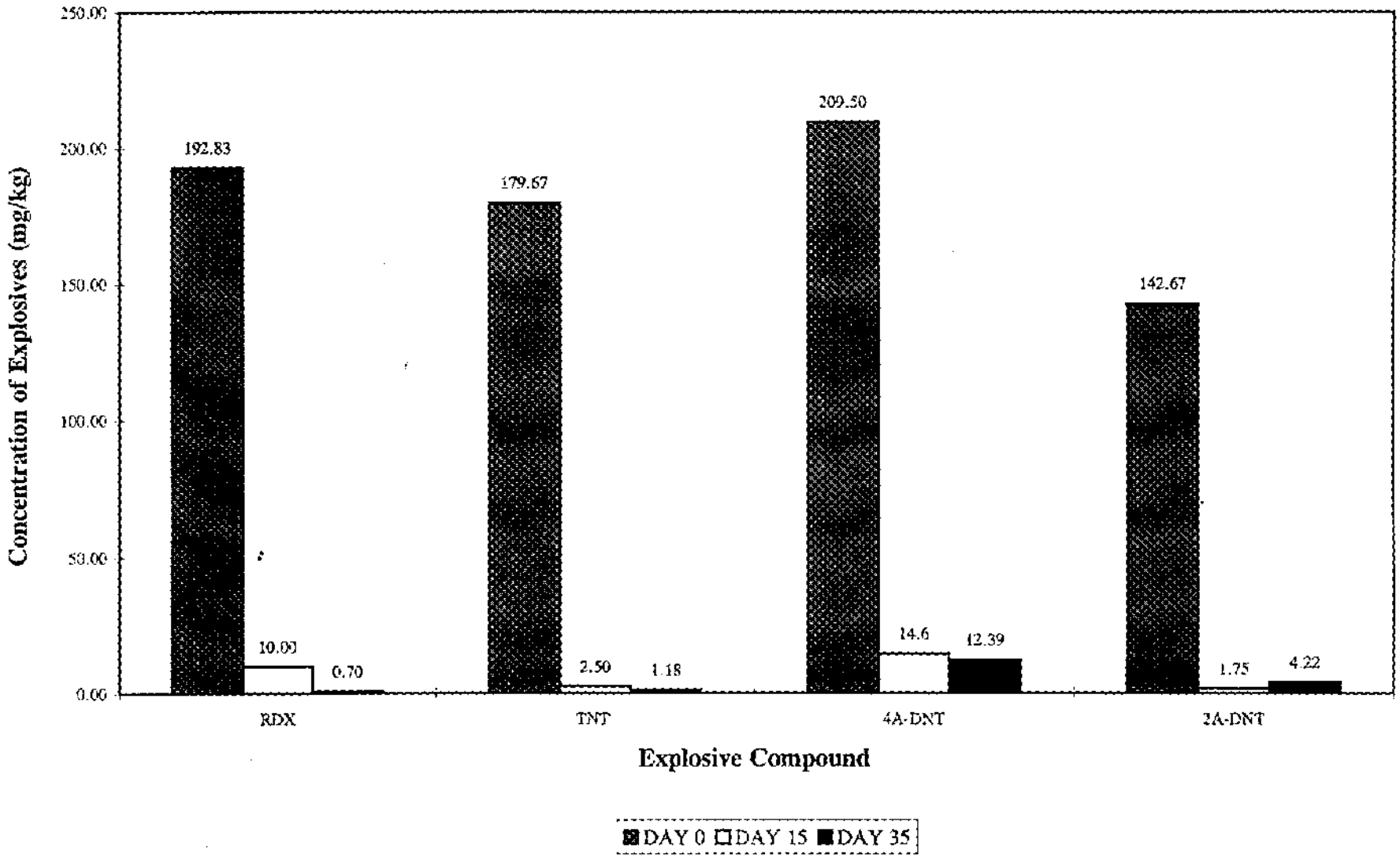


Figure 10. Explosive analysis results for Mixture 7.

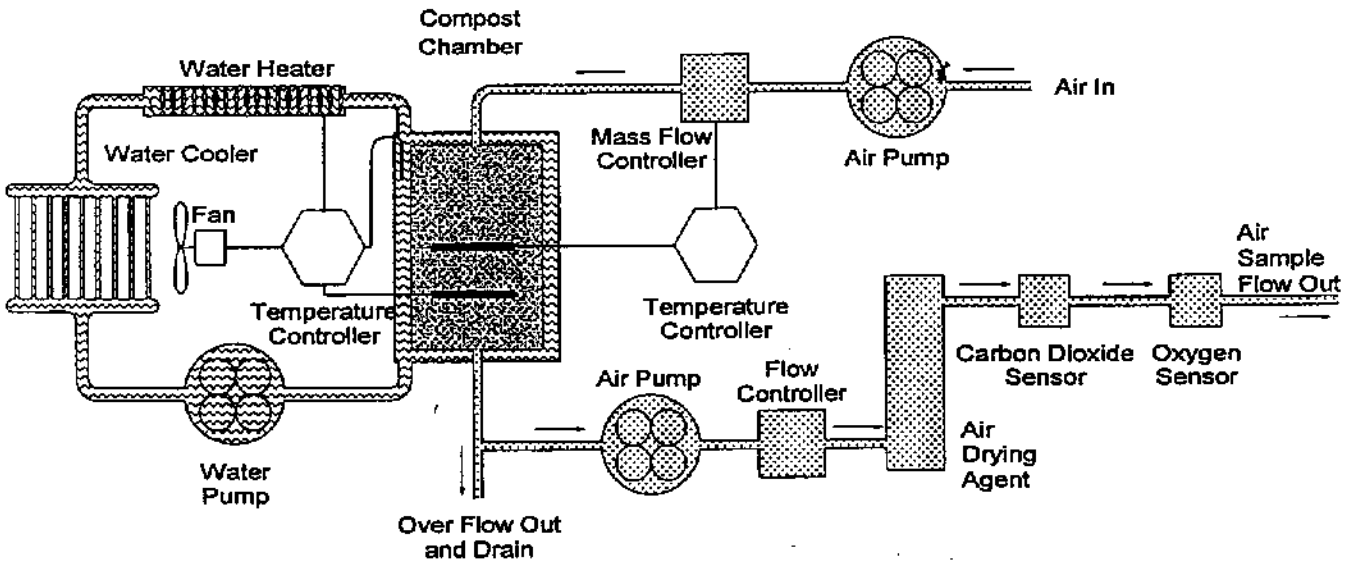


Figure 11. Schematic of Oxymax system with an adiabatic chamber.

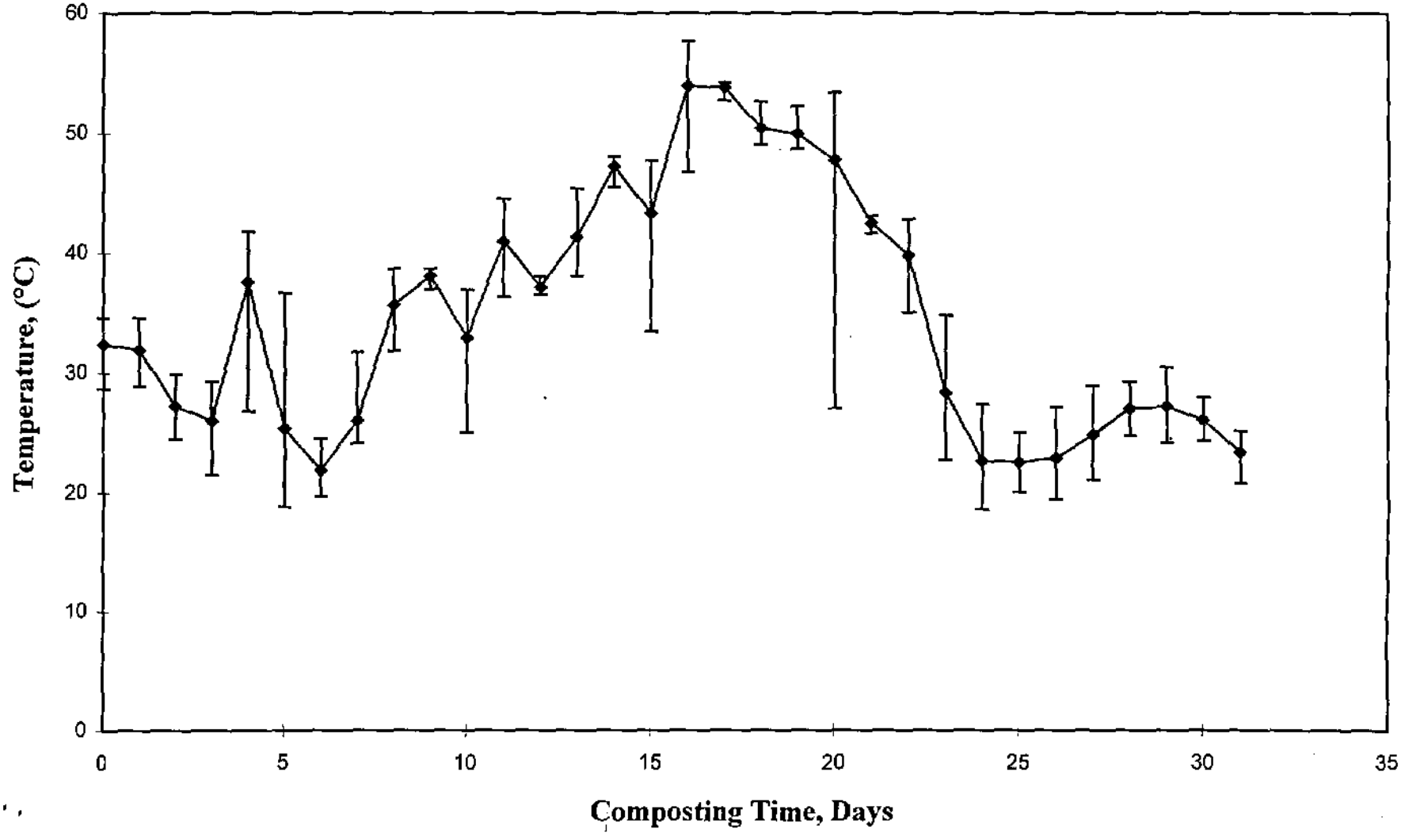


Figure 12. Mix 1 temperature profile.

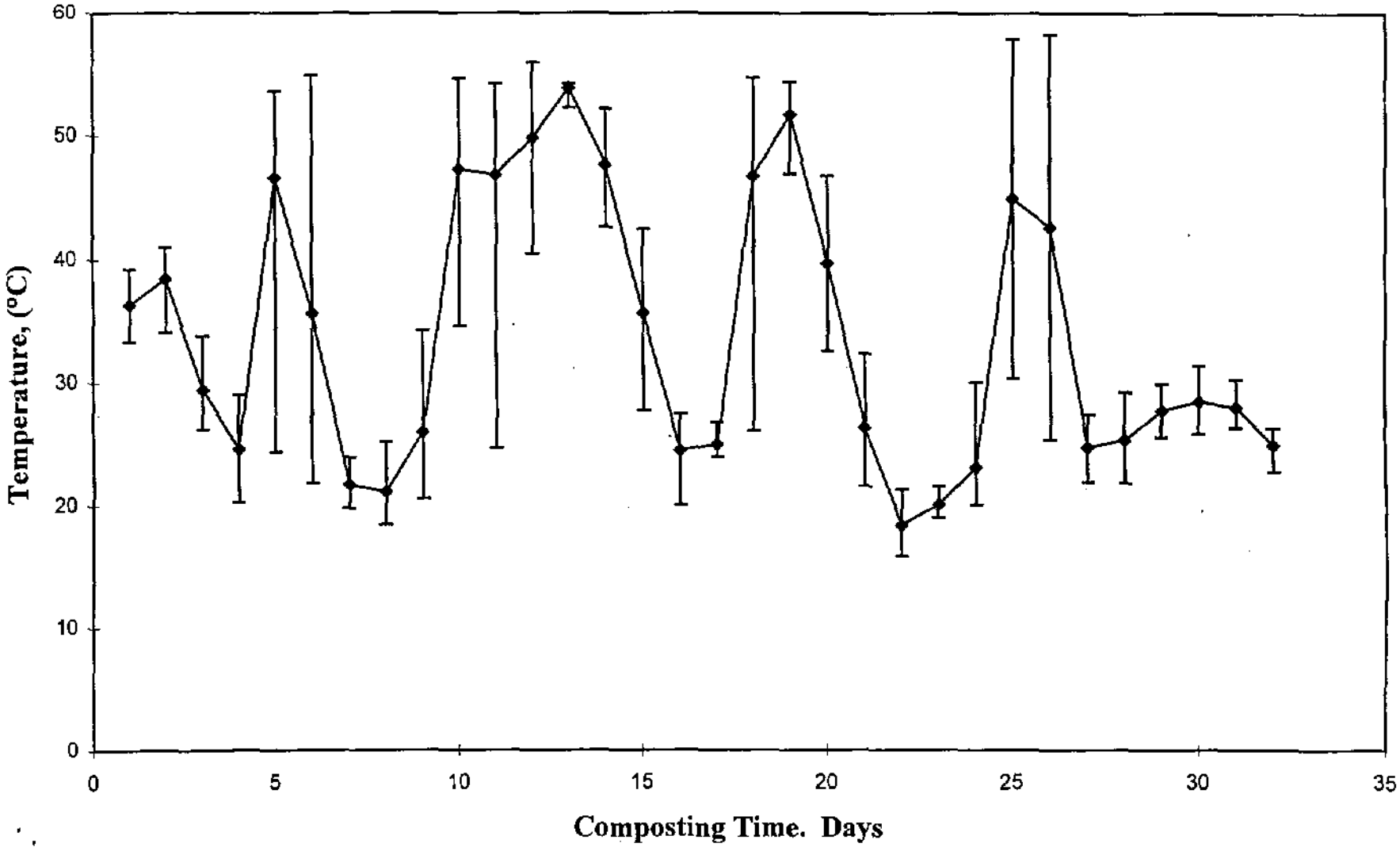


Figure 13. Mix 2 temperature profile.

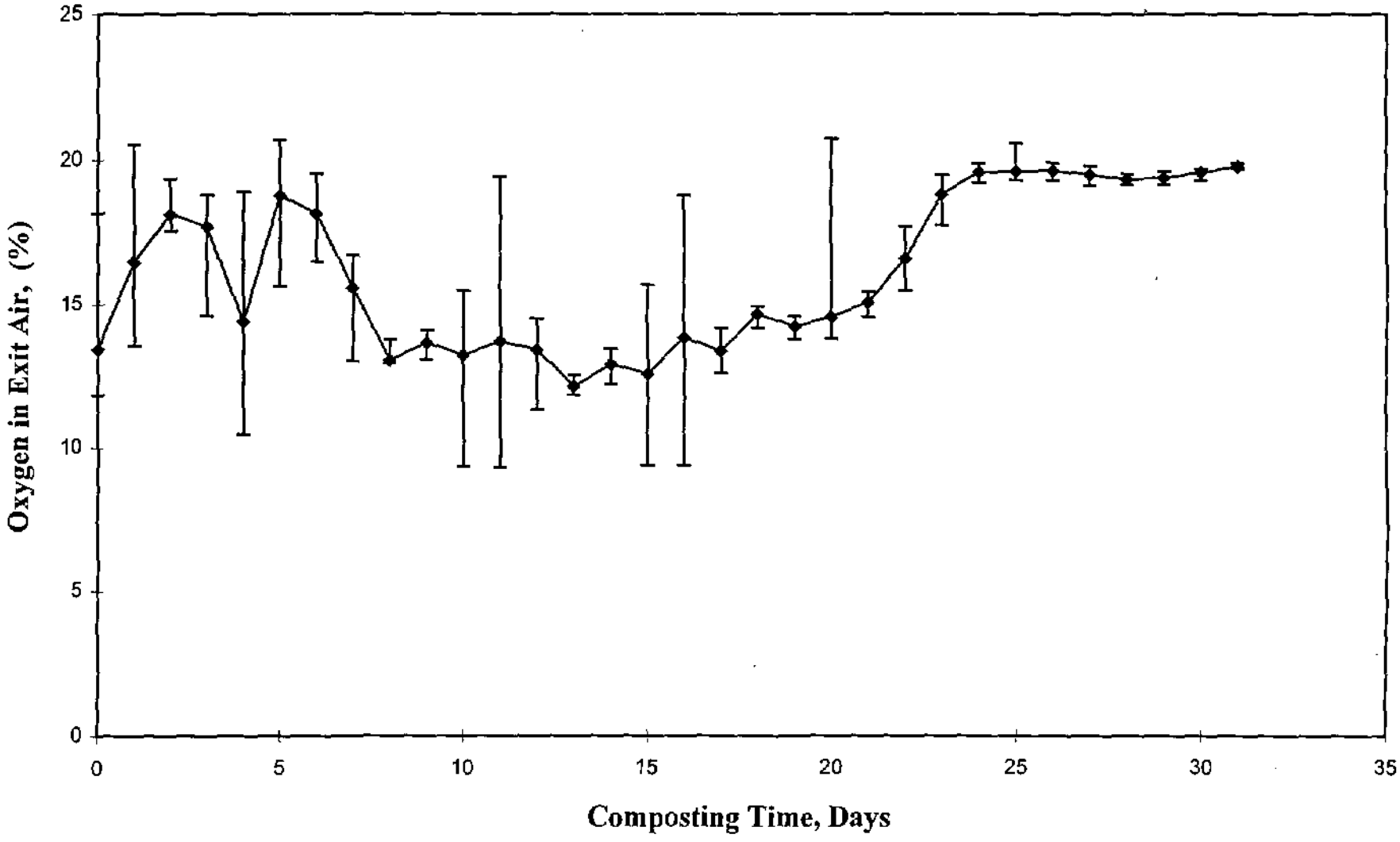


Figure 14. Mix 1 maximum and minimum oxygen in exit air profile.

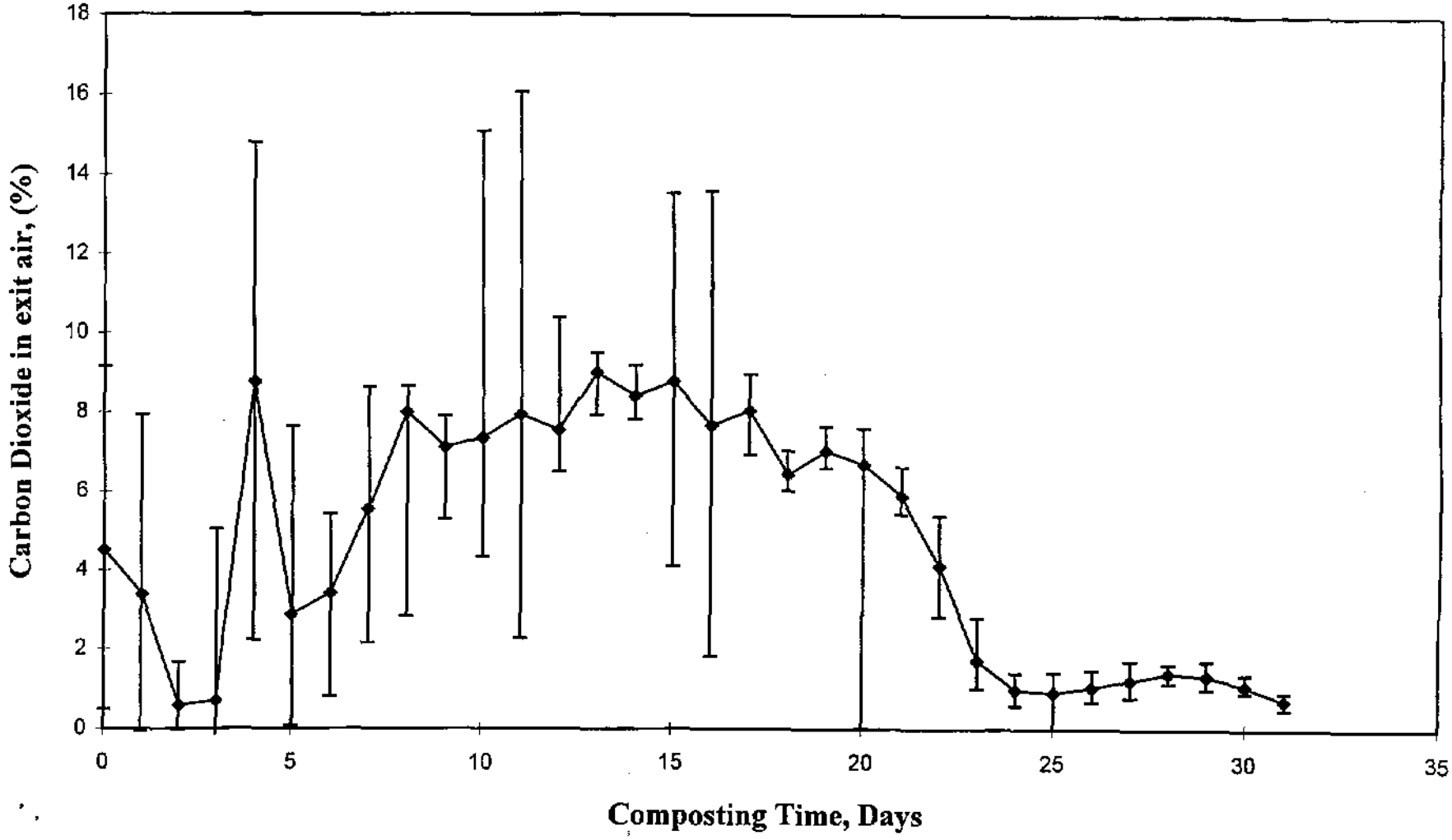


Figure 15. Mix 1 maximum and minimum carbon dioxide in exit air profile.

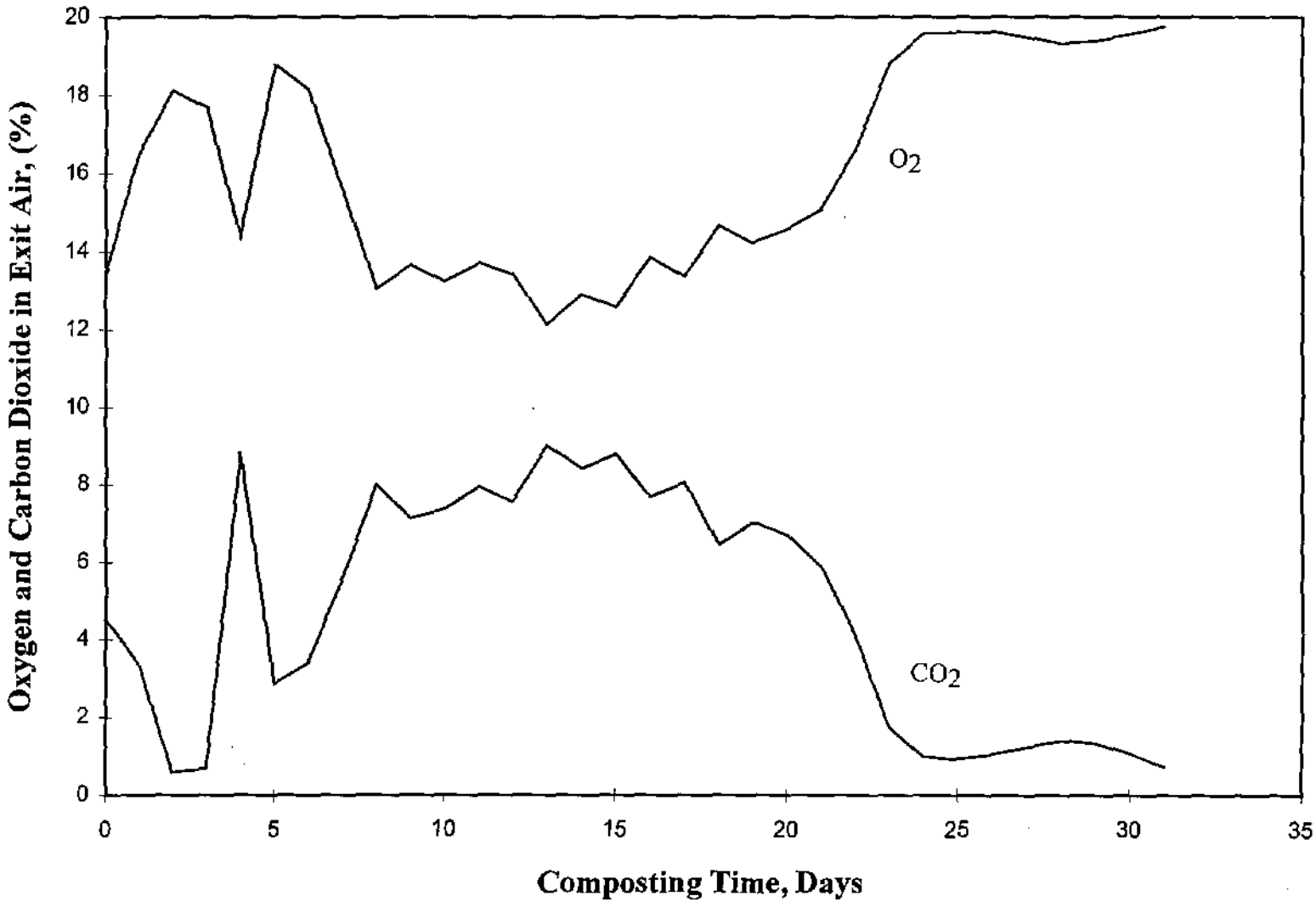


Figure 16. Mix 1 respiration rate during composting.

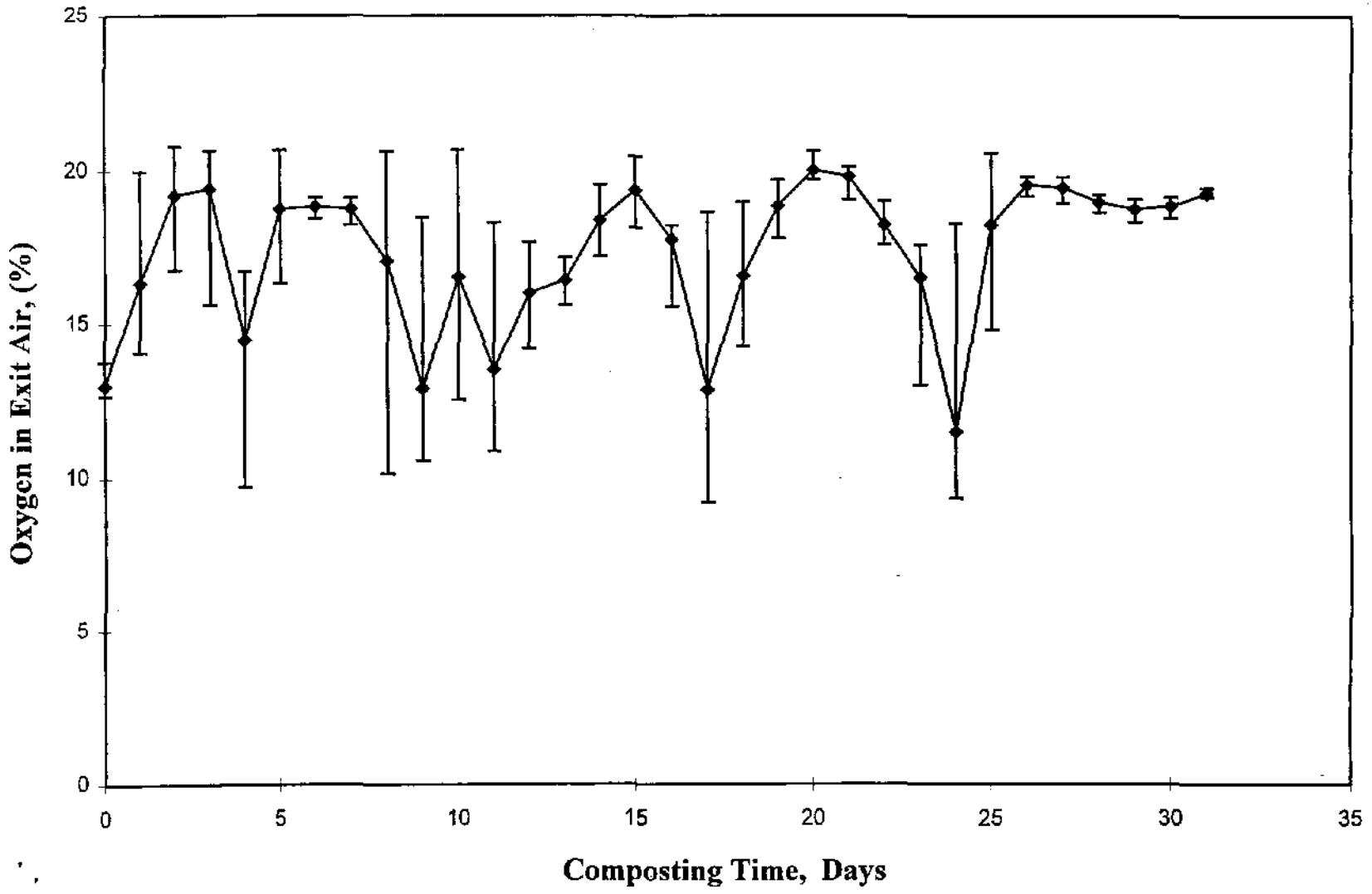


Figure 17. Mix 2 maximum and minimum oxygen in exit air profile.

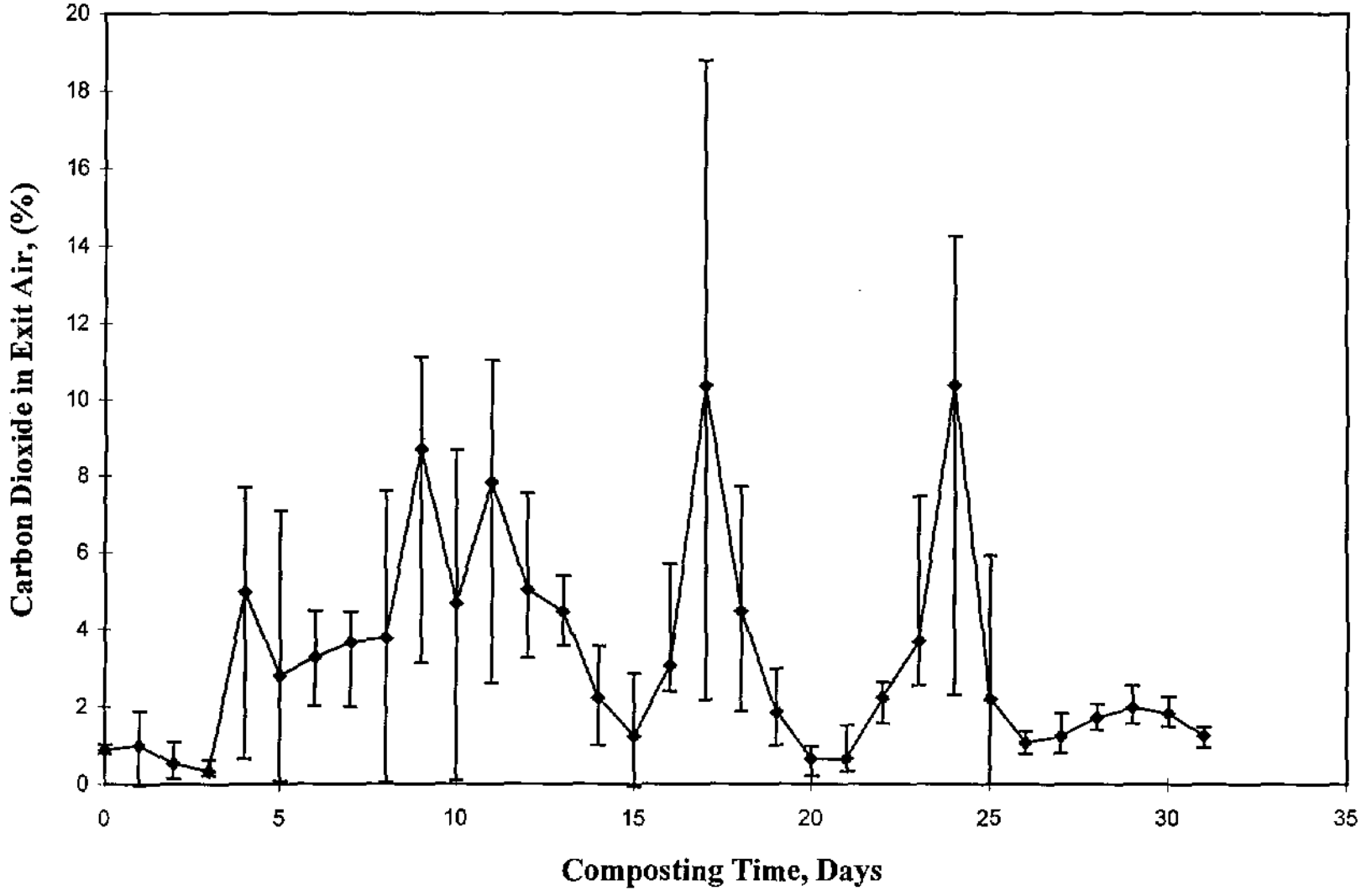


Figure 18. Mix 2 mzximum and minimum carbon dioxide in exit air profile.

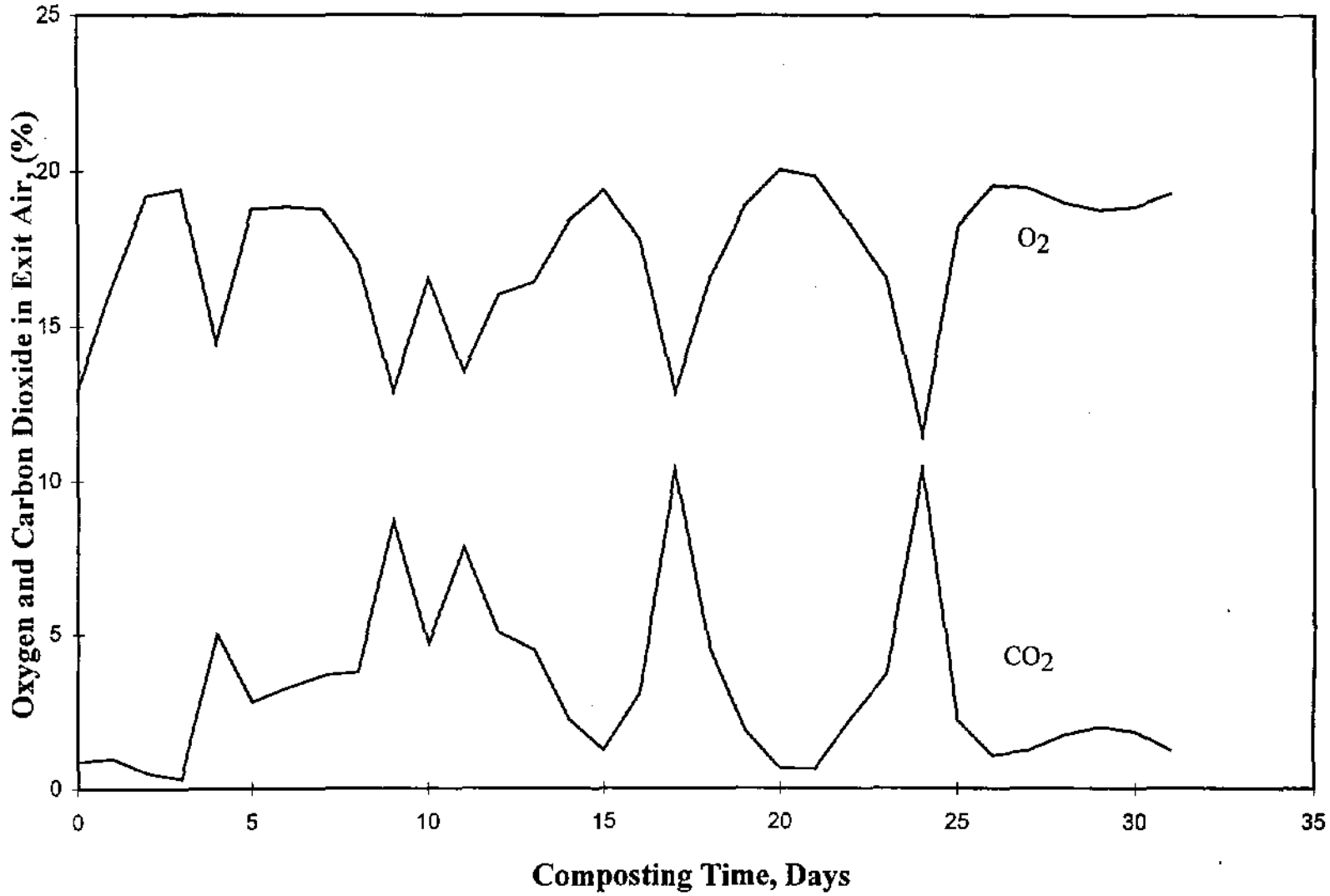


Figure 19. Mix 2 respiration rate during composting.

## Table 1
## Physical Characteristics of Crane's Soil

| Physical Properties | |
|---|---|
| Color | 2.5YR 4/3, Olive Brown |
| pH | 7.28 |

| Average Densities of Fractions (oven dried at 60°C) | |
|---|---|
| **Sample Description** | **Average Density, g/cc** |
| Bulk < 2.00mm, dry sieved | 2.59 |
| Bulk < 0.85mm, dry sieved | 2.60 |
| Bulk < 0.85mm, wet sieved | 2.63 |

**Sample Fractions**

| Dry-Sieve Analysis (2712.45g as-is, 2483.29g air-dried, 2368.89g Dry Wt.) | | | | |
|---|---|---|---|---|
| **Sieve Fraction** | **Raw Wt., g** | **Solids per 1 Gram Sample** | **Oven-Dried Wt. (Moisture Test)** | **Percent Dry Fraction** |
| >2.00mm | 12.97 | 0.9884 | 12.82 | 0.54 |
| 0.063 - 2.00mm | 2,151.50 | 0.9648 | 2,075.75 | 87.63 |
| <0.063mm | 290.38 | 0.9687 | 281.30 | 11.87 |
| Gain | 28.44 | --- | 0.98 | 0.04 |
| **Wet - Sieve Analysis (2822.95 g as-is, 2465.08g Dry Wt.), 14.84L rinse water** | | | | |
| >2.00mm | 113.06 | 0.8519 | 96.31 | 3.91 |
| 0.063 - 2.00mm | 1273.54 | 0.7556 | 962.29 | 39.04 |
| 0.0027 - 0.063mm | 238 g/L | 69 g/L | 1,023.96 | 41.54 |
| <0.0027mm | 5.35 g/L | 0 g/L | 0 | 0 |
| Loss | --- | --- | --- | 15.52 |

| Moisture Tests (oven-dried at 60°C) | | | | |
|---|---|---|---|---|
| **Sample** | **Initial Wt., g** | **Dry Wt., g** | **Percent Moisture** | **Percent Solids** |
| Bulk <2.00mm dry-sieved | 17.73 | 14.36 | 19.01 | 80.99 |
| Bulk <0.85mm dry-sieved | 51.03 | 48.79 | 4.39 | 95.61 |
| Bulk <0.85mm wet-sieved | 336.92 | 37.83 | 88.77 | 11.23 |

| Hydrometer Procedure | | | |
|---|---|---|---|
| **Time** | **Temp., °F** | **Hydrometer Reading** | **Reading Correction** |
| 0 hr | 86.0 | --- | --- |
| 40 sec | 86.0 | 25 | 28.6 |
| 2 hr | 81.5 | 6 | 8.7 |
| 24 hr | 77.9 | 3 | 4.98 |

| Percent (Silt + Clay) | Percent Sand | Percent Silt | Percent Clay (Coll + Noncoll) | Colloidal Clay | Noncolloidal Clay |
|---|---|---|---|---|---|
| 57.2 | 42.8 | 39.8 | 17.4 | 9.96 | 7.44 |

USDA Classification: Loam

**Table 2**
**Respirometric Result-Composition and Physicochemical Properties Of The Compost Mixtures**

| Mixture Number | Amendments and Bulking Agents | pH | Percent Moisture | C/N Ratio |
|---|---|---|---|---|
| 1 | Turkey Manure and Sawdust | 8.2 | 55.1 | 23 |
| 2 | Turkey Manure and Recycled Paper | 7.5 | 61.5 | 16 |
| 3 | Swine Manure and Sawdust | 7.2 | 55.7 | 39 |
| 4 | Swine Manure and Recycled Paper | 6.2 | 55.8 | 30 |
| 5 | POTW Sludge and Sawdust | 7.9 | 53.1 | 28 |
| 6 | POTW Sludge, Recycled Paper, and Sawdust | 7.2 | 63.8 | 414 |
| 7 | Cow Manure and Alfalfa | 7.7 | 63.9 | 70 |
| 8 | Swine Manure, POTW Sludge, Sawdust, and Recycled Paper | 6.3 | 55.0 | 93 |

* - All mixtures contain 20% soil (vol/vol).

**Table 3**
**Biodegradation Kinetic Coefficients of Compost Mixtures**

| Mixture Number | Total Oxygen Consumed (g) | Maximum OUR (g/d) | Degraded Organic-C (g) | Initial Organic-C (g) | Rate Coefficient ($d^{-1}$) | SBR ($d^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | 4.75 | 1.50 | 1.73 | 9.37 | 0.020 | 0.018 |
| 2 | 4.20 | 6.03 | 1.53 | 7.20 | 0.024 | 0.021 |
| 3 | 5.87 | 2.87 | 2.13 | 11.95 | 0.020 | 0.018 |
| 4 | 4.04 | 2.02 | 1.47 | 12.31 | 0.013 | 0.012 |
| 5 | 10.03 | 6.68 | 3.65 | 12.63 | 0.034 | 0.029 |
| 6 | 6.17 | 3.42 | 2.24 | 9.54 | 0.027 | 0.023 |
| 7 | 5.71 | 5.22 | 2.08 | 8.07 | 0.030 | 0.026 |
| 8 | 5.33 | 2.15 | 1.94 | 12.61 | 0.017 | 0.015 |

**Table 4**
**Result Of Explosive Analysis, Half-Live Calculations, And Degradation Ranking**

| Mixture Number | Explosive Results | | | | | | | | | | | | | | | Ranking |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TNT | | | RDX | | | HMX | | | 4A-DNT | | | 2A-DNT | | | |
| | *Initial Conc. (mg/kg) | Final Conc. (mg/kg) | Half-Lives (day) | *Initial Conc. (mg/kg) | Final Conc. (mg/kg) | Half-Lives (day) | *Initial Conc. (mg/kg) | Final Conc. (mg/kg) | Half-Lives (day) | *Initial Conc. (mg/kg) | Final Conc. (mg/kg) | Half-Lives (day) | *Initial Conc. (mg/kg) | Final Conc. (mg/kg) | Half-Lives (day) | |
| 1 | 1,054 | 0.2 | 0.83 | 121 | 2.8 | 1.84 | 3,913 | 1,180 | 5.78 | 146 | 5.3 | 2.09 | 45 | 5.7 | 3.35 | 4.0 |
| 2 | 1,140 | 1.6 | 1.05 | 163 | 1.6 | 1.49 | 5,797 | 3,880 | 17.26 | 168 | 7.5 | 2.23 | 57 | 1.8 | 2.00 | 5.0 |
| 3 | 2,747 | 10.7 | 1.25 | 184 | 0.3 | 1.05 | 5,620 | 3,320 | 13.17 | 33 | 6.1 | 4.09 | 18 | 2.2 | 3.28 | 5.0 |
| 4 | 1,897 | 0.9 | 0.91 | 164 | 0.3 | 1.07 | 5,420 | 3,260 | 13.63 | 153 | 2.5 | 1.69 | 94 | 1.6 | 1.71 | 2.8 |
| 5 | 828 | 0.4 | 0.90 | 121 | 0.3 | 1.12 | 3,743 | 2,310 | 14.36 | 194 | 3.0 | 1.66 | 54 | 7.0 | 3.39 | 4.2 |
| 6 | 925 | 1.6 | 1.09 | 152 | 8.7 | 2.43 | 5,607 | 4,700 | 39.29 | 124 | 18.3 | 3.63 | 50 | 6.3 | 3.35 | 7.0 |
| 7 | 975 | 0.8 | 0.97 | 186 | 0.3 | 1.05 | 6,227 | 3,710 | 13.38 | 230 | 2.6 | 1.55 | 57 | 2.1 | 2.09 | 2.8 |
| 8 | 996 | 0.5 | 0.92 | 99 | 2.2 | 1.82 | 3,510 | 3,250 | 90.05 | 67 | 6.1 | 2.89 | 29 | 0.6 | 1.82 | 5.2 |

* - average concentrations

**Table 5**
**Compost Composition of Mixture 7**

| Ingredients | Percent Volume | Wet Weight (g) | Percent Wet Weight | Percent Moisture | Dry Weight (g) | Percent Dry Weight | Free Air Space (%) |
|---|---|---|---|---|---|---|---|
| Cow Manure | 40 | 4,343.7 | 53 | 75 | 1,085.9 | 24 | |
| Alfalfa | 40 | 780.4 | 10 | 4 | 747.6 | 16 | |
| Soil | 20 | 3,068 | 37 | 9 | 2,782.7 | 60 | |
| | | | | | | | |
| Total | | 8,192.1 | 100 | | 4,616.2 | 100 | 65 |

**Table 6**
**Result of Explosives Analysis and Standard Deviation For Reactor 1 and Reactor 2**

| Day | TNT | | RDX | | HMX | | 4A-DNT | | 2A-DNT | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Avg. | SD | Avg | SD | Avg | SD | Avg | SD | Avg | SD |
| **Reactor 1 Explosive Concentrations, mg/kg** | | | | | | | | | | |
| 0 | 21,203 | 1,428 | 1,633 | 72 | 7,412 | 957 | 360 | 15 | 382 | 5 |
| 3 | 17,522 | 251 | 1,518 | 87 | 7,480 | 1,963 | 367 | 34 | 309 | 37 |
| 5 | 12,630 | 1,368 | 1,352 | 103 | 5,128 | 862 | 602 | 81 | 537 | 98 |
| 15 | 246 | 100 | 1,176 | 45 | 5,486 | 336 | 866 | 96 | 342 | 66 |
| 20 | 22 | 2 | 825 | 90 | 5,429 | 785 | 338 | 37 | 68 | 13 |
| 25 | 21 | 8 | 579 | 133 | 5,255 | 559 | 199 | 38 | 28 | 7 |
| 30 | 20 | 2 | 291 | 67 | 5,580 | 905 | 129 | 24 | 22 | 9 |
| **Reactor 2 Explosive Concentrations, mg/kg** | | | | | | | | | | |
| 0 | 9,599 | 1,312 | 906 | 113 | 6,950 | 1,743 | 644 | 122 | 304 | 89 |
| 3 | 8,641 | 730 | 1,313 | 57 | 7,516 | 1,091 | 807 | 11 | 789 | 29 |
| 5 | 2,130 | 175 | 1,223 | 107 | 8,107 | 531 | 1,292 | 140 | 1,141 | 144 |
| 15 | 22 | 2 | 839 | 41 | 5,066 | 587 | 420 | 18 | 56 | 9 |
| 20 | 23 | 2 | 751 | 106 | 6,105 | 229 | 319 | 35 | 51 | 10 |
| 25 | 17 | 1 | 240 | 27 | 5,361 | 250 | 88 | 9 | 21 | 4 |
| 30 | 17 | 1 | 107 | 14 | 5,003 | 722 | 55 | 3 | 13 | 1 |

**Table 7**
**Mutatox™ Results**

| Dilution | Rockeye Soil | Mixture 1 | | Mixture 2 | |
|---|---|---|---|---|---|
| | | Initial | Final | Initial | Final |
| 1:1 | Toxic | Toxic | 972 | Toxic | 2,176 |
| 1:2 | Toxic | Toxic | 5,077 | Toxic | 2,961 |
| 1:4 | Toxic | Toxic | 2,578 | Toxic | 1,282 |
| 1:8 | Toxic | 183 | 3,644 | Toxic | 199 |
| 1:16 | Toxic | 124 | 489 | Toxic | 51 |
| 1:32 | Toxic | 56 | 55 | Toxic | 13 |
| 1:40 | Toxic | 38 | 13 | 147 | 7 |
| 1:64 | Toxic | 37 | 8 | 25 | 7 |
| 1:80 | 54 | -- | 7 | 36 | 7 |
| 1:128 | 19 | -- | 6 | 6 | 4 |
| 1:160 | 12 | -- | -- | -- | -- |

Note: Value indicates range of mutagenicity.

**Table 8**
**Percent Mortality From The Earthworm Acute Toxicity Results**

| Dilution | Rockeye Soil | Mixture 1 | | Mixture 2 | |
|---|---|---|---|---|---|
| | | Initial | Final | Initial | Final |
| 1:1 | 100 | 100 | 100 | 100 | 50 |
| 1:2 | 100 | 100 | 100 | 100 | 0 |
| 1:4 | 100 | 100 | 0 | 100 | 0 |
| 1:8 | 100 | 100 | 0 | 100 | 0 |
| 1:16 | 100 | 100 | 0 | 100 | 0 |
| 1:32 | 100 | 0 | 0 | 0 | 0 |