July 1, 1993
LCMR Final Status Report - Summary - Research

I. REMEDIATION OF SOILS CONTAMINATED WITH SEMI-VOLATILES BY COMPOSTING WITH LEAVES - Waste 1

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A. LEGAL CITATION 12(a)

An appropriation of $110,000 was made to the Office of Waste Management (OWM) for a grant to the Minneapolis Community Development Agency (MCDA) to develop a treatment method for soils contaminated with semi-volatile compounds by composting with leaves. The study was conducted with the assistance of Braun Intertec Corporation staff and City of Minneapolis staff.

Funding for the project was approved by the Minnesota Legislature (M.L. 91, Ch. 254, Art. 1, Sec. 14, Subd.12(a)), as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Environment and Natural Resources Trust Fund.

The total amount invoiced for this project as a whole (as of July 1, 1993) was $110,000. The balance for this project as a whole (as of July 1, 1993) was $0.

B. COMPATIBLE DATA. Not applicable.

C. MATCH REQUIREMENT. $2,000

II. NARRATIVE

A. STATEMENT OF PROBLEM

Soils which are contaminated with petroleum products and solvents such as gasoline, diesel fuel, and creosote are being encountered on numerous redevelopment and other construction projects on old industrial or railroad sites. Many of these contaminants do not easily evaporate (volatilize) under ordinary temperatures, and are commonly categorized as semi-volatile compounds. Over time, these contaminants become part of the soil matrix and may need to be subjected to remediation (or cleaning) processes which typically use high temperatures to destroy the remaining compounds (incineration), or agitation to release the remaining compounds (land application).

Of particular importance is the classification of the semi-volatile compounds which are known as polynuclear aromatic hydrocarbons (PAHs). The concern for this classification is that many of the PAHs are known carcinogens and in certain quantities, create a public health concern. PAHs are universal products of the combustion of organic matter. Major sources of PAHs, in addition to petroleum leakage and spills, can be heat and power generation utilizing fossil fuels or refuse, uncontrolled burning of most materials, motor vehicle emissions, industrial processes, coal liquefaction and gasification, forest and prairie fires, and volcanic ash. From a chemical point of view, PAHs contain carbon and hydrogen with fused single and multiple benzene rings in linear, angular and cluster arrangements. The PAHs may also contain alkyl and nitro substituents or can be considered

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heterocyclic molecules with the substitution of an aromatic ring carbon with nitrogen, oxygen, or sulfur.

The drawbacks to the current remediation methods for semi-volatile-contaminated soils is they require large allotments of land and time (land application) or significant expenditures of capital and operating costs (incineration). Also, land application is feasible only if the semi-volatiles are in low concentrations, the soil is microbially active, and dilution will result in satisfactory resolution of the public health concerns. Incineration is often economically prohibitive due to the large volume of soil which is often encountered and the tipping fees which are charged. Some risk assessments have reported that soils contaminated with semi-volatile compounds may have relatively low environmental and health risks (especially for short-term exposure). As a result, it has been argued that it may not be cost-effective policy to use the limited existing incineration capacity on marginally hazardous materials when other methods of achieving soil cleaning maybe were appropriate.

One of the oldest naturally occurring processes on earth is the degradation of organic matter (such as yard waste) by microbial activity. Humans have learned to control and optimize this naturally occurring process, and generally refer to the process as "composting." Composting has been one of the alternative technologies which have been openly discussed for use in the cleanup of semi-volatile contaminated sites. This focus has come about because municipalities are pursuing composting as a means to dispose of large volumes of yard waste (namely leaves and grass clippings). Yard waste is banned from disposal in Minnesota landfills, resulting in a need for implementation of alternative waste reduction and disposal methods. Concern for the cost effectiveness of many of the disposal methods is an issue commonly shared by municipalities and developers of the sites, who are often experiencing budget and revenue constraints.

B. IMPORTANCE

Providing an additional approach to the available options for remediating semi-volatile compound contaminated soil at a site provides a greater range of flexibility in the decision process. By facilitating the cleanup of semi-volatile contaminated sites and ultimately the recycling of the property into inhabitable, tax producing property, the city environment becomes more sustainable.

C. EXTENT OF PROBLEM

The extent of semi-volatile soil contamination in the state of Minnesota is not known. To our knowldege, research to quantify or even qualify the total number of sites or the extent of contaminated soils has not been investigated by state or private industry. However, discoveries of properties contaminated with semi-volatile compounds is increasing in frequency. As old industrial properties are being redeveloped in an attempt to increase a communities' tax base and encourage job creation, property owners are being required to incur additional cost to remediate the site. Within the commercial banking and real estate industries, there is increasing awareness of the financial risks associated with ownership of contaminated soils and its potential liabilities.

III. OBJECTIVES

The objectives of the study are to: 1) assess the technical feasibility of using composting as a remedial technology for soils contaminated with PAHs; and 2) optimize conditions for composting to produce a usable end product from yard waste. It was the original intent of this study to evaluate a full spectrum of semi-volatiles and the effect which the composting process may have on their degradation. However, a source of semi-volatile compound contaminated soil was not available, and as a result, a PAH-contaminated soil was used. As previously indicated, PAHs are a commonly occurring group of the semi-volatile compounds and in certain quantities create a public health concern. The importance of focusing on PAHs is that they are also one of the more stable groups of the semi-volatile compounds. Their stability is due to their limited water solubility, requirement for large amounts of oxygen to initiate chemical degradation, and their diverse and complex chemical structure. In addition, some of the PAH compounds and their by-products (of metabolism) may be toxic to microorganisms. Should the results of the study identify the composting process as a method for achieving breakdown and distribution of the PAH molecule, it could be implied that most other semi-volatile compounds may react the same.

Recent data suggests that composting with organic materials (like yard waste) may be a valid remediation technology for treating PAH compounds in contaminated soil. Researchers have shown that various microorganisms that live in soil (bacteria and fungi) are able to degrade the 2- to 5-ring PAHs (Cerniglia, 1984; Alexander, 1981; DeRenzo, 1980; Epstein and Alpert, 1980; and Cerniglia and Heitkamp, 1989). The degradation of organic materials (like PAHs or yard waste) by microorganisms is called "biodegradation." Substantiating this, the biodegradation of PAHs (2- to 5-ring) in soils has been reported in the laboratory (Park et al., 1990) and in sediment in a marine environment (2- to 3-ring PAHs) (Lee et al., 1978). Because composting involves the biodegradation of organics under conditions that are managed to facilitate biodegradation, it was assumed that the composting process could facilitate the biodegradation of PAH by microbial activity. Recently, pilot studies using soils contaminated with low level petroleum hydrocarbons combined with a mixture of leaves in static piles (Braun Intertec, 1991) and with a mixture of manure and wood chips using aerated static piles resulted in data which indicated that remediation had occurred (Kamnikar, 1992).

If composting is effective at remediating PAHs in soil, composting PAH contaminated soil may offer significant economic and technological advantages over incineration and land application. The composting process can be controlled, is more expedient, may break down a broader range of compounds, requires less space, and should produce a usable end product when compared to land application. It is assumed that the composting process may be significantly less expensive than incineration, though a full life cycle cost analysis, comparing both approaches, should be completed to verify such claims.

Presented in this section of the report are the procedures, budget, timeline, results and discussion (status), benefits, and costs for each objective (Sections A and B, respectively). The conclusions, and recommendations for the project as a whole are presented in Section IV (Evaluation). Also provided in this document are a discussion of future needs (Section IV), related current and previous work (Section V), project team qualifications (Section VI), reporting requirements (Section VII), and references (Section VIII).

A. Objective 1: PAH REMEDIATION

A.1. Narrative.

The primary purpose of this project was to assess the technical feasibility of using composting to remediate PAHs in contaminated soil. Assessment of feasibility was expressed in terms of the completeness and rate of degradation of extractable PAH compounds under the composting conditions of the study. A cost benefit or life cycle cost analysis and an evaluation of PAH fate was not part of the scope of this project. A literature search, however, was conducted in conjunction with this study and inferences were made as to the mechanisms influencing PAH degradation and fate.

Biodegradation sometimes raises concerns because, for specific classifications of compounds such as organophosphorus pesticides, biodegradation can result in the formation of compounds more toxic than the original contaminant. This, however, is not the case with the PAHs. Despite their diversity, the PAHs are biodegraded in the presence of oxygen to one of three common intermediates (catechol, protocatechuic acid, or gentisic acid), none of which are considered toxic or carcinogenic. The bacterial degradation of the PAHs normally involves the formation of a *cis*-dihydrodiol followed by a diacid. Eukaryotic organisms such as the fungi oxidize aromatics by forming a *trans*-

dihydrodiol (Cerniglia, 1984). These compounds are not normally considered toxic or carcinogenic. PAHs containing four or more condensed rings are not easily biodegraded, but may be cometabolized or cooxidized in the presence of more easily degraded compounds (Cerniglia and Heitkamp, 1989; Keck et al., 1989). Degradation of PAHs containing substituents such as nitro, chloro, or bromo requires that one or more of the substituents be replaced by a hydroxyl group prior to oxidation of the aromatic ring. Complete mineralization of the PAH molecule produces compost, carbon dioxide and water.

A concern raised with regard to composting semi-volatile compounds for the purpose of remediation of these compounds is that the heat and agitation associated with the composting process may cause the contaminants and their metabolites to be volatilized at levels that would require treatment. Although limited, research on the fate of PAHs indicates that the 2- and 3-ring PAHs are susceptible to volatilization (Lee et al., 1978; Park et al., 1990), whereas the 4- and 5-ring PAHs are predominantly biodegraded (Park et al., 1990), abiotically degraded (Lee et al., 1978), or mineralized (Xiujin and McFarland, 1991). The team of Lee et al. (1978) evaluated the fates of 2- to 5-ring PAHs added as a crude oil dispersion to controlled ecosystem enclosures suspended in Saanich Inlet, Canada. They noted that both biodegradation and volatilization were the primary removal processes for the 2- and 3-ring PAHs (with biodegradation being significant for naphthalene) and that abiotic processes were responsible for the decrease in concentration of the 4- and 5-ring PAHs. The group of Par et al. (1990) evaluated the fate of fourteen 2- to 5-ring PAHs in two soils with regard to interphase transfer potential and mechanisms of treatment under unsaturated laboratory conditions. They concluded that biodegradation accounted for the predominant loss of the 2- to 5-ring PAHs studied and noted that volatilization was a significant mechanism for 2-ring PAHs. Xiujin and McFarland (1991) using mass balance considerations noted that the enhanced removal of a 5-ring PAH (benzo(a)pyrene) in a compost microcosm reactors using soil enriched with a microorganism (Phanerochaete chrysosporium) resulted in mineralization of most of the contaminated carbon.

A.2. Procedures.

General. The field study began on June 1, 1992 and concluded 21 weeks later on October 20, 1992. Five static piles were constructed to be about 25 cubic yards each of a varied ratio of soil contaminated with 2- to 4-ring PAHs and yard waste. The ratios were varied to enable an assessment of the affect which soil ratio has on the composting conditions. A source of nutrients in addition to yard waste (such as manure) was not used in order to limit the number of study variables. To lessen the potential contribution of volatilization, it would have been desirable to use a soil contaminated with 4, 5 and 6-ring PAHs which do not readily volatilize as do the 2-and 3-ring PAHs. Such a source, however, was not available for use in the study.

Following construction, the piles were sampled for chemical analyses to establish initial experimental conditions and form the baseline for analyses to evaluate the degradation of the PAH contaminants. Sampling of the piles for chemical analyses was conducted periodically throughout the field study to monitor the degradation of the contaminants or the composting conditions of the piles. Temperature and oxygen content of the piles were also regularly recorded to monitor the composting condition of the piles. To maintain the composting process, the piles were frequently (twice per week) watered and turned.

The complexity of operating conditions for this study were partly determined by limited funds. A small-scale pilot study conducted utilizing low technical composting processes was employed. In-field process equipment used included:

- a front-end loader (to form and turn the piles);
- a water truck (to add moisture to the piles);
- a mercury thermometer and a Gastech meter (to monitor the piles); and
- a hand-auger (to sample the piles for chemical analyses).

Because of the concern for introducing contaminants from off-site sources, all equipment used was dedicated to this project.

Throughout the study, City of Minneapolis (City) staff dedicated to the project operated the front-end loader and the water truck, and Braun Intertec staff dedicated to the project conducted the monitoring and sampling, and directed the turning and watering of the piles. These activities were conducted on the Tuesday and Friday of each week between the time periods of 7:00 a.m. and 9:00 a.m..

Samples collected for chemical analyses were placed in clean, labeled, laboratory-supplied bottles, placed on ice to preserve the samples, and transported to the Braun Intertec laboratory located in Eden Prairie, Minnesota according to Braun Intertec chain-of-custody procedures. All analyses were performed using U.S. EPA or other recognized standard procedures. A quality control assessment of the data has been conducted prior to release and all quality control guidelines have been met.

Site Description. The site used to conduct the field study is a former railroad yard located in southeast Minneapolis, Minnesota. The site is presently owned by the City of Minneapolis and is used for temporary storage of materials. The site is secured and bituminous-surfaced with a slight grade (1 to 2 percent slope). The site did not require preparation other than the clearing of debris.

Feedstock Description.

The Soil. The PAH-contaminated soil used for this study was excavated from a former bulk petroleum storage site located within 1/4 mile of the study site. The soil was excavated and hauled to the site on May 28, 1992 where it was stockpiled in one pile. The soil consisted of medium-grained silty sand and clayey sand fill, with some demolition debris consisting of rocks and bricks.

On June 1, 1992, the large demolition debris were hand-sorted out of the soil. The soil was then mixed with itself until it appeared homogenous and then formed into a pile using the front-end loader. The soil was not shredded or otherwise reduced in particle size, as a shredder was not available for use in the study.

A representative sample of the prepared soil was then collected (June 1, 1992) and analyzed to determine contaminants and suitability for use in the study. The parameters analyzed and results for the soil are summarized in Table 1.

Table 1: Soil Feedstock Chemical Characterization
(June 1, 1992)

Analyses (Method)	Compounds Detected	Concentration (mg/kg)
base/neutral extractables (GC)	naphthalene (2-ring) 2-methylnaphthalene (2-ring) fluorene (2-ring) acenaphthene (2-ring) phenanthrene (3-ring) fluoranthene (3-ring) pyrene (4-ring) n-nitrodoiphenylamine	47 2.9 7.1 4.9 17 4.4 8.8 6.9
RCRA metals (TCLP)	barium lead silver arsenic (total)	1.2 0.15 0.03 5 μg/L
VOCs (GC)	(see laboratory report for individual compounds)	51.2 (total)
PCBs (GC)	none detected	none detected

Analytical results of the soil sample indicated total PAH compound concentrations of 92.1 mg/kg, total other semi-volatile compound concentration of 6.9 mg/kg, total VOC concentrations of 51.2 mg/kg, and non-hazardous levels of metals (arsenic, barium, lead, and silver). The laboratory report dated July 20, 1992 is provided in Appendix A. It was assumed that PAH compound concentrations at this level (92.1 mg/kg total) would be high enough to allow for the degradation to be evaluated without being masked by the variability inherent in PAH analyses at low concentrations.

The Yard Waste. The yard waste used for the study was from the first run of street collection conducted by the City during the fall of 1991 and consisted predominantly of leaves. The yard waste was stored uncovered at the site in one pile for use in the study the following spring. By spring of 1992, only the upper 6 inches of the material appeared to not have undergone decomposition. On June 1, 1992, the surface of the pile was scraped down to a depth of approximately 6 inches. The scraped material was thoroughly mixed with itself, and then formed into a second pile using the front-end loader.

A representative sample of the second pile was then collected (June 1, 1992) and analyzed to determine contaminants and suitability for use in the study. In addition to establishing the baseline soil conditions for this study, this analysis is also of importance since studies have shown that street collected yard waste can have significant metal concentrations. Of special concern are the metals lead and chromium. The parameters analyzed and results for the yard waste are summarized in Table 2.

Table 2: Yard Waste Feedstock Chemical Characterization (June 1, 1992)

Analyses (Method)	Compounds Detected	Concentration (mg/kg)
base/neutral extractables (GC)	phenols and benzoic acid	57.4 (total)
RCRA metals (TCLP)	barium	1.1
PCBs (GC)	none detected	none detected

Analytical results of the yard waste sample indicated no detectable PAHs, total other semi-volatile compound concentrations of 57.4 mg/kg, and one metal (barium). No other RCRA metals were detected. The laboratory report dated July 20, 1992 is provided in Appendix A.

Static Pile Description. Following preparation and sampling, the soil pile and the yard waste pile were watered using the water truck until they appeared wet to the touch. The front-end loader was then used to combine the soil and the yard waste into five static piles of approximately 25 cubic yards each, as described below:

Static Piles	Yard Waste/Soil Ratio (volume)
A	100:0
B	70:30
C	50:50
D	30:70
E	0:100

Piles A and E served as controls and piles B, C, and D were varied to enable an assessment of the affect which soil ratio has on the composting conditions.

Each pile was again watered using the truck, lifted and dumped three to five times with the loader to mix the materials and then reformed with the loader into static piles. Per Minnesota Pollution Control Agency (MPCA) recommendations for composting yard waste (Worth, 1992), each static pile measured 7 feet in height and twice its height in width (about 14 feet). To reduce the volume of materials that would need to be managed, a length equal to the width was selected, producing piles that were conical in shape.

To establish initial experimental conditions and form the baseline for analyses to evaluate the degradation of PAHs, a representative sample from each static pile was collected (June 1, 1992). The parameters analyzed and results for the static piles are summarized in Table 3.

Table 3: Static Pile Chemical Characterization (June 1, 1992)

Analyses (Method)	Compounds Detected (concentration in mg/kg)		
base/neutral/acid extractables (GC)	naphthalene (2-ring)	Pile A	-
		Pile B	2.2
		Pile C	-
		Pile D	13
		Pile E	41
	2-methylnaphthalene (2-ring)	Pile A	-
		Pile B	-
		Pile C	5.9
		Pile D	9.1
		Pile E	11
	acenaphthene (2-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	4.0
		Pile E	5.1
	fluorene (2-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	5.0
		Pile E	6.3
	phenanthrene (3-ring)	Pile A	-
		Pile B	-
		Pile C	4.6
		Pile D	14
		Pile E	18
	anthracene (3-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	3.3
		Pile E	3.6
	fluoranthene (3-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	5.7
		Pile E	5.0

	pyrene (4-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	13
		Pile E	22
	benzo(a)anthracene (4-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	-
		Pile E	3.5
	chrysene (4-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	3.9
		Pile E	4.3
	di-n-butyphthalate	Pile A	6.2
		Pile B	22
		Pile C	73
		Pile D	11
		Pile E	3.3
	n-nitrodoiphenylamine	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	-
		Pile E	4.9
VOCs (GC)	(see laboratory report for individual compounds)	Pile A	-
		Pile B	-
		Pile C	21.2
		Pile D	13.7
		Pile E	53.9
PCBs (GC)		Pile A	-
		Pile B	-
		Pile C	-
		Pile D	-
		Pile E	-
lead (total - AA)		Pile A	13
		Pile B	70
		Pile C	45
		Pile D	50
		Pile E	63
ash (ignition loss)		Pile A	7.3%
		Pile B	20%
		Pile C	56%
		Pile D	54%
		Pile E	82%
total carbon		Pile A	22.8%
		Pile B	10.5%
		Pile C	13.4%
		Pile D	8.7%
		Pile E	4.8%
total kjeldahl nitrogen		Pile A	14,000
		Pile B	7,000
		Pile C	2,000
		Pile D	2,500
		Pile E	750
pH		Pile A	8.0
		Pile B	8.2
		Pile C	8.4
		Pile D	8.0
		Pile E	8.0
moisture content		Pile A	73%
		Pile B	75%
		Pile C	33%
		Pile D	36%
		Pile E	13%

- = compound not detected at or above method detection limit.

Analytical results of the static pile samples indicated total PAH concentrations of 2.2 mg/kg, 10.5 mg/kg, 71 mg/kg, and 119.8 mg/kg for piles B, C, D, and E, respectively. PAHs were not detected in pile A. PAHs detected included the 2- and 3-ring PAHs for piles B, C, D, and E, and the 4-ring PAHs for piles D and E. Also detected in the static pile samples were low levels of total VOCs (from 13.7 to 53.9 mg/kg), and total lead (from 13 to 70 mg/kg). PCBs were not detected. The composting parameters analyzed (carbon/nitrogen ratio, moisture pH, and percent ash) are discussed in Section B.5. of this document. The laboratory report dated July 20, 1992 for the static pile samples is provided in Appendix A.

Data for the sample from pile E (100 percent soil) was generally consistent with the data for the soil feedstock sample. However, total concentrations of PAHs were slightly higher, and several PAHs (anthracene, chrysene, and benzo(a)anthracene) which were not detected in the soil feedstock sample were detected in the sample from pile E.

Monitoring, Sampling and Turning/Watering. Monitoring, sampling for chemical analyses, and turning/watering activities were conducted for each pile, as indicated in Table 4.

Table 4: Monitoring, Sampling and Turning/Watering Activities

Frequency	Activity
Twice per week (Tuesday and Friday)	Temperatures recorded Sample collected for analysis of moisture content Turned and watered
Once per week (Tuesday)	Sample collected for analysis of pH Oxygen content*
Once every two weeks (Tuesday)	Sample collected for analysis of: • total carbon • total nitrogen • VOCs (GC) • PCBs (GC) • base/neutral/acid extractables (GC/MS) • ash (ignition loss)
Quarterly (Tuesday)	Sample collected for analysis of base/neutral/acid extractables (GC/MS)

* Attempts were made to measure oxygen content of the piles weekly using a Gastech meter and inserting the probe into a preformed hole in the center of each pile. However, the readings could not be repeated and this appeared not to be representative of the mass soil air voids, and thus, oxygen measurements were ceased.

The results of these activities were used to make procedural changes in an effort to optimize the composting process. Procedural changes made included increasing the volume of water additions. Temperatures were recorded and samples were collected for analyses of moisture content, pH, total carbon, total nitrogen and ash to monitor the composting condition of the piles. Samples were collected for analyses of base/neutral/acid extractables, and VOCs to monitor the degradation of the contaminants. The piles were turned and watered in an effort to optimize the composting process. Turning and watering were conducted at a frequency of twice per week per MPCA recommendations for composing yard waste (Worth, 1992).

The piles were monitored, sampled, and then turned/watered in consecutive order beginning with pile A and ending with pile E. Temperatures were recorded at three locations for each pile (top, middle, bottom) using the thermometer driven approximately 1.5 feet from the surface of each pile into each pile. Sampling for chemical analyses was conducted using the soil auger driven approximately 3 feet from the surface of each pile into the middle of each pile. Turning and watering consisted of thin-spreading, watering until moist or wet to the touch, and reforming each pile.

The analytical results for base/neutral/acid extractables and VOCs for the soil samples are summarized in Table 5. PCBs were not detected. Temperatures and analytical results for composting parameters (moisture content, pH, carbon/nitrogen ratio, and ash) are discussed in Section B.5. of this document. The laboratory reports date June 22, 1992 through October 26, 1992 are provided in Appendix A.

Table 5: Static Pile Chemical Analyses
(June 16, 1992 through October 13, 1992)

Analyses (method)	Compounds Detected (Concentration in mg/kg)												
base/neutral/acid extractables (GC/MS)			Date (Week of Study)										
			6/16/92 (3)	6/30/92 (5)	7/14/92 (7)	7/28/92 (9)	8/04/92 (10)	8/11/92 (11)	8/25/92 (13)	9/3/92 (15)	9/22/92 (17)	10/6/92 (19)	10/13/92 (20)
	naphthalene (2-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	19	2.4	2.6	1.2	-	-	-	-	-	-	-
		Pile C	-	9.0	3.9	3.6	-	1.7	-	-	-	-	-
		Pile D	180	11	8.6	-	-	1.8	1.2	-	-	-	-
		Pile E	29	12	4.8	6.0	-	-	1.3	1.1	-	-	-
	2-methylnaphthalene (2-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	8.4	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	-	-	-	-	-	-	-	-
		Pile D	4.6	-	-	-	-	-	-	-	-	-	-
		Pile E	3.3	-	-	-	-	-	-	-	-	-	-
	fluorene (2-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	-	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	-	-	-	-	-	-	-	-
		Pile D	-	-	-	-	-	-	-	-	-	-	-
		Pile E	-	-	-	-	-	-	-	-	-	-	4.8
	phenanthrene (3-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	3.7	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	4.0	-	-	-	-	-	-	-
		Pile D	5.1	-	-	-	-	3.8	-	-	-	-	-
		Pile E	6.1	6.6	-	-	-	-	-	-	-	-	-
	fluoranthene (3-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	-	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	-	-	-	-	-	-	-	-
		Pile D	-	-	-	-	-	3.5	-	-	-	-	-
		Pile E	4.0	-	-	-	-	-	-	3.7	-	-	-
	pyrene (4 ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	-	-	-	-	-	-	-	-	-	-	-
		Pile C	5.5	6.0	-	6.0	3.3	-	-	-	-	-	-
		Pile D	5.3	5.5	-	-	5.0	3.7	-	3.7	-	-	-
		Pile E	9.1	9.3	-	5.1	8.5	4.1	3.9	7.7	3.3	-	5.6
	di-n-butylphthalate	Pile A	NA	6.6	NA	NA	-	NA	NA	-	NA	NA	16
		Pile B	NA	-	NA	NA	4.3	NA	NA	-	NA	NA	12
		Pile C	NA	35	NA	NA	-	NA	NA	5.9	NA	NA	4.3
		Pile D	NA	-	NA	NA	30	NA	NA	-	NA	NA	10
		Pile E	NA	-	NA	NA	-	NA	NA	6.5	NA	NA	11
	n-nitrodoiphenylamine	Pile A	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile B	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile C	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile D	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile E	NA	-	NA	NA	3.7	NA	NA	-	NA	NA	-
VOCs (GC)	(see laboratory reports for individual compounds)	Pile A	0.3	0.8	-	-	-	-	-	-	-	-	-
		Pile B	24.1	-	-	-	-	-	-	-	-	-	-
		Pile C	7.3	3.4	1.6	-	-	-	-	-	-	-	-
		Pile D	40.6	3.9	11.9	0.2	-	-	-	-	-	-	-
		Pile E	48.9	9.7	-	1.7	-	-	0.3	-	-	-	-

- = Compound not detected at or above method detection limit.
NA = Compound not analyzed.

At the conclusion of the 21-week field study, a sample was collected (October 20, 1992) from each pile. The parameters analyzed and results are summarized in Table 6. The laboratory report dated November 17, 1992 is provided in Appendix A.

Table 6: Static Pile Final Chemical Characterization (October 20, 1992)

Analyses (method)	Compounds Detected (Concentration in mg/kg)	
base/neutral/acid extractables (GC)	Pile A	-
	Pile B	-
	Pile C	-
	Pile D	-
	Pile E	-
VOCs (GC)	Pile A	-
	Pile B	-
	Pile C	-
	Pile D	-
	Pile E	-
PCBs (GC)	Pile A	-
	Pile B	-
	Pile C	-
	Pile D	-
	Pile E	-
RCRA metals (TCLP)	Pile A	arsenic (52 µg/L), barium (0.59)
	Pile B	arsenic (5 µg/L), barium (0.89)
	Pile C	arsenic (4 µg/L), barium (0.71)
	Pile D	arsenic (3 µg/L), barium (0.66)
	Pile E	- , barium (0.84)
lead (total - AA)	Pile A	27
	Pile B	48
	Pile C	54
	Pile D	60
	Pile E	72
ash (ignition loss)	Pile A	83%
	Pile B	84%
	Pile C	88%
	Pile D	89%
	Pile E	94%
total solids	Pile A	48%
	Pile B	67%
	Pile C	77%
	Pile D	78%
	Pile E	84%

total volatile solids	Pile A	16%
	Pile B	16%
	Pile C	10%
	Pile D	7.6%
	Pile E	3.9%
total carbon	Pile A	17%
	Pile B	9.4%
	Pile C	7.1%
	Pile D	6.5%
	Pile E	4.1%
total kjeldahl nitrogen	Pile A	4,400
	Pile B	2,600
	Pile C	2,000
	Pile D	1,300
	Pile E	430
pH	Pile A	8.1
	Pile B	7.9
	Pile C	8.1
	Pile D	7.7
	Pile E	7.8
ammonia as N	Pile A	7.4
	Pile B	1.9
	Pile C	0.49
	Pile D	0.49
	Pile E	0.49
nitrate as N	Pile A	14
	Pile B	4.9
	Pile C	1.4
	Pile D	1.0
	Pile E	1.0
moisture content	Pile A	52%
	Pile B	33%
	Pile C	23%
	Pile D	22%
	Pile E	16%

A.3. Budget

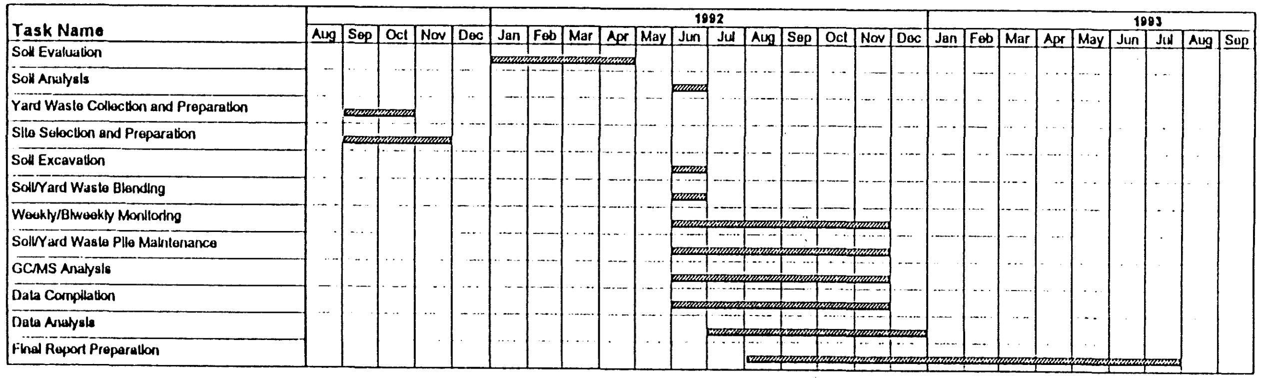
		LCMR Funds	Matching Funds
a.	Amount Budgeted:	$110,000	$2,000
b.	Balance:	$0	$2,000

The amount budgeted for this project is $112,000, $110,000 of which is requested from the LCMR. The remaining $2,000, necessary for construction and maintenance of the compost piles, will be funded by the Minneapolis Community Development Agency.

The balance as of July 1, 1993 was $0.

A.4. Timeline for Study

The schedule for this study was limited by the date on which funding became available and the season during which large quantities of street sweepings become available. Once funding became available, efforts began to identify a suitable soil for treatment. Collection of street sweepings took place during fall, 1991. The yard waste was stockpiled for the winter months. June 1, 1992, contaminated soil was excavated and blended with the yard waste. Composting took place over a 21-week period from June 1, 1992 through October 20, 1992.



A.5. Status.

Results. Analytical data for the soil feedstock characterization, and static pile characterization and monitoring were used to construct Figures 1 and 2 which show the rate of disappearance (degradation) of total PAH compounds and of total volatile organic compounds (VOCs), respectively, as measured in solvent extract from samples collected.

Figure 1: Relationship of PAH Concentration/Time

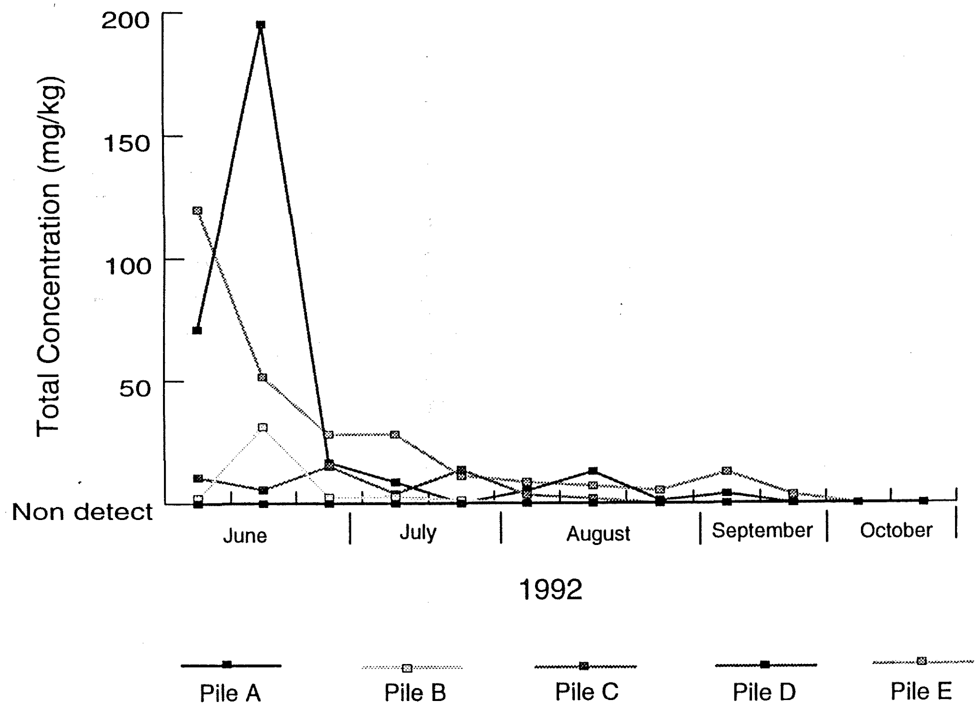
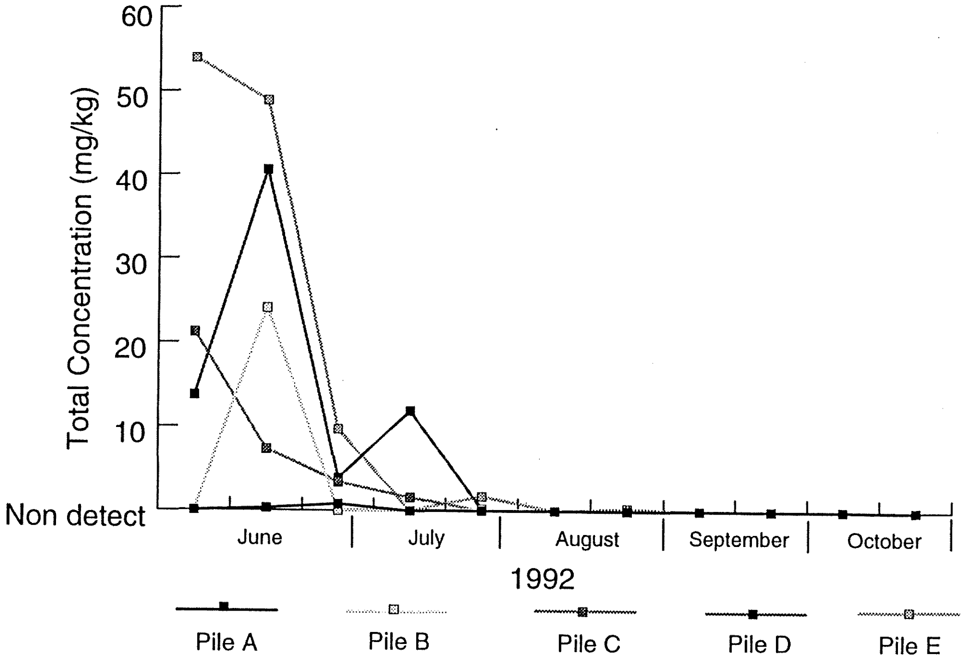


Figure 2: Relationship of VOC Concentration/Time



The total concentration of extractable PAHs (2- to 4-ring) were reduced by 100 percent over the duration of field study (21 weeks). About 90 percent of the decrease in the total concentration of extractable PAHs occurred during the first nine weeks of the study, as did about 100 percent of the decrease in the total concentration of extractable VOCs. During the initial nine weeks following construction, the reduction in total PAHs was 100 percent for piles B and C, 98 percent for pile D, and 95 percent for pile E. The feedstock ratio did not affect the extent of degradation of the PAH (or volatile organic) compounds. Increasing the soil content appeared to decrease the rate of degradation of the PAH (and volatile organic) compounds slightly.

PAH compounds that were evaluated (i.e., present in the piles) included:

- naphthalene (2-ring) (piles B,C,D,E);
- 2-methylnaphthalene (2-ring) (piles B,C,D,E);
- phenanthrene (3-ring) (piles C,D,E);
- fluoranthene (3-ring) (piles D,E); and
- pyrene (4-ring)(piles C,D,E).

Several, PAH compounds were detected for the pile characterization, but not afterwards during the monitoring including:

- acenaphthene (2-ring) (detected at 4.0 and 5.1 mg/kg, piles D and E, respectively)
- fluorene (2-ring) (detected at 5.0 and 6.3 mg/kg, piles D and E, respectively)
- anthracene (3-ring) (detected at 3.3 and 3.6 mg/kg, piles D and E, respectively)
- benzo(a)anthracene (4-ring) (detected at 3.5 mg/kg, pile E)
- chrysene (4-ring) (detected at 3.9 and 4.3 mg/kg, piles D and E, respectively)

The concentration of metals for the piles did not change over the 21-week study period.

Discussion. As discussed earlier (Section II.A.1.), 2- to 3- ring PAHs will volatilize (or strip) from soil due to aeration and low heat. The similar patterns apparent between PAH and VOC degradation for the piles suggests that the PAHs may have been volatilized (or stripped). The variability apparent in the data suggests that the mixing and blending of the feedstock and the turning of the piles may need to be greater.

A.6. Benefits.

As discussed earlier (Sections I.A. and I.B.), if effective at remediating PAHs in soil, composting may:

- offer an additional approach to the existing options for remediating semi-volatile compound contaminated soil at a site;

- offer significant economic and technical advantages over the most commonly used options of semi-volatile remediation (incineration or land-spreading); and

- facilitate the cleanup of semi-volatile-contaminated sites and ultimately the recycling of contaminated properties into inhabitable, tax paying property.

A.7. Costs. Discussed under Section B.7.

B. Objective 2: COMPOSTING

B.1. Narrative.

The secondary objective of this project was to optimize conditions for composting to produce a usable end product from yard waste. Composting condition was expressed in terms of the temperature, moisture content, carbon/nitrogen ratio, pH, and percent decomposition (maturity) of the end products.

In the composting process, there are essentially six parameters which are essential for providing the optimum conditions for microbial activity. The optimal compost environment is characterized by controlled temperatures (90°F to 140°F), balanced nutrients (carbon:nitrogen 30:1), consistent moisture level (50 to 60 percent by weight), sufficient aeration and oxygen content (>5 percent), and near neutral pH (6 to 8). Continuous microbial activity will occur if the temperature, carbon/nitrogen ratio, moisture, aeration, pH, and mixing and blending of the feedstock is balanced until a mature product is obtained. Under optimal conditions, microbes will quickly biodegrade organics. In a less than optimal compost environment, biodegradation will occur at a slower rate and a longer time period will be required to achieve a mature product. The importance of each of these parameters is discussed below.

Temperature. For low-tech yard waste composting processes, temperature could be considered the most important parameter to monitor and is easily measured. Temperature can indicate the excess or deficiency of the other six variables and is an excellent reflection of the microbial activity that is taking place. Maintaining satisfactory temperature range is essential to providing a thermal environment which is beneficial to the microbes consumption of organic matter, air and water. Sustaining a temperature of 113°F (45°C) optimizes the microbial activity, thus decreasing the time needed for the bio-conversion of the feedstock into stable product.

Temperatures will rise quickly at the beginning of a composting process as the microbes digest easily accessible organic matter. Upon depletion of the easily accessible sugars, starches, amino acids, and proteins, the microbes will begin acting on the remaining complex compounds which break down slowly. This is likely when the microbes would begin biodegradation of the 2- and 3-ring PAHs followed by the 4- and 5-ring PAH compounds. If one of the above-mentioned parameters has not been satisfied, the temperature climb will be gradual and the time required to achieve a mature product will be extended.

The destruction of pathogens and weed seed is an important aspect of the thermodynamics of the composting process. When using a static pile, it is suggested that a temperature of 131°F (55°C) be maintained within the pile for a period of at least 21 consecutive days to destroy pathogens and weed seeds. This temperature and time factor results in meeting pathogen control standards commonly referred to as PFRP (Process to Further Reduce Pathogens).

Carbon to Nitrogen Ratio. Microorganisms require organic compounds to form cellular material for growth and reproduction. The carbon content of these materials is the major energy source for microorganisms. Because microorganisms cell mass is approximately 50 percent carbon and 8 percent nitrogen, attention to the C/N ratio is a key factor in determining how rapidly a material will decompose. A 10:1 carbon to nitrogen ratio is typically found in mature microbes and is also found in mature soil. Achieving a 10:1 ratio in a compost pile after a period of time is an indicator of a mature, and stable compost material. The greater the imbalance between the C/N ratio, the lower the metabolic rate of the microbes. Because microbes are less than 100 percent efficient, it has been found that they must take in about three times as much carbon as they actually incorporate into their cells. Thus, a 30:1 soil carbon to nitrogen ratio (available nutrients) presents the ideal conditions for the microbes. Feedstocks for a compost are most often selected and combined so as to obtain a 30:1 carbon to nitrogen ratio. After composting is initiated, nitrogen can be added in controlled amounts in the form of urea.

A nitrogen deficiency (C/N ratio greater than 40:1) or too little carbon in relation to nitrogen (C/N ratio less than 30:1) will result in a slower rate of biodegradation, lower temperatures and an additional time period to achieve a mature product. The C/N ratio decreases as composting progresses due to the conversion of organic carbon to carbon dioxide, which is released from the compost pile.

Moisture. Microorganisms require moisture to dissolve nutrients and to provide a suitable environment for their growth. Organic contaminants that are adsorbed into the soil matrix are not available for biodegradation until desorbed into the soil-water matrix. Water, like nitrogen, is added in controlled amounts. Moisture is perhaps the most important parameter to be determined and controlled. The optional moisture content is 55 percent by weight. During the early phases of the composting process, moisture losses can be as significant as 5 to 7 percent per day. Thus, a feedstock having a moisture content of 60 percent on Monday could have a moisture deficient atmosphere (<45 percent) by Friday. For this reason, rapid moisture determination followed by quick moisture adjustments are important.

In a moisture deficient environment (< 45 percent moisture by weight), bacteria will begin to go dormant or die. This results in a slower rate of biodegradation, lower temperatures, and an additional time period to achieve a mature product. Colonies of fungi and actinomycetes, which are less active consumers in the compost environment, are more prevalent in and tolerant of host materials having low moisture contents. Excess moisture (>50 to 60 percent moisture by weight), decreases the proportion of pore space available for oxygen and an oxygen deficient environment (<5 percent oxygen) may result. Though this condition may enhance nutrient movement and breakdown of the structure of certain materials, this condition retards air movement. In such an environment, anaerobic microorganisms increase in number. The metabolism of the anaerobic microbes is slower than that of the aerobic microbes, resulting in a slower rate of biodegradation (lower temperatures), and an additional time period to achieve a mature product. Also, end products of anaerobic respiration include methane and odorous compounds such as hydrogen sulfide and phytotoxins (toxic to plants).

Aeration. Microorganisms require oxygen to support aerobic biological activity. Aeration of the feedstock is required, which allows for the removal of heat, carbon dioxide, moisture, phytotoxins and volatile organic compounds. Aerations function in controlling the heat necessary for pathogen and weed seed destruction and is essential in providing a safe product. The oxygen requirement of the biomass is dependent on the rate of biodegradation (the higher the rate, the greater the oxygen requirement) and is determined by the moisture content of the feedstock. Biodegradation is most efficient at 113°F (45°C), which is at the upper end of the mesophilic temperature range (68°F to 113°F) and the lower end of the thermophilic range (113°F to 160°F). It is essential that adequate aeration be supplied to optimize the microbial activity. A relationship exists between oxygen consumption which is an indication of microbial activity and temperature. As temperatures increase from 50°F to 113°F, the oxygen demand of the microbial colonies rapidly increases. Increasing temperatures above 122°F, up to 176°F results in a rapid decrease in microbial activity and oxygen demand.

The optimum oxygen measurement in an active compost pile would be >5 percent oxygen content. If the oxygen content falls below 5 percent, the process can become anaerobic, resulting in a slower rate of biodegradation and the generation of phytotoxins and odors. This oxygen-starved condition can occur as soon as 15 minutes after turning a static pile or the turning off of blowers in a forced aeration system.

pH. The pH of a compost environment is generally self-adjusting, and is a function of the end products that are being formed from the composted materials. A pH of between 6 and 8 is generally considered ideal for composting. As is the case of temperature and the C/N ratio, the pH of the compost varies with time during the composting process and is a good indicator of the extent of organic decomposition within the pile. In general, in the initial stages of decomposition, soluble carbohydrates are decomposed first and the pH drops below neutrality (pH 7), followed by proteins causing the pH to gradually rise. The decomposition of PAHs and VOCs produces organic acids too weak to measurably influence the pH.

Mixing and Blending. These physical parameters may be enhanced through feedstock selection, feedstock particle size reduction, and turning the matrix during the composting. Turning equalizes temperature, moisture, nutrients, and pH within the matrix, prevents the channeling of air and the caking of the mass, and reoxygenates the mass.

B.2. Procedures. Discussed in Section A.2..

B.3. Budget. The budget for this portion of the project has been included in the figure provided in Section A.3.

B.4. Timeline. See A.4. above.

B.5. Status

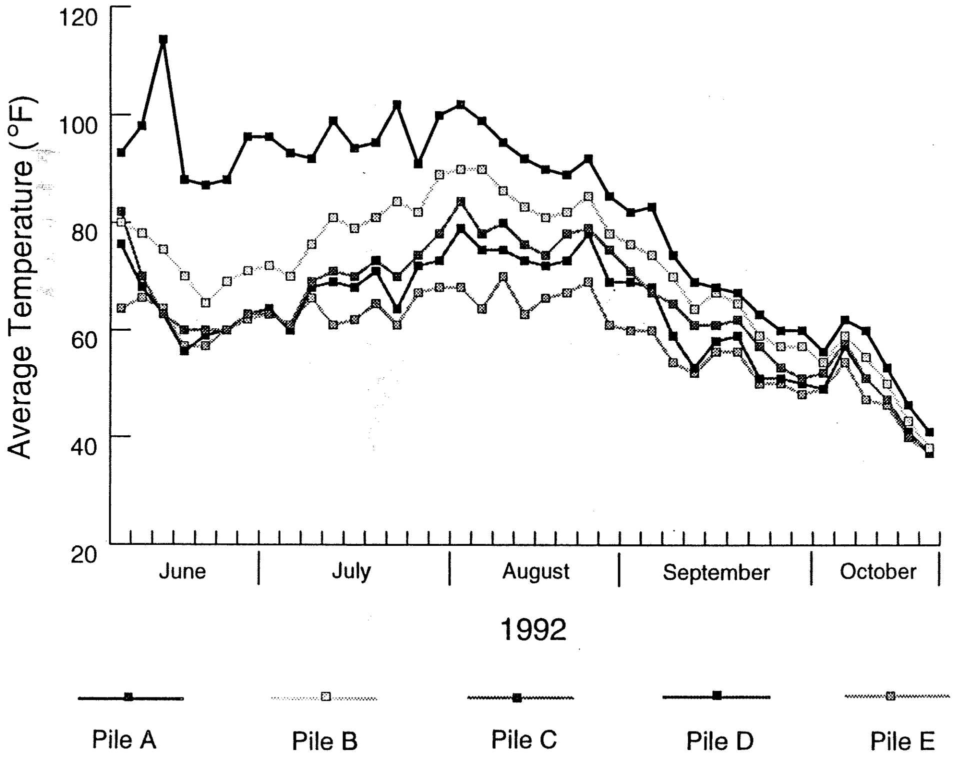
Results.

Static Pile Characterization. Analytical results of static pile characterization samples (collected following static pile construction) indicated that the conditions for composting at the start of the field study were not optimized to facilitate the rapid biodegradation of the organics of the piles. Specifically, piles A and B had too little carbon in relation to nitrogen (16:1 and 15:1, respectively); and piles C and E were nitrogen deficient (67:1 and 64:1, respectively). Pile D had a ratio of 35:1 which is within the acceptable range. The moisture contents were deficient for C, D and E (33 percent, 36 percent, 13 percent, respectively) and slightly above ideal for piles A and B (73 percent and 75 percent, respectively). The pH of the piles ranged between 8.0 and 8.4, which is within the exceptable range.

Static Pile Monitoring.

Temperature Readings. Figure 3 shows the change in the average value of the top, middle, and bottom temperatures recorded for each pile over the 21 weeks of the field study.

Figure 3: Relationship of Average Temperature/Time

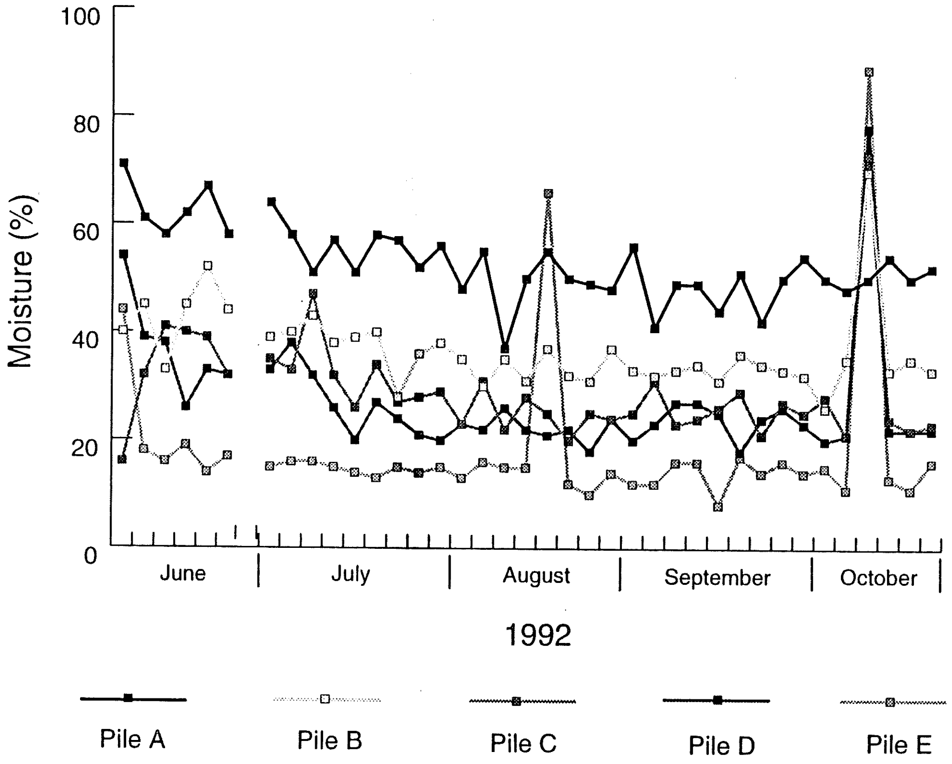


Temperature readings of the piles showed a quick increase from ambient during the first few days, a slight decrease through the 18th day, followed by a slower rate of increase during the following 12 weeks, and a steady decrease throughout the remaining eight weeks of the study. Temperatures were consistently highest in pile A and then B, followed by C, D and E in order of decreasing temperature (i.e. the average temperature was observed to decrease with increasing soil/yard waste ratio).

In general, piles A and B maintained temperatures sufficient to support mesophilic biodegradation until the 19th week of the 21-week study period, and piles C, D, and E maintained temperatures sufficient to support mesophilic biodegradation through the 17th week of the study, after which time temperatures were consistently below 50°F. Only pile A approached optimal temperature for microbial activity (113°F) and only on the 16th day following construction.

Moisture Contents. Figure 4 shows the change in moisture content for each pile over the 21 weeks of the field study.

Figure 4: Relationship of Moisture Content/Time

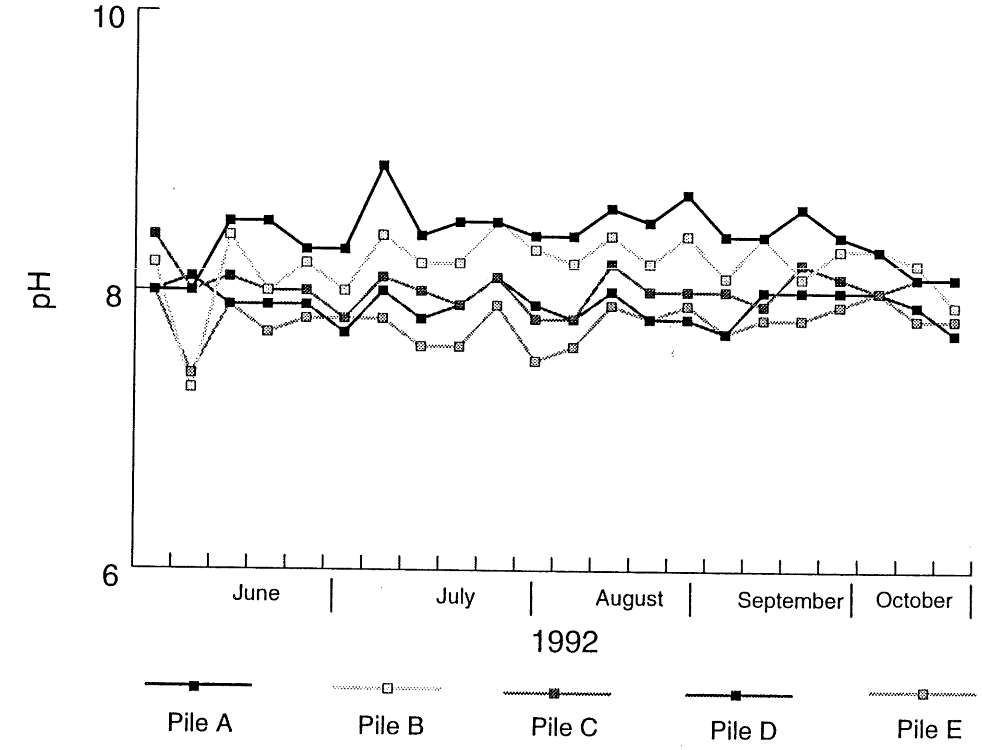


Moisture contents of the piles were relatively constant, and were consistently highest for piles A followed by B, C, D, E in order of decreasing moisture content (i.e. the moisture content was observed to decrease with increasing soil/yard waste ratio).

Only pile A maintained moisture levels sufficient to support microbial activity (50 to 60 percent moisture by weight). Piles B, C, D, and E had moisture levels deficient for microbial activity (less than 45 percent moisture by weight). This occurred despite the increased additions of water added to the piles throughout the study.

pH. Figure 5 shows the change in pH for each pile over the 21 weeks of the field study.

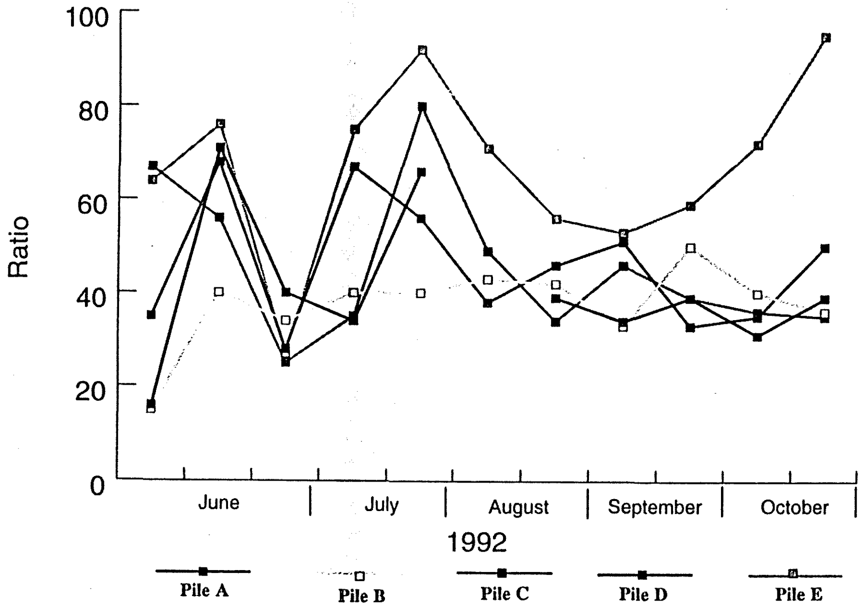
Figure 5: Relationship of pH/Time



The pH measurements of the piles were relatively constant, and were generally highest for pile A, followed by B, C, D and E in order of decreasing pH (i.e., the pH was observed to decrease with increasing soil/yard waste ratio).
The piles maintained pHs sufficient to support microbial activity (pH between 6 and 8).

Total Carbon, Total Nitrogen, and C/N Ratio. Figure 6 shows the change in the C/N ratio for each pile over the 21 weeks of the field study.

Figure 6: Relationship of C/N Ratio/Time



The C/N ratio of the piles slightly increased in a random fashion, and was generally highest for E, followed by D, C, B, and A in order of decreasing C/N ratio (i.e. the C/N ratio was observed to increase with increasing soil/yard waste ratio).

The piles maintained C/N ratios detrimental to optimizing microbial activity (greater than 40:1). The C/N ratio for D and E indicated a nitrogen deficiency and the ratios for A, B and C indicated near deficient conditions.

Maturity. A mature compost has been defined by the Minnesota Pollution Control Agency (MPCA) as compost where more that 60 percent decomposition (percent volatile solids reduction) has been achieved as determined by an ignition-loss analysis (percent ash). The MPCA is using the following formula to determine percent decomposition.

$$\text{Decomposition (\%)} = \frac{VSF - VSP}{VSF - (VSF \times VSP)} \times 100$$

VSF = the decimal fraction of volatile (i.e, organic) solids in the compost materials prior to composting

VSP = the decimal fraction of volatile solids in the final compost product

The percent decomposition, as calculated from ignition-loss analysis, of the piles was 6 percent (pile A), 4 percent (pile B), 1 percent (piles C and D), and <1 percent (pile E), all of which were far less than the 60 percent decomposition of a "mature" compost.

Discussion. Conditions for composting were not optimized to facilitate the rapid biodegradation of the organic constituents of the piles and a usable ("mature") end product was not produced from yard waste. During the study period, temperatures within the piles were sufficient to support mesophilic microorganisms (> 50°F), but remained below levels required to support thermophilic microbial colonies (113°F) indicating reduced microbial activity and biodegradation of the organics. Except for pile A (100 percent yard waste), moisture levels were near consistently deficient (< 50 percent by weight) to support microbial activity. The imbalance of carbon to nitrogen would likely not have seriously impeded the composting process if satisfactory moisture levels were maintained. These data suggest that the piles may have not been large enough to maintain temperatures in the thermophilic range necessary for active composting. The occurrence of moisture deficiencies despite the increased volumes of water added throughout the study suggests the need for a more effective method of moisture application. A quicker method of moisture determination would allow for the additions to be quantified and to better meet immediate moisture requirements.

The data identifies that as the soil to yard waste ratio increased, the conditions for each parameter were less favorable and the calculated percent decomposition (maturity) decreased. This observation and the variability apparent in the data suggest that the mixing and blending of feedstocks to assure definable proportions and a more homogenized mixture may be needed. In addition, the texture and structure of the piles having greater soil content than yard waste may not have been favorable to obtain optimum aeration or moisture penetration. This would further suggest the need for a more elaborate approach to mixing and blending.

B.6. Benefits.

If a useable product from yard waste could be produced when composted with soil, an additional outlet for yard waste could result.

B.7. Costs.

a. Initial Testing

Compost sample from each pile, five samples

Initial base/neutral extractables (GC)	2 ~~1~~ smpl @ $399.50 = 799.00 ~~399.50~~
Initial VOCs (GC)	1 1 smpl @ $148.75 = 148.75
Initial PCB (GC)	2 1 smpl @ $123.25 = 246.50 ~~123.25~~
Initial 8 RCRA metals (TCLP)	2 ~~1~~ smpl @ $243.50 = 487.00
Initial total volatile solids	2 smpl @ $15.00 = 30.00
VOCs (GC)	5 smpl @ $148.75 = 743.75
PCB (GC)	5 smpl @ $123.25 = 616.25
PAH (GC/MS)	5 smpl @ $382.50 = 1,912.50
lead (total-AA method)	5 smpl @ $141.50 = 707.50
pH	5 smpl @ $8.50 = 42.50
moisture content	5 smpl @ $12.75 = 63.75
ignition loss	5 smpl @ $15.30 = 76.50
total carbon	5 smpl @ $29.75 = 148.75
total nitrogen	5 smpl @ $48.45 = 242.25
C/N ratio (calculation)	
base/neutral/acid extractables (GC/MS)	5 smpl @ $382.50 = 1,912.50
Subtotal	**$8,177.50** ~~**$7,381.25**~~

b. Process Monitoring

Moisture content (samples taken to the lab) and temperature will be monitored two times per week. Oxygen content and pH will be monitored once per week.

Moisture content and temperature	39 events X 5 smpl @ $17.00	$3,315.00
Oxygen content	19 events X 2 hrs @ $15.00	570.00
pH	19 events X 5 smpl @ $8.50	807.50
Subtotal		**$4,692.50**

c. Periodic Sampling

Compost sample from each pile, five samples every two weeks for 20 weeks, total of 45 samples and compost sample from each pile, five samples quarterly.

VOCs (GC)	45 smpl @ $148.75	$6,693.75
PCB (GC)	45 smpl @ $123.25	5,546.25
PAH (GC/MS)	45 smpl @ $382.50	17,212.50
ignition loss	45 smpl @ $15.30	688.50
total carbon	45 smpl @ $29.75	1,338.75
total nitrogen	45 smpl @ $48.45	2,180.25
C/N ration (calculation)		
base/neutral/acid extractables (GC/MS)	20 smpl @ $382.50	7,650.00
Subtotal		**$41,310.00**

d. Final Testing

Compost sample from each pile, five samples total

VOCs (GC)	5 smpl @ $148.75	743.75
PCB (GC)	5 smpl @ $123.25	616.25
PAH (GC/MS)	5 smpl @ $382.50	1,912.50
pH	5 smpl @ $8.50	42.50
moisture content	5 smpl @ $12.75	63.75
8 RCRA metals (TCLP)	5 smpl @ $243.50	1,217.50
lead (total-AA method)	5 smpl @ $141.50	707.50
ignition loss	5 smpl @ $15.30	76.50
total carbon	5 smpl @ $29.75	148.75
total, ammonia, nitrate nitrogen	5 smpl @ $75.25	376.25
total and volatile solids	5 smpl @ $51.00	255.00
inorganic ions (K and P)	5 smpl @ $48.90	244.50
base/neutral/acid extractables	5 smpl @ $382.50	1,912.50
dry weight percent	5 smpl @ $15.00	75.00
Subtotal		**$8,392.25** ~~**$8,317.25**~~

Analytical Total	**$62,572.25** ~~**$61,701.00**~~

e. Sampling and Coordination

Per week:		
Technician	10 hours @ $58	580
Project Manager	2 hours @ $63	126
	Per week	**706**
	Project duration	**14,120**
Initial set-up:		
Technician	12 hours @ $58	696
Project Manager	15 hours @ $63	945
Laboratory Person	5 hours @ $60	300
Subtotal		**$16,061**

f. Project Management & Report Preparation

Technician	40 hours @ $58	2,320
Project manager	180 hours @ $63	11,340
Supervisor	40 hours @ $85	3,400
Principal	20 hours @ $130	2,600
Clerical	20 hours @ $43	903
Subtotal		**$20,563**

g. Meetings & Presentations

Technician	8 hours @ $58	464
Project manager	24 hours @ $63	1,512
Supervisor	12 hours @ $85	1,020
Principal	16 hours @ $130	2,080
Clerical	12 hours @ $43	516
Subtotal		**$5,592**

h. Expenses/Other

	$5,211.75
~~Subtotal~~	**~~$6,083~~**
PROJECT TOTAL	**$110,000**

IV. EVALUATION

Soil contaminated with low levels of 2- to 4-ring PAHs mixed with yard waste in small static piles experienced a reduction in the total concentration of extractable 2-to 4-ring PAH compounds 100 percent within approximately 21 weeks under the conditions of this study. About 90 percent of this decrease occurred during the first nine weeks of the study period. The ratio of the feedstocks did not affect the extent of degradation of the PAH compounds. Increasing soil content appeared to decrease the rate of degradation of the PAH compounds only slightly.

Review of data for the monitored parameters and the calculated percent decomposition (maturity) of the end products indicated that conditions for compositing were not optimized to facilitate the rapid biodegradation of the organic constituents of the piles, and a mature end product was not produced. Temperatures within the piles, while sufficient to support mesophilic microorganisms, remained below levels sufficient to support thermophilic microbial colonies, indicating reduced microbial activity and biodegradation of the organics. The slight increase in temperatures may have increased the volatilization of the PAHs. The slow composting process, calculated percent decomposition, and the available carbon source which is identified by the end product C/N ratio would indicate the microbes did not act on the PAH compounds. As suggested earlier, the microbes would most likely act first on the easily accessible carbon sources (sugars, starches, proteins), and then seek out the 2-and 3-ring PAHs followed by the more complex and stable 4-ring PAHs.

The study data suggest:

- the mixing and blending of feedstocks to assure definable proportions and a more homogenized mixture may be needed. In addition, the texture and structure of the piles having greater soil content than yard waste may not have been favorable to obtain optimum aeration or moisture penetration, further suggesting the need for a more elaborate approach to mixing and blending;
- the piles may not have been large enough to maintain temperatures in the thermophilic range necessary for active composting; and
- the need for improved moisture application and quicker moisture determination.

Perhaps for future experiments of this type, it would be best to proportion and otherwise prepare the piles so as to optimize conditions for composting. This would require the addition of a source of nitrogen (such as manure or urea). Homogenizing the feedstocks at the beginning of the process could be achieved by tub grinding and screening the materials. Mixing and blending could be improved by using a mechanical turner having a flail or lifting mechanism (which agitates and aerates the material) and a spray turner (to wet the material as the turner moves through the pile). The use of a turner would be most beneficial if the materials were formed into windrows and large quantities of material were being treated. Once actively composting, the differing weights of contaminated soil could be added to the piles. Thus, an assessment of the effect which soil ratio has on the composting conditions and the degradation of the contaminants in the compost environment could be more accurately measured. If PAHs are to be the evaluated contaminant, it would be best to use a source high in total concentration of the 4- to 6-ring PAHs. These PAHs are not subject to volatilization to the degree experienced by the 2- and 3-ring PAHs. Assuming that optimal composting conditions are maintained throughout the study, it could then be suggested that the degradation of PAHs (if observed) could be largely attributed to biodegradation. High PAH concentration will allow for the degradation to be evaluated without being masked by the variability inherent in PAH analyses at low concentrations.

The results of this study demonstrate that the concentration of 2- to 4-ring PAHs in soil can be reduced through the composting processes used. Although a fate analyses was not conducted, study data suggest that the PAHs were largely volatilized. The literature reviewed suggest that the PAHs may have been largely biodegraded if optimal composting conditions had been maintained throughout the study. The results of this study suggest that it is technically feasible to remediate semi-volatile compounds in soil when composted with organic materials (such as yard waste). The reduction of the semi-volatile compounds is sufficient to permit unrestricted use of the soil/compost mixture.

V. CONTEXT: RELATED CURRENT AND PREVIOUS WORK

A. FUTURE NEEDS

Considerations of cost and the limits of composting as a remediation method for PAHs, at a minimum, need to be addressed prior to implementation of full scale composting efforts for semi-volatile contaminated soils. These considerations should include:

- the ultimate fate of the organic compounds (released or destroyed) in mixtures to be composted;
- the effectiveness of composting soils contaminated with 4- to 6-ring PAHs and high concentrations of PAHs;
- the potential for adverse impacts arising from organic and inorganic compounds which may remain in compost; and
- a comparison of the economics of various remedial approaches.

If composting can be demonstrated to be a valid remediation technology for PAHs in contaminated soil, research is needed to:

- define optimal operating conditions (which may be waste specific) and develop compost systems that match these criteria;
- define and optimize specific parameters that control the degradation rate of organics;
- define criteria for acceptable treatment;
- improve methods for chemical analyses of compost for primary contaminants and degradation products; and
- define contaminant degradation rate-limiting parameters.

B. PROPOSED WORK IS SUPPLEMENTARY

The proposed work will help to determine both the rate of decomposition and the field conditions necessary to achieve optimum breakdown. In addition, the completeness of the decomposition process will be important in assessing whether the process achieves breakdown of the soil contaminants adequate to permit utilization of the soil/compost mixture in unrestricted usage.

C. RELATED PAST ACCOMPLISHMENTS

The past two studies Braun Intertec has performed will be reviewed to evaluate co-composting methodologies as a means of remediation. Other studies available to Braun Intertec, such as breakdown of petroleum refining wastes in soil, will be reviewed to assess their relevance to this project.

D. PREVIOUS RELATED BIENNIAL BUDGET SYSTEM PROGRAM TITLE AND BUDGET AMOUNT FOR FY 90-91

The previous related studies were funded by MCDA, and no state funding was involved.

E. BIENNIAL BUDGET SYSTEM PROGRAM TITLE AND BUDGET FOR PROJECT FOR FY 92-93

Not applicable.

VI. QUALIFICATIONS

The program was initiated by the Minneapolis Community Development Agency (MCDA), Minneapolis, Minnesota and Braun Intertec Corporation (Braun Intertec), Mendota Heights, Minnesota. Braun Intertec Corporation was formerly known as Braun Environmental Laboratories, Inc. The MCDA served as program manager and Braun Intertec was responsible for designing and conducting the project work, including report preparation. The field study was designed by Braun Intertec staff, Mr. Paul Book and Mr. Steve Riner, and managed by Ms. Laurie Kania. Mr. Charles Lederer, who recently joined Braun Intertec, has assisted Ms. Kania in preparation of the final report and assessments related to the composting process.

1. Program Manager

a. and b. Qualifications, Institutional Association and Specializations:

Lawrence H. Heinz
Supervisor of Engineering
Minneapolis Community Development Agency

St. Thomas Military Academy, Mendota Heights, MN, 1961
University of Minnesota, Minneapolis, Civil Engineering, 1961-64
International Correspondence School, Scranton, PA, Civil Engineering, 1972.

c. Note for Research Proposals:
(1) Summary of Work Accomplished: a study performed by Braun Intertec for MCDA, July 1989 - October 1990, and another study performed by Braun Intertec for MCDA, July 1990 - October 1990 (no state funding used for these projects).

(2) List of Principal Publications: None

2. Cooperators/other Investigators

a. and b. Qualifications, Institutional Association and Specializations:

Paul R. Book, CPG
Director, Environmental Consulting Services Division
Braun Intertec Environmental, Inc.

M.S. Geology, University of New Hampshire, Keene, 1980.
B.S. Geology, University of Massachusetts, Amherst, 1977

Mr. Book has been Director of Consulting Services (formerly Environmental Geology) for Braun Intertec Environmental, Inc., since 1987. In that capacity, he has been responsible for all environmental consulting projects performed at Braun Intertec. Prior to that time, he was a Senior Hydrogeologist for the Minnesota Pollution Control Agency, where he provided hydrogeologic analysis of sanitary landfill and superfund sites. He will be Principal-in-Charge for this project.

c. Note for Research Proposals:
(1) Summary of work accomplished: a study performed by Braun Intertec for MCDA, July 1989 - October 1990, and another study performed by Braun Intertec for MCDA, July 1990 - October 1990 (no state funding used for these projects).

(2) List of principal publications:

Stephen D. Riner, REA
Supervisor, Regulatory Assistance Section,
Site Assessment Department
Braun Intertec Environmental, Inc.

M.S. Chemistry/biochemistry, New Mexico State University, Las Cruces, 1974
B.S. Chemistry, Loyola University of Los Angeles, 1971

Mr. Riner has been in his position with Braun Intertec since 1989. He supervises environmental compliance audits and phase I and phase II property assessments. Prior to that time, he was Hazardous Waste Coordinator for the Minnesota Department of Transportation and, for five years, a Project Manager in the Minnesota Pollution Control Agency's superfund program. Among his superfund projects was the Reilly Tar & Chemical Co. site in St. Louis Park, which involved contamination of soils and groundwater with PAHs from a creosoting plant. He will provide technical supervision for this project.

c. Note for Research Proposals

(1) Summary of Work Accomplished: a study performed by Braun Intertec for MCDA, July 1989 - October 1990, and another study performed by Braun Intertec for MCDA, July 1990 - October 1990 (no state funding used for these projects).

(2) List of Principal Publications: None

a and b. Qualifications, Institutional Association and Specializations:

Charles A. Lederer
Senior Technical Consultant
Braun Intertec Corporation

B.S. Business Administration, minor studies in Land Capability Analysis, University of Wisconsin, River Falls, 1983.

Mr. Lederer recently joined Braun Intertec in this capacity. Prior to this, he worked at R.W. Beck as a Senior Technical Consultant. In this capacity, Mr. Lederer has assisted states, counties and municipalities in the planning and implementation of solid waste and resource recovery facilities. He was responsible for analysis of waste generation, evaluation of the impact of recycling and analysis of markets associated with various technologies. He has served as project manager during the implementation phase of project development providing assistance in permitting, financing, procurement, contract negotiations, construction and operations monitoring for waste to energy, landfill, recycling and composting facilities.

Mr. Lederer has six years experience in the independent review and procurement activities related to composting facilities. He is familiar with the DANO, OTVD, Buhler, Daneco, Ferst, Bedminster, IPS and Recomp Systems. Beyond the review of the technologies applied in the preprocessing, composting and post-processing activities of these systems, Mr. Lederer has evaluated the impacts which markets, permitting and residue disposal have on facility economics and the vendors' contractual commitments.

A concentration of his work has been on that fraction of the waste stream which is considered to consist of special or unprocessible waste, such as tires, ferrous metals and plastics. Mr. Lederer has prepared requests for qualifications and reviewed technical proposals for the processing and recycling of these items. Mr. Lederer has ten years experience providing technical assistance with tire disposal issues throughout the United States and in Europe.

c. Note for Research Proposals:

(1) Summary of Work Accomplished:

Procurement and Permitting, Yard Waste Management Facility, City of Miami, Florida, Technical Consultant. Mr. Lederer has provided technical assistance to City staff in the preparation of design criteria, procurement documents, permitting documentation and opera ions and maintenance manuals for a 20,000 TPY yard waste processing facility which produces end products of compost and mulch materials.

Procurement and Permitting, 120-TPD Municipal Solid Waste Composting Project, Crow Wing County, Minnesota, Project Manager. Mr. Lederer provided project management and technical services relative to the development of a 120 TPD MSW composting facility which would serve a rural county in Minnesota. As project coordinator, he has been responsible for preparation of a $2 million MWMB grant application, facility permit, environmental worksheet, investigation of financing alternatives and preliminary design evaluation.

Mr. Lederer directed the procurement effort for an $11 million composting facility which included preparation of Request for Proposals, vendor evaluations and selection, and contract negotiations with the selected vendor.

Independent Review, MSW Composting/Recycling Facility, St. Cloud, Minnesota, Technical Consultant. Mr. Lederer assisted in the review of technical and operation conditions of the Recomp Recycling and MSW Composting Facility which utilizes a Eweson digestor. The review included examination of the general process flow, facilities capacities and contractual arrangements.

The review identified the operating conditions which existed, a technical opinion of the overall process and the risk posture of the Facility as related to environmental regulations and equipment performance.

Independent Review, MSW Composting Facility, Okeechobee County, Florida, Technical Consultant. R. W. Beck conducted a technical feasibility review of a MSW composting facility which coupled a Eweson Digester with a Royer system windrow composting process. Mr. Lederer focused on evaluation of markets for the end products.

Development of Composting Facility Operating Guide, The Procter & Gamble Company, Technical Advisor. Mr. Lederer contributed to the creation of the *Composting Facility Operating Guide* for the U.S. Solid Waste Composting Council. The *Operating Guide* will be a detailed, practical document describing process control parameters necessary for successful operation of composting facilities. The project included preparation of the draft *Operating Guide*, week-long field verifications at seven operating municipal solid waste composting facilities, and preparation of the final *Operating Guide*. The application of a statistical process control procedure as part of the composting facilities operating program is a unique feature of the operating guide. The work was directed by the Solid Waste Composting Council and funded by the Procter & Gamble Company.

Compost Facility Upgrade Evaluation, Solid Waste Composting Council, Chertsey, Quebec, Technical Advisor. Mr. Lederer was a member of a review committee which was invited to evaluate the technical and operational aspects of the only operating MSW composting facility in Chertsey, Quebec, Canada. The Committee was asked to suggest changes which would enhance the facility's performance. The facility had experienced a fire in the receiving area, was having difficulty in meeting its identified processing capacities and was producing an immature compost which resulting in a significant quantity. The committee identified facility upgrades in the areas of materials receiving and handling, recovery and removal of non-biodegradable components, working conditions, process monitoring, waste decomposition process and end product enhancement.

The facility operators prepared a business plan for the needed improvements, have received funding and have completed implementation of many of the process related recommendations.

Municipal Solid Waste Composting Feasibility Study, City of Cedar Rapids, Iowa, Technical Consultant. Mr. Lederer provided technical and economic analysis in the evaluation of the impacts and risks associated with the addition of a MSW Composting Facility to the City's existing integrated waste management system. Particular attention was given to the composting facilities' ability to be the corner stone of a regional program serving the East Central Iowa Council of Governments. A review of technologies, feed stocks, project economics and end-product characteristics were provided.

(2) List of Principal Publications:

Compost Facility Operations Guide for Municipal Solid Waste, Solid Waste Composting Council, First Addition, September 1992.

Composting Municipal Solid Waste, The Fifth Annual Winter Conference Resource Recovery Institute, February 22-23, 1990, Miami, Florida, co-authored with Mr. David Brown, PMA.

Compost Facility Planning Guide, Solid Waste Composting Council, January, 1992.

a. and b. Qualifications, Institutional Association and Specialization:

Laurie M. Kania
Associate Environmental Scientist, Regulatory
Assistance Section
Braun Intertec Environmental, Inc.

B.S., Geography, Northern Illinois University, 1987.

Ms. Kania has been the project manager for environmental compliance audits of manufacturing and commercial facilities; RCRA tank closures; environmental subsurface evaluations of properties impacted by manufacturing activities, waste disposal activities, and failed petroleum and waste storage tanks; and environmental property assessments.

Prior to joining Braun Intertec in 1989, Laurie served for one-half year as a member of the Field Investigation Team (FIT) and one year as sample management coordinator for Ecology and Environment, Inc. (E & E). Her duties at E & E included serving as project manager for inspections at sites listed on the U.S. Environmental Protection Agency's (USEPA's) Comprehensive Environmental Response, Compensation and Liability Information System (CERCLIS), developing recommendation for further work at CERCLIS sites, serving as a liaison between E & E and the U.S. EPA for FIT contract sample management activities, training field technicians in field sampling methods and procedures, and conducting internal site audits of field sampling activities.

Laurie also served two summer internships with the Morton Arboretum located in Lisle, Illinois, working on the Des Plaines River Wetland Demonstration project in which she participated in soil water monitoring and other plant/soil reserach as part of a larger investigation into the reconstruction of a riverine wetland.

c. Note for Research Proposals:

(1) Summary of work accomplished: None

(2) List of principal publications: None

VII. REPORTING REQUIREMENTS

Semiannual status reports will be submitted not later than January 1, 1992, July 1, 1992, [January 1, 1993], and a final status report by July 1, 1993.

VIII. REFERENCES

Alexander, M. 1981. "Biodegradation of Chemicals of Environmental Concern." Science 211(9):132-138.

Braun Intertec Environmental, Inc., "Composting Study", Report CMJX-91-0028, dated February 1, 1991.

Cerniglia, C.E. 1984. "Microbial Metabolism of Polycyclic Aromatic Hydrocarbons." Advances in Applied Microbiology 30:31-71.

Cerniglia, C.E. and M.A. Heitkamp. 1989. "Microbial Degradation of Polycyclic Aromatic Hydrocarbons (PAH) in the Aquatic Environment." In U. Varanasi (Ed.) Metabolism of Polycyclic Aromatic Hydrocarbons in the Aquatic Environment, CRC Press, Inc., Boca Raton, FL, pp. 42-64.

DeRenzo, D.J., ed. 1980. Biodegradation Techniques for Industrial Organic Waste, Noyes Data Corp., New Jersey, pp. 97-100.

Epstein, E. and J.E. Alpert. 1980. "Composting Hazardous Wastes" in Toxic and Hazardous Waste Disposal Vol. 4, Ann Arbor Sciences Publishers/Theutterworth Group, Ann Arbor, MI, pp. 243-252.

Kamnikar, B. 1992. "Bioremediation of Contaminated Soil." Pollution Engineering (11):50-52.

Keck, J., Sims, R.C., Coover, M., Park, K., and B. Symons. 1989. "Evidence for Co-oxidation of Polynuclear Aromatic Hydrocarbons in Soil." Water Resources 23(12):1467-1476.

Lee, R.F., Gardner, W.S., Anderson, J.W., Blaylock, J.W. and C.J. Barwell, 1978. "Fate of Polycyclic Aromatic Hydrocarbons in Controlled Ecosystem Enclosures." Environmental Science and Technology 12(7):832-838.

Park, K.S., Sims, R.C., Dupont, R.R., Doucette, W.J., and J.E. Matthews. 1990. "Fate of PAH Compounds in Two Soil Types: Influence of Volatilization, Abiotic Loss and Biological Activity. "Environmental Toxicology and Chemistry 9:187-195.

Worth, Roberta. 1992. Introduction to Composting. Minnesota Pollution Control Agency.

Xiujin, Q. and M.J. McFarland. 1991. "Bound Residue Formation at PAH Contaminated Soil Composting Using Phanerochaete Chrysosporium." Hazardous Waste and Hazardous Materials 8(2):115-127.

lkf: cmjx\91-0028\0028.R04

1991 RESEARCH PROJECT ABSTRACT

FOR THE PERIOD ENDING JUNE 30, 1993

This project was supported by MN Environment and Natural Resources Trust Fund

TITLE:	Remediation of Soils Contaminated With Semi-volatiles By Composting With Leaves
PROGRAM MANAGER:	Larry Heinz
ORGANIZATION:	Minneapolis Community Development Agency (MCDA)
LEGAL CITATION:	M.L. 1991, Chp. 254, Art. 1, Sec. 29, Subd. 12 (a)
APPROP. AMOUNT:	$110,000

STATEMENT OF OBJECTIVES

A study was undertaken by Braun Intertec Corporation (Braun Intertec) for the Minneapolis Community Development Agency (MCDA) to assess the technical feasibility of remediating soils contaminated with with polynuclear aromatic hydrocarbon (PAH) and other semi-volatile compounds by composting with yard waste predominantly consisting of leaves. It was the original intent of this study to evaluate a full spectrum of semi-volatiles and the effects which the composting process may have on their degradation. However, a source of semi-volatile compound contaminated soil was not available and a PAH-contaminated soil was used. Assessment of feasibility was expressed in terms of the completeness and rate of degradation of extractable PAH compounds under the composting conditions of the study. Composting condition was expressed in terms of the temperature, moisture content, carbon/nitrogen ratio, pH, and percent decomposition (maturity) of the end products. A cost benefit or life cycle cost analyses and an evaluation of PAH fate was not part of this project's scope. A literature search, however, was conducted in conjunction with this study and inferences were made as to the mechanisms influencing PAH degradation and fate.

RESULTS

Soil contaminated with low levels of 2- to 4-ring PAHs mixed with yard waste in small static piles experienced a reduction in the total concentration of extractable 2- to 4-ring PAH compounds 100 percent within approximately 21 weeks under the conditions of this study. About 90 percent of this decrease occurred during the first nine weeks of the study period. The ratio of the feedstocks did not affect the extent of degradation of the PAH compounds. Increasing soil content appeared to decrease the rate of degradation of the PAH compounds only slightly.

Review of data for the monitored parameters and the calculated percent decomposition (maturity) of the end products indicated that conditions for composting were not optimized to facilitate the rapid biodegradation of the organic constituents of the piles and a mature end product was not produced. Temperatures within the piles, while sufficient to support mesophilic microorganisms, remained below levels sufficient to support thermophilic microbial colonies, indicating reduced microbial activity and biodegradation of the organics. The slight increase in temperatures may have increased the volatilization of the PAHs. The slow composting process, calculated percent decomposition, and the available carbon source which is identified by the end product C/N ratio would indicate the microbes did not act on the PAH compounds.

The study data suggest:

- the mixing and blending of feedstocks to assure definable proportions and a more homogenized mixture may be needed. In addition, the texture and structure of the piles having greater soil content than yard waste may not have been favorable to obtain optimum aeration or moisture penetration, further suggesting the need for a more elaborate approach to mixing and blending;

- the piles may not have been large enough to maintain temperatures in the thermophilic range necessary for active composting; and

- the need for improved moisture application and quicker moisture determination.

Perhaps for future experiments of this type, it would be best to proportion and otherwise prepare the piles so as to optimize conditions for composting. This would require the addition of a source of nitrogen (such as manure or urea). Homogenizing the feedstocks at the beginning of the process could be achieved by tub grinding and screening the materials. Mixing and blending could be improved by using a mechanical turner having a flail or lifting mechanism (which agitates and aerates the material) and a spray turner (to wet the material as the turner moves through the pile). The use of a turner would be most beneficial if the materials were formed into windrows and large quantities of material were being treated. Once actively composting, differing weights of contaminated soil could be added to the piles. Thus, an assessment of the effect which soil ratio has on the composting conditions and the degradation of the contaminants in the compost environment could be more accurately measured. If PAHs are to be the evaluated contaminant, it would be best to use a source high in total concentration of the 4- to 6-ring PAHs. These PAHs are not subject to volatilization to the degree experienced by the 2- and 3-ring PAHs. Assuming that optimal composting conditions are maintained throughout the study, it could then be suggested that the degradation of PAHs (if observed) could be largely attributed to biodegradation. High PAH concentration will allow for the degradation to be evaluated without being masked by the variability inherent in PAH analyses at low concentrations.

The results of this study demonstrate that the concentration of 2- to 4-ring PAHs in soil can be reduced through the composting processes used. Although a fate analyses was not conducted, study data suggest that the PAHs were largely volatilized. The literature reviewed suggest that the PAHs may have been largely biodegraded if optimal composting conditions had been maintained throughout the study. The results of this study suggest that it is technically feasible to remediate semi-volatile compounds in soil when composted with organic materials (such as yard waste). The reduction of the semi-volatile compounds is sufficient to permit unrestricted use of the soil/compost mixture.

PROJECT RESULTS USE AND DISSEMINATION

Information from this study was incorporated into a presentation given at the International In-Situ and On-Site Bioreclamation Symposium (held on April 8, 1993 in San Diego, California) and at a Soil Remediation Seminar sponsored by the University of Minnesota Soil Science Department (held on April 27, 1993 in St. Paul, Minnesota). The final results of this study are intended to be published as an article in a magazine such as "Biocycle" or "Biomass and BioEnergy."

July 1, 1993
LCMR Final Status Report - Detailed for Peer Review - Research

I. REMEDIATION OF SOILS CONTAMINATED WITH SEMI-VOLATILES BY COMPOSTING WITH LEAVES - Waste 1

Program Manager: **Larry Heinz**
Minneapolis Community Development Agency
105 Fifth Avenue South, Suite 200
Minneapolis, MN 55401
612/673-5028

A. LEGAL CITATION

An appropriation of $110,000 was made to the Office of Waste Management (OWM) for a grant to the Minneapolis Community Development Agency (MCDA) to develop a treatment method for soils contaminated with semi-volatile compounds by composting with leaves. The study was conducted with the assistance of Braun Intertec Corporation staff and City of Minneapolis staff.

Funding for the project was approved by the Minnesota Legislature (M.L. 91, Ch. 254, Art. 1, Sec. 14, Subd.12(a)), as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Environment and Natural Resources Trust Fund.

The total amount invoiced for this project as a whole (as of July 1, 1993) was $110,000. The balance for this project as a whole (as of July 1, 1993) was $0.

B. COMPATIBLE DATA. Not applicable.

C. MATCH REQUIREMENT. $2,000

II. NARRATIVE

A. STATEMENT OF PROBLEM

Soils which are contaminated with petroleum products and solvents such as gasoline, diesel fuel, and creosote are being encountered on numerous redevelopment and other construction projects on old industrial or railroad sites. <u>Many of these contaminants do not easily evaporate (volatilize) under ordinary temperatures, and are commonly categorized as semi-volatile compounds. Over time, these contaminants become part of the soil matrix and may need to be subjected to remediation (or cleaning) processes which typically use high temperatures to destroy the remaining compounds (incineration), or agitation to release the remaining compounds (land application).</u>

<u>Of particular importance is the classification of the semi-volatile compounds which are known as polynuclear aromatic hydrocarbons (PAHs). The concern for this classification is that many of the PAHs are known carcinogens and in certain quantities, create a public health concern. PAHs are universal products of the combustion of organic matter. Major sources of PAHs, in addition to petroleum leakage and spills, can be heat and power generation utilizing fossil fuels or refuse, uncontrolled burning of most materials, motor vehicle emissions, industrial processes, coal liquefaction and gasification, forest and prairie fires, and volcanic ash. From a chemical point of view, PAHs contain carbon and hydrogen with fused single and multiple benzene rings in linear, angular and cluster arrangements. The PAHs may also contain alkyl and nitro substituents or can be considered</u>

heterocyclic molecules with the substitution of an aromatic ring carbon with nitrogen, oxygen, or sulfur.

The drawbacks to the current remediation methods for semi-volatile-contaminated soils is they require large allotments of land and time (land application) or significant expenditures of capital and operating costs (incineration). Also, land application is feasible only if the semi-volatiles are in low concentrations, the soil is microbially active, and dilution will result in satisfactory resolution of the public health concerns. Incineration is often economically prohibitive due to the large volume of soil which is often encountered and the tipping fees which are charged. Some risk assessments have reported that soils contaminated with semi-volatile compounds may have relatively low environmental and health risks (especially for short-term exposure). As a result, it has been argued that it may not be cost-effective policy to use the limited existing incineration capacity on marginally hazardous materials when other methods of achieving soil cleaning may be more appropriate.

One of the oldest naturally occurring processes on earth is the degradation of organic matter (such as yard waste) by microbial activity. Humans have learned to control and optimize this naturally occurring process, and generally refer to the process as "composting." Composting has been one of the alternative technologies which have been openly discussed for use in the cleanup of semi-volatile contaminated sites. This focus has come about because municipalities are pursuing composting as a means to dispose of large volumes of yard waste (namely leaves and grass clippings). Yard waste is banned from disposal in Minnesota landfills, resulting in a need for implementation of alternative waste reduction and disposal methods. Concern for the cost-effectiveness of many of the disposal methods is an issue commonly shared by municipalities and developers of the sites, who are often experiencing budget and revenue constraints.

B. IMPORTANCE

Providing an additional approach to the available options for remediating semi-volatile compound contaminated soil at a site provides a greater range of flexibility in the decision process. By facilitating the cleanup of semi-volatile contaminated sites and ultimately the recycling of the property into inhabitable, tax producing property, the city environment becomes more sustainable.

C. EXTENT OF PROBLEM

The extent of semi-volatile soil contamination in the state of Minnesota is not known. To our knowledge, research to quantify or even qualify the total number of sites or the extent of contaminated soils has not been investigated by state or private industry. However, discoveries of properties contaminated with semi-volatile compounds is increasing in frequency. As old industrial properties are being redeveloped in an attempt to increase a communities' tax base and encourage job creation, property owners are being required to incur additional cost to remediate the site. Within the commercial banking and real estate industries, there is increasing awareness of the financial risks associated with ownership of contaminated soils and its potential liabilities.

III. OBJECTIVES

The objectives of the study are to: 1) assess the technical feasibility of using composting as a remedial technology for soils contaminated with PAHs; and 2) optimize conditions for composting to produce a usable end product from yard waste. It was the original intent of this study to evaluate a full spectrum of semi-volatiles and the effect which the composting process may have on their degradation. However, a source of semi-volatile compound contaminated soil was not available, and as a result, a PAH-contaminated soil was used. As previously indicated, PAHs are a commonly occurring group of the semi-volatile compounds and in certain quantities create a public health concern. The importance of focusing on PAHs is that they are also one of the more stable groups of the semi-volatile compounds. Their stability is due to their limited water solubility, requirement for large amounts of oxygen to initiate chemical degradation, and their diverse and complex chemical structure. In addition, some of the PAH compounds and their by-products (of metabolism) may be toxic to microorganisms. Should the results of the study identify the composting process as a method for achieving breakdown and distribution of the PAH molecule, it could be implied that most other semi-volatile compounds may react the same.

Recent data suggests that composting with organic materials (like yard waste) may be a valid remediation technology for treating PAH compounds in contaminated soil. Researchers have shown that various microorganisms that live in soil (bacteria and fungi) are able to degrade the 2- to 5-ring PAHs (Cerniglia, 1984; Alexander, 1981; DeRenzo, 1980; Epstein and Alpert, 1980; and Cerniglia and Heitkamp, 1989). The degradation of organic materials (like PAHs or yard waste) by microorganisms is called "biodegradation." Substantiating this, the biodegradation of PAHs (2- to 5-ring) in soils has been reported in the laboratory (Park et al., 1990) and in sediment in a marine environment (2- to 3-ring PAHs) (Lee et al., 1978). Because composting involves the biodegradation of organics under conditions that are managed to facilitate biodegradation, it was assumed that the composting process could facilitate the biodegradation of PAH by microbial activity. Recently, pilot studies using soils contaminated with low level petroleum hydrocarbons combined with a mixture of leaves in static piles (Braun Intertec, 1991) and with a mixture of manure and wood chips using aerated static piles resulted in data which indicated that remediation had occurred (Kamnikar, 1992).

If composting is effective at remediating PAHs in soil, composting PAH contaminated soil may offer significant economic and technological advantages over incineration and land application. The composting process can be controlled, is more expedient, may break down a broader range of compounds, requires less space, and should produce a usable end product when compared to land application. It is assumed that the composting process may be significantly less expensive than incineration, though a full life cycle cost analysis, comparing both approaches, should be completed to verify such claims.

Presented in this section of the report are the procedures, budget, timeline, results and discussion (status), benefits, and costs for each objective (Sections A and B, respectively). The conclusions, and recommendations for the project as a whole are presented in Section IV (Evaluation). Also provided in this document are a discussion of future needs (Section IV), related current and previous work (Section V), project team qualifications (Section VI), reporting requirements (Section VII), and references (Section VIII).

A. Objective 1: PAH REMEDIATION

A.1. Narrative.

The primary purpose of this project was to assess the technical feasibility of using composting to remediate PAHs in contaminated soil. Assessment of feasibility was expressed in terms of the completeness and rate of degradation of extractable PAH compounds under the composting conditions of the study. A cost benefit or life cycle cost analysis and an evaluation of PAH fate was not part of the scope of this project. A literature search, however, was conducted in conjunction with this study and inferences were made as to the mechanisms influencing PAH degradation and fate.

Biodegradation sometimes raises concerns because, for specific classifications of compounds such as organophosphorus pesticides, biodegradation can result in the formation of compounds more toxic than the original contaminant. This, however, is not the case with the PAHs. Despite their diversity, the PAHs are biodegraded in the presence of oxygen to one of three common intermediates (catechol, protocatechuic acid, or gentisic acid), none of which are considered toxic or carcinogenic. The bacterial degradation of the PAHs normally involves the formation of a *cis*-dihydrodiol followed by a diacid.

Eukaryotic organisms such as the fungi oxidize aromatics by forming a *trans*-dihydrodiol (Cerniglia, 1984). These compounds are not normally considered toxic or carcinogenic. PAHs containing four or more condensed rings are not easily biodegraded, but may be cometabolized or cooxidized in the presence of more easily degraded compounds (Cerniglia and Heitkamp, 1989; Keck et al., 1989). Degradation of PAHs containing substituents such as nitro, chloro, or bromo requires that one or more of the substituents be replaced by a hydroxyl group prior to oxidation of the aromatic ring. Complete mineralization of the PAH molecule produces compost, carbon dioxide and water.

A concern raised with regard to composting semi-volatile compounds for the purpose of remediation of these compounds is that the heat and agitation associated with the composting process may cause the contaminants and their metabolites to be volatilized at levels that would require treatment. Although limited, research on the fate of PAHs indicates that the 2- and 3-ring PAHs are susceptible to volatilization (Lee et al., 1978; Park et al., 1990), whereas the 4- and 5-ring PAHs are predominantly biodegraded (Park et al., 1990), abiotically degraded (Lee et al., 1978), or mineralized (Xiujin and McFarland, 1991). The team of Lee et al. (1978) evaluated the fates of 2- to 5-ring PAHs added as a crude oil dispersion to controlled ecosystem enclosures suspended in Saanich Inlet, Canada. They noted that both biodegradation and volatilization were the primary removal processes for the 2- and 3-ring PAHs (with biodegradation being significant for naphthalene) and that abiotic processes were responsible for the decrease in concentration of the 4- and 5-ring PAHs. The group of Par et al. (1990) evaluated the fate of fourteen 2- to 5-ring PAHs in two soils with regard to interphase transfer potential and mechanisms of treatment under unsaturated laboratory conditions. They concluded that biodegradation accounted for the predominant loss of the 2- to 5-ring PAHs studied and noted that volatilization was a significant mechanism for 2-ring PAHs. Xiujin and McFarland (1991) using mass balance considerations noted that the enhanced removal of a 5-ring PAH (benzo(a)pyrene) in a compost microcosm reactors using soil enriched with a microorganism (Phanerochaete chrysosporium) resulted in mineralization of most of the contaminated carbon.

~~In the case of PAHs, acute toxicity of the parent compounds is not the environmental concern relating to these compounds. Rather, a few of the many PAH compounds (particularly some of the 5- and 6 ring compounds) are known or suspected carcinogens. The carcinogenicity is believed to be related to the particular geometric orientation of the ring structures of these compounds. Therefore, when these compounds break down to simpler compounds, this geometric orientation will be altered, and the carcinogenic property of the parent molecule would be expected to disappear. Furthermore, the relatively simple chemical structure of PAH molecules and the lack of substituent atoms other than carbon and hydrogen (such as halogens) which could rearrange during decomposition to form other toxic compounds make it highly unlikely that decomposition processes will form other toxic compounds which are refractory to further biodegradation.~~

~~Furthermore, although PAH molecules are relatively large, their chemical structure is relatively simple (benzene rings fused together) and they generally contain only carbon and hydrogen atoms (although a few "heterocyclic" PAH related molecules contain oxygen or nitrogen within the ring). PAH compounds lack other substituent atoms such as halogens which could, during decomposition, rearrange to form other toxic compounds. Thus, it is highly unlikely that decomposition processes will have adverse environmental impacts.~~

~~Co composting is a process which takes advantage of increased biological activity resulting from decay of organic matter (leaves) to simultaneously act on organic contaminants such as PAH. Biodegradation is enhanced by providing adequate nutrients and by maintaining optimum oxygen and temperature levels. Co composting contaminated soils with leaves may be a way of destroying the contaminants at a relatively low cost and environmental risk, while allowing for reuse of the soils. This process will evaluate utilizing natural biodegradation processes acting on plant matter (the composting process) to enhance concurrent biodegradation of organic contaminants in soil.~~

~~Outside reviewers have suggested that it would be appropriate to conduct a "bench scale" study of the co composting process to better define what is happening during the composting process and to provide data to further refine the process. After considering this concept, we have determined that such a study is not practical. The process of composting takes place in relatively large piles, and it would be very difficult to create a microcosm of these piles under laboratory conditions. The dynamics of a miniature compost pile may be quite different from that of a full size pile, especially with respect to temperature. Furthermore, simulation of natural conditions such as temperature and rain would be difficult to attain without building an expensive test chamber specifically for this project. Finally, the purpose of this project is to measure what happens in the natural environment, and there is little to be achieved by altering sunlight or ambient temperature conditions to optimize composting when operators of compost operations have little or no control over these. We have added GC/MS analyses of compost during the project to attempt to evaluate breakdown products of PAH, as noted below.~~

A.2. Procedures.

General. The field study began on June 1, 1992 and concluded 21 weeks later on October 20, 1992. Five static piles were constructed to be about 25 cubic yards each of a varied ratio of soil contaminated with 2- to 4-ring PAHs and yard waste. The ratios were varied to enable an assessment of the affect which soil ratio has on the composting conditions. A source of nutrients in addition to yard waste (such as manure) was not used in order to limit the number of study variables. To lessen the potential contribution of volatilization, it would have been desirable to use a soil contaminated with 4, 5 and 6-ring PAHs which do not readily volatilize as do the 2-and 3-ring PAHs. Such a source, however, was not available for use in the study.

Following construction, the piles were sampled for chemical analyses to establish initial experimental conditions and form the baseline for analyses to evaluate the degradation of the PAH contaminants. Sampling of the piles for chemical analyses was conducted periodically throughout the field study to monitor the degradation of the contaminants or the composting conditions of the piles. Temperature and oxygen content of the piles were also regularly recorded to monitor the composting condition of the piles. To maintain the composting process, the piles were frequently (twice per week) watered and turned.

The complexity of operating conditions for this study were partly determined by limited funds. A small-scale pilot study conducted utilizing low technical composting processes was employed. In-field process equipment used included:

- a front-end loader (to form and turn the piles);
- a water truck (to add moisture to the piles);
- a mercury thermometer and a Gastech meter (to monitor the piles); and
- a hand-auger (to sample the piles for chemical analyses).

Because of the concern for introducing contaminants from off-site sources, all equipment used was dedicated to this project.

Throughout the study, City of Minneapolis (City) staff dedicated to the project operated the front-end loader and the water truck, and Braun Intertec staff dedicated to the project conducted the monitoring and sampling, and directed the turning and watering of the piles. These activities were conducted on the Tuesday and Friday of each week between the time periods of 7:00 a.m. and 9:00 a.m..

Samples collected for chemical analyses were placed in clean, labeled, laboratory-supplied bottles, placed on ice to preserve the samples, and transported to the Braun Intertec laboratory located in Eden Prairie, Minnesota according to Braun Intertec chain-of-custody procedures. All analyses were performed using U.S. EPA or other recognized standard procedures. A quality control assessment of the data has been conducted prior to release and all quality control guidelines have been met.

Site Description. The site used to conduct the field study is a former railroad yard located in southeast Minneapolis, Minnesota. The site is presently owned by the City of Minneapolis and is used for temporary storage of materials. The site is secured and bituminous-surfaced with a slight grade (1 to 2 percent slope). The site did not require preparation other than the clearing of debris.

Feedstock Description.
The Soil. The PAH-contaminated soil used for this study was excavated from a former bulk petroleum storage site located within 1/4 mile of the study site. The soil was excavated and hauled to the site on May 28, 1992 where it was stockpiled in one pile. The soil consisted of medium-grained silty sand and clayey sand fill, with some demolition debris consisting of rocks and bricks.

On June 1, 1992, the large demolition debris were hand-sorted out of the soil. The soil was then mixed with itself until it appeared homogenous and then formed into a pile using the front-end loader. The soil was not shredded or otherwise reduced in particle size, as a shredder was not available for use in the study.

A representative sample of the prepared soil was then collected (June 1, 1992) and analyzed to determine contaminants and suitability for use in the study. The parameters analyzed and results for the soil are summarized in Table 1.

Table 1: Soil Feedstock Chemical Characterization (June 1, 1992)

Analyses (Method)	Compounds Detected	Concentration (mg/kg)
base/neutral extractables (GC)	naphthalene (2-ring) 2-methylnaphthalene (2-ring) fluorene (2-ring) acenaphthene (2-ring) phenanthrene (3-ring) fluoranthene (3-ring) pyrene (4-ring) n-nitrodoiphenylamine	47 2.9 7.1 4.9 17 4.4 8.8 6.9
RCRA metals (TCLP)	barium lead silver arsenic (total)	1.2 0.15 0.03 5 µg/L
VOCs (GC)	(see laboratory report for individual compounds)	51.2 (total)
PCBs (GC)	none detected	none detected

Analytical results of the soil sample indicated total PAH compound concentrations of 92.1 mg/kg, total other semi-volatile compound concentration of 6.9 mg/kg, total VOC concentrations of 51.2 mg/kg, and non-hazardous levels of metals (arsenic, barium, lead, and silver). The laboratory report dated July 20, 1992 is provided in Appendix A. It was assumed that PAH compound concentrations at this level (92.1 mg/kg total) would be high enough to allow for the degradation to be evaluated without being masked by the variability inherent in PAH analyses at low concentrations.

The Yard Waste. The yard waste used for the study was from the first run of street collection conducted by the City during the fall of 1991 and consisted predominantly of leaves. The yard waste was stored uncovered at the site in one pile for use in the study the following spring. By spring of

1992, only the upper 6 inches of the material appeared to not have undergone decomposition. On June 1, 1992, the surface of the pile was scraped down to a depth of approximately 6 inches. The scraped material was thoroughly mixed with itself, and then formed into a second pile using the front-end loader.

A representative sample of the second pile was then collected (June 1, 1992) and analyzed to determine contaminants and suitability for use in the study. In addition to establishing the baseline soil conditions for this study, this analysis is also of importance since studies have shown that street collected yard waste can have significant metal concentrations. Of special concern are the metals lead and chromium. The parameters analyzed and results for the yard waste are summarized in Table 2.

Table 2: Yard Waste Feedstock Chemical Characterization (June 1, 1992)

Analyses (Method)	Compounds Detected	Concentration (mg/kg)
base/neutral extractables (GC)	phenols and benzoic acid	57.4 (total)
RCRA metals (TCLP)	barium	1.1
PCBs (GC)	none detected	none detected

Analytical results of the yard waste sample indicated no detectable PAHs, total other semi-volatile compound concentrations of 57.4 mg/kg, and one metal (barium). No other RCRA metals were detected. The laboratory report dated July 20, 1992 is provided in Appendix A.

Static Pile Description. Following preparation and sampling, the soil pile and the yard waste pile were watered using the water truck until they appeared wet to the touch. The front-end loader was then used to combine the soil and the yard waste into five static piles of approximately 25 cubic yards each, as described below:

Static Piles	Yard Waste/Soil Ratio (volume)
A	100:0
B	70:30
C	50:50
D	30:70
E	0:100

Piles A and E served as controls and piles B, C, and D were varied to enable an assessment of the affect which soil ratio has on the composting conditions.

Each pile was again watered using the truck, lifted and dumped three to five times with the loader to mix the materials and then reformed with the loader into static piles. Per Minnesota Pollution Control Agency (MPCA) recommendations for composting yard waste (Worth, 1992), each static pile measured 7 feet in height and twice its height in width (about 14 feet). To reduce the volume of materials that would need to be managed, a length equal to the width was selected, producing piles that were conical in shape.

To establish initial experimental conditions and form the baseline for analyses to evaluate the degradation of PAHs, a representative sample from each static pile was collected (June 1, 1992). The parameters analyzed and results for the static piles are summarized in Table 3.

Table 3: Static Pile Chemical Characterization
(June 1, 1992)

Analyses (Method)	Compounds Detected (concentration in mg/kg)		
base/neutral/acid extractables (GC)	naphthalene (2-ring)	Pile A	-
		Pile B	2.2
		Pile C	-
		Pile D	13
		Pile E	41
	2-methylnaphthalene (2-ring)	Pile A	-
		Pile B	-
		Pile C	5.9
		Pile D	9.1
		Pile E	11
	acenaphthene (2-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	4.0
		Pile E	5.1
	fluorene (2-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	5.0
		Pile E	6.3
	phenanthrene (3-ring)	Pile A	-
		Pile B	-
		Pile C	4.6
		Pile D	14
		Pile E	18
	anthracene (3-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	3.3
		Pile E	3.6
	fluoranthene (3-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	5.7
		Pile E	5.0
	pyrene (4-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	13
		Pile E	22
	benzo(a)anthracene (4-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	-
		Pile E	3.5
	chrysene (4-ring)	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	3.9
		Pile E	4.3
	di-n-butyphthalate	Pile A	6.2
		Pile B	22
		Pile C	73
		Pile D	11
		Pile E	3.3
	n-nitrodoiphenylamine	Pile A	-
		Pile B	-
		Pile C	-
		Pile D	-
		Pile E	4.9
VOCs (GC)	(see laboratory report for individual compounds)	Pile A	-
		Pile B	-
		Pile C	21.2
		Pile D	13.7
		Pile E	53.9
PCBs (GC)		Pile A	-
		Pile B	-
		Pile C	-
		Pile D	-
		Pile E	-

lead (total - AA)		Pile A Pile B Pile C Pile D Pile E	13 70 45 50 63
ash (ignition loss)		Pile A Pile B Pile C Pile D Pile E	7.3% 20% 56% 54% 82%
total carbon		Pile A Pile B Pile C Pile D Pile E	22.8% 10.5% 13.4% 8.7% 4.8%
total kjeldahl nitrogen		Pile A Pile B Pile C Pile D Pile E	14,000 7,000 2,000 2,500 750
pH		Pile A Pile B Pile C Pile D Pile E	8.0 8.2 8.4 8.0 8.0
moisture content		Pile A Pile B Pile C Pile D Pile E	73% 75% 33% 36% 13%

- = compound not detected at or above method detection limit.

Analytical results of the static pile samples indicated total PAH concentrations of 2.2 mg/kg, 10.5 mg/kg, 71 mg/kg, and 119.8 mg/kg for piles B, C, D, and E, respectively. PAHs were not detected in pile A. PAHs detected included the 2- and 3-ring PAHs for piles B, C, D, and E, and the 4-ring PAHs for piles D and E. Also detected in the static pile samples were low levels of total VOCs (from 13.7 to 53.9 mg/kg), and total lead (from 13 to 70 mg/kg). PCBs were not detected. The composting parameters analyzed (carbon/nitrogen ratio, moisture pH, and percent ash) are discussed in Section B.5. of this document. The laboratory report dated July 20, 1992 for the static pile samples is provided in Appendix A.

Data for the sample from pile E (100 percent soil) was generally consistent with the data for the soil feedstock sample. However, total concentrations of PAHs were slightly higher, and several PAHs (anthracene, chrysene, and benzo(a)anthracene) which were not detected in the soil feedstock sample were detected in the sample from pile E.

Monitoring, Sampling and Turning/Watering. Monitoring, sampling for chemical analyses, and turning/watering activities were conducted for each pile, as indicated in Table 4.

Table 4: Monitoring, Sampling and Turning/Watering Activities

Frequency	Activity
Twice per week (Tuesday and Friday)	Temperatures recorded Sample collected for analysis of moisture content Turned and watered
Once per week (Tuesday)	Sample collected for analysis of pH Oxygen content*
Once every two weeks (Tuesday)	Sample collected for analysis of: • total carbon • total nitrogen • VOCs (GC) • PCBs (GC) • base/neutral/acid extractables (GC/MS) • ash (ignition loss)
Quarterly (Tuesday)	Sample collected for analysis of base/neutral/acid extractables (GC/MS)

* Attempts were made to measure oxygen content of the piles weekly using a Gastech meter and inserting the probe into a preformed hole in the center of each pile. However, the readings could not be repeated and this appeared not to be representative of the mass soil air voids, and thus, oxygen measurements were ceased.

The results of these activities were used to make procedural changes in an effort to optimize the composting process. Procedural changes made included increasing the volume of water additions. Temperatures were recorded and samples were collected for analyses of moisture content, pH, total carbon, total nitrogen and ash to monitor the composting condition of the piles. Samples were collected for analyses of base/neutral/acid extractables, and VOCs to monitor the degradation of the contaminants. The piles were turned and watered in an effort to optimize the composting process. Turning and watering were conducted at a frequency of twice per week per MPCA recommendations for composing yard waste (Worth, 1992).

The piles were monitored, sampled, and then turned/watered in consecutive order beginning with pile A and ending with pile E. Temperatures were recorded at three locations for each pile (top, middle, bottom) using the thermometer driven approximately 1.5 feet from the surface of each pile into each pile. Sampling for chemical analyses was conducted using the soil auger driven approximately 3 feet from the surface of each pile into the middle of each pile. Turning and watering consisted of thin-spreading, watering until moist or wet to the touch, and reforming each pile.

The analytical results for base/neutral/acid extractables and VOCs for the soil samples are summarized in Table 5. PCBs were not detected. Temperatures and analytical results for composting parameters (moisture content, pH, carbon/nitrogen ratio, and ash) are discussed in Section B.5. of this document. The laboratory reports date June 22, 1992 through October 26, 1992 are provided in Appendix A.

Table 5: Static Pile Chemical Analyses
(June 16, 1992 through October 13, 1992)

Analyses (method)	Compounds Detected (Concentration in mg/kg)												
base/neutral/acid extractables (GC/MS)			Date (Week of Study)										
			6/16/92 (3)	6/30/92 (5)	7/14/92 (7)	7/28/92 (9)	8/04/92 (10)	8/11/92 (11)	8/25/92 (13)	9/3/92 (15)	9/22/92 (17)	10/6/92 (19)	10/13/92 (20)
	naphthalene (2-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	19	2.4	2.6	1.2	-	-	-	-	-	-	-
		Pile C	-	9.0	3.9	3.6	-	1.7	-	-	-	-	-
		Pile D	180	11	8.6	-	-	1.8	1.2	-	-	-	-
		Pile E	29	12	4.8	6.0	-	-	1.3	1.1	-	-	-
	2-methylnaphthalene (2-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	8.4	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	-	-	-	-	-	-	-	-
		Pile D	4.6	-	-	-	-	-	-	-	-	-	-
		Pile E	3.3	-	-	-	-	-	-	-	-	-	-
	fluorene (2-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	-	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	-	-	-	-	-	-	-	-
		Pile D	-	-	-	-	-	-	-	-	-	-	-
		Pile E	-	-	-	-	-	-	-	-	-	-	4.8
	phenanthrene (3-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	3.7	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	4.0	-	-	-	-	-	-	-
		Pile D	5.1	-	-	-	-	3.8	-	-	-	-	-
		Pile E	6.1	6.6	-	-	-	-	-	-	-	-	-
	fluoranthene (3-ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	-	-	-	-	-	-	-	-	-	-	-
		Pile C	-	-	-	-	-	-	-	-	-	-	-
		Pile D	-	-	-	-	-	3.5	-	-	-	-	-
		Pile E	4.0	-	-	-	-	-	-	3.7	-	-	-
	pyrene (4 ring)	Pile A	-	-	-	-	-	-	-	-	-	-	-
		Pile B	-	-	-	-							
		Pile C	5.5	6.0	-	6.0	3.3	-	-	-	-	-	-
		Pile D	5.3	5.5	-	-	5.0	3.7	-	3.7	-		-
		Pile F	9.1	9.3	-	5.1	8.5	4.1	3.9	7.7	3.3	-	5.6
	di n butylphthalate	Pile A	NA	6.6	NA	NA	-	NA	NA	-	NA	NA	16
		Pile B	NA	-	NA	NA	4.3	NA	NA	-	NA	NA	12
		Pile C	NA	35	NA	NA	-	NA	NA	5.9	NA	NA	4.3
		Pile D	NA	-	NA	NA	30	NA	NA	-	NA	NA	10
		Pile E	NA	-	NA	NA	-	NA	NA	6.5	NA	NA	11
	n nitrodoiphenylamine	Pile A	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile B	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile C	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile D	NA	-	NA	NA	-	NA	NA	-	NA	NA	-
		Pile E	NA	-	NA	NA	3.7	NA	NA	-	NA	NA	-
VOCs (GC)	(see laboratory reports for individual compounds)	Pile A	0.3	0.8	-	-	-	-	-	-	-	-	-
		Pile B	24.1	-	-	-	-	-	-	-	-	-	-
		Pile C	7.3	3.4	1.6	-	-	-	-	-	-	-	-
		Pile D	40.6	3.9	11.9	0.2	-	-	-	-	-	-	-
		Pile E	48.9	9.7	-	1.7	-	-	0.3	-	-	-	-

- = Compound not detected at or above method detection limit.
NA = Compound not analyzed.

At the conclusion of the 21-week field study, a sample was collected (October 20, 1992) from each pile. The parameters analyzed and results are summarized in Table 6. The laboratory report dated November 17, 1992 is provided in Appendix A.

Table 6: Static Pile Final Chemical Characterization
(October 20, 1992)

Analyses (method)	Compounds Detected (Concentration in mg/kg)	
base/neutral/acid extractables (GC)	Pile A	-
	Pile B	-
	Pile C	-
	Pile D	-
	Pile E	-
VOCs (GC)	Pile A	-
	Pile B	-
	Pile C	-
	Pile D	-
	Pile E	-
PCBs (GC)	Pile A	-
	Pile B	-
	Pile C	-
	Pile D	-
	Pile E	-
RCRA metals (TCLP)	Pile A	arsenic (52 µg/L), barium (0.59)
	Pile B	arsenic (5 µg/L), barium (0.89)
	Pile C	arsenic (4 µg/L), barium (0.71)
	Pile D	arsenic (3 µg/L), barium (0.66)
	Pile E	- , barium (0.84)
lead (total - AA)	Pile A	27
	Pile B	48
	Pile C	54
	Pile D	60
	Pile E	72
ash (ignition loss)	Pile A	83%
	Pile B	84%
	Pile C	88%
	Pile D	89%
	Pile E	94%
total solids	Pile A	48%
	Pile B	67%
	Pile C	77%
	Pile D	78%
	Pile E	84%
total volatile solids	Pile A	16%
	Pile B	16%
	Pile C	10%
	Pile D	7.6%
	Pile E	3.9%
total carbon	Pile A	17%
	Pile B	9.4%
	Pile C	7.1%
	Pile D	6.5%
	Pile E	4.1%
total kjeldahl nitrogen	Pile A	4,400
	Pile B	2,600
	Pile C	2,000
	Pile D	1,300
	Pile E	430
pH	Pile A	8.1
	Pile B	7.9
	Pile C	8.1
	Pile D	7.7
	Pile E	7.8
ammonia as N	Pile A	7.4
	Pile B	1.9
	Pile C	0.49
	Pile D	0.49
	Pile E	0.49
nitrate as N	Pile A	14
	Pile B	4.9
	Pile C	1.4
	Pile D	1.0
	Pile E	1.0
moisture content	Pile A	52%
	Pile B	33%
	Pile C	23%
	Pile D	22%
	Pile E	16%

A.3. Budget

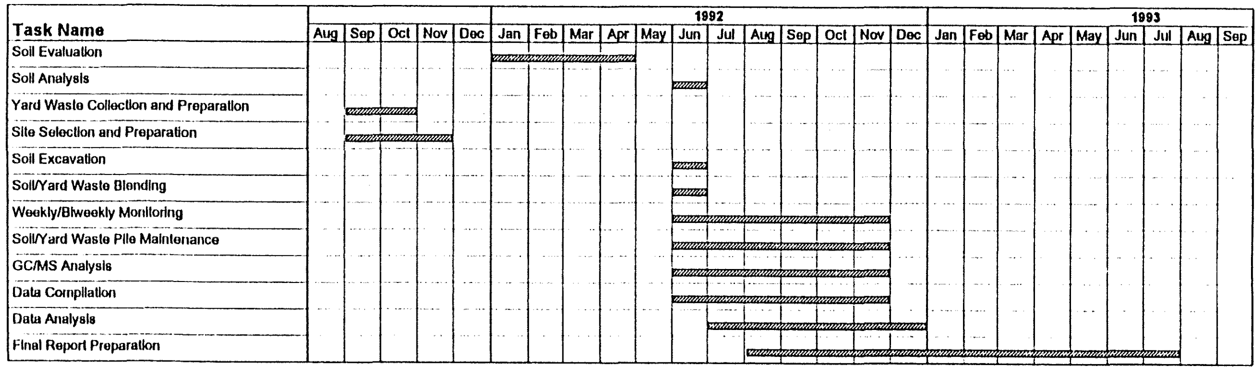
		LCMR Funds	Matching Funds
a.	Amount Budgeted:	$110,000	$2,000
b.	Balance:	$0	$2,000

The amount budgeted for this project is $112,000, $110,000 of which is requested from the LCMR. The remaining $2,000, necessary for construction and maintenance of the compost piles, will be funded by the Minneapolis Community Development Agency.

The balance as of July 1, 1993 was $0.

A.4. Timeline for Study

The schedule for this study was limited by the date on which funding became available and the season during which large quantities of street sweepings become available. Once funding became available, efforts began to identify a suitable soil for treatment. Collection of street sweepings took place during fall, 1991. The yard waste was stockpiled for the winter months. June 1, 1992, contaminated soil was excavated and blended with the yard waste. Composting took place over a 21-week period from June 1, 1992 through October 20, 1992.



A.5. Status.

Results. Analytical data for the soil feedstock characterization, and static pile characterization and monitoring were used to construct Figures 1 and 2 which show the rate of disappearance (degradation) of total PAH compounds and of total volatile organic compounds (VOCs), respectively, as measured in solvent extract from samples collected.

Figure 1: Relationship of PAH Concentration/Time

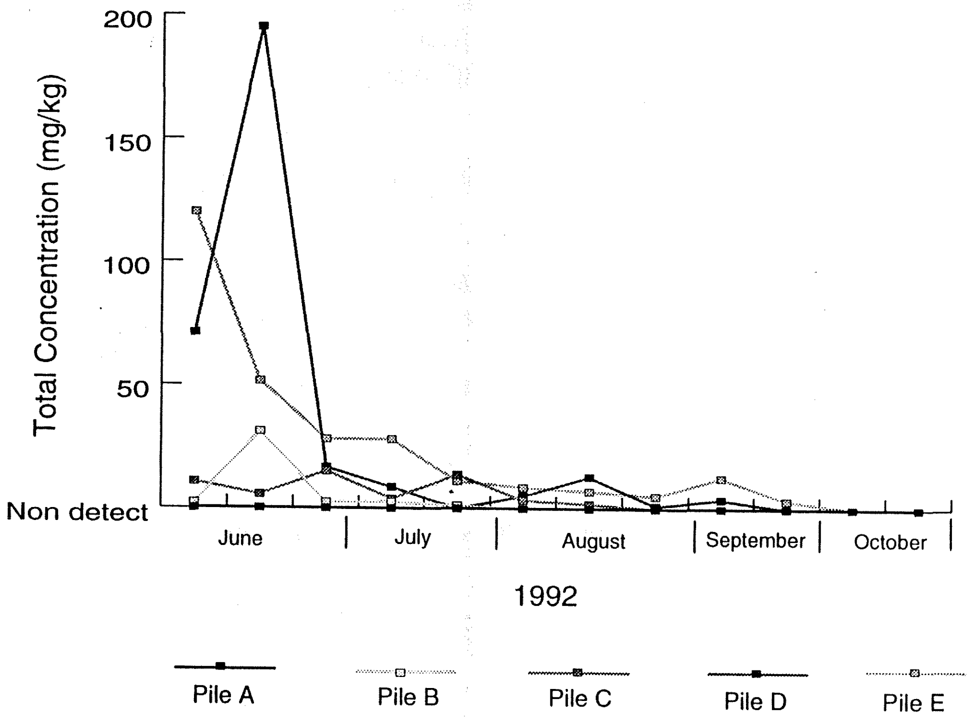
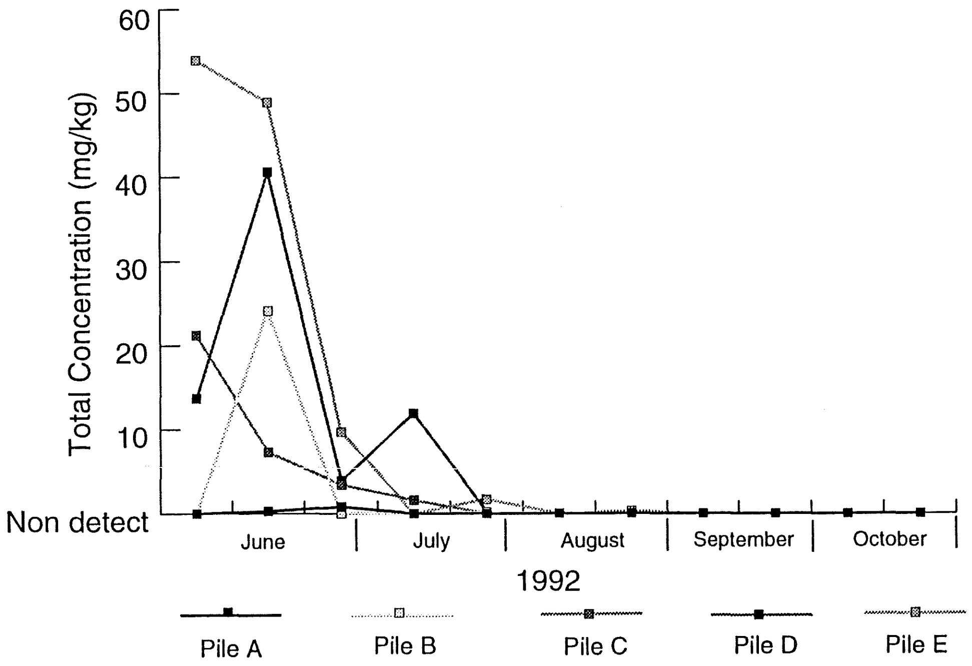


Figure 2: Relationship of VOC Concentration/Time



The total concentration of extractable PAHs (2- to 4-ring) were reduced by 100 percent over the duration of field study (21 weeks). About 90 percent of the decrease in the total concentration of extractable PAHs occurred during the first nine weeks of the study, as did about 100 percent of the decrease in the total concentration of extractable VOCs. During the initial nine weeks following construction, the reduction in total PAHs was 100 percent for piles B and C, 98 percent for pile D, and 95 percent for pile E. The feedstock ratio did not affect the extent of degradation of the PAH (or volatile organic) compounds. Increasing the soil content appeared to decrease the rate of degradation of the PAH (and volatile organic) compounds slightly.

PAH compounds that were evaluated (i.e., present in the piles) included:

- naphthalene (2-ring) (piles B,C,D,E);
- 2-methylnaphthalene (2-ring) (piles B,C,D,E);
- phenanthrene (3-ring) (piles C,D,E);
- fluoranthene (3-ring) (piles D,E); and
- pyrene (4-ring)(piles C,D,E).

Several, PAH compounds were detected for the pile characterization, but not afterwards during the monitoring including:

- acenaphthene (2-ring) (detected at 4.0 and 5.1 mg/kg, piles D and E, respectively)
- fluorene (2-ring) (detected at 5.0 and 6.3 mg/kg, piles D and E, respectively)
- anthracene (3-ring) (detected at 3.3 and 3.6 mg/kg, piles D and E, respectively)
- benzo(a)anthracene (4-ring) (detected at 3.5 mg/kg, pile E)
- chrysene (4-ring) (detected at 3.9 and 4.3 mg/kg, piles D and E, respectively)

The concentration of metals for the piles did not change over the 21-week study period.

Discussion. As discussed earlier (Section II.A.1.), 2- to 3- ring PAHs will volatilize (or strip) from soil due to aeration and low heat. The similar patterns apparent between PAH and VOC degradation for the piles suggests that the PAHs may have been volatilized (or stripped). The variability apparent in the data suggests that the mixing and blending of the feedstock and the turning of the piles may need to be greater.

A.6. Benefits.

As discussed earlier (Sections I.A. and I.B.), if effective at remediating PAHs in soil, composting may:

- offer an additional approach to the existing options for remediating semi-volatile compound contaminated soil at a site;

- offer significant economic and technical advantages over the most commonly used options of semi-volatile remediation (incineration or land-spreading); and

- facilitate the cleanup of semi-volatile-contaminated sites and ultimately the recycling of contaminated properties into inhabitable, tax paying property.

~~Results from this study can be used with large scale composting projects as a potential outlet for treating soil contaminated with semi-volatile compounds. Co-composting may prove to be a relatively low-cost, easy to implement remedial technology which can be performed at a variety of sites using virtually any amount of contaminated soil.~~

A.7. Costs. Discussed under Section B.7.

B. Objective 2: COMPOSTING

B.1. Narrative.

The secondary objective of this project was to optimize conditions for composting to produce a usable end product from yard waste. Composting condition was expressed in terms of the temperature, moisture content, carbon/nitrogen ratio, pH, and percent decomposition (maturity) of the end products.

In the composting process, there are essentially six parameters which are essential for providing the optimum conditions for microbial activity. The optimal compost environment is characterized by controlled temperatures (90°F to 140°F), balanced nutrients (carbon:nitrogen 30:1), consistent moisture level (50 to 60 percent by weight), sufficient aeration and oxygen content (>5 percent), and near neutral pH (6 to 8). Continuous microbial activity will occur if the temperature, carbon/nitrogen ratio, moisture, aeration, pH, and mixing and blending of the feedstock is balanced until a mature product is obtained. Under optimal conditions, microbes will quickly biodegrade organics. In a less than optimal compost environment, biodegradation will occur at a slower rate and a longer time period will be required to achieve a mature product. The importance of each of these parameters is discussed below.

Temperature. For low-tech yard waste composting processes, temperature could be considered the most important parameter to monitor and is easily measured. Temperature can indicate the excess or deficiency of the other six variables and is an excellent reflection of the microbial activity that is taking place. Maintaining satisfactory temperature range is essential to providing a thermal environment which is beneficial to the microbes consumption of organic matter, air and water. Sustaining a temperature of 113°F (45°C) optimizes the microbial activity, thus decreasing the time needed for the bio-conversion of the feedstock into stable product.

Temperatures will rise quickly at the beginning of a composting process as the microbes digest easily accessible organic matter. Upon depletion of the easily accessible sugars, starches, amino acids, and proteins, the microbes will begin acting on the remaining complex compounds which break down slowly. This is likely when the microbes would begin biodegradation of the 2- and 3-ring PAHs followed by the 4- and 5-ring PAH compounds. If one of the above-mentioned parameters has not been satisfied, the temperature climb will be gradual, and the time required to achieve a mature product will be extended.

The destruction of pathogens and weed seed is an important aspect of the thermodynamics of the composting process. When using a static pile, it is suggested that a temperature of 131°F (55°C) be maintained within the pile for a period of at least 21 consecutive days to destroy pathogens and weed seeds. This temperature and time factor results in meeting pathogen control standards commonly referred to as PFRP (Process to Further Reduce Pathogens).

Carbon to Nitrogen Ratio. Microorganisms require organic compounds to form cellular material for growth and reproduction. The carbon content of these materials is the major energy source for microorganisms. Because microorganisms cell mass is approximately 50 percent carbon and 8 percent nitrogen, attention to the C/N ratio is a key factor in determining how rapidly a material will decompose. A 10:1 carbon to nitrogen ratio is typically found in mature microbes and is also found in mature soil. Achieving a 10:1 ratio in a compost pile after a period of time is an indicator of a mature, and stable compost material. The greater the imbalance between the C/N ratio, the lower the metabolic rate of the microbes. Because microbes are less than 100 percent efficient, it has been found that they must take in about three times as much carbon as they actually incorporate into their cells. Thus, a 30:1 soil carbon to nitrogen ratio (available nutrients) presents the ideal conditions for the microbes. Feedstocks for a compost are most often selected and combined so as to obtain a 30:1 carbon to nitrogen ratio. After composting is initiated, nitrogen can be added in controlled amounts in the form of urea.

A nitrogen deficiency (C/N ratio greater than 40:1) or too little carbon in relation to nitrogen (C/N ratio less than 30:1) will result in a slower rate of biodegradation, lower temperatures and an additional time period to achieve a mature product. The C/N ratio decreases as composting progresses due to the conversion of organic carbon to carbon dioxide, which is released from the compost pile.

Moisture. Microorganisms require moisture to dissolve nutrients and to provide a suitable environment for their growth. Organic contaminants that are adsorbed into the soil matrix are not available for biodegradation until desorbed into the soil-water matrix. Water, like nitrogen, is added in controlled amounts. Moisture is perhaps the most important parameter to be determined and controlled. The optional moisture content is 55 percent by weight. During the early phases of the composting process, moisture losses can be as significant as 5 to 7 percent per day. Thus, a feedstock having a moisture content of 60 percent on Monday could have a moisture deficient atmosphere (<45 percent) by Friday. For this reason, rapid moisture determination followed by quick moisture adjustments are important.

In a moisture deficient environment (< 45 percent moisture by weight), bacteria will begin to go dormant or die. This results in a slower rate of biodegradation, lower temperatures, and an additional time period to achieve a mature product. Colonies of fungi and actinomycetes, which are less active consumers in the compost environment, are more prevalent in and tolerant of host materials having low moisture contents. Excess moisture (>50 to 60 percent moisture by weight), decreases the proportion of pore space available for oxygen and an oxygen deficient environment (<5 percent oxygen) may result. Though this condition may enhance nutrient movement and breakdown of the structure of certain materials, this condition retards air movement. In such an environment, anaerobic microorganisms increase in number. The metabolism of the anaerobic microbes is slower than that of the aerobic microbes resulting in a slower rate of biodegradation (lower temperatures), and an additional time period to achieve a mature product. Also, end products of anaerobic respiration include methane and odorous compounds such as hydrogen sulfide and phytotoxins (toxic to plants).

Aeration. Microorganisms require oxygen to support aerobic biological activity. Aeration of the feedstock is required, which allows for the removal of heat, carbon dioxide, moisture, phytotoxins and volatile organic compounds. Aerations function in controlling the heat necessary for pathogen and weed seed destruction and is essential in providing a safe product. The oxygen requirement of the biomass is dependent on the rate of biodegradation (the higher the rate, the greater the oxygen requirement) and is determined by the moisture content of the feedstock. Biodegradation is most efficient at 113°F (45°C), which is at the upper end of the mesophilic temperature range (68°F to 113°F) and the lower end of the thermophilic range (113°F to 160°F). It is essential that adequate aeration be supplied to optimize the microbial activity. A relationship exists between oxygen consumption which is an indication of microbial activity and temperature. As temperatures increase from 50°F to 113°F, the oxygen demand of the microbial colonies rapidly increases. Increasing temperatures above 122°F, up to 176°F results in a rapid decrease in microbial activity and oxygen demand.

The optimum oxygen measurement in an active compost pile would be >5 percent oxygen content. If the oxygen content falls below 5 percent, the process can become anaerobic, resulting in a slower rate of biodegradation and the generation of phytotoxins and odors. This oxygen-starved condition can occur as soon as 15 minutes after turning a static pile or the turning off of blowers in a forced aeration system.

pH. The pH of a compost environment is generally self-adjusting, and is a function of the end products that are being formed from the composted materials. A pH of between 6 and 8 is generally considered ideal for composting. As is the case of temperature and the C/N ratio, the pH of the compost varies with time during the composting process and is a good indicator of the extent of organic decomposition within the pile. In general, in the initial stages of decomposition, soluble carbohydrates are decomposed first and the pH drops below neutrality (pH 7), followed by proteins causing the pH to gradually rise. The decomposition of PAHs and VOCs produces organic acids too weak to measurably influence the pH.

Mixing and Blending. These physical parameters may be enhanced through feedstock selection, feedstock particle size reduction, and turning the matrix during the composting. Turning equalizes temperature, moisture, nutrients, and pH within the matrix, prevents the channeling of air and the caking of the mass, and reoxygenates the mass.

B.2. Procedures. Discussed in Section A.2..

B.3. Budget. The budget for this portion of the project has been included in the figure provided in Section A.3.

B.4. Timeline. See A.4. above.

B.5. Status

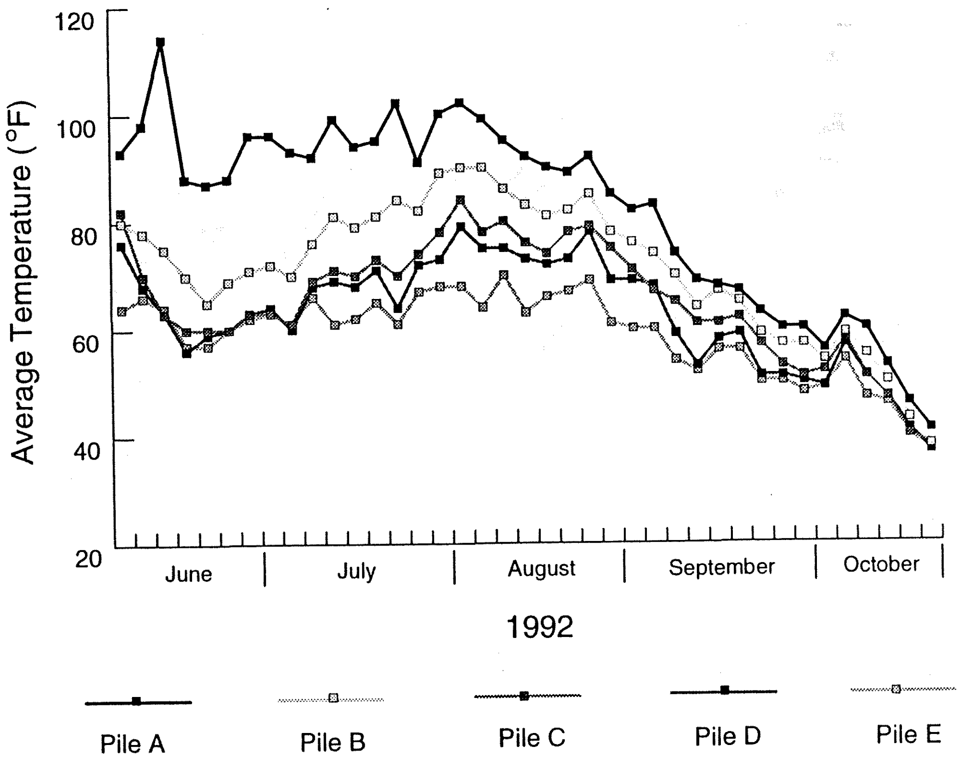
Results.

Static Pile Characterization. Analytical results of static pile characterization samples (collected following static pile construction) indicated that the conditions for composting at the start of the field study were not optimized to facilitate the rapid biodegradation of the organics of the piles. Specifically, piles A and B had too little carbon in relation to nitrogen (16:1 and 15:1, respectively); and piles C and E were nitrogen deficient (67:1 and 64:1, respectively). Pile D had a ratio of 35:1 which is within the acceptable range. The moisture contents were deficient for C, D and E (33 percent, 36 percent, 13 percent, respectively) and slightly above ideal for piles A and B (73 percent and 75 percent, respectively). The pH of the piles ranged between 8.0 and 8.4, which is within the exceptable range.

Static Pile Monitoring.

Temperature Readings. Figure 3 shows the change in the average value of the top, middle, and bottom temperatures recorded for each pile over the 21 weeks of the field study.

Figure 3: Relationship of Average Temperature/Time

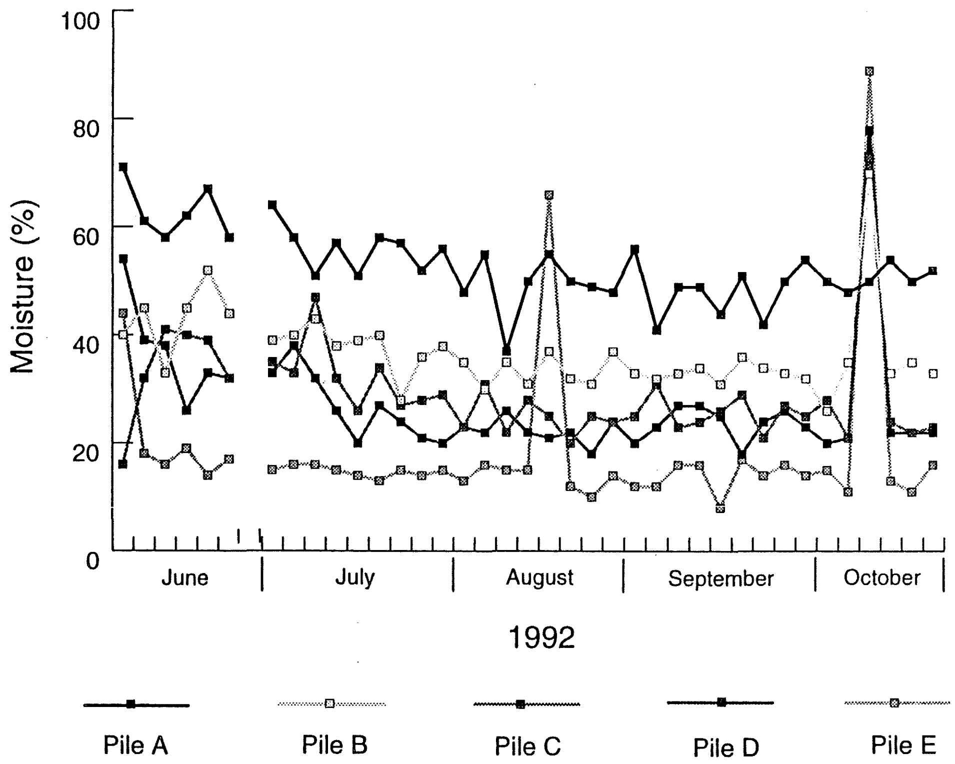


Temperature readings of the piles showed a quick increase from ambient during the first few days, a slight decrease through the 18th day, followed by a slower rate of increase during the following 12 weeks, and a steady decrease throughout the remaining eight weeks of the study. Temperatures were consistently highest in pile A and then B, followed by C, D and E in order of decreasing temperature (i.e. the average temperature was observed to decrease with increasing soil/yard waste ratio).

In general, piles A and B maintained temperatures sufficient to support mesophilic biodegradation until the 19th week of the 21-week study period, and piles C, D, and E maintained temperatures sufficient to support mesophilic biodegradation through the 17th week of the study, after which time temperatures were consistently below 50°F. Only pile A approached optimal temperature for microbial activity (113°F) and only on the 16th day following construction.

Moisture Contents. Figure 4 shows the change in moisture content for each pile over the 21 weeks of the field study.

Figure 4: Relationship of Moisture Content/Time



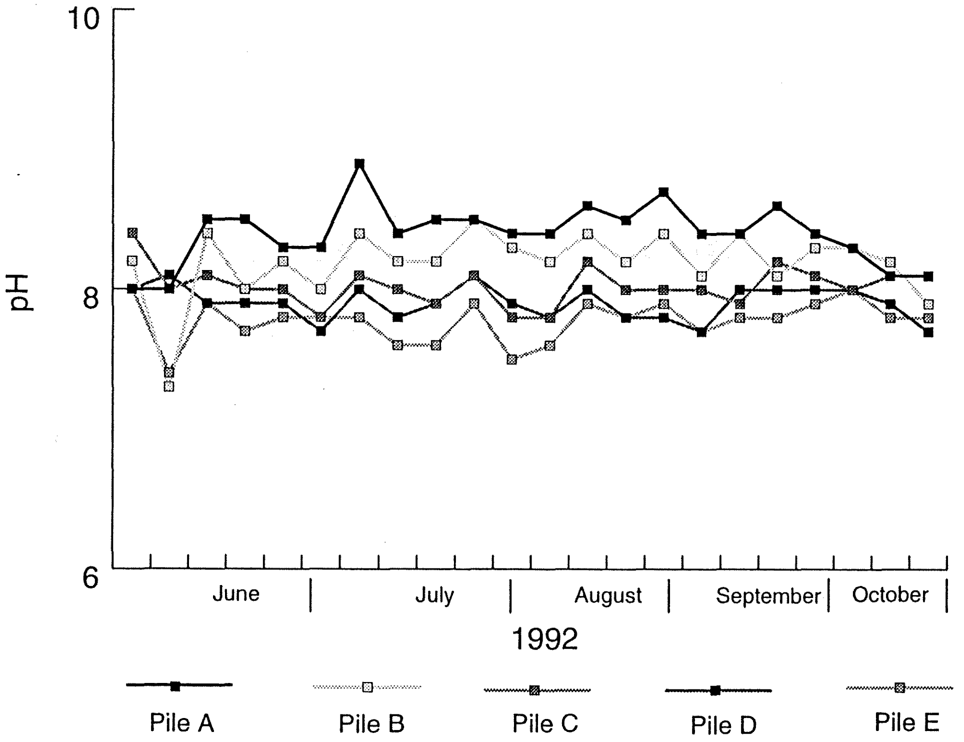
Moisture contents of the piles were relatively constant, and were consistently highest for piles A followed by B, C, D, E in order of decreasing moisture content (i.e. the moisture content was observed to decrease with increasing soil/yard waste ratio).

Only pile A maintained moisture levels sufficient to support microbial activity (50-60% moisture by weight). Piles B, C, D, and E had moisture levels deficient for microbial activity (less than 45% moisture by weight). This occurred despite the increased additions of water added to the piles throughout the study.

Only pile A maintained moisture levels sufficient to support microbial activity (50-60% moisture by weight). Piles B, C, D, and E had moisture levels deficient for microbial activity (less than 45% moisture by weight). This occurred despite the increased additions of water added to the piles throughout the study.

pH. Figure 5 shows the change in pH for each pile over the 21 weeks of the field study.

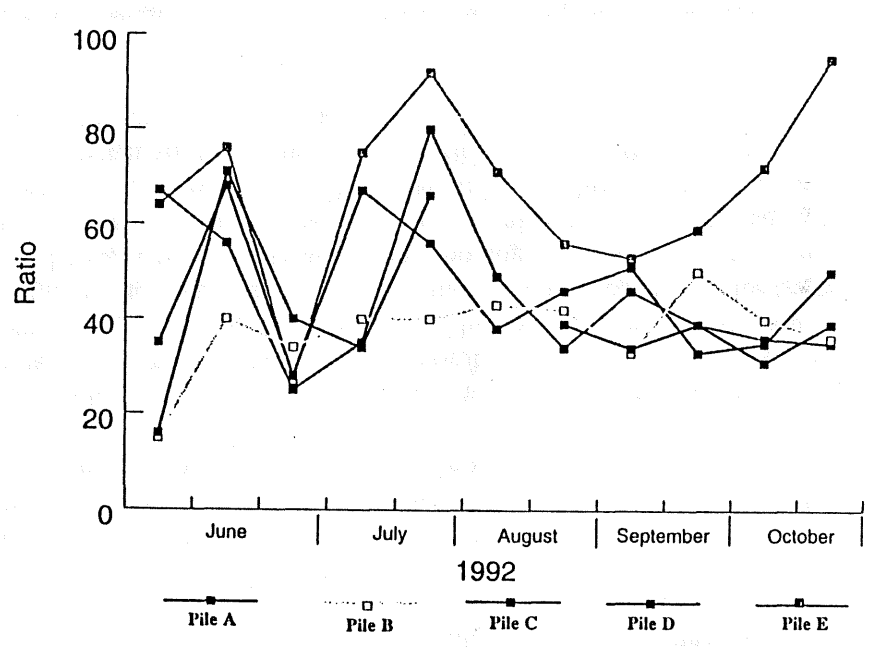
Figure 5: Relationship of pH/Time



The pH measurements of the piles were relatively constant, and were generally highest for pile A, followed by B, C, D and E in order of decreasing pH (i.e., the pH was observed to decrease with increasing soil/yard waste ratio). The piles maintained pHs sufficient to support microbial activity (pH between 6 and 8).

Total Carbon, Total Nitrogen, and C/N Ratio. Figure 6 shows the change in the C/N ratio for each pile over the 21 weeks of the field study.

Figure 6: Relationship of C/N Ratio/Time



The C/N ratio of the piles slightly increased in a random fashion, and was generally highest for E, followed by D, C, B, and A in order of decreasing C/N ratio (i.e. the C/N ratio was observed to increase with increasing soil/yard waste ratio).

The piles maintained C/N ratios detrimental to optimizing microbial activity (greater than 40:1). The C/N ratio for D and E indicated a nitrogen deficiency and the ratios for A, B and C indicated near deficient conditions.

Maturity. A mature compost has been defined by the Minnesota Pollution Control Agency (MPCA) as compost where more that 60 percent decomposition (percent volatile solids reduction) has been achieved as determined by an ignition-loss analysis (percent ash). The MPCA is using the following formula to determine percent decomposition.

$$\text{Decomposition (\%)} = \frac{VSF - VSP}{VSF - (VSF \times VSP)} \times 100$$

VSF = the decimal fraction of volatile (i.e, organic) solids in the compost materials prior to composting

VSP = the decimal fraction of volatile solids in the final compost product

The percent decomposition, as calculated from ignition-loss analysis, of the piles was 6 percent (pile A), 4 percent (pile B), 1 percent (piles C and D), and <1 percent (pile E), all of which were far less than the 60 percent decomposition of a "mature" compost.

Discussion. Conditions for composting were not optimized to facilitate the rapid biodegradation of the organic constituents of the piles and a usable ("mature") end product was not produced from yard waste. During the study period, temperatures within the piles were sufficient to support mesophilic microorganisms (> 50°F), but remained below levels required to support thermophilic microbial colonies (113°F) indicating reduced microbial activity and biodegradation of the organics. Except for pile A (100 percent yard waste), moisture levels were near consistently deficient (< 50 percent by weight) to support microbial activity. The imbalance of carbon to nitrogen would likely not have seriously impeded the composting process if satisfactory moisture levels were maintained. These data suggest that the piles may have not been large enough to maintain temperatures in the thermophilic range necessary for active composting. The occurrence of moisture deficiencies despite the increased volumes of water added throughout the study suggests the need for a more effective method of moisture application. A quicker method of moisture determination would allow for the additions to be quantified and to better meet immediate moisture requirements.

The data identifies that as the soil to yard waste ratio increased, the conditions for each parameter were less favorable and the calculated percent decomposition (maturity) decreased. This observation and the variability apparent in the data suggest that the mixing and blending of feedstocks to assure definable proportions and a more homogenized mixture may be needed. In addition, the texture and structure of the piles having greater soil content than yard waste may not have been favorable to obtain optimum aeration or moisture penetration. This would further suggest the need for a more elaborate approach to mixing and blending.

B.6. Benefits.

~~This aspect study should provide "real world" experience in composting of yard waste under Minnesota weather conditions. While there is considerable information on the theory of composting and the operating conditions which provide optimum composting conditions, this study will document variations in composting techniques which are used to achieve optimum conditions of oxygen, temperature, moisture, and nutrient ratio.~~ If a useable product from yard waste could be produced when composted with soil, an additional outlet for yard waste could result.

B.7. Costs.

a. Initial Testing

Compost sample from each pile, five samples

Initial base/neutral extractables (GC)	2 ~~1~~ smpl @ $399.50 = 799.00 ~~399.50~~
Initial VOCs (GC)	1 1 smpl @ $148.75 = 148.75
Initial PCB (GC)	2 1 smpl @ $123.25 = 246.50 ~~123.25~~
Initial 8 RCRA metals (TCLP)	2 ~~1~~ smpl @ $243.50 = 487.00
Initial total volatile solids	2 smpl @ $15.00 = 30.00
VOCs (GC)	5 smpl @ $148.75 = 743.75
PCB (GC)	5 smpl @ $123.25 = 616.25
PAH (GC/MS)	5 smpl @ $382.50 = 1,912.50
lead (total-AA method)	5 smpl @ $141.50 = 707.50
pH	5 smpl @ $8.50 = 42.50
moisture content	5 smpl @ $12.75 = 63.75
ignition loss	5 smpl @ $15.30 = 76.50
total carbon	5 smpl @ $29.75 = 148.75
total nitrogen	5 smpl @ $48.45 = 242.25
C/N ratio (calculation)	
base/neutral/acid extractables (GC/MS)	5 smpl @ $382.50 = 1,912.50
Subtotal	**$8,177.50** ~~$7,381.25~~

b. Process Monitoring

Moisture content (samples taken to the lab) and temperature will be monitored two times per week. Oxygen content and pH will be monitored once per week.

Moisture content and temperature	39 events X 5 smpl @ $17.00	$3,315.00
Oxygen content	19 events X 2 hrs @ $15.00	570.00
pH	19 events X 5 smpl @ $8.50	807.50
Subtotal		**$4,692.50**

c. Periodic Sampling

Compost sample from each pile, five samples every two weeks for 20 weeks, total of 45 samples and compost sample from each pile, five samples quarterly.

VOCs (GC)	45 smpl @ $148.75	$6,693.75
PCB (GC)	45 smpl @ $123.25	5,546.25
PAH (GC/MS)	45 smpl @ $382.50	17,212.50
ignition loss	45 smpl @ $15.30	688.50
total carbon	45 smpl @ $29.75	1,338.75
total nitrogen	45 smpl @ $48.45	2,180.25
C/N ration (calculation)		
base/neutral/acid extractables (GC/MS)	20 smpl @ $382.50	7,650.00
Subtotal		**$41,310.00**

d. Final Testing

Compost sample from each pile, five samples total

VOCs (GC)	5 smpl @ $148.75	743.75
PCB (GC)	5 smpl @ $123.25	616.25
PAH (GC/MS)	5 smpl @ $382.50	1,912.50
pH	5 smpl @ $8.50	42.50
moisture content	5 smpl @ $12.75	63.75
8 RCRA metals (TCLP)	5 smpl @ $243.50	1,217.50
lead (total-AA method)	5 smpl @ $141.50	707.50
ignition loss	5 smpl @ $15.30	76.50
total carbon	5 smpl @ $29.75	148.75
total, ammonia, nitrate nitrogen	5 smpl @ $75.25	376.25
total and volatile solids	5 smpl @ $51.00	255.00
inorganic ions (K and P)	5 smpl @ $48.90	244.50
base/neutral/acid extractables	5 smpl @ $382.50	1,912.50
dry weight percent	5 smpl @ $15.00	75.00
Subtotal		**$8,392.25** **~~$8,317.25~~**

Analytical Total **$62,572.25** **~~$61,701.00~~**

e. Sampling and Coordination

Per week:		
Technician	10 hours @ $58	580
Project Manager	2 hours @ $63	126
	Per week	**706**
	Project duration	**14,120**
Initial set-up:		
Technician	12 hours @ $58	696
Project Manager	15 hours @ $63	945
Laboratory Person	5 hours @ $60	300
Subtotal		**$16,061**

f. Project Management & Report Preparation

Technician	40 hours @ $58	2,320
Project manager	180 hours @ $63	11,340
Supervisor	40 hours @ $85	3,400
Principal	20 hours @ $130	2,600
Clerical	20 hours @ $43	903
Subtotal		**$20,563**

g. Meetings & Presentations

Technician	8 hours @ $58	464
Project manager	24 hours @ $63	1,512
Supervisor	12 hours @ $85	1,020
Principal	16 hours @ $130	2,080
Clerical	12 hours @ $43	516
Subtotal		$5,592

h. Expenses/Other

Subtotal	**$5,211.75** **~~$6,083~~**
PROJECT TOTAL	**$110,000**

IV. EVALUATION

~~During the course of the study, the compost piles will be monitored for parameters which are indicative of the rate of composting, such as oxygen, carbon/nitrogen ratio, and temperature. This information will be used to take steps to optimize the rate of decomposition. At the conclusion of the study, experimental results will be summarized graphically and in text form. Significant parameters which will have been monitored during the course of the study will be graphed over time to track their disappearance and/or formation. The report will identify compounds which appear to be critical for assessing the disappearance of PAH and will offer opinions, where possible, of the significance of these compounds. The data will be plotted over time to show the breakdown over time and the relative breakdown among the various windrows with different leaf soil ratios. At the conclusion of the project, the data will be used to assess the optimum conditions for breakdown of contaminants, and to provide information necessary to design further research projects.~~

Soil contaminated with low levels of 2- to 4-ring PAHs mixed with yard waste in small static piles experienced a reduction in the total concentration of extractable 2-to 4-ring PAH compounds 100 percent within approximately 21 weeks under the conditions of this study. About 90 percent of this decrease occurred during the first nine weeks of the study period. The ratio of the feedstocks did not affect the extent of degradation of the PAH compounds. Increasing soil content appeared to decrease the rate of degradation of the PAH compounds only slightly.

Review of data for the monitored parameters and the calculated percent decomposition (maturity) of the end products indicated that conditions for compositing were not optimized to facilitate the rapid biodegradation of the organic constituents of the piles, and a mature end product was not produced. Temperatures within the piles, while sufficient to support mesophilic microorganisms, remained below levels sufficient to support thermophilic microbial colonies, indicating reduced microbial activity and biodegradation of the organics. The slight increase in temperatures may have increased the volatilization of the PAHs. The slow composting process, calculated percent decomposition, and the available carbon source which is identified by the end product C/N ratio would indicate the microbes did not act on the PAH compounds. As suggested earlier, the microbes would most likely act first on the easily accessible carbon sources (sugars, starches, proteins), and then seek out the 2-and 3-ring PAHs followed by the more complex and stable 4-ring PAHs.

The study data suggest:

- the mixing and blending of feedstocks to assure definable proportions and a more homogenized mixture may be needed. In addition, the texture and structure of the piles having greater soil content than yard waste may not have been favorable to obtain optimum aeration or moisture penetration, further suggesting the need for a more elaborate approach to mixing and blending;
- the piles may not have been large enough to maintain temperatures in the thermophilic range necessary for active composting; and
- the need for improved moisture application and quicker moisture determination.

Perhaps for future experiments of this type, it would be best to proportion and otherwise prepare the piles so as to optimize conditions for composting. This would require the addition of a source of nitrogen (such as manure or urea). Homogenizing the feedstocks at the beginning of the process could be achieved by tub grinding and screening the materials. Mixing and blending could be improved by using a mechanical turner having a flail or lifting mechanism (which agitates and aerates the material) and a spray turner (to wet the material as the turner moves through the pile). The use of a turner would be most beneficial if the materials were formed into windrows and large quantities of material were being treated. Once actively composting, differing weights of contaminated soil could be added to the piles. Thus, an assessment of the effect which soil ratio has on the composting conditions and the degradation of the contaminants in the compost environment could be more accurately measured. If PAHs are to be the evaluated contaminant, it would be best to use a source high in total concentration of the 4- to 6-ring PAHs. These PAHs are not subject to volatilization to the degree experienced by the 2- and 3-ring PAHs. Assuming that optimal composting conditions are maintained throughout the study, it could then be suggested that the degradation of PAHs (if observed) could be largely attributed to biodegradation. High PAH concentration will allow for the degradation to be evaluated without being masked by the variability inherent in PAH analyses at low concentrations.

The results of this study demonstrate that the concentration of 2- to 4-ring PAHs in soil can be reduced through the composting processes used. Although a fate analyses was not conducted, study data suggest that the PAHs were largely volatilized. The literature reviewed suggest that the PAHs may have been largely biodegraded if optimal composting conditions had been maintained throughout the study. The results of this study suggest that it is technically feasible to remediate semi-volatile compounds in soil when composted with organic materials (such as yard waste). The reduction of the semi-volatile compounds may be sufficient to permit unrestricted utilization of the soil compost mixture.

V. CONTEXT: RELATED CURRENT AND PREVIOUS WORK

A. FUTURE NEEDS

Considerations of cost and the limits of composting as a remediation method for PAHs, at a minimum, need to be addressed prior to implementation of full scale composting efforts for semi-volatile contaminated soils. These considerations should include:

- the ultimate fate of the organic compounds (released or destroyed) in mixtures to be composted;
- the effectiveness of composting soils contaminated with 4- to 6-ring PAHs and high concentrations of PAHs;
- the potential for adverse impacts arising from organic and inorganic compounds which may remain in compost; and
- a comparison of the economics of various remedial approaches.

If composting can be demonstrated to be a valid remediation technology for PAHs in contaminated soil, research is needed to:

- define optimal operating conditions (which may be waste specific) and develop compost systems that match these criteria;
- define and optimize specific parameters that control the degradation rate of organics;
- define criteria for acceptable treatment;
- improve methods for chemical analyses of compost for primary contaminants and degradation products; and
- define contaminant degradation rate-limiting parameters.

~~Current and previous work has concentrated on soils contaminated with petroleum compounds. While this work is very useful in dealing with common soil contamination problems, the chemical differences between petroleum compounds and PAH is great enough that success in this previous work does not prove that co-composting PAH contaminated soils will be successful. Once the feasibility of the PAH co-composting process is shown, the process will need to be further tested with contaminants of varying types and concentrations to assess general feasibility and to determine how critical the test conditions are for breakdown of contaminants. Ultimate goal is to devise a method which can be utilized with little monitoring or feasibility study.~~

B. PROPOSED WORK IS SUPPLEMENTARY

The proposed work will help to determine both the rate of decomposition and the field conditions necessary to achieve optimum breakdown. In addition, the completeness of the decomposition process will be important in assessing whether the process achieves breakdown of the soil contaminants adequate to permit utilization of the soil/compost mixture in unrestricted usage.

C. RELATED PAST ACCOMPLISHMENTS

The past two studies Braun Intertec has performed will be reviewed to evaluate co-composting methodologies as a means of remediation. Other studies available to Braun Intertec, such as breakdown of petroleum refining wastes in soil, will be reviewed to assess their relevance to this project.

D. PREVIOUS RELATED BIENNIAL BUDGET SYSTEM PROGRAM TITLE AND BUDGET AMOUNT FOR FY 90-91

The previous related studies were funded by MCDA, and no state funding was involved.

E. BIENNIAL BUDGET SYSTEM PROGRAM TITLE AND BUDGET FOR PROJECT FOR FY 92-93

Not applicable.

VI. QUALIFICATIONS

The program was initiated by the Minneapolis Community Development Agency (MCDA), Minneapolis, Minnesota and Braun Intertec Corporation (Braun Intertec), Mendota Heights, Minnesota. Braun Intertec Corporation was formerly known as Braun Environmental Laboratories, Inc. The MCDA served as program manager and Braun Intertec was responsible for designing and conducting the project work, including report preparation. The field study was designed by Braun Intertec staff, Mr. Paul Book and Mr. Steve Riner, and managed by Ms. Laurie Kania. Mr. Charles Lederer, who recently joined Braun Intertec, has assisted Ms. Kania in preparation of the final report and assessments related to the composting process.

1. Program Manager

a. and b. Qualifications, Institutional Association and Specializations:

Lawrence H. Heinz
Supervisor of Engineering
Minneapolis Community Development Agency

St. Thomas Military Academy, Mendota Heights, MN, 1961
University of Minnesota, Minneapolis, Civil Engineering, 1961-64
International Correspondence School, Scranton, PA, Civil Engineering, 1972.

b. Note for Research Proposals:
(1) Summary of Work Accomplished: a study performed by Braun Intertec for MCDA, July 1989 - October 1990, and another study performed by Braun Intertec for MCDA, July 1990 - October 1990 (no state funding used for these projects).

(2) List of Principal Publications: None

2. Cooperators/other Investigators

a. and b. Qualifications, Institutional Association and Specializations:

~~Paul R. Book, CPG~~
~~Director, Environmental Consulting Services Division~~
~~Braun Intertec Environmental, Inc.~~

~~M.S. Geology, University of New Hampshire, Keene, 1980.~~
~~B.S. Geology, University of Massachusetts, Amherst, 1977~~

Mr. Book has been Director of Consulting Services (formerly ~~Environmental Geology) for Braun Intertec Environmental, Inc., since 1987. In that capacity, he has been responsible for all environmental consulting projects performed at Braun Intertec. Prior to that time, he was a Senior Hydrogeologist for the Minnesota Pollution Control Agency, where he provided hydrogeologic analysis of sanitary landfill and superfund sites. He will be Principal in Charge for this project.~~

~~c. Note for Research Proposals:~~

~~(1) Summary of work accomplished: a study performed by Braun Intertec for MCDA, July 1989 - October 1990, and another study performed by Braun Intertec for MCDA, July 1990 - October 1990 (no state funding used for these projects).~~

~~(2) List of principal publications:~~

~~Stephen D. Riner, REA~~
~~Supervisor, Regulatory Assistance Section,~~
~~Site Assessment Department~~
~~Braun Intertec Environmental, Inc.~~

~~M.S. Chemistry/biochemistry, New Mexico State University, Las Cruces, 1974~~
~~B.S. Chemistry, Loyola University of Los Angeles, 1971~~

~~Mr. Riner has been in his position with Braun Intertec since 1989. He supervises environmental compliance audits and phase I and phase II property assessments. Prior to that time, he was Hazardous Waste Coordinator for the Minnesota Department of Transportation and, for five years, a Project Manager in the Minnesota Pollution Control Agency's superfund program. Among his superfund projects was the Reilly Tar & Chemical Co. site in St. Louis Park, which involved~~

~~contamination of soils and groundwater with PAHs from a creosoting plant. He will provide technical supervision for this project.~~

~~**c. Note for Research Proposals**~~

~~(1) Summary of Work Accomplished: a study performed by Braun Intertec for MCDA, July 1989 - October 1990, and another study performed by Braun Intertec for MCDA, July 1990 - October 1990 (no state funding used for these projects).~~

~~(2) List of Principal Publications: None~~

a and b. Qualifications, Institutional Association and Specializations:

Charles A. Lederer
Senior Technical Consultant
Braun Intertec Corporation

B.S. Business Administration, minor studies in Land Capability Analysis, University of Wisconsin, River Falls, 1983.

Mr. Lederer recently joined Braun Intertec in this capacity. Prior to this, he worked at R.W. Beck as a Senior Technical Consultant. In this capacity, Mr. Lederer has assisted states, counties and municipalities in the planning and implementation of solid waste and resource recovery facilities. He was responsible for analysis of waste generation, evaluation of the impact of recycling and analysis of markets associated with various technologies. He has served as project manager during the implementation phase of project development providing assistance in permitting, financing, procurement, contract negotiations, constructionand operations monitoring for waste to energy, landfill, recycling and composting facilities.

Mr. Lederer has six years experience in the independent review and procurement activities related to composting facilities. He is familiar with the DANO, OTVD, Buhler, Daneco, Ferst, Bedminster, IPS and Recomp Systems. Beyond the review of the technologies applied in the preprocessing, composting and post-processing activities of these systems, Mr. Lederer has evaluated the impacts which markets, permitting and residue disposal have on facility economics and the vendors' contractual commitments.

A concentration of his work has been on that fraction of the waste stream which is considered to consist of special or unprocessible waste, such as tires, ferrous metals and plastics. Mr. Lederer has prepared requests for qualifications and reviewed technical proposals for the processing and recycling of these items. Mr. Lederer has ten years experience providing technical assistance with tire disposal issues throughout the United States and in Europe.

c. Note for Research Proposals:
(1) Summary of Work Accomplished:

Procurement and Permitting, Yard Waste Management Facility, City of Miami, Florida, Technical Consultant. Mr. Lederer has provided technical assistance to City staff in the preparation of design criteria, procurement documents, permitting documentation and operations and maintenance manuals for a 20,000 TPY yard waste processing facility which produces end products of compost and mulch materials.

Procurement and Permitting, 120-TPD Municipal Solid Waste Composting Project, Crow Wing County, Minnesota, Project Manager. Mr. Lederer provided project management and technical services relative to the development of a 120 TPD MSW composting facility which would serve a rural county in Minnesota. As project coordinator, he has been responsible for preparation of a $2 million MWMB grant application, facility permit, environmental worksheet, investigation of financing alternatives and preliminary den evaluation.

Mr. Lederer directed the procurement effort for an $11 million composting facility which included preparation of Request for Proposals, vendor evaluations and selection, and contract negotiations with the selected vendor.

Independent Review, MSW Composting/Recycling Facility, St. Cloud, Minnesota, Technical Consultant. Mr. Lederer assisted in the review of technical and operation conditions of the Recomp Recycling and MSW Composting Facility which utilizes a Eweson digestor. The review included examination of the general process flow, facilities capacities and contractual arrangements.

The review identified the operating conditions which existed, a technical opinion of the overall process and the risk posture of the Facility as related to environmental regulations and equipment performance.

Independent Review, MSW Composting Facility, Okeechobee County, Florida, Technical Consultant. R. W. Beck conducted a technical feasibility review of a MSW composting facility which coupled a Eweson Digester with a Royer system windrow composting process. Mr. Lederer focused on evaluation of markets for the end products.

Development of Composting Facility Operating Guide, The Procter & Gamble Company, Technical Advisor. Mr. Lederer contributed to the creation of the *Composting Facility Operating Guide* for the U.S. Solid Waste Composting Council. The *Operating Guide* will be a detailed, practical document describing process control parameters necessary for successful operation of composting facilities. The project included preparation of the draft *Operating Guide*, week-long field verifications at seven operating municipal solid waste composting facilities, and preparation of the final *Operating Guide*. The application of a statistical process control procedure as part of the composting facilities operating program is a unique feature of the operating guide. The work was directed by the Solid Waste Composting Council and funded by the Procter & Gamble Company.

Compost Facility Upgrade Evaluation, Solid Waste Composting Council, Chertsey, Quebec, Technical Advisor. Mr. Lederer was a member of a review committee which was invited to evaluate the technical and operational aspects of the only operating MSW composting facility in Chertsey, Quebec, Canada. The Committee was asked to suggest changes which would enhance the facility's performance. The facility had experienced a fire in the receiving area, was having difficulty in meeting its identified processing capacities and was producing an immature compost which resulting in a significant quantity. The committee identified facility upgrades in the areas of materials receiving and handling, recovery and removal of non-biodegradable components, working conditions, process monitoring, waste decomposition process and end product enhancement.

The facility operators prepared a business plan for the needed improvements, have received funding and have completed implementation of many of the process related recommendations.

Municipal Solid Waste Composting Feasibility Study, City of Cedar Rapids, Iowa, Technical Consultant. Mr. Lederer provided technical and economic analysis in the evaluation of the impacts and risks associated with the addition of a MSW Composting Facility to the City's existing integrated waste management system. Particular attention was given to the composting facilities' ability to be the corner stone of a regional program serving the East Central Iowa Council of Governments. A review of technologies, feed stocks, project economics and end-product characteristics were provided.

(2) List of Principal Publications:

Compost Facility Operations Guide for Municipal Solid Waste, Solid Waste Composting Council, First Addition, September 1992.

Composting Municipal Solid Waste, The Fifth Annual Winter Conference Resource Recovery Institute, February 22-23, 1990, Miami, Florida, co-authored with Mr. David Brown, PMA.

Compost Facility Planning Guide, Solid Waste Composting Council, January, 1992.

a. and b. Qualifications, Institutional Association and Specialization:

Laurie M. Kania
Associate Environmental Scientist, Regulatory
Assistance Section
Braun Intertec Corporation

B.S., Geography, Northern Illinois University, 1987.

Ms. Kania has been the project manager for environmental compliance audits of manufacturing and commercial facilities; RCRA tank closures; environmental subsurface evaluations of properties impacted by manufacturing activities, waste disposal activities, and failed petroleum and waste storage tanks; and environmental property assessments.

Prior to joining Braun Intertec in 1989, Laurie served for one-half year as a member of the Field Investigation Team (FIT) and one year as sample management coordinator for Ecology and Environment, Inc. (E & E). Her duties at E & E included serving as project manager for inspections at sites listed on the U.S. Environmental Protection Agency's (USEPA's) Comprehensive Environmental Response, Compensation and Liability Information System (CERCLIS), developing recommendation for further work at CERCLIS sites, serving as a liaison between E & E and the U.S. EPA for FIT contract sample management activities, training field technicians in field sampling methods and procedures, and conducting internal site audits of field sampling activities.

Laurie also served two summer internships with the Morton Arboretum located in Lisle, Illinois, working on the Des Plaines River Wetland Demonstration project in which she participated in soil water monitoring and other plant/soil reserach as part of a larger investigation into the reconstruction of a riverine wetland.

c. Note for Research Proposals:
(1) Summary of Work Accomplished: None

(2) List of Principal Publications: None

VII. REPORTING REQUIREMENTS

Semiannual status reports will be submitted not later than January 1, 1992, July 1, 1992, [January 1, 1993], and a final status report by July 1, 1993.

VIII. REFERENCES

Alexander, M. 1981. "Biodegradation of Chemicals of Environmental Concern." Science 211(9):132-138.

Braun Intertec Environmental, Inc., "Composting Study", Report CMJX-91-0028, dated February 1, 1991.

Cerniglia, C.E. 1984. "Microbial Metabolism of Polycyclic Aromatic Hydrocarbons." Advances in Applied Microbiology 30:31-71.

Cerniglia, C.E. and M.A. Heitkamp. 1989. "Microbial Degradation of Polycyclic Aromatic Hydrocarbons (PAH) in the Aquatic Environment." In U. Varanasi (Ed.) Metabolism of Polycyclic Aromatic Hydrocarbons in the Aquatic Environment, CRC Press, Inc., Boca Raton, FL, pp. 42-64.

DeRenzo, D.J., ed. 1980. Biodegradation Techniques for Industrial Organic Waste, Noyes Data Corp., New Jersey, pp. 97-100.

Epstein, E. and J.E. Alpert. 1980. "Composting Hazardous Wastes" in Toxic and Hazardous Waste Disposal Vol. 4, Ann Arbor Sciences Publishers/Theutterworth Group, Ann Arbor, MI, pp. 243-252.

Kamnikar, B. 1992. "Bioremediation of Contaminated Soil." Pollution Engineering (11):50-52.

Keck, J., Sims, R.C., Coover, M., Park, K., and B. Symons. 1989. "Evidence for Co-oxidation of Polynuclear Aromatic Hydrocarbons in Soil." Water Resources 23(12):1467-1476.

Lee, R.F., Gardner, W.S., Anderson, J.W., Blaylock, J.W. and C.J. Barwell, 1978. "Fate of Polycyclic Aromatic Hydrocarbons in Controlled Ecosystem Enclosures." Environmental Science and Technology 12(7):832-838.

Park, K.S., Sims, R.C., Dupont, R.R., Doucette, W.J., and J.E. Matthews. 1990. "Fate of PAH Compounds in Two Soil Types: Influence of Volatilization, Abiotic Loss and Biological Activity. "Environmental Toxicology and Chemistry 9:187-195.

Worth, Roberta. 1992. Introduction to Composting. Minnesota Pollution Control Agency.

Xiujin, Q. and M.J. McFarland. 1991. "Bound Residue Formation at PAH Contaminated Soil Composting Using Phanerochaete Chrysosporium." Hazardous Waste and Hazardous Materials 8(2):115-127.

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