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Life Cycle Inventory and Cost Model for Mixed Municipal and Yard Waste Composting

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with

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Notice

This report was developed as part of ongoing research funded by the U.S. Environmental Protection Agency under Cooperative Agreement No. CR823052 with the Research Triangle Institute. It has been subjected to U.S. Environmental Protection Agency internal peer and administrative review and approved for publication. Approval does not signify that the contents reflect the views and policies of the U.S. Environmental Protection Agency, neither does mention of trade names or commercial products constitute endorsement or recommendation for use. This document presents a generic model and default data for mixed municipal waste and yard waste compost operations. The results from this study are not intended to be used to judge which materials or products are environmentally preferable. This report is subject to review and modification prior to conclusion of the research.

Abstract

Life cycle inventories (LCIs) are used to evaluate overall materials and energy flows of processes or systems. EPA is conducting research to evaluate the cost and environmental burdens of different municipal solid waste (MSW) management systems, based on the development of models for each of the processes that constitute the system (EPA, 1999). This work's objective is to develop a model to estimate cost, energy and material requirements, and environmental releases for mixed MSW and yard waste (YW) compost operations.

MSW components studied include branches, leaves, grass, food, waste, and newsprint. Thirty-nine model coefficients, including total cost, total energy, air emissions, waterborne effluents, and solid wastes were tracked and ultimately expressed on a per unit wet mass basis of a mixture of MSW or YW entering an MSW or YW composting facility. The boundary of the model includes the composting facility as well as application of the compost to land.

Using "typical" composting facility designs, the predicted total cost is $16/ton for a yard waste composting facility (YWCF), $28/ton for a low-quality MSW compost facility (LQCF), and $49/ton for a high-quality MSW compost facility (HQCF), all 1998 dollars. Costs are comparable to actual values of composting facilities in the United States. Total energy requirements, including precombustion and combustion energies, are 102,000, 330,000, and 570,000 Btu/ton for the YWCF, LQCF, and HQCF, respectively.

More than 90 percent of the total emitted CO_2 is due to solid waste decomposition with the rest being emitted due to fossil fuel combustion and precombustion for all facilities. For an HQCF, approximately 35 percent of the total energy requirements is due to diesel fuel combustion, 58 percent to electricity generation, and 7 percent to diesel fuel manufacturing and delivery processes.

The model cost and energy predictions are sensitive to the compost retention time and odor-control design elements, because each factor accounts for a large fraction of the total capital costs of MSW composting facilities. Labor costs, electricity, and diesel costs account for 70, 16.6, and 8 percent of total operating costs.

Foreword

Today's rapidly developing and changing technologies and industrial products and practices frequently increase the generation of material that, if improperly dealt with, can threaten public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and carry out actions that lead to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to do research to define environmental problems, measure their impacts, and search for their solutions.

The National Risk Management Research Laboratory is responsible for planning, implementing, and managing research development and demonstration programs. These programs provide an authoritative defensible engineering basis in support of the policies, programs, and regulation of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is a product of that research and provides a vital communication link between researchers and users.

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Acronyms

C	Capital
CMTF	Combustion material flows
DER	Diesel energy requirement
EER	Electrical energy requirements
FEL	Front-end loader
HC	Hydrocarbon
HQCF	High-quality compost facility
ISWM	Integrated solid waste management
LCI	Life cycle inventory
LQCF	Low-quality compost facility
M	Maintenance
MSW	Municipal solid waste
MTF	Material flows
O	Operating
PC	Precombustion energy
PMTF	Precombustion material flows
RDF	Refuse derived fuel
VOC	Volatile organic compound
VS	Volatile solids
YW	Yard waste
YWCF	Yard waste compost facility

Acknowledgments

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1. Introduction

A project to develop tools and information to support integrated solid waste management (ISWM) systems is under development by the United States Environmental Protection Agency (U.S. EPA, 1999). The objective of the overall project is to develop models for common municipal solid waste (MSW) management processes so that integrated waste management strategies can be compared and optimized based on constraints and criteria set by a community or solid waste planner.

A key element of this approach is that optimization may not be based solely on the traditionally used minimization of cost, but also on the minimization of individual material or energy usage or emissions produced by the system. Processes modeled are landfilling, composting, recovery of recyclable materials, waste to energy (combustion), refuse derived fuel, and solid waste collection.

The objective of this report is to present the development and result of the process model for one of the six MSW processes, namely solid waste composting. "Typical" composting facilities were designed using established procedures and tools as the basis for development of the model. Two types of MSW composting facilities and one typical yard waste composting facility (YWCF) were designed. In the original project, MSWs were assumed to consist of 48 components, of which 18 are organic and 30 are inorganic. The 18 organic components consist of one food waste component; three yard waste components, namely leaves, grass, and branches; and 14 paper components, which includes office paper, old newsprint, old corrugated cardboard, phone books, books, old magazines, third class mail, mixed paper, and nonrecyclable paper. The inorganic components consist of nine types of plastics, ferrous cans, ferrous metals, aluminum cans, two other types of aluminum, aluminum nonrecyclable, clear glass, brown glass, green glass, mixed glass, and other nonrecyclable inorganic materials. More information on the types and identities of these materials can be found in project documentation (e.g., U.S. EPA, 1999).

Because no detailed data exist for several of the MSW components mentioned, certain components were grouped and treated as one category. This is coupled with the fact that laboratory work related to this study (Ham and Komilis, 1999) was based on simulating the organic fraction of MSW using three organic components. Therefore, the 14 paper components were grouped as one category, referred to as "mixed paper," and the three YW components were treated as one component, hereafter referred to as "yard wastes," consisting of grass and leaves. Food wastes were treated as one category. Other components, which do not biodegrade during composting but are part of the MSW stream, were broken down into four categories: plastics/refractory organics, glass, tin cans and aluminum, and other inorganics. Therefore, in this report, MSW will be represented by three organic components and four refractory organic/inorganic components.

Calculated model coefficients include total annual cost, total annual energy requirements (combined precombustion and combustion energy requirements), and 37 selected annual material flows (MTF) (including environmental emissions). These coefficients were calculated for each of the compost facility designs. From the 35 material flows, 12 are atmospheric flows, 22 are liquid flows, and 3 are solid material flows. The solid material flows are broken down into the solid rejects, produced during processing in the compost facility (e.g., screen rejects); the compost product itself; and solid waste produced from the diesel and electricity precombustion and combustion processes.

The composting models were developed so that all 39 coefficients are expressed per wet ton of combined MSW or YW entering each of the three types of composting facilities, based on a U.S. MSW composition before and after recycling and a YW typical composition. The units for cost, energy, and material flows are $/ton, Btu/ton, and lb/ton.

The laboratory work investigated interactions upon mixing the three MSW organic components together. The equations developed in that work are used to predict CO_2, NH_3, and volatile organic compound (VOC) emissions during composting of any MSW mixture consisting of mixed paper, yard wastes, and food wastes. These equations account for interactions among components and were therefore implemented during the development of this model. The equations are based on achieving "full" decomposition of uncontaminated waste, such as that accomplished in a laboratory bench-scale experiment. Any contamination, such as by household hazardous waste or hazardous waste from commercial or industrial sources, would add to the VOC emissions. Essentially complete decomposition (cessation of CO_2 production) was modeled because decomposition of compost will continue essentially to completion whether in the compost facility or after the compost is placed on land or in a landfill.

This report describes the selected model coefficients, the design and life cycle inventory (LCI) boundaries of the typical composting facilities, and results for three typical solid waste composting facilities as predicted by the model. Model results are compared to available field data from U.S. solid waste composting facilities. Separate sections are dedicated to discussion of the cost and energy breakdown for the three facilities. In addition, a sensitivity analysis is performed and results are discussed. Finally, a section is dedicated to the allocation of the predicted coefficients separately to each of the seven individual components entering a facility.

The process model development was performed in Microsoft Excel '97, allowing changes of the default input coefficients, such as cost, that may vary for each community.

2. Model Coefficients

The following section describes the derivation of the model coefficients. The equations developed to design the composting facilities are given in detail in Appendix A.

2.1 Cost

All costs are adjusted to 1998 dollars.

Capital cost: Capital cost includes the purchase of land and equipment and facility preparation and construction. This cost was amortized using a 15-year design basis and a 5 percent interest rate for all parts of the facility. Most of the typical land acquisition and land development costs were based on Flow rate et al. (1994). Other cost figures were provided by sales literature, equipment manufacturers, composting facility operators, and literature, as referenced. Table 1 presents the capital cost related data.

Table 1. Capital (C), Operating (O), and Maintenance (M) Costs for All Three Types of Solid Waste Composting Facilities [a,b]

Item / equipment	Cost ($ / unit shown)	Source
Paving	$72,500/acre	Renkow et al., 1994
Grading	$5,000/acre	Renkow et al., 1994
Fencing	$7.0/ft	Renkow et al., 1994
Land acquisition	$1,240 / acre	Renkow et al., 1994
Compost pad building (includes paving)	$6.5/ft[b]	Personal communication with W. Casey (1996)
Office cost	$40 / ft[b]	U.S. EPA (1991b)
Windrow turner	C: $180,000 M: $22 / h	Scarab sales literature
Front-end loader	C: $150,000	Tchobanoglous et al., 1993
Odor-control system	C: $52/cfm [c]	Based on Kong et al., 1996
Screens	C: $100,000	Tchobanoglous et al., 1993
Hammermill	C: $250,000 M: $0.741/ ton	Tchobanoglous et al., 1993, and Diaz et al., 1982
Tub grinder	C: $180,000 M: same as hammermill	Tchobanoglous et al., 1993
Diesel	O: $1.2/gal	1999 retail value
Electricity	O: $0.075 / kWh	1999 value from Madison Gas & Electric in Madison, WI
Labor / overhead cost	$8/h equipment operator (overhead taken as 40% of labor cost)	Assumed value

[a] Costs shown are default values that are changeable if desired or if more accurate information is available; all costs are adjusted to 1998.
[b] Engineering cost was taken as 15 percent of construction cost, and equipment installation cost was taken as 30 percent of equipment capital cost.
[c] Cubic feet per minute.

Operational cost: This is the operation and maintenance cost including labor, overhead, fuel, electricity, and equipment maintenance. Certain assumptions had to be made when accurate data were not available. Table 1 includes the operating and maintenance cost related data. Relevant calculations are shown in Appendix A.

2.2 Energy

Electrical energy requirements: Electrical energy requirements (EER) include precombustion and combustion requirements. Precombustion EER are for mining, processing, and transporting the fuel used to produce a kWh of electricity, and combustion EER reflects the energy content of the fuel used during its combustion to produce a kWh of electricity delivered for consumption. In the case of electricity, it was necessary to define fuel usage by type for national and regional grids (Dumas, 1997). Table 2 shows the various fuel and energy sources used in the United States, along with the average overall U.S. combined precombustion and combustion energy requirements for electricity of 10,431 Btu/kWh.

Table 2. Electrical Energy Precombustion and Combustion Energy Requirements Based on the U.S. Electrical Grid (Dumas, 1997)

	Btu/kWh			% Generation
	PC[a] Energy	Comb[b] Energy	Total Energy	
Coal (lb)	259	10,474	10,734	56.45
Natural Gas (ft)	1,440	12,845	14,284	9.75
Residual Oil (gal)	1,432	11,644	13,076	2.62
Distillate Oil (gal)	1,967	16,104	18,071	0.23
Uranium (lb)	557	11,401	11,957	22.13
Hydro	0	3,413	3,413	8.59
Wood (lb)	0	10,504	10,504	0.24
Other	0	10,504	10,504	0.00
Average			**10,431**	**100**

[a] Precombustion energy requirements.
[b] Combustion energy requirements.

Diesel energy requirements: Diesel energy requirements (DERs) are divided into precombustion and combustion requirements. Precombustion DERs are used during mining, processing, and transportation of diesel fuel, and combustion DERs reflect the energy content of diesel fuel used during combustion in diesel-fueled equipment. The precombustion and combustion energies for diesel fuel were calculated to be 25,900 Btu/gal and 137,000 Btu/gal (Dumas, 1997).

Net energy requirements: The method used for the overall project was to calculate net energy or net material flows. This means that model coefficients associated with a specific end product are reduced by the amounts of the same coefficients for a product that the solid waste process end product is assumed to replace. Therefore, if X Btu are required to produce 1 ton of refuse derived fuel (E_{RDF}) and that ton of refuse derived fuel can replace Y amount of diesel fuel that would be normally used in a boiler instead of the RDF, then the net energy requirements per ton of RDF is [$E_{RDF} - E_{diesel}$], where E_{diesel} is the amount of energy required to produce the Y amount of diesel fuel plus the energy content of the fuel itself. Note that both X and Y include the precombustion energy requirements, namely, the energy needed to mine, transport, and process the RDF or diesel fuel.

In the case of composting, MSW- or YW-derived compost was not considered to replace any chemical fertilizer because of the low fertilizer value of both composts. When MSW- or YW-derived compost is used for land application, chemical fertilizer is also used if fertilization is required. Other potential uses of compost identified by EPA's Office of Solid Waste that were not included in developing this model may be reviewed at: http://www.epa.gov/epaoswer/non-hw/compost/index.htm

2.3 Material Flows

The 37 MTF can be categorized as precombustion material flows (PMTF) and combustion material flows (CMTF). They are further categorized as fossil-related and biomass-related material flows. PMTF are produced during the production and transportation of fuel or electricity used by the facility, and CMTF are produced from the combustion of fuel within the facility.

Fossil MTF are produced from the combustion of fossil fuels, such as coal, natural gas, residual and distillate oil, and non-fossil MTF are produced from combustion of non-fossil fuel (e.g., wood) or from the biodegradation processes (e.g., decomposition of the organic fraction of solid wastes) outside or within the facility. Fossil and non-fossil MTF can belong to the precombustion or combustion categories. The MTF associated with precombustion of diesel and combined precombustion and combustion of electricity are shown in Table 3. Table 4 shows seven diesel fuel MTF for each type of vehicle separately, as used throughout this study. The values in Table 4 are expressed in lb per kWh, where the energy units refer to the power requirements of the specific equipment.

Similar MTF from precombustion, combustion, and biodegradation processes are summed to give one overall value. The only exception is CO_2, which is reported separately as fossil fuel-related carbon dioxide ($CO_{2\ fossil}$) and biomass-related carbon dioxide ($CO_{2\ biomass}$).

3. Model Boundaries

The boundaries over which the modeling was performed are shown in Figure 1. Compost land application was assumed to be included in the overall model boundaries, because the environmental emissions produced after land application are an environmental burden created by a mass of solid wastes that originally entered the composting facility. Biologically induced emissions were calculated based on the extent of decomposition of the organic fraction of MSW, regardless of whether this extent was reached within the facility or not. It is assumed that biologically degradable solid waste will ultimately degrade even if complete degradation is not achieved in the compost process.

As Figure 1 shows, the energy requirements and MTF associated with construction of the facility were not accounted for. The material input to the system, used for

Table 3. Electricity and Diesel Precombustion and Combustion Material Flows (Dumas, 1997)

Airborne / solid waste material flows	a	b	Waterborne material flows	a	b
Particulate matter (Total)	2.60E-03	1.82E+00	BOD	4.51E-07	1.00E-01
Nitrogen Oxides	6.46E-03	7.19E+00	COD	2.23E-06	4.91E-01
Hydrocarbons (non CH_4)	1.02E-03	6.75E+01	Iron	2.79E-04	8.10E-02
Sulfur Oxides	1.37E-02	8.80E+00	Ammonia	6.15E-08	1.40E-02
Carbon Monoxide	2.14E-03	5.01E+00	Copper	0.00E+00	0.00E+00
CO_2 (biomass)	0.00E+00	0.00E+00	Cadmium	0.00E+00	0.00E+00
CO_2 (non biomass / fossil)	1.49E+00	3.59E+03	Mercury	0.00E+00	0.00E+00
Ammonia (as N)	1.76E-07	3.90E-02	Phosphate	0.00E+00	0.00E+00
Lead	4.91E-11	1.10E-05	Chromium	7.10E-11	3.40E-05
Methane	9.85E-06	5.00E-02	Lead	6.57E-11	1.50E-05
Hydrochloric Acid	5.31E-09	1.20E-03	Zinc	9.82E-10	2.20E-04
Solid Waste (miscellaneous)[c]	1.91E-01	8.24E+01			

Table 4. Diesel Fuel Combustion Emission Factors (lb/kWh[a])

Type of vehicle	HC[b]	CO	NO_x	PM (total)	SO_x	CO_2 (lb/gal diesel)
Front-end loader (values obtained from a tracked loader)	2.08E-03	7.11E-03	2.96E-02	1.96E-03	2.52E-03	23.005
Tub grinder (values obtained from chipper/stump)	3.78E-03	1.48E-02	2.37E-02	2.45E-03	2.76E-03	23.005
Windrow turner	6.55E-03	2.03E-02	3.11E-02	0.00E+00	0.00E+00	23.005

Source: U.S. EPA, 1991a.

[a] Refers to the power of the diesel-powered equipment.
[b] Includes aldehydes.

HC = total exhaust and crankcase hydrocarbons; CO = carbon monoxide; NO_x = nitrogen oxides; PM = total particulate matter; SO_x = sulfur oxides

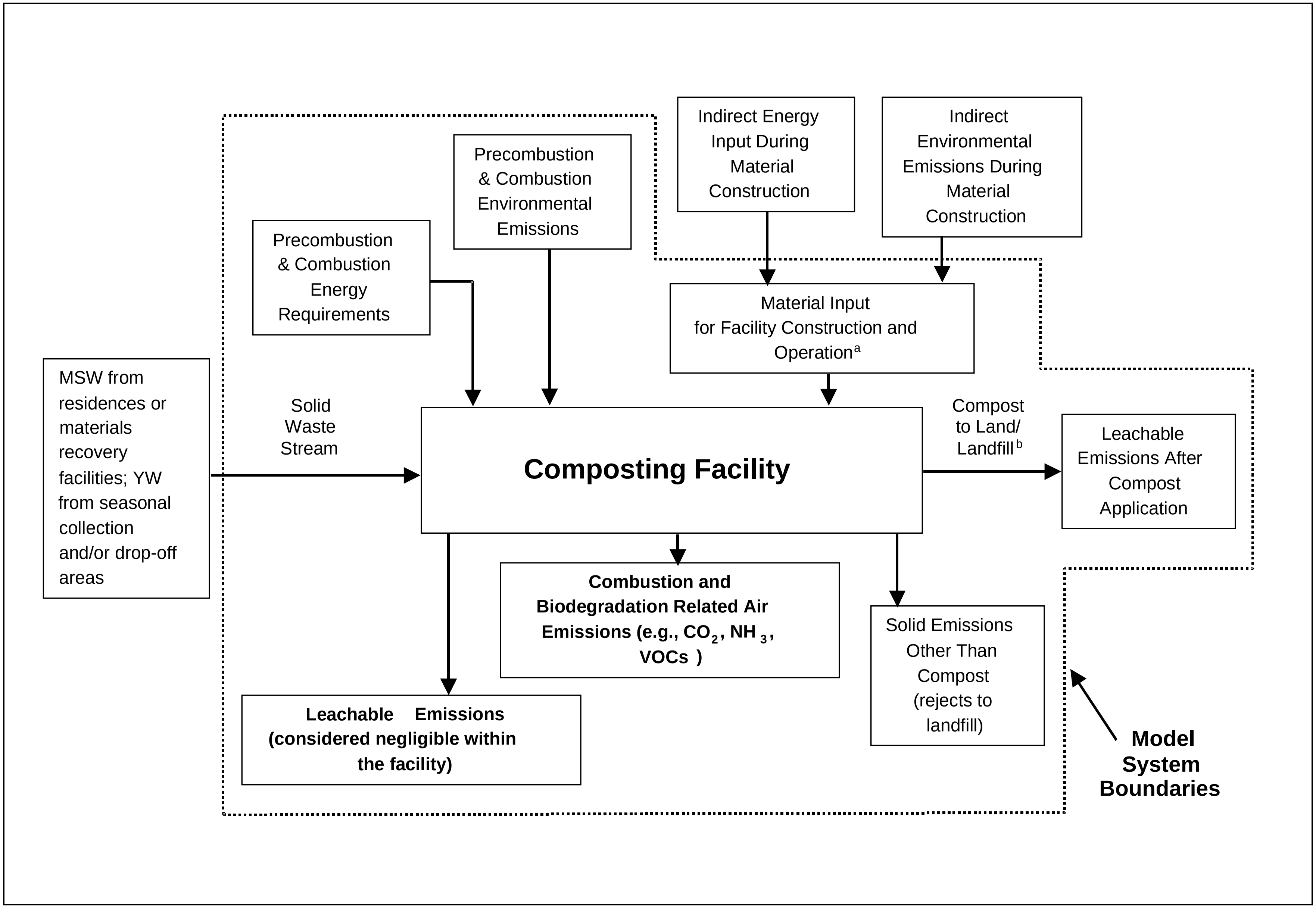

Figure 1. Model composting facility boundaries.

construction and operation of the facility, was actually reflected in the capital and operational costs. Transportation of compost to land or landfill is not accounted for as part of the model presented here.

4. Composting Facilities Design

The three types of composting facilities are summarized in Table 5 and are briefly described below. Designs were partly based on Taylor and Kashmanian (1988) and U.S. EPA (1994).

Table 5. Selected Design Criteria for the Three Solid Waste Composting Facilities

Design parameter	LQCF	HQCF	YWCF
Turning equipment	Windrow turner	Windrow turner	Front-end loader
Turning frequency	once weekly	three times weekly	once monthly
Composting pad retention time	4 weeks	8 weeks	24 weeks
Composting pad building	Yes	Yes	No
Odor/VOC control system	Yes	Yes	No
Curing retention time	0	4 weeks	Combined with composting time
Post-screening oversize fraction	0%	15%	5%
Buffer distance	500 ft (167 yd)	500 ft (167 yd)	200 ft (66 yd)

4.1 Low-Quality Compost Facility (LQCF)

An LQCF is designed to produce partially composted MSW for either landfill cover or direct landfilling. This facility aims to reduce the MSW volume and the amount of readily degradable organic matter prior to landfilling, therefore reducing gaseous and leachate emissions associated with landfilling. A trommel screen is used for bag removal and preselection of large items, followed by a horizontal hammermill to shred the undersized fraction. Water is assumed to be added to the wastes prior to composting to achieve an initial moisture content of approximately 50 percent (wet weight). Composting takes place in windrows that are turned using a windrow turner, and odor is controlled using biofiltration. No curing is used, and compost is transported directly to a landfill. Reject materials are also transferred to landfill, after temporary storage within the facility. The typical floor diagrams for all three facilities are shown in Figures A-1, A-2, and A-3 in Appendix A.

4.2 High-Quality Compost Facility (HQCF)

The HQCF produces compost for soil amendment and landscaping purposes and for use at farms, nurseries, and mines (for land reclamation). A materials recovery facility is assumed to precede this type of composting facility; therefore, preprocessing operations that remove recyclables and noncompostable items will not be part of the HQCF design. The composting facility begins with a horizontal hammermill. Water is assumed to be added to the wastes prior to composting to achieve an initial moisture content of approximately 50 percent (wet weight). Wastes are composted in windrows, and compost material is turned using a windrow turner. An odor-control system using biofiltration is included, as in the case of the LQCF. Curing follows in piles approximately 3 yd high. A postprocessing trommel screen is placed at the end of the curing stage to produce a finer compost fraction better fit for compost application. Reject materials are transferred to a landfill, after temporary storage within the facility.

4.3 Yard Waste Composting Facility (YWCF)

The YWCF accepts yard wastes dropped off by residents or brought in after collection by dedicated vehicles. Unlike mixed waste composting, only one YWCF design is needed. It is assumed that plastic bags with leaves and grass clippings are manually opened and removed upon reaching the facility. The YWCF uses a tub grinder, primarily to shred branches. No water is added here because yard wastes usually have an initial moisture content higher than 50 percent (wet weight). Composting and curing takes place on one windrow pad. The piles are turned monthly using a front-end loader instead of the windrow turner used in the MSW compost facilities. The composting pad is uncovered, and no odor-control system is installed. Finally, a postprocessing trommel screen produces a fine fraction for potential marketing of the YW-derived compost.

4.4 Compost Facility Design Approach

A mass balance was performed for each waste component or MSW/YW mixture as it flowed through the facility by accounting for moisture contents, densities of the materials at different stages in the facility, efficiencies of screens, and dry matter reductions during composting. The facilities were designed for a typical MSW mixture before and after recycling for the LQCF and HQCF, respectively, and for a typical YW mixture for the YWCF. All model coefficients derived were assigned to a wet ton of each solid waste mixture entering a facility. Default values for several of the physicochemical coefficients of the MSW components and composted substrate were based on Tchobanoglous et al. (1993), Diaz et al. (1993), and Alter (1983), as summarized in Table 6. Any waste mixture entering either of the MSW facilities or YW entering the YW facility is then simulated by using the percentage of each of the seven components in the waste and the proportionate share of each coefficient associated with each component.

A single retention time is used for each of the three composting facilities. If each of the MSW organic components was to be composted individually in a composting facility, different retention times would probably be needed for each component to reach its “full” extent of decomposition. However, that is not the case here, and the approach followed is that all seven MSW components will always be part of a mixture of MSW. Although the composition of MSW depends on variations during waste generation and the extent of recycling, one retention time will be used for each facility. Interactions among waste components are accounted for when estimating CO_2, NH_3, and VOC emissions from MSW mixtures.

Table 6. Moisture Contents, Bulk Densities, and Screening Efficiencies at Several Stages of Composting

Component	Moisture contents (% wet weight) *	Bulk densities (lb / yd^3) +	Screening efficiencies ++
Mixed paper	10.2	95	58%
Yard waste[a]	60.0	122	79%
Food waste[a]	70.0	594	79%
Plastic / leather / textiles	5.0	68	58%
Glass	2.0	460	95%
Tin / aluminum	5.0	122	55%
Other inorganic components	2.0	68	95%
In windrows	50.0 **	500[b]	
Cured compost	40.0[g]	700[c]	100%[d] , 85%[e], 95%[f]

* From Tchobanoglous et al., 1993 (pp.79).
** After water addition to windrows.
\+ Based on data from Diaz et al. (1993) for loose MSW components at tipping floor, unless specified otherwise.
++ % of feed passing through the trommel assuming a trommel screen with a 120-mm mesh size screen and a 50 tph feed rate (based on experimental data from Alter, 1983). Used in the LQCF only.

a Components with similar particle size range to aluminum, based on information in Tchobanoglous et al. (1993).
b Based on a value of 400 lb/yd^3 for shredded mixed MSW (Diaz et al., 1993) and assuming an increase to 500 after water is added to achieve a 50 percent moisture content.
c On a dry weight basis as applies to both MSW- and YW-derived compost (Diaz et al., 1993).
d Assumed post screening efficiency for LQCF because no screen was used.
e Assumed post screening efficiency for HQCF.
f Assumed post screening efficiency for YWCF.
g based on Diaz et al., 1993.

4.5 Design of Specific Elements of Compost Facilities

The following sections briefly describe the design approach followed for the key elements that constitute all three types of compost facilities. Differences among the designs of the three facilities are discussed in these sections. It is noted that part-time use of equipment was allowed and a linear correlation of all design parameters to waste flow rate was implemented with an intercept. Therefore, a minimum number of units was assumed to exist for each type of facility, regardless of waste flow rate, to allow more accurate comparison with data from actual solid waste composting facilities.

4.5.1 Trommel Screens

A 12-cm opening precomposting trommel screen was used for the LQCF to remove large items. Because recycling and preprocessing of wastes has already taken place prior to the wastes entering the HQCF, wastes are assumed to be directly shredded by the hammermill prior to composting without the use of a precomposting screen. A 1.25-cm (0.5-in.) opening postcomposting trommel screen was used in the case of the HQCF and the YWCF. In the case of the precomposting trommel screen, relevant efficiencies (or undersized fractions) for each of the seven components were calculated by knowledge of their particle size range—as reported in Tchobanoglous et al. (1993) and also based on experimental data reported in Alter (1983). Prescreening efficiencies, or the fraction of waste entering the trommel leaving as fines, for the different MSW components are summarized in Table 6. For the postcomposting trommel, different efficiencies were used for each facility, as shown in Table 6. The efficiency of 100 percent shown for the LQCF indicates that no postcomposting screening is employed. The postscreening efficiencies for the other two facilities were based on Gould and Meckert (1994).

Diaz et al. (1982) suggested a gross specific energy consumption (freewheeling energy plus network energy) of 1.1 kWh/ton for precomposting trommel screens and a 0.8 kWh/ton for screening of the light fraction of solid wastes (assumed to apply to the postprocessing trommel screen). The former value was applied to the preprocessing screens of the LQCF, and the latter value to the postprocessing screen of the HQCF and YWCF, to calculate relevant energy requirements.

At least one trommel screen was used for all facilities, and a coefficient of 0.0025 units per tons per day (tpd) was derived for estimating the partial number of units needed for different input flow rates (see Table 7). This was done by assuming 1 trommel screen unit is required for the processing of 50 tph at 8 h per day.

4.5.2 Hammermill/Tub Grinders

A value of 20 hp•h/ton was used as the operating hammermill horsepower requirement. This is the high operating range for hammermill shredding of municipal solid wastes (Tchobanoglous et al., 1993, pp. 549). The above value was multiplied by a coefficient of 1.64, which corresponds to the additional energy needed to achieve a final product size of 2 in. (Tchobanoglous et al., 1993), because this particle size is near the optimal size for composting of organics (Diaz et al., 1993). In the case of the HQCF, the above energy requirement product (20 x 1.64) was reduced by multiplying by 0.65, to account for the fact that the MSW entering that type of facility is already presorted compared to the LQCF (Tchobanoglous et al., 1993). Therefore, less energy is required to shred to the same particle size than when shredding unsorted MSW.

At least one hammermill was used for MSW facilities, and a coefficient of 0.0029 units per tpd was derived for estimating the partial number of units needed for different input flow rates (see Table 7). This was done by assuming 1 hammermill unit is required for processing 42.5 tph at 8 h per day. The maintenance cost for a hammermill is based on buildup of the hammers once per week, which is a relatively inexpensive option as concluded by Diaz et al. (1982, pp. 59).

In the case of the tub grinder, the energy requirements were calculated to be 13.7 hp•h/ton, based on a linear regression of horsepower and the corresponding input mass flow rates (in tph) from different tub grinder models, using the sales literature from Toro tub grinders.

Table 7. Energy Requirements for Various Parts of the Three Types of Solid Waste Composting Facilities

Equipment	Number of units/tpd	Energy requirements	Source
Trommel screens[e]	0.0025	1.47 hp•h/ton (pre-composting) 1.07 hp•h/ton (post-composting)	Diaz et al., 1982
Hammermill[e]	0.0029	20 hp•h/ton•(CF)•1.64[b]	Tchobanoglous et al., 1993
Tub grinder[d]	0.0038	13.7 hp•h/ton	Based on data from Toro tub grinders
Windrow turner[d]	0.173[a]	0.173 hp/tph	Based on Scarab windrow turner manufacturer data
Front-end loader[d]	0.003	0.5 hp/tpd[c]	Based on John Deere sales literature
Odor-control system[e]	Correlation of airflow rate to cost and energy	0.0028 hp/cfm	Based on Kong et al., 1996
Building operation[e]	Correlation of area units to cost and energy	320 kWh/m^2/year (office)	DOE (1994) and DOE (1995)

[a] Coefficient is based on the number of tons of compost present on the composting pad multiplied by the turning frequency.
[b] Values of 1.00 and 0.65 were used for raw and presorted municipal solids wastes (see text), respectively, and 1.64 is the correction factor used to correct for additional energy required to reach a final product size of 5 cm.
[c] Based on regression as discussed in text, assuming 150 hp for one unit.
[d] Diesel powered.
[e] Electricity powered.

At least one tub grinder was used for the YWCF, and a coefficient of 0.0038 units per tpd was derived for estimating the partial number of units needed for different input flow rates (see Table 7). The maintenance cost for the tub grinder was assumed to be equal to the maintenance cost of the hammermill, because in both cases this cost is primarily associated with maintenance of the hammers or flails and because an accurate analysis had been performed for the hammermill.

4.5.3 Windrow Turner

To correlate windrow turner horsepower with the turner waste turning capacity (in tph), four values, ranging from 177 hp to 450 hp, which correspond to waste handling capacities from 900 tph to 2,625 tph (based on Scarab windrow turners sales literature), were used. A coefficient of 0.173 hp•h/ton was derived as the basis for calculating the energy requirements of this equipment. It is noted that the typical range of waste flow rates reported for windrow turners does not refer to the composting pad input mass flow rate, but to the mass of wastes present on the composting pad. For this reason, the flow rate, the retention time, and the turning frequency were used to relate the input mass of wastes entering the facility to the windrow turner power as shown in Appendix

A. At least one windrow turner was assumed to be used for each MSW composting facility.

4.5.4 Front-End Loaders (FELs)

Front-end loaders were assumed to be used for transferring material within the facility (e.g., hauling reject material, hauling compost to curing pad, handling wastes at tipping floor). Also, in the YWCFs, FELs are used for turning the compost windrows. To estimate the number and horsepower requirements for the FELs, certain assumptions were made. For facilities accepting 0, 50, 300, and 1,000 tpd of wastes, there were assumed to be 0, 1, 2, and 3 FELs, respectively. The horsepower of each FEL unit was assumed to be 150 hp. The above reasonable assumptions are partially based on information from the MSW composting facility near Portage, WI. Based on linear regression of the above data, coefficients of 0.003 units/tpd and 0.50 hp/tpd were derived. A minimum of 1 FEL was used for all facilities.

4.5.5 Odor-Control System

The composting pad was assumed to be enclosed for both types of MSW composting facilities with ventilation provided by fans that continuously direct the air to an odor-control system. The number of fans selected provides capacity to draw air from the enclosed composting pad as well as the tipping floor. A building height of 15 ft was used, and an air exchange rate of 12 times daily (every 120 min) was provided. Horsepower requirements were based on Kong et al. (1996), which provided design parameters for a biofilter aimed to treat styrene latent industrial emissions. Based on linear regression of biofilter flow rates to total energy requirements, as reported by Kong et al. (1996), a coefficient of 0.00278 hp/cfm was used. The odor-control system was assumed to operate 24 h per day.

4.5.6 Area Requirements

The total facility area was assumed to comprise the tipping floor, treatment area (for trommeling and shredding), composting pad, curing area, buffer zone, offices, roads, and storage of reject material and equipment. The tipping floor design is based on an average waste height of 2.2 yd, a maximum retention (storage) time of 2 days, and a maneuverability factor of 2.0 (U.S. EPA, 1991b). The tipping floor area requirements are calculated based on the daily flow rate (in tpd) and the bulk densities of each component entering the tipping floor, as shown in Table 6.

The composting pad is the largest area of the facility and was designed based on the typical geometry of the piles when turned by a windrow turner. Design guidelines, which provide for equipment turning clearance (1.3 yd), space between windrows (1.0 yd), side clearance (1.75 yd), windrow height (1.97 yd), windrow base (4.6 yd), windrow crown (0.6 yd), and seven windrows in parallel, from Scarab windrow turner sales literature were used.

For the YWCF, windrows were assumed to have the same geometry as the windrows in the LQCF and HQCF, because turning is done with a front-end loader; however, a maneuverability factor of 2.5 was used for composting pad total area determination (Diaz et al., 1993).

For the HQCF, a curing pile height of 3 yd was used, with a base-to-height ratio of 2 and a maneuverability factor of 2.0. Office space was based on a coefficient of 180 ft^2/person. Reject material is stored in piles of the same geometry as the curing piles for the HQCF for a 2-day maximum storage period. The road width was set to 5.0 yd, and two roads were designed perpendicular to each other, over the length and the width of the facility, respectively. The treatment (for shredding and screening) and equipment storage areas were designed based on a typical footprint area of all pertinent equipment, the number of units, and a maneuverability factor of 2.0. Finally, the buffer area was calculated based on the buffer distances shown in Table 5 and the geometry of the facility. The facility's aspect ratio was set at 2:1.

4.5.7 Diesel and Electrical Energy Requirements

Table 7 summarizes the energy requirement coefficients for each type of equipment used in the facility. Equipment diesel consumption was derived using data from manufacturers or, if that was not available, by converting equipment horsepower to diesel consumption using a coefficient of 0.025 gph/hp (John Deere front-end loader sales literature).

4.5.8 Labor Cost

Based on Curtis et al. (1992), between three to eight operators were employed in three U.S. MSW composting facilities that had waste input flow rates of between 5 tpd and 18 tpd. A 1,000 tpd facility occupied approximately 100 operators. Using a linear regression on the above data, 0.1 operators/tpd were used for the MSW and YW composting facilities. The coefficient of 0.1 was derived because the regression is controlled by the 1,000 tpd, 100 operators data point.

5. Material Flows

The material flows entering and exiting the facility are discussed below. Water added to the substrate to promote decomposition is not included because it is highly variable, does not have to be high quality, and is evaporated as pure water to the atmosphere.

5.1 Diesel- and Electricity-Related Material Flows

The diesel and electricity precombustion and combustion emissions were discussed in Section 2.2 (see Tables 3 and 4).

5.2 Biodegradation-Related Gaseous Material Flows

$CO_{2\ biomass}$, ammonia (NH_3), and VOCs are considered the main gaseous compounds produced during the decomposition of wastes during composting. Laboratory bench-scale experiments (Ham and Komilis, 1999) were performed to predict these gaseous emissions from mixtures of three organic MSW components (food wastes, mixed paper, and yard wastes). The experimental design was based on investigating the interactions upon mixing these components together. Experiments extended until "complete" degradation was reached, as measured by the $CO_{2\ biomass}$ flow rate and after ensuring that this was not due to moisture limitations. Results from these experiments were analyzed using empirical models and produced equations that estimate $CO_{2\ biomass}$, NH_3, and VOC yields per dry ton of MSW of various compositions. It is noted that 12 VOCs were targeted and quantified, and the pertinent equation is based on the total mass loadings of only those VOCs from uncontaminated waste components. Hazardous household, commercial, and industrial wastes, the likely major sources of VOCs in MSW, were not accounted for because of the inherent variability and the lack of reliable information. Among the three degradable MSW components used, mixed paper was found to yield the most emissions of the targeted VOCs per unit weight (Ham and Komilis, 1999). It is suggested that information regarding the VOC content of a specific waste be used by adding the additional amounts, above the minimum values reported here, to predict VOC emissions from a given compost facility.

In addition, an equation was developed from the laboratory study to predict dry mass reduction as a function of the $CO_{2\ biomass}$ yield of the MSW mixture. Dry matter reduction is important to determine the fraction of raw solid wastes that will end up as finished compost. All of the above equations are incorporated in this model and are given in appendix A.

The targeted and quantified 12 VOCs are toluene, ethylbenzene, p/m xylene, styrene, isopropylbenzene, n-propylbenzene, 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, 1,4-dichlorobenzene, p-isopropyltoluene, n-butylbenzene, and naphthalene. Knowledge of actual concentrations of any of these VOCs, or any other VOC, in a specific waste should be used to increase the VOC emissions modeled. Most VOCs will volatilize quickly in a compost facility given the exposure to air and the temperatures attained, as supported by using VOC spikes in the laboratory investigation (Ham and Komilis, 1999).

In the case of YW composting, gaseous emissions from YW were calculated using a fixed YW mixture, without varying the YW subcomponents, namely grass and leaves. Study of interactions among YW subcomponents was beyond the scope of this work.

5.3 Leachable Material Flows

Generally, no significant amounts of leachate are produced in composting facilities, as long as compost is covered and the moisture content is kept near optimal values (Cole, 1994). For this reason, leachate production within the composting facility was assumed negligible.

Leachable emissions were accounted for during compost land application, which is the case for the HQCF and the YWCF. The LQCF-derived compost was assumed to still leach in a landfill, as in the land, and therefore leachable emissions were calculated for this type of facility in the same manner as for the other two. Data on the leachable emissions after MSW compost land application were based on the work by Christensen et al. (1983a,b and 1984a,b), who performed lysimeter experiments to determine the leachate characteristics of MSW-derived compost. This work involved the introduction of MSW-derived compost to specially designed lysimeters and analysis of the leachate produced over a period of 2.5 years. A 600 mm/year precipitation rate was used. The results from Christensen's work provide leachable mass loadings of several environmental pollutants expressed per unit dry mass of MSW compost initially placed in the lysimeter. Experiments showed that 50 percent less organic matter was leached per unit mass of the thick layer (35 cm to 64 cm) compost compared to the thin layer (12 cm to 19 cm) compost. The values used here are average values from all lysimeters, including both thick and thin layer composts. The results of Christensen are summarized in Table 8.

Data on leachable emissions from YW compost were based on work by Cole (1994). Cole investigated the fate of various inorganic compounds in a YW composting facility and provided mass loadings of water-extracted metals from YW composts. Because some leachable pollutants measured in MSW compost were not measured by Cole (1994), it was assumed that the same loadings of leachable pollutants found from MSW compost apply to YW compost as well. Mass loadings of leachable pollutants from YW-derived compost are summarized in Table 8. Although the LQCF compost is directed to a landfill, where anaerobic environments prevail, the leachable mass loadings from MSW compost, as shown in Table 8, will be used for that type of compost.

Because leachable pollutants given in Table 8 are expressed per dry mass of compost, the dry matter reduction—as calculated by the model—and the initial moisture contents were used to express those loadings per wet ton of MSW or YW entering the facilities.

6. Results And Discussion

6.1 Model results for three typical composting facilities

The objective of this section is to calculate and compare results after running the model separately for each of the three types of composting facilities. The models were run using typical U.S. MSW compositions separately for the LQCF and HQCF, and using a typical YW mixture for the YWCF. An input flow rate of 100 tpd was used for all three facilities. The compositions used are based on Tchobanoglous et al. (1993) and are discussed below.

LQCF: The 1990 U.S. MSW composition before recycling was used, which is 8 percent food wastes; 42.2 percent mixed paper (cardboard and other types of paper); 17.3 percent yard wastes; 11.3 percent various refractory organics (e.g., plastics, leather); 9.1 percent glass; 5.8 percent tins; and 6.3 percent aluminum, other metals, and ash.

HQCF: The 1990 U.S. MSW composition after recycling was used, which is 9 percent food wastes; 40 percent mixed paper (cardboard and other types of paper); 18.5 percent yard wastes; 12 percent various refractory organics (e.g., plastics, leather); 8 percent glass; 6 percent tins; and 6.5 percent aluminum, other metals, and ash (Tchobanoglous et al., 1993).

YWCF: No typical composition of yard wastes has been published. There are seasonal variations in YW composition, so high percentages of grass are expected in spring and summer, and high percentages of leaves are expected in the fall. Yard wastes were treated as one component and were arbitrarily assumed to be 75 percent wet grass and 25 percent wet leaves, which corresponds to approximately 1.5:1 dry grass to dry leaves. This ratio was used in the laboratory experimental work and is used here because environmental emissions from yard wastes were calculated based

Table 8. Leachable Mass Loadings of Selected Pollutants from MSW- and YW-Derived Compost

Material flow (pollutant)	Loading (lb/dry ton of MSW-derived compost)[a]	Loading (lb/dry ton of YW-derived compost)[b]
COD	4.8E+00	4.8E+00[d]
BOD	4.8E-01[c]	4.8E-01[d]
NH_4-N	1.3E-01	1.3E-01[d]
NO_3-N	4.4E-01	4.4E-01[d]
TKN-N	2.6E-01	2.6E-01[d]
Na	3.2E+00	1.3E-02
K	2.7E+00	5.8E-01
Ca	1.6E+00	1.6E+00[d]
Mg	5.6E-01	5.6E-01[d]
Mn	2.6E-03	1.0E-03
Fe	1.4E-02	2.2E-02
Cl	3.6E+00	3.6E+00[d]
SO_4-S	1.5E+00	1.5E+00[d]
F	1.8E-03	1.8E-03[d]
P	1.9E-02	1.9E-02[d]
Cd	2.4E-05	3.3E-04
Ni	2.3E-03	2.3E-03[d]
Co	9.5E-05	9.5E-05[d]
Zn	1.3E-02	4.4E-04
Cu	3.8E-03	1.3E-04
Pb	6.0E-04	6.0E-04[d]
Cr	2.0E-04	4.4E-05

[a] Data based on Christensen et al. (1983a,b and 1984a,b).
[b] Based on Cole (1994).
[c] Estimated by Christensen to be approximately 10 percent of the COD for all samples.
[d] Assumed similar to MSW compost corresponding value, because of data unavailability.

on that work. The same equations used for MSW for estimation of gaseous emissions were also used for yard wastes by assigning zero fractions to mixed paper and food wastes.

Table 9 presents the predictions of the compost process models for each of the three composting facilities. Table 9 includes total cost and total energy in $ and Btu, respectively, per wet ton of MSW (or YW) entering the facility. Table 9 also includes material flows addressed in this paper, namely gaseous and leachable material flows, and Table 10 includes solid waste flows into and out of the facility. Each material flow is the sum of all flows of that material present in various streams or processes. For example, iron is a waterborne effluent produced during diesel and electrical energy precombustion but is also a leachable effluent produced from compost land application. All iron emissions are therefore summed together and reported as one value in Table 9, in units of lb/ton.

Table 9 shows that the least expensive facility is the YWCF, with a total cost of $15.90. This value is within the range of actual total costs of YW composting facilities in the United States, as reported by Steuteville (1996). According to Steuteville (1996), total costs for seven YW composting facilities in the United States range from $8/ton for a facility with no shredding and screening to $25.6/ton for a facility that uses open-air windrows with turning. The costs by Steuteville (1996) are expressed per ton of feedstock, which is used in Table 9.

The total costs for the LQCF and HQCF are $27.90/ton and $49.30/ton. Differences are primarily due to the larger retention time of the HQCF compared with LQCF, which results in a larger composting pad and therefore a higher cost for odor control and compost pad building. Also, the prescreening step in the LQCF removes approximately 30 percent of the waste, which is therefore neither shredded nor composted, reducing overall cost. According to Renkow and Rubin (1996), total costs for MSW composting facilities range from $35/ton to $54/ton (MSW processed). Values reported are based on seven U.S. MSW composting facilities with an average total cost of $53/ton. Differences in designs of the actual facilities compared to the “typical” design used here are expected. Several facilities use vessel systems, which are generally more expensive and may have larger operating costs than the systems used in facilities with windrow turners; however, model predictions are comparable to actual data. Economy of scale is also important. Values in Table 9 refer to a 100 tpd facility.

The capital cost accounts for 58 percent and 72 percent of the total cost for the LQCF and the HQCF, respectively, while it accounts for 34 percent of the total cost of the YWCF. According to Renkow and Rubin (1996), 48 percent of the total cost is capital (or debt) cost, based on averaging from the reported actual data.

Total energies shown in Table 9 are the sum of electrical and diesel precombustion and combustion energies for each facility and are expressed in Btu/ton. Total energy of the YWCF is much less than the energy from the LQCF and HQCF, primarily because no odor-control system is employed. The HQCF energy requirements are approximately twice that of the LQCF. This is primarily due to the larger odor-control system. In addition, removal of about 30 percent of the incoming material during prescreening in the LQCF results in even lower total energy requirements than that of the HQCF, in which no prescreening is used.

Table 9. Total Costs ($/ton), Energy Requirements (Btu/ton), and Material Flows (Pollutants) (lb/ton) for 100 tpd MSW and YW Composting Facilities

LCI coefficient	LQCF	HQCF	YWCF
Total Cost (1998 $/ton)	$27.90	$49.27	$15.86
Total Energy (Btu/ton)	3.3E+05	5.7E+05	1.0E+05
Atmospheric pollutants (lb/ton)			
Particulate Matter (Total)	8.4E-02	1.3E-01	3.9E-02
Nitrogen Oxides	3.1E-01	6.3E-01	3.5E-01
Hydrocarbons (non CH_4, incl. aldehydes)	5.1E-02	1.3E-01	7.8E-02
Sulfur Oxides	4.2E-01	6.8E-01	7.8E-02
Carbon Monoxide	1.0E-01	2.7E-01	1.8E-01
VOCs	1.3E-03	2.2E-03	7.3E-04
$CO_{2\ biomass}$	5.5E+02	8.5E+02	7.7E+02
$CO_{2\ fossil}$	4.8E+01	8.2E+01	1.6E+01
Ammonia	8.1E-01	1.1E+00	5.5E+00
Lead	2.9E-09	6.2E-09	5.0E-09
Methane	3.0E-04	5.0E-04	5.0E-05
Hydrochloric Acid	3.1E-07	6.7E-07	5.5E-07
Solid Waste (miscellaneous) [a]	5.7E+00	9.4E+00	5.8E-01
Leachable pollutants (lb/ton)			
COD	1.9E+00	2.3E+00	9.7E-01
BOD	1.9E-01	2.3E-01	9.7E-02
NH_3-N	5.2E-02	6.3E-02	2.6E-02
NO_3-N	1.7E-01	2.1E-01	8.8E-02
TKN-N	1.0E-01	1.3E-01	5.3E-02
Na	1.3E+00	1.5E+00	2.5E-03[b]
K	1.1E+00	1.3E+00	1.2E-01[b]
Ca	6.4E-01	7.8E-01	3.2E-01
Mg	2.2E-01	2.7E-01	1.1E-01
Mn	1.0E-03	1.2E-03	2.0E-04[b]
Fe	1.4E-02	2.1E-02	5.2E-03[b]
Cl	1.4E+00	1.7E+00	7.2E-01
SO_4-S	6.0E-01	7.2E-01	3.0E-01
F	6.9E-04	8.4E-04	3.5E-04
P	7.4E-03	9.0E-03	3.7E-03
Cd	9.4E-06	1.1E-05	6.6E-05[b]
Ni	9.0E-04	1.1E-03	4.5E-04
Co	3.8E-05	4.6E-05	1.9E-05
Zn	5.2E-03	6.3E-03	8.8E-05[b]
Cu	1.5E-03	1.8E-03	2.6E-05[b]
Pb	2.4E-04	2.9E-04	1.2E-04
Cr	7.7E-05	9.4E-05	8.8E-06[b]

[a] Does not include screen rejects and is associated with precombustion and combustion emissions.
[b] Indicates leaching data were available for YW-derived compost.

Table 10. Solid Waste Flows Through a Facility (100 tpd basis)

	LQCF		HQCF		YWCF	
	Wet tons	**Dry tons**	**Wet tons**	**Dry tons**	**Wet tons**	**Dry tons**
Mass at tipping floor	100.0	78.6	100	77.3	100	40.0
Mass removed by prescreening	31.2	25.6	0.0 [c]	0.0	0.0 [c]	0.0
Mass exiting compost pad[a]	65.6	39.3	93.6	56.1	34.9	21.0
Mass exiting facility (compost)[b]	65.6	39.3	79.5	47.7	33.2	19.9
% overall reduction[d]	34.5	50.0	20.5	38.3	66.8	50.3

[a] Note that both decomposed organics and (undecomposed) inorganics exit the composting pad.
[b] Reduced by post-composting screening.
[c] No pre-composting screening is used in the HQCF and YWCF.
[d] (Mass flow rate at tipping floor – mass flow rate exiting facility) / mass flow rate at tipping floor.

According to Diaz et al. (1986), average energy requirements in an MSW composting facility were calculated to be 34.4 kWh/ton of MSW. The values predicted by the model are 97 kWh/ton and 166 kWh/ton for the LQCF and HQCF. The higher predictions are partially because precombustion and combustion energy requirements are included in the total energy requirements. The values by Diaz et al. (1986) refer to energy consumed directly within the facility and include extensive preprocessing prior to composting (e.g., size reduction, screening). No odor-control system was used by Diaz et al. (1986).

The atmospheric pollutants, excluding $CO_{2\ biomass}$, NH_3, and VOCs, are primarily a function of the energy usage and energy distribution. All energy-related atmospheric emissions are higher for the HQCF than for the LQCF. This reflects the greater electricity and diesel requirements for the HQCF. In the case of the YWCF, the hydrocarbon (HC), CO, and NO_x material flows values are similar to those values for the LQCF. This is a result of the higher usage of diesel in the YWCF compared to the MSW facilities, although total energy is less for the YWCF than both MSW composting facilities. The $CO_{2\ biomass}$, NH_3, and the VOC predicted values are based on equations (3) through (6) and refer to the gases produced from substrate decomposition within the facility as well as during compost land application. It is noted that the total gaseous ammonia emitted from the YWCF (as reported in Table 9) contains some ammonia produced as part of precombustion emissions for diesel and electricity; however, that fraction is less than 0.0001 percent of the ammonia emissions produced from decomposition. The relatively low ammonia value for the LQCF is due to the high percentage of paper contained in the MSW entering the composting pad. A higher percentage of yard waste and food waste is entering the composting pad of the HQCF, because no prescreening took place for this facility.

Among the leachable emissions, COD, Cl, and Na have the largest mass loadings. Leachable pollutants are slightly higher in the HQCF than in the LQCF because compost production is 61 percent (in dry mass per dry initial ton) for the LQCF compared with 50 percent for the HQCF, because of more processing in the former than in the latter. The lower leachable values in the YWCF are due to the higher dry mass reduction of the incoming substrate compared to the dry matter reductions in the MSW composting facilities. However, because certain leachable pollutants from the YW compost were taken equal to those from MSW compost because of the lack of information, comparisons of the leachable pollutants between the YWCF and the MSW facilities should be made with caution. It is worth noting that the Cd mass loading is much higher in the YWCF compared with the MSW facilities. According to Cole (1994), the leaching tests used were designed to simulate extreme situations, using excess water for extraction, and therefore the expected actual leachable mass loadings of some of the studied elements may represent upper boundaries. The MSW compost testing was not as aggressive.

6.1.1 Comparison with Field Data

The dry matter reduction, predicted by the LCI model, was compared to available field values in order to check the validity of the model to predict the extent of decomposition of solid wastes. In the case of the YWCF, three grab samples of YW compost were collected in February 1996 from a YWCF compost pile near Madison, WI, and were combined into one composite sample. The compost samples were collected from a 4- to 5-year-old compost pile and subjected to a volatile solids (VS) content analysis. This was the only "oldest" compost pile in the facility and was selected to ensure that an "advanced" extent of decomposition had been reached within the facility. The VS content was measured to be 23 percent (on a dry matter basis), which is below the approximately 51 percent measured in Ham and Komilis (1999) for finished YW composted in laboratory simulators. The difference might be attributed to two factors. The first is the longer decomposition time of the field-derived compost compared with the decomposition time of the laboratory-derived YW compost, which was approximately 2 months. This is in spite of the fact that very low CO_2 production rates were recorded at the end of the laboratory experiment, which indicates that decomposition continues, albeit at slow rates, in the field. The second is that the YW field-derived compost might have been mixed with soil during generation and collection of the waste and turning of the piles, resulting in the relatively low VS content. Based on the final field measured value and assuming that yard wastes have a VS content of 74 percent prior to composting (see laboratory study report), the field dry mass reduction, calculated on a constant ash basis, is 66 percent. The model calculates a dry matter reduction of 47.5 percent.

In the case of MSW compost, cured compost from the MSW compost facility near Portage, WI, was sampled, and its VS content was determined to be 63.1 percent (dry matter). Based on typical national figures for MSW composition, an initial 25 percent inorganics content (dry weight), and an initial 20 percent MSW moisture (wet weight) are assumed. Based on the measured final VS content of 63.1 percent for finished compost (dry weight), the VS and the dry matter reductions in the actual MSW composting plant are calculated to be 22.3 and 15.3 percent. The VS reduction in the laboratory experimental work for an MSW mixture simulated based on a U.S. MSW composition was 70 percent, which corresponds to a 20.6 percent dry matter reduction (using above typical national figures). From the above, it appears that waste in the actual MSW composting plant may not have reached its “full” extent of decomposition, and some additional decomposition would be expected after land application.

Figure 2 is an example of model results expressed in diagram form for the HQCF, based on Tables 9 and 10. Note that solid waste inputs and outputs are given in (wet) tons, while other material flows (pollutants) are given in pounds. Total energy requirements are given in Btu. Table 10 presents the mass flows at different parts of each of the three facilities. Note that wet masses after composting were calculated by assuming a moisture content of 40 percent wet weight and by accounting for the dry matter reduction. Although the initial moisture contents of MSW (at the tipping floor) is approximately 25 percent (wet weight), the increase observed is primarily due to the assumed addition of water to the wastes prior to composting. Dry matter reductions are based on equations (3) and (4) and the MSW compositions mentioned earlier. As Table 10 shows, the lower dry matter reduction observed for MSW facilities compared with YW is largely because inorganic components are included in MSW that do not decompose during composting.

6.2 Breakdown of Costs, Energy, and Material Flows

The following section describes the breakdown of total cost, total energy, and material flows to components or processes within the facility.

The breakdown of the capital and operating/maintenance costs is presented in Figure 3 based on a typical 100 tpd HQCF. Relative responses were the same for both MSW facilities. and therefore results for only the HQCF are shown. As shown in Figure 3, the composting pad building and the odor-control system account for approximately 77 percent of the total capital cost. Building cost is primarily the building over the composting pad; only 10 percent of it is for a building for offices and storage. Engineering and hammermill costs are next highest.

Figure 4 presents a breakdown of the operating costs. Combined labor cost and overhead costs account for approximately 62 percent of the total operating cost. Electricity- and diesel-related costs rank next highest with 28.6 percent of total operating cost. Sixty-two percent of the total electricity cost is due to odor control operation, while the other 38 percent is mostly due to hammermill operation. Maintenance costs for the hammermill and windrow turner are less than 10 percent of the total operating cost.

Based on the HQCF, 29.2, 55.9, 2.9, 6.9, and 1.4 percent of the total energy requirements are due to hammermill, odor control, front-end loaders, windrow turner and trommel screen operation, and 3.8 percent is due to building operation.

Relatively similar values are true for the LQCF. In the case of the YWCF, 55.1 percent, 16.1 percent, 7.7percent, and 21.1 percent of total energy are due to the tub grinder, the front-end loader, screens, and building operation.

Of the total diesel energy requirements, 84 percent is combustion energy requirement and the rest is precombustion for all facilities. At least 95 percent of the total electrical-energy-related requirement is due to combustion, as also shown in Table 2, for all three facilities. In the LQCF and HQCF, electricity-related energy accounts for more than 90 percent of the total energy with the rest being diesel-related energy. In the YWCF,

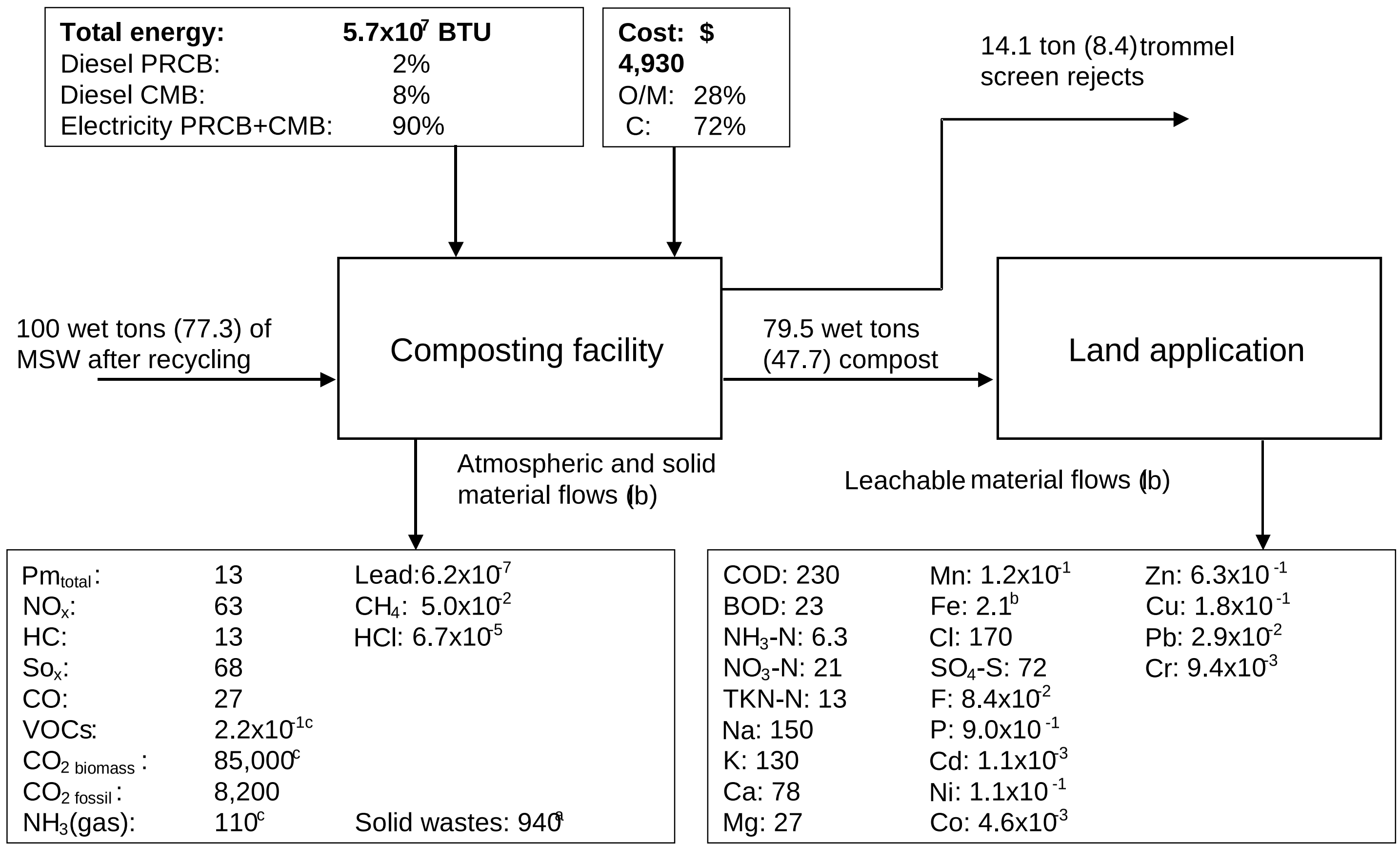

Figure 2. Flow diagram for 100 (wet) tons of MSW entering an HQCF (values in parenthesis are dry tons).

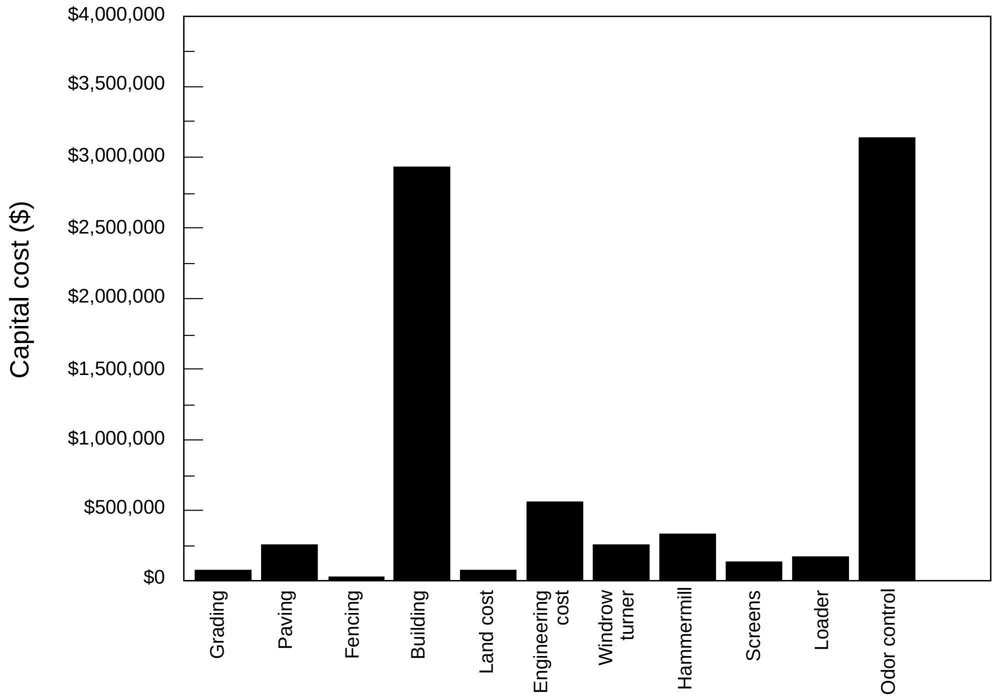

Figure 3. Capital cost breakdown for a 100 tpd HQCF.

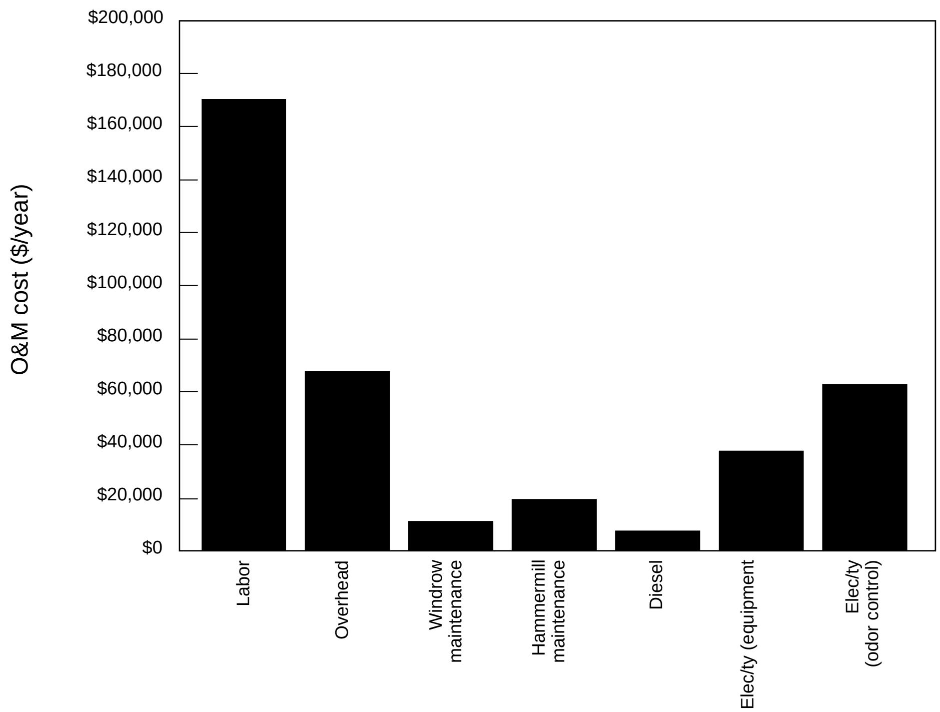

Figure 4. Operating/maintenance cost breakdown for a 100 tpd HQCF.

60 percent of the total energy is diesel combustion energy, 29 percent is electricity, and the rest is diesel precombustion energy. This is apparently because only diesel-powered equipment is used in the YWCF, and electricity is limited to the building operation.

Table 11 presents the fraction (in %) of the atmospheric pollutants attributed to diesel combustion only, for all three facilities. The percentage of the pollutants shown in Table 11 is produced within the boundaries of the facility. Because of the extensive use of electricity in the LQCF and HQCF (because of the odor control and hammermill operation), diesel combustion is responsible for less than 50 percent of all the emissions shown in Table 11. Diesel combustion in the HQCF accounts for 61 percent of the CO emissions. Diesel combustion is generally responsible for a production of a relatively large percent of the NO_x and CO emissions from both the MSW compost facilities. As Table 11 shows, SO_x emissions are primarily produced from electricity consumption. These emissions are therefore produced outside the boundaries of the facility. There is limited use of electricity in the YWCF because no odor-control system is used and the tub grinder runs on diesel; therefore, the six atmospheric pollutants are primarily due to the operation of diesel equipment within the facility.

Table 11. Fraction (in %) of Atmospheric Pollutants Emitted from Direct Diesel Combustion in All Three Composting Facilities (the Rest is due to Diesel Precombustion and Electricity Precombustion/Combustion Emissions)

Facility	Percent					
	PM (total)	NO_x	HC	SO_x	CO	CO_2 (fossil)
MSW LQCF	6.9	37.0	22.8	1.8	37.1	6.1
MSW HQCF	4.3	49.3	42.0	1.1	61.0	9.5
YWCF	79.2	93.9	57.8	45.8	95.5	63.9

Total HCs are much higher than VOCs (see Table 9). The lowest VOC emissions are from the YWCF, because mixed paper is absent from the YW feed stream. As discussed in Ham and Komilis (1999), mixed paper is the major contributor of the 12 selected VOCs compared to yard wastes and food wastes. No external addition of hazardous or industrial wastes was performed in their experiments.

It is worth noting that of the total carbon dioxide emitted, 91.9 percent, 91.2 percent, and 98.0 percent, respectively, for the LQCF, HQCF, and YWCF is due to the decomposition of the organic substrate. The rest is fossil-fuel-related CO_2. Approximately 100 percent of the ammonia emitted in all facilities is due to decomposition.

Approximately 100 percent of the leachable pollutants emitted are due to leaching after compost land application. The only exception is iron. Approximately 40.2 percent, 33.3 percent, and 84.2 percent of the total iron emitted is due to compost leaching for the LQCF, HQCF and YWCF, with the rest due to diesel precombustion-related emissions.

6.3 *Economy of Scale*

A typical economy of scale based on the model is shown in Figure 5 for the HQCF. Similar economies of scale are modeled for the LQCF and YWCF. The left axis represents the total cost in dollars per ton of MSW entering the facility. As shown, composting for an HQCF is affected by economy of scale for facilities less than 100 tpd, with unit costs between $45.5/ton and $49.3/ton for input mass flow rates higher than 100 tpd.

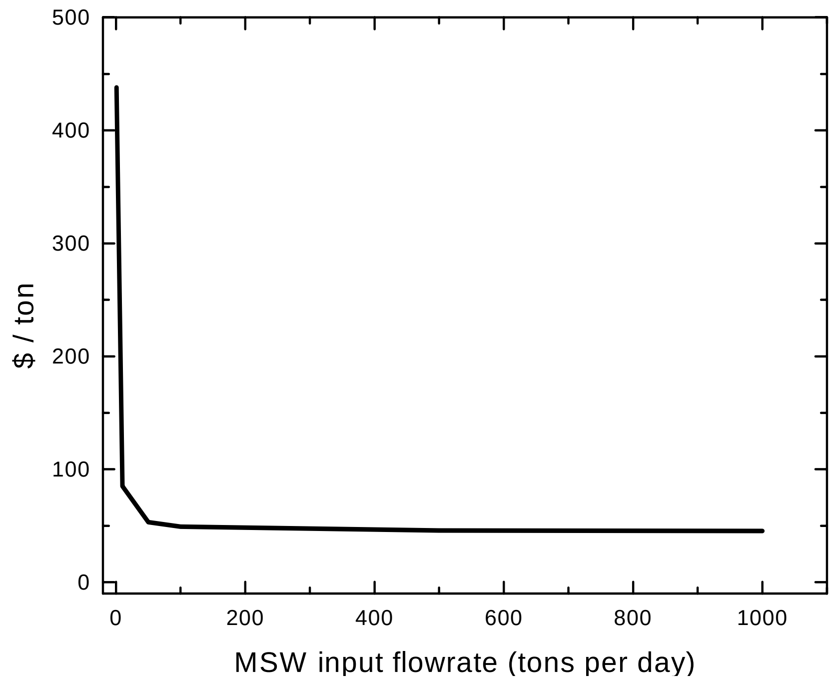

Figure 5. Economy of scale for the HQCF; cost includes combined amortized capital cost and operating/maintenance cost based on a 5 percent amortization rate and 15-year design life.

6.4 *Sensitivity Analysis*

Table 12 presents a sensitivity analysis for key elements of the LQCF as an example of impacts of various factors and assumptions. The baseline of the analysis was an input waste flow rate of 100 tpd. To perform the sensitivity, a 50 percent change (increase or decrease) of the selected parameter was specified, and the change from the baseline value recorded as a percentage is shown. The change was recorded for total cost, total energy, and the sum of the mass loadings of nine atmospheric material flows (pollutants), which are a function of electricity and diesel precombustion and combustion processes. $CO_{2\ biomass}$, NH_3, and VOCs were not included because they are functions of decomposition only and therefore are affected by the initial waste composition only. Leachable material flows (excluding iron) are emitted only because of compost land application, and they change only as a function of the dry matter reduction. Therefore, they are not included in Table 12.

As Table 12 shows, the presence of an odor-control system, retention time, and employee salaries and numbers have the greatest effect on total cost. The first two

Table 12. Sensitivity Analysis on Selected Parameters Using a 100 tpd LQCF as the Baseline

Parameter	Change from	Change to	Percent		
			Change in total cost (%)	Change in total energy (%)	Change in sum of nine atmospheric pollutants (%)[a]
Grading cost ($/acre)	5,000	7,500	0.2	0.0	0.0
Paving cost ($/acre)	72,500	08,750	0.7	0.0	0.0
Land acquisition cost ($/acre)	1,240	1,860	0.3	0.0	0.0
Composting pad building cost ($/ft^2)	6.5	9.75	9.5	0.0	0.0
Interest rate (%)	5	7.5	10.1	0.0	0.0
Facility design life (years)	15	22.5	-12.7	0.0	0.0
Wages ($/h)	8	12	16.1	0.0	0.0
Number of employees	10	15	16.1	0.0	0.0
Turning frequency (No./week)	1	1.5	0.2	0.7	0.8
Retention time (days)	30	45	18.5	16.1	16.0
Buffer distance (ft)	500	750	0.7	0.0	0.0
Odor control air change rate (min)	120	80	12.4	18.8	18.6
No odor control system	-	-	-24.8	-37.7	-37.2
Compost windrow height (yd)	2.0	3.0	-12.6	-10.6	-10.5
Change of hammermill shredding coefficient (raw and presorted waste)	1.0 (raw)	0.67 (presorted)	-1.5	-17.4	-17.2

[a] $PM_{(total)}$, NO_x, SO_x, HC, SO_x, CO, $CO_{2\ fossil}$, Lead, and $CH_{4,}$ excluding $CO_{2\ biomass}$, VOCs, NH_3.

parameters and odor control air exchange rate and hammermill shredding requirements have the largest effects on energy and material flows. Interest rate and design life also have large effects on total cost. Composting pad cost has a relatively large effect on total cost, but no effect on energy and pollutants.

Hammermill design has a marked effect on total energy and emissions. This is because the hammermill accounts for a large use of electrical energy. The use of presorting will change the waste and the shredding coefficient from a value of 1 to a smaller value, as discussed earlier. Therefore, waste presorting can result in a significant reduction in total energy and gaseous environmental pollutants.

It also appears that windrow geometry affects total cost, energy, and emissions. A higher windrow height than the one used as the default value will result in a smaller composting pad for the same mass of wastes entering the pad. Windrow geometry, however, is limited by the type of turning equipment used. Buffer distance, grading cost, paving cost, and turning frequency have minor effects on the total cost.

Using no odor-control system reduces total cost, energy, and environmental emissions by more than 25 percent.

Model results indicate that similar conclusions to those discussed above for the LQCF are valid for the HQCF and YWCF.

6.5 Allocation of Cost, Energy, and Material Flows to MSW Components

This allocation section refers to the two MSW composting facilities, because the MSW mixture consisted of seven components. Total cost and total energy coefficients (in $/ton of MSW and Btu/ton of MSW) were allocated equally to all components. Therefore, if the cost of the facility is $x/ton of MSW entering the facility, the cost for treating food wastes will also be $x/ton of food waste, etc. This was done because it was assumed that all components will always be a part of a MSW mixture. For example, in the case of inorganic components, an infinite time would be theoretically needed for their being "composted." This would result in a composting pad of infinite area. However, because inorganic components will always be mixed with organic components, the same time requirement was used.

Because all atmospheric material flows, excluding $CO_{2\ biomass}$, NH_3, and the VOCs, are functions of total energy, they were also allocated equally to all seven MSW components. Allocation of the degradation-related gaseous emissions ($CO_{2\ biomass}$, NH_3, and the VOCs) was done using equations (3), (5), and (6), which relate to the organic content of the incoming waste. No biodegradation-related emissions are allocated to the inorganic components. Leachable emissions are allocated equally to all waste components, as shown in Table 9.

7. Model Use

The results presented here—particularly the cost-related results—are based on the specific default cost values used during development of the compost model. These default values can vary significantly, especially for land acquisition costs, and may be changed by the user if site-specific data is available. In this sense, the model does not suggest a standard or proper design for composting facilities. The main goal was to develop a tool to estimate global environmental burdens during solid waste composting. The value of this model for composting is more evident when used in relative comparisons with other similarly developed models for other facilities in an ISWM system.

Several assumptions had to be made regarding the allocation of certain pollutants to the individual components. Though experiments can provide information on pollutants from individual waste components, one must not ignore the interactions among components when combined together in an MSW mixture. The equations used here do include interactions among food, mixed paper, and YW as determined in laboratory experiments.

Finally, it should be emphasized that gaseous emissions and dry matter reductions are based on laboratory work in which "clean" (not mixed with other wastes) components were degraded to the "full" extent. Any contamination of these organic components, or inorganic components that are assumed to be inert with regard to decomposition and subject only to leaching as part of the finished compost, would result in higher emissions than projected here. These results do not discriminate between degradation-related emissions resulting from the compost facility itself and emissions resulting from continued degradation once the finished compost is placed on land or in a landfill. The environmental burden associated with "full" decomposition is given and is the same regardless of the extent of decomposition achieved within the facility. Because of the wide range in facility design and operation, it was deemed impractical to model decomposition within a facility.

8. Conclusions

Based on the model for composting facilities developed in this report, the following can be concluded:

1. Total costs for the LQCF, HQCF, and the YWCF are $27.9/ton, $49.3/ton, and $15.9/ton for 100 tpd facilities and are comparable to total costs of actual MSW and YW composting facilities in the United States (1998 dollars).

2. The odor-control system and the building (primarily the enclosed composting pad building) constitute approximately 77 percent of the total capital cost in MSW composting facilities, followed by the engineering cost and equipment cost.

3. Total energy requirements are $3.3x10^5$, $5.7x10^5$, and $1.0x10^5$ Btu/ton for the LQCF, HQCF, and YWCF.

4. Approximately 90 percent, 8 percent, and 2 percent of the total energy requirements is due to electricity precombustion/combustion, diesel combustion, and diesel precombustion for the HQCF. At least 95 percent of the total electricity energy requirements are combustion related. Similar conclusions are true for the LQCF and YWCF.

5. Compost retention time and odor control air exchange rate are the factors most affecting total cost, total energy, and gaseous emissions. Energy requirements are sensitive to the type of wastes (raw or presorted) handled by the hammermill and windrow geometry.

6. Overall dry weight losses (including screen rejects), as predicted by the model for the HQCF, are approximately 38 percent. Actual dry weight losses were estimated to be approximately 15 percent from one MSW composting facility based on sampling cured compost, a volatile solids content analysis, and an assumed initial typical U.S. MSW composition. Wastes in actual MSW composting facilities may not reach their “full” extent of decomposition during composting.

7. MSW in LQCF and HQCF produces 550 lb and 850 lb of CO_2/ton of incoming material. Ammonia emissions from these facilities are 0.8 lb/ton and 1.1 lb/ton, respectively. Yard wastes in the YWCF produce 770 lb CO_2/ton and 5.5 lb

NH_3/ton. Interactions among components were accounted for during calculation of the CO_2 and NH_3 yields.

8. More than 90 percent of the emitted CO_2 is from solid waste decomposition ($CO_{2\ biomass}$), with the rest emitted from fossil fuel combustion and precombustion processes.

9. The HQCF has approximately 10 percent to 20 percent higher leachable mass loadings than the LQCF. COD, Cl, and Na are the largest mass loadings among all leachable pollutants. The YWCF had smaller leachable mass loadings compared with the MSW facilities because of a smaller amount of compost produced per unit mass of waste entering the facility. Only Cd had a larger mass loading from the YWCF compared with the LQCF and HQCF.

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Appendix A

EQUATIONS FOR DESIGN OF COMPOSTING FACILITIES

1. Mass flow equations

This appendix includes the equations used to develop the three process models. The equations were developed based on the flow diagrams depicted in Figures A-1, A-2, and A-3, for the low-quality MSW, high-quality MSW, and YW compost facilities, respectively. The equations correspond to the flow streams (indicated by numbers) that are included in figures A-1, A-2, and A-3. As mentioned in the text, the 48 components used in the original project are represented by seven components.

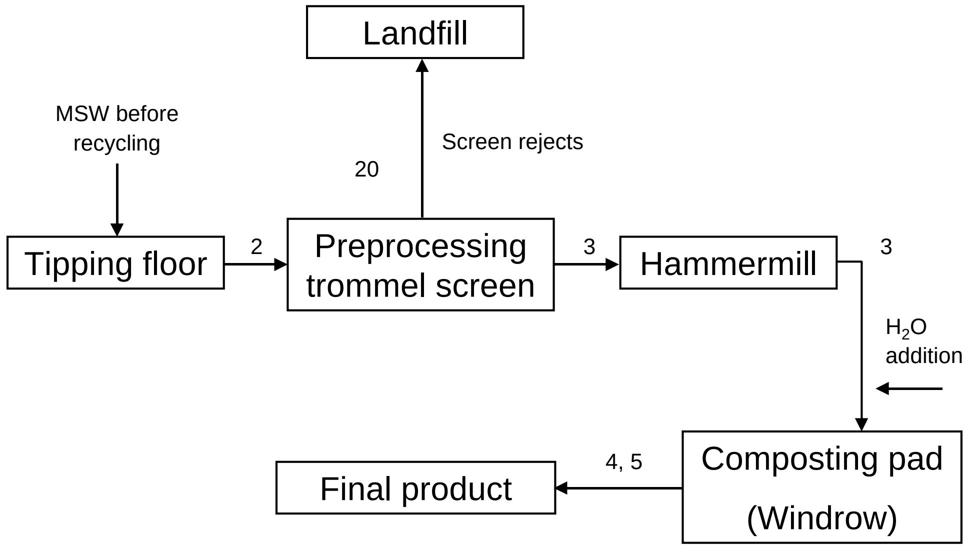

Figure A-1. Flow diagram for the LQCF.

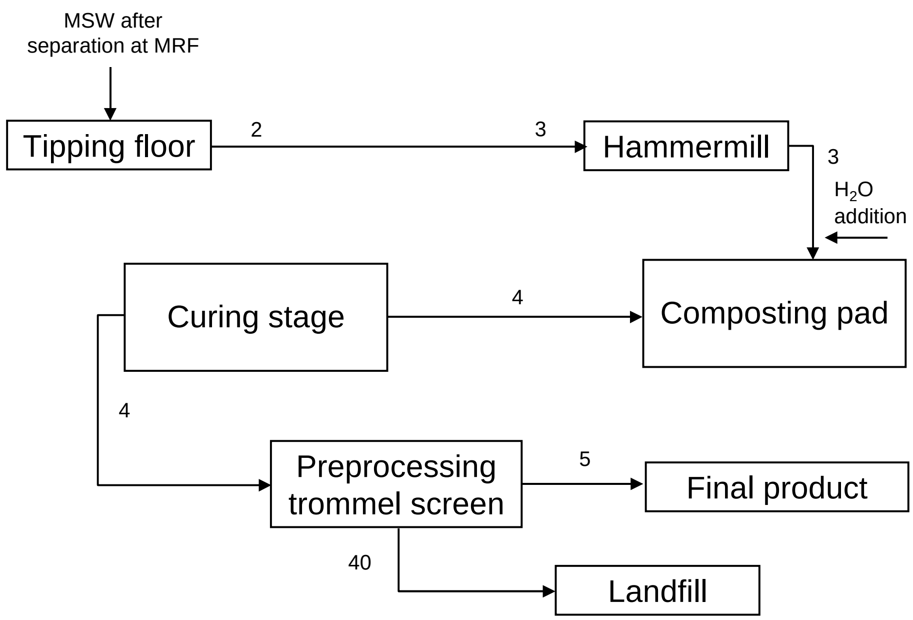

Figure A-2. Flow diagram for the HQCF.

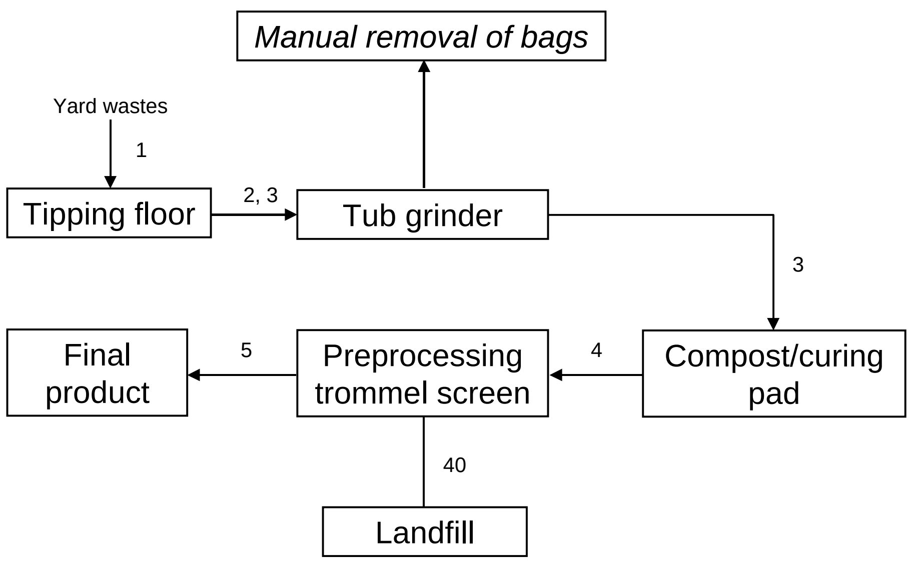

Figure A-3. Flow diagram for the YWCF.

Equation A-1

$dry\_mass\_1_i = (1 - moist_i) \times mass\_1_i$

$dry\_mass\_1_i$:	dry mass of waste component i entering the facility on the tipping floor (tpd)
$moist_i$:	moisture content of waste component i at tipping floor; % wet weight;
$mass\_1_i$:	wet mass of component i entering the facility (tpd); this is part of the model solution
i:	waste component, where i varies from 1 to 7

Equation A-2

$dry\_mass\_1 = dry\_mass\_1_1 + dry\_mass\_1_2 + ... + dry\_mass\_1_k$

dry_mass_1:	initial dry mass flow rate of incoming wastes at tipping floor (tpd)

Equation A-3

$vol\_1_i = mass\_1_i \times 2{,}000 / waste\_dens_i$

vol_1_i:	waste volume flow rate of component i entering the tipping floor (yd^3/d)
$waste\_dens_i$:	bulk wet density of incoming waste component i at the tipping floor (lb/yd^3); default values shown in Table 6.
2,000:	lb/ton

Equation A-4

$moist\_1 = (mass\_1_1 \times moist_1 + mass\_1_2 \times moist_2 + .. mass\_1_k \times moist_k) / mass\_1$

moist_1:	initial moisture content of daily waste entering the facility (% moisture on a wet weight basis)
$moist_{1...k}$:	moisture content of waste component i (1 to 7); % wet weight (default values shown in Table 6)

Equation A-5

$vol\_1 = vol\_1_1 + vol\_1_2 + ... + vol\_1_k$

vol_1:	total volume flow rate of wastes entering the tipping floor (yd^3/d)

Equation A-6

$mass\_2 = mass\_1$

mass_2:	waste mass flow rate after tipping floor (tpd)

Equation A-7

$mass\_3_i = pre\_screen_i \times mass\_2_i$

$mass\_3_i$:	wet mass flow of undersized fraction of component i after screening at the preprocessing step (tpd)
pre_screen_i:	trommel screen efficiency, that is the fraction of undersize material as a function of waste material into screen; efficiency depends on the particle size distribution of each component, the flow rate and the trommel screen mesh opening. Table 6 (in the main text) presents trommel efficiencies (for the LQCF only) used for each of the seven components based on information from Alter (1985). No

prescreening is used for the HQCF and the YWCF and therefore a pre_screen_i value of 100% (fraction of 1) is used for these facilities.

Equation A-8

$mass\_3 = mass\_3_1 + mass\_3_2 + ... + mass\_3_k$

$dry\_mass\_3 = dry\_mass\_3_1 + dry\_mass\_3_2 + ... + dry\_mass\_3_k$

mass_3: total waste wet mass flow rate entering the composting pad after shredding (tpd)

dry_mass_3: total dry mass flow rate entering the composting pad after shredding (tpd)

Equation A-9

$mass\_2o = mass\_2 – mass\_3$

mass_2o: wet mass flow rate of rejects during prescreening (tpd)

[Note that mass_2 = mass_3 for the HQCF and YWCF, and therefore mass_2o = 0.]

Equation A-10

$water\_3 = [(0.50 - moist\_1) \times mass\_3] / 0.50$

water_3: daily water amount (tpd) requirements to increase the moisture of the waste stream (mass_3) entering the composting pad to a near optimal value of 50% wet weight.

[Note that the water addition is used during the mass balance calculations; however it is not included in the capital cost.]

After combining the different MSW components, the MSW mixture is treated as one "component." Therefore, all following equations are based on one component, namely the mixture of MSW.

Equation A-11

$vol\_3 = (mass\_3 + water\_3) \times 2{,}000 / comp\_dens$

vol_3: volume flow rate of MSW entering the composting pad and forming windrows (yd^3/d)

comp_dens: wet bulk density of MSW in the windrows (or piles) at the beginning of the composting process; default value of 500 lb/yd^3 (see Table 6).

Equation A-12

$YCO_2 = 217.4 \bullet F_P + 237.3 \bullet F_Y + 370.5 \bullet F_F$

YCO_2: the CO_2 yield (in gr C/dry kg of the organic fraction of MSW);

F_P, F_Y, F_F: the dry fractions of mixed paper, YW, and food waste, respectively, in the organic fraction of MSW, with each of the F_P, F_Y, F_F values ranging from 0 to 1 and with $F_P+F_Y+F_F$ always equal to 1.

[Note that inorganics are not included when estimating the F_P, F_Y, F_F functions.]

Equation A-13

$YNH_3 = 1.29\ (\pm 1.38) \bullet F_P + 5.15\ (\pm 1.37) \bullet F_Y + 37.6\ (\pm 1.56) \bullet F_F - 68.9\ (\pm 23.4) \bullet F_P \bullet F_F$

YNH_3 is the mass of NH_3 (in gr N/dry kg of the organic fraction of MSW).

Equation A-14

$DryRed = YCO_2 / 489.3\ (\pm 17.9)$

DryRed is the dry weight reduction of the organic fraction of MSW (expressed as a fraction).

Equation A-15

$Y_{VOC} = 4{,}162\ (\pm 1{,}701)\ F_P + 831\ (\pm 1{,}890)\ F_Y + 458\ (\pm 2{,}340)\ F_F - 7{,}558\ (\pm 17{,}662)\ F_P F_Y - 6{,}006\ (\pm 28{,}770)\ F_P F_F$

Y_{VOC} is the sum of 12 VOCs volatilized from an MSW mixture (expressed in μg VOCs/dry kg of the organic fraction of MSW).

[Note: VOCs not included in the 12 VOCs quantified in the laboratory study are in addition to those calculated by Eq. A-15.]

The dry matter reduction for the total MSW, including the inorganics, is calculated as follows:

Equation A-16

*comp_red = DryRed * [(dry_mass_food + dry_mass_paper + dry_mass_yard) / dry_mass_3]*

comp_red:	overall dry mass reduction of MSW (including inorganics) during composting [Note that dry mass reduction of MSW in the composting pad is assumed due to dry mass reduction of the organics only.]
dry_mass_food:	dry mass flow rate of food wastes entering composting pad (tpd)
dry_mass_paper:	dry mass flow rate of mixed paper entering composting pad (tpd)
dry_mass_yard:	dry mass flow rate of yard wastes entering composting pad (tpd)

Equation A-17

dry_mass_4 = dry_mass_3 x (1 − comp_red)

dry_mass_4:	dry mass flow rate of MSW (sum of all components) exiting the composting pad (tpd)

Equation A-18

vol_4 = dry_mass_4 x 2,000 / cur_dens

vol_4: waste volume flow rate at the end of the composting process (yd^3/d)

cur_dens: bulk density (dry mass basis) of produced compost. It is assumed that composted material has the same density, despite the composition of the incoming wastes. A default value of 700 lb/yd^3 is used (see Table 6)

[Note that dry mass is used in the above equation, since the MSW compost bulk density is expressed on a dry mass basis.]

Equation A-19

mass_4 = dry_mass_4 / (1 - comp_moist)

mass_4: wet mass flow rate of MSW at the end of the curing pad (tpd)

comp_moist: moisture of MSW at the end of curing; default value of 40% wet weight basis (Diaz et al., 1993)

Equation A-20

comp_vol = vol_3 x comp_res

comp_vol: maximum volume of wastes present on composting pad as windrows or piles (yd^3)

comp_res: residence time in composting pad (days); default values shown in Table 5

Equation A-21

comp_mass = (mass_3 + water_3) x comp_res

comp_mass: maximum mass of wastes on composting pad (tn); this is the mass to be aerated by the windrow turner at each turning time

Equation A-22

cur_vol = vol_4 x cur_res

cur_vol: volume of wastes in curing stage (yd^3)

cur_res: retention time of waste in curing stage (days); default values will be 0, 30, and 0 days for the LCQF, HCQF, and YWCF, respectively.

[Note that one area is designated for composting and curing in the YWCF, so a separate area is not required.]

Equation A-23

Dry_mass_5 = post_screen x dry_mass_4

Dry_mass_5: dry mass flow of undersized fraction of composted MSW after screening at the postprocessing step (tpd)

post_screen: post-trommel screen efficiency, which is percentage of undersize material as a function of waste material into screen; assumed default value is 0, 0.15, and 0.05 for LQCF, HQCF, and YWCF, respectively (adapted from Gould and Meckert, 1994).

Equation A-24

mass_5 = dry_mass_5 / (1 - comp_moist)

mass_5: wet mass flow rate of MSW after postscreening (tpd)

Equation A-25

mass_4o = mass_4 - mass_5

mass_4o: waste mass flow rejected to landfill during postscreening step (tpd)

[Note that for the LQCF mass_4 = mass_5 and therefore mass_4o = 0.]

Equation A-26

land_mass = mass_2o + mass_4o

land_mass: wet mass flow of waste rejected and directed to landfill after the preprocessing and postprocessing steps (tpd)

Equation A-27

land_vol = (land_mass x 2,000 / stor_dens) x stor_res

land_vol: volume of waste rejected and temporarily stored within the facility prior to landfilling (yd^3)

stor_dens: density of rejects at the temporary storage piles; default value 450 lb/yd^3 (Diaz et al., 1993)

stor_res: residence time of reject piles prior to landfilling; default time of 2 days

Windrow Turner Design

Equation A-28

turn_req = (comp_mass x turn_freq) / (oper_hrs x days_week)

turn_req: mass of compost required to be turned on an operational hourly basis (tph)

turn_freq: compost piles turning frequency per week (# turns/week; default of 1 and 3 for the LQCF and HQCF, respectively)

oper_hrs: number of operating hours per day; default 8 h/day

days_week: operating days per week; default 5 days/week

Equation A-29

turner_hp = 0.173 x turn_req

turner_hp: required horsepower of windrow turner (hp)

0.173: coefficient (hp/tph)

Equation A-30

num_turner = turn_req / 1,700 + 1

num_turner: number of operating windrow turners

1,700: turning capacity of typical windrow turner (tph)

[Note that one windrow turner is used as a minimum, and fractional use of units is allowed.]

Equation A-31

turner_diesel = 0.025 x turner_hp

turner_diesel: diesel consumed during hourly operation of windrow turner (gph)
0.025: coefficient in gph/hp

[Note that for a typical John Deere engine, the average diesel consumption is 0.025 gph/gross hp. This coefficient will be used to calculate the diesel consumption for the tub grinder as well as for the front-end loader.]

Equation A-32

turner_hours = (comp_mass x turn_freq) / 1,700

turner_hours: hours of operation of windrow turner per week (hrs/week)
1,700: turning capacity of an average windrow turner (tph)

Hammermill design

Equation A-33

hammer_hp = 20 x (mass_3 / oper_hrs) x input_coeff x size_coeff

hammer_hp: required net power of hammermill (hp)
20: power coefficient (hp / tph) depending on product particle size
input_coeff: input material factor; default of 1.00 and 0.65 for the LQCF and HQCF, respectively; values correspond to municipal solid wastes and presorted municipal solid wastes, respectively
size_coeff: product size factor; default of 1.64 for both facilities, corresponding to a product size of 2 in.

[Note: The above three parameter default values are all discussed in the text.]

Equation A-34

num_hammer = hammer_coeff x mass_1 + 1

num_hammer: number of operating hammermills
hammer_coeff: coefficient that relates number of hammermills to incoming waste flow rate (# hammermills/tpd); default of 0.00294 units/tpd as discussed in the text

Tub grinder design

The equation that relates tub grinder horsepower to waste flow rate was based on four power values from 325 hp to 575 hp that correspond to waste input capacities from 25 tph to 40 tph. A coefficient of 13.7 hp/tph is derived and used, as shown below:

Equation A-35

tubgrinder_hp =13.7 x (mass_1 / oper_hrs)

tubgrinder_hp: yard waste composting facility's tub grinders required gross horsepower (hp)
13.7: coefficient that relates horsepower to waste capacity (hp/tph) (see text)

The number of tub grinders was expressed as a function of the waste throughput capacity (tpd) by using an average value of 32.5 tph (average value based on tub grinder manufacturers data). The equation that correlates the number of tub grinders with waste flow rate is as follows:

Equation A-36

num_tubgrinder = grinder_coeff x mass_1 + 1

num_tubgrinder: number of operating tub grinders

grinder_coeff: coefficient that relates number of tub grinders with waste flow rate (# tub grinders/tpd); default of 0.00385 for the YWCF (see text)

For a typical John Deere engine, the average diesel consumption is 0.025 gph/gross hp. This coefficient will be used to calculate the diesel consumption for the tub grinder as well as for the front-end loaders later.

Equation A-37

tubgrinder_diesel = 0.025 x tubgrinder_hp

tubgrinder_diesel: tub grinder average diesel consumption (gph)

Trommel screen design

Diaz et al. (1982, pp.120) have suggested a gross specific energy consumption (freewheeling plus net work) of 1.1 kWh/ton for pre-trommeling with typical equipment, and 0.8 kWh/ton for trommeling of the light fraction (postscreening step). The above values will be used for the pre-trommeling and postscreening steps.

Equation A-38

pre_trommel_hp = pre_trm_hp_coeff x (mass_2 / oper_hrs)

pre_trommel_hp: preprocessing screening required horsepower (hp)

pre_trm_hp_coeff: unit gross energy requirements per ton of waste treated (hp/tph); default of 1.47 hp/tph (Diaz et al., 1982)

Equation A-39

post_trommel_hp = post_trm_hp_coeff x (mass_4 / oper_hrs)

post_trommel_hp: postprocessing screening required horsepower (hp)

post_trm_hp_coeff: unit gross energy requirements per ton of waste treated (hp/tph); default of 1.07 hp/tph (Diaz et al., 1982)

A typical trommel screen of 50 tph capacity was used, resulting in a coefficient of 0.0025 units/tpd. The corresponding equation is as follows:

Equation A-40

num_trommel = (screen_coeff x mass_1 + screen_coeff x mass_4) + 1

num__trommel: number of operating trommel screens

screen_coeff: number of preprocessing screens per amount of waste entering the facility (# trommels/tpd); default value of 0.0025

Front-end loader design

Equation A-41

num_fel = 0.003 x mass_1 + 1

num_fel: number of front-end loaders

0.003: coefficient (# fel/tpd) as discussed in the text

Based on linear regression (see main text), the power requirements for the operation of the front-end loader(s) are 0.5 hp/ton of combined MSW entering the facility per day. Based on the above, the following is the power and fuel consumption of the front-end loader:

Equation A-42

FEL_hp = 0.5 x mass_1

FEL_hp:	required FEL horsepower (hp)
0.5:	hp/tpd

Equation A-43

FEL_diesel = 0.025 x FEL_hp

FEL_diesel:	diesel consumption by FEL (gph)

Odor-control system design

The energy requirements (operational cost) for the biofilters are mainly associated with the operation of the blowers that direct air to the filters. Linear regression was done between the total airflow through the filter and the corresponding biofilter horsepower based on Kong et al. (1996). A coefficient of 0.00278 hp/cfm was derived, and the relevant equation used to design the odor-control system is as follows:

Equation A-44

air_vol = (compost_pad + stag_area) x 9 x pad_height

air_vol:	building volume to be ventilated (ft^3)
pad_height:	building height (default of 15 ft)
9:	ft^2/yd^2

Equation A-45

tot_flow = air_vol / 120

tot_flow:	flow through biofilters (cfm)
120:	time period (min) during which the whole building air has been exchanged; default 120 min

Equation A-46

odor_hp = 0.00278 x tot_flow x (24/8)

odor_hp:	total required fan horsepower (hp)
0.00278:	coefficient based on linear regressions from operating data; hp/cfm
24/8:	this coefficient is used to correct for the continuous daily operation (24 h daily) of the odor control system.

Building operation

Energy is consumed during operation of the buildings. Energy consumption data for two types of buildings (office and warehouses) are available. The source of energy can be electricity or natural gas, and a U.S. average has been established. Only the facility's office space will be assumed to consume electricity and natural gas. The following are the relevant equations:

Equation A-47

build_hp = 319.7 x office_area x 0.84 x (1 / 2,096) x 1.341

build_hp:	electricity power requirements due to building operation (hp)
319.7:	kwh/m^2-year (Table 7)
0.84:	m^2/yd^2
office_area:	office space designated for facility operators; calculated in sec. 15 (yd^2)
2,096:	number of operating hours on an annual basis (h/year)
1.341:	hp/kW

Fuel combustion power requirements

The power requirements supplied by fuel combustion are calculated below.

Equation A-48

fuel_hp = turner_hp + grinder_hp + fel_hp

fuel_energy:	power requirements supplied by fuel combustion (hp)

Electrical equipment power requirements

The electrical power requirements due to equipment operation are:

Equation A-49

electr_hp = hammer_hp + trommel_hp + odor_hp + build_hp

electr_hp:	electrical power requirements due to equipment operation (hp)

Combustion and precombustion energy requirements

Energy requirements associated with the production of a volume unit of 1 gallon of diesel fuel as well as with the generation of 1 kWh of electricity are presented in the text, including Table 2. Default values used are for diesel precombustion energy 25,900 Btu/gal, diesel combustion energy 137,000 Btu/gal, and electricity combustion and precombustion energies 10,431 Btu/kWh. The equations used to calculate the precombustion and combustion energy requirements are as follows:

Equation A-50

elec_engr = coeffeng x electr_hp x 0.746 / (mass_1 / oper_hrs)

elec_engr:	combustion and precombustion energy required per ton of waste (Btu/ton)
coeffeng:	10,431 Btu/kWh
0.746:	kW/hp

Equation A-51

fuel_engr = (coefffuelprec + coefffuelcomb) x (turner_diesel + FEL_diesel + tubgrinder_diesel) / (mass_1 / oper_hrs)

fuel_engr:	combustion and precombustion energy requirements per ton of waste (Btu/ton)
coefffuelprec:	precombustion fuel related energy; default 25,900 Btu/gal
coefffuelcomb:	combustion fuel related energy; default 137,000 Btu/gal

Staging area

The staging area includes the tipping floor, the area for the screening and shredding of the wastes, and the area designated for storage of the windrow turner and the front-end loaders. The staging area is calculated as follows:

Equation A-52

stag_area = tipp_area x tipp_mvr + scr_area x scr_mvr

stag_area:	total staging area (yd^2)
tipp_area:	tipping floor area (yd^2)
tipp_mvr:	tipping floor maneuverability factor; default value 2.0 (U.S. EPA, 1991b)
scr_area:	area for screening, shredding, and storage of equipment (yd^2)
scr_mvr:	screening area maneuverability factor; default value 2.0

Equation A-53

tipp_area = (stor_tipp x vol_1) / tipp_height

tipp_area:	tipping floor area (yd^2)
stor_tipp:	time requirements for storage and equipment downtime; default value 2 days
tipp_height:	height of wastes in tipping floor; default value 2.19 yd (2 m)

The shredding/screening area is calculated as a function of the number of operating screens and hammermills at the staging area and their unit footprint areas. A certain space will be designated for the storage of the windrow turners and front-end loaders.

Equation A-54

$$scr\_area = equip\_coef_{scr} \times (num\_prescreen + num\_postscreen) + equip\_coef_{ham} \times num\_hammer + equip\_coef_{fel} \times num\_fel + equip\_coef_{turner} \times num\_turner$$

scr_area:	screening, shredding and storage area (yd^2)
$equip\_coef_{scr}$:	trommel screen footprint area; default values shown in Table A-1
$equip\_coef_{ham}$:	hammermill footprint area; default values shown in Table A-1
$equip\_coef_{fel}$:	front-end loader footprint area; default values shown in Table A-1 based on dimensions of a typical FEL with a bucket
$equip\_coef_{turner}$:	windrow turner footprint area; default values shown in Table A-1.

Table A-1. Footprint Areas for One Unit of Equipment
(Based on typical dimensions from manufacturers' data)

Type of equipment	Equipment footprint area (yd^2)
Hammermill (with a conveyor)	29.90
Tub grinder	43.10
Trommel screen	59.80
Windrow turner	59.80
Front-end loaders (includes bucket)	35.88

Composting pad area

The composting pad area calculations are shown below and are based on geometry of a typical self-propelled windrow turner pile. This design will be used for the LQCF, HQCF, and YWCF. Piles in the YWCF will, however, be turned by a front-end loader.

Equation A-55

vol_windrow_l = [(windrow_width + windrow_crown) / 2] x windrow_height

vol_windrow_l: volume of material per linear yard of windrow (yd^3/yd or yd^2)
windrow_width: windrow width at base (default value 4.6 yd; range 3.3 - 6.6 yd)
windrow_crown: windrow width at top-crown (default 0.65 yd; range 0.33 - 1.97 yd)
windrow_height: windrow height (default value 1.97 yd; range 1.64 - 2.3 yd)
[Note: Above dimensions discussed in the text.]

Equation A-56

tot_windrow_length = comp_vol / vol_windrow_l

tot_windrow_length: total required windrow length (yd)

Equation A-57

windrow_length = tot_windrow_length / num_windrows

windrow_length: one windrow's length (m)
num_windrows: number of windrows in parallel (default 6)

Equation A-58

alley_area = (num_windrows - 1) x alley_width x windrow_length

alley_area: total alley (space between windrows) area (yd^2)
alley_width: alley width between windrows (default 1.1 yd; range 0.66 - 1.31 yd)

Equation A-59

side_area = 2 x side_width x windrow_length

side_area: total side clearance area (yd^2)
side_width: side clearance (default 1.75 yd; range 1.42 - 1.86 yd based on Scarab™ sales literature)

Equation A-60

turn_area = 2 x turn_clear x [(side_width x 2) + (num_windrows x windrow_width) + (num_windrows - 1) x alley_width]

turn_area: total turning clearance area (yd^2)

turn_clear: windrow vehicle turning clearance (yd) (default of 6.9 yd; range 6.9 –B 11.5 yd based on Scarab™ sales literature).

Raw daily waste is placed at the head end of a windrow, and composted refuse is removed from another windrow. This, in effect, requires an additional windrow, so that a front-end loader can remove waste from a finished windrow while placing raw waste in the new one. This additional "maneuvering" windrow is accounted for in the calculation of the composting pad area.

Equation A-61

windrow_area = (num_windrows + 1) x windrow_width x windrow_length

windrow_area: total windrow area (yd^2)

Equation A-62

compost_pad = alley_area + side_area + turn_area + windrow_area

compost_pad: total required composting pad area (yd^2)

A front-end loader will be used in the case of YWCF. The same windrow geometry is used as for the LQCF and HQCF.

Equation A-63

compost_pad = windrow_area x pile_mnv

compost_pad: area required for the composting and turning of yard waste compost piles (yd^2)

pile_mnv: front-end loader maneuverability factor for turning of piles; default of 2.5; range of 2 to 2.5 (Diaz et al., 1993)

Curing pad area

Curing is used in the HQCF only. The design calculations are presented below.

Equation A-64

cur_pad = cur_area x cur_mvr

cur_pad: total required curing stage area (yd^2)

cur_area: area required for curing of wastes in HQCF (yd^2)

cur_mvr: curing area maneuverability factor; default of 2.0

Equation A-65

curpl_crossec = curpl_height x (curpl_height x curpl_ratio) / 2

curpl_crossec: curing pile cross section area (yd^2)

curpl_height: height of curing piles, default value of 3 yd (9 ft)

curpl_ratio: base to height ratio in curing pile; default of 2

Equation A-66

curpl_length = cur_vol / curpl_crossec

curpl_length: curing pile total length (yd)
cur_vol: volume of wastes in curing stage (yd^3)

Equation A-67
cur_area = curpl_length x curpl_height x curpl_ratio
cur_area: area required for the curing piles (yd^2)

Office area
The office area is taken as a function of the number of employees.

Equation A-68
office_area = off_coef x num_employee
office_area: total area of office space (yd^2)
num_employee: total number of employees working in the facility
off_coef: office space coefficient; default of 20 yd^2/employee

Rejects storage area
A storage time of 2 days will be assigned for the rejected material prior to its transfer to a landfill. The area will be calculated as follows:

Equation A-69
reject_vol = land_vol x rej_res_time
reject_vol: volume of rejected wastes (yd^3)
rej_res_time: reject material storage time; default 2 days

Equation A-70
rejpl_crossec = rejpl_height x (rejpl_height x rejpl_ratio) / 2
rejpl_crossec: reject waste piles cross section area (yd^2)
rejpl_ratio: base to height ratio in rejected material piles, default of 2.0
rejpl_height: height of rejected material piles, default value of 3 yd (9 ft)

Equation A-71
rejpl_length = reject_vol / rejpl_crossec
rejpl_length: rejected material pile total length (yd)

Equation A-72
rej_area = rejpl_length x rejpl_height x rejpl_ratio
rej_area: area required for temporary storage of rejected wastes (yd^2)

Buffer zone area
Buffer distance depends on local legislation. Different buffer distances are assigned for inhabited areas, wells, springs, airports, etc. A typical range of buffer distances can be 100 ft (30 m) to 1,000 ft (300 m). Based on the buffer zone distance, the facility length-to-width ratio, and the total area of the facility, the buffer area is calculated as follows:

Equation A-73

$$fac\_width = ((stag\_area + compost\_pad + cur\_pad + office\_area + rej\_area) / lw\_ratio)^{0.5} + road\_width$$

fac_width: facility width (yd)
lw_ratio: ratio of facility length to facility width; default of 2

Equation A-74

$$fac\_length = lw\_ratio \times (fac\_width - road\_width) + road\_width$$

fac_length: facility length (yd)
road_width: road width; default 5 yd

Equation A-75

$$buffer\_area = 4 \times buffer\_dist^2 + 2 \times buffer\_dist \times (fac\_length + fac\_width)$$

buffer_area: buffer zone area (yd^2)
buffer_dist: buffer zone distance; varies with local legislation and is a function of the location of the composting facility and adjacent sites (e.g., rivers, lakes, wells, airports); since odor control systems are used for the LQCF and HQCF, a default of 500 ft (166 yd) will be used; a 200 ft (66 yd) buffer distance will be used for the YWCF.

Access road area

A typical design will include two access roads, one along the length and one along the width of the facility. The section of the road that crosses the buffer zone is also included in the calculations below:

Equation A-76

$$road\_area = road\_width \times (fac\_length + fac\_width - road\_width) + buffer\_dist \times road\_width$$

road_area: total area of access roads (yd^2); includes entrance road that crosses the buffer zone
fac_width: facility width (yd)
fac_length: facility length (yd)
road_width: road width; default 5 yd

Total facility area

The total facility area is calculated as follows:

Equation A-77

$$fac\_area = stag\_area + compost\_pad + cur\_pad + office\_area + rej\_area + road\_area + buffer\_area$$

fac_area: total facility area required for purchase (yd^2)

Facility perimeter

Steel fencing will be installed on the perimeter of the facility excluding the buffer area. The perimeter of the facility is calculated by the following equation:

Equation A-78

fac_perim = 2 x fac_length + 2 x fac_width
fac_perim: facility perimeter (yd)

Environmental emissions
Twenty-three lb of CO_2 per combusted gallon of diesel are produced (Table 4). This coefficient will be applied to all fuel combustion equipment. The diesel-related emission coefficients are calculated as follows:

Equation A-79
$diesel\_poll_{1...6} = [(turner\_hp \times coeff\_poll_{1...6} + tubgrinder\_hp \times coeff\_poll_{1...6} + fel\_hp \times coeff\_poll_{1...6}) / (1,000 \times 0.454)] / (mass\_1 / oper\_hrs)$

$diesel\_CO_2 = (turner\_diesel + FEL\_diesel + tubgrinder\_diesel) \times 23 / (mass\_1 / oper\_hrs)$

$diesel\_poll_{1...6}$: environmental emissions coefficients for each of the six pollutants produced due to the direct combustion of diesel fuel for that type of equipment (lb/ton)
$coeff\_poll_{1..6}$: pollution coefficients (in gr/hp-hr) for six air contaminants (see main text)
oper_hrs: operating hours per day; default of 8
$diesel\_CO_2$: fossil related CO_2 produced from direct combustion of diesel in lb/ton of initial wet waste entering facility
23: lb CO_2 produced per combustion of 1 diesel gallon

The above equations apply to seven pollutants: CO_2, CO, HC, particulate matter, NO_x, SO_x, and aldehydes, as shown in Table 4.

Precombustion emissions are expressed in lb/ton wet waste entering facility using the following equations:

Equation A-80
$elec\_precomb_{1...i} = lbkwhcf_{1...i} \times electr\_hp \times 0.746 / (mass\_1 / oper\_hrs)$
$elec\_precomb_{1...i}$: precombustion emission due to generation of electricity in lb/ton; applies to 23 pollutants (Table 3)
$lbkwhcf_{1...i}$: electrical precombustion emissions (Table 3) (lb/kWh)
0.746: kW/hp

Equation A-81
$fuel\_precomb_{1...i} = (lbgalcf_{1...i} / 1,000) \times (turner\_diesel + FEL\_diesel + tubgrinder\_diesel) \times 0.746 / (mass\_1 / oper\_hrs)$
$fuel\_precomb_{1...i}$: precombustion emissions due to diesel use lb/ton; applies to 23 pollutants (Table 3)
$lbgalcf_{1...i}$: diesel related precombustion emissions (Table 3) (lb/1000 gal)
0.746: kW/hp
Leachable emissions after land application

Equation A-82

$MSW\_leach\_load_{1..p} = (leach\_poll_{1..p}\ x\ dry\_mass\_5) x (1 / 0.454) / (mass\_1)$

$MSW\_leach\_load_{1..p}$: loading of pollutants 1 to p after application of produced compost (lb/ton)

$leach\_poll_{1..p}$: kg of pollutant p produced per ton of dry compost (Table 8)

Annual CF cost

The annual cost is the amortized capital facility cost plus the annual operational cost, as described below:

Equation A-83

annual_cost = CRF x capital_cost + annual_operating_cost

annual_cost: annual cost of composting facility ($/year)

CRF: capital recovery factor

annual_oper_cost: annual operating cost ($/year)

The capital recovery factor is used to obtain the amortized capital cost for a year and is based on a useful facility design life and interest rate, as shown in the following equation:

Equation A-84

$CRF = 1 / (1 + i)^n$

n: facility useful life (default 15 years)

i: interest rate (default 5%)

Note that the function PMT was used in the Microsoft Excel software to calculate the capital recovery factor.

Capital cost

Capital cost comprises construction cost, land acquisition cost, engineering cost, and equipment cost. This is shown in the following equation. These costs are further subdivided in the following sections.

Equation A-85

capital_cost = constr_cost + land_cost + engr_cost + equip_cost

Construction cost

Construction cost includes cost of structures/buildings, landscaping/grading, paving, access roads, and fencing. Structure involves the cost of buildings. Default values for grading and paving were taken from Renkow et al. (1994), as shown in Table 1.

Equation A-86

constr_cost = grad_cost + pav_cost + fenc_cost + build_cost

constr_cost: total construction cost

Grading cost

The buffer area will not be graded. The facility grading cost is as follows:

Equation A-87

grad_cost = grad_unit_cost x (fac_area - buffer_area) x 2.066 x 10^{-4} or 2.066 x 10exp$^{(-4)}$

grad_cost: grading cost ($)

grad_unit_cost: a default of $5,000/acre is used

2.066 x 10^{-4}: acres/yd^2

Paving cost

Paving will differ for different parts of the facility. Roads, the staging area, the rejects area, and the curing pad will be paved with 4 in. asphalt and 8 in. gravel, and the composting pad will be paved with 2 in. asphalt and 8 in. gravel. The office area will be assigned a direct cost coefficient (in $/$ft^2$) that includes the paving and the building. The buffer zone will not be paved.

Equation A-88

pav_cost = pav_unitcst x (stag_area + road_area + cur_pad + rej_area) x 2.066 x 10^{-4}

pav_cost: paving cost

pav_unitcst: unit cost of paving with 4 in. asphalt and 8 in. gravel; default of $72,500/acre (Renkow et al., 1994)

Fencing cost

Steel fencing will be placed around the main facility area, including the buffer zone.

Equation A-89

fenc_cost = fenc_unit_cost x fac_perim_model x 3

fenc_cost: cost for facility fencing ($)

fenc_unit_cost: unit cost of fencing with steel fence; default value of $7/ft (Renkow et al., 1994)

fac_perim: facility perimeter (yd)

3: ft/yd

Building cost

This cost can vary significantly depending on whether the composting and curing pads will be covered. The LQCF is designed so that the composting pad, including side walls, is covered. In the HQCF, composting and curing pads will be covered. The staging area will also be covered in both MSW compost facilities. A building for office space will be provided for all three composting facilities.

Equation A-90

build_cost = off_unit_cost x office_area x 9 + build_unit_cost x (stag_area + compost_pad) x 9

build_cost: cost of buildings, includes office, equipment storage, and staging areas ($)

off_unit_cost: unit cost for office building including the paving; default $40/$ft^2$

build_unit_cost: unit cost for buildings of the staging area and composting pad; default $6.5/$ft^2$ including paving

9: ft^2/yd^2

Land acquisition
This is based on local real estate costs. More remote sites will require less capital cost, but transportation costs will be higher.

Equation A-91
land_cost = land_unit_cost x fac_area x 2.066 x 10^{-4}

land_cost:	land acquisition cost ($)
land_unit_cost:	land cost per acre; default $1,240/acre

Engineering cost
This consists of the fees paid for consulting and technical services including facility design, construction supervision, and communication with the community/municipality for siting issues. This is taken as a percentage of the construction cost. A default value of 15 percent is used.

Equation A-92
engr_cost = perc_const x constr_cost

engr_cost:	engineering cost ($)
perc_const:	percentage of construction cost representing engineering cost; default 15%

Equipment cost
The costs below are in 1991 dollars and the source was Tchobanoglous et al. (1993) and U.S. EPA (1994). Costs are adjusted to 1998 in the model.

Equation(s) A-93
1. *turner_cost = num_turner x unit_turner_cost*
2. *hammer_cost = num_hammer x unit_hammer_cost*
3. *grinder_cost = num_grinder x unit_grinder_cost*
4. *trommel_cost = num_trommel x unit_trommel_cost*
5. *FEL_cost = num_fel x unit_fel_cost*

turner_cost:	cost of windrow turners ($)
unit_turner_cost:	unit cost of windrow turner; default $180,000/unit
hammer_cost:	cost of hammermills ($)
unit_hammer_cost:	unit cost of hammermill; default $250,000/unit
grinder_cost:	cost of tub grinders ($)
unit_grinder_cost:	unit cost of tub grinders; default $150,000/unit
trommel_cost:	cost of trommel screens ($)
unit_trommel_cost:	unit cost of trommel screens; default $100,000/unit
FEL_cost:	cost of front-end loaders ($)
unit_fel_cost:	unit cost of front-end loader; default $150,000/unit

The capital cost of the odor control system is calculated as follows.

Equation A-94
odor_cap_cost = 52.3 x tot_flow

odor_cap-cost: capital cost of biofilters including biofilters and blowers ($, 1995)
52.3: coefficient in ($, 1995/cfm) based on regression using equipment costs and biofilter flow rates from Kong et al. (1996)

Equation A-95

eqp_cost = turner_cost + hammer_cost + grinder_cost + trommel_cost + FEL_cost + odor_cap_cost

eqp_cost: equipment capital cost ($)

Equation A-96

eqp_inst_cost = 30% x eqp_cost

eqp_inst_cost: equipment installation cost; default is 30% of equipment capital cost

Equation A-97

equip_cost = eqp_cost + eqp_inst_cost

equip_cost: total equipment capital and installation cost (in $)

Operating cost

The operating cost includes labor cost, overhead, management, equipment and building maintenance, fuel consumption, and utilities (electricity). The annual operating cost is given by the following equation:

Equation A-98

oper_cost = labor_cost + overhead_cost + manag_cost + mainten_cost + fuel_cost + util_cost

lab_cost: labor cost for both managers and operators in facility ($/ton)
overhead cost: overhead cost ($/ton); will be taken as percentage of labor cost
manag_cost: cost for management ($/ton); will be taken as percentage of labor cost
mainten_cost: equipment maintenance cost ($/ton)
fuel_cost: cost of fuel used for engine operation in facility ($/ton)
util_cost: cost of utilities, i.e., electricity, water ($/ton)

Labor cost

Labor cost was calculated based on the information shown in Table A-2. A default value of 0.1 employees per tpd plant capacity was selected, which is within the range of values shown in the table. This value will also be applied to the YWCF as a default number but is highly dependent on the local situation and should be modified as appropriate.

Equation(s) A-99

num_empl = 0.1 x mass_1

num_empl: total number of employees working in the facility
0.1: coefficient that correlates number of employees with initial waste flow rate (# employees/tpd); derived based on regression from actual data (note that the regression is controlled by the 1000 tpd, 100 employees data point)

Table A-2. Number of Employees in Actual MSW Composting Facilities (adapted from Curtis et al., 1992; personal communication with Bill Casey, Columbia County Solid Waste Director)

Location	Mass flow rate (tpd)	Employees	Employee/tpd
Delaware	1,000	50[a]	0.05
Swift County, MI	17	6	0.35
Fillmore County, MI	18	8	0.44
Lake of the Woods, MI	5	3	0.60
Columbia County, WI	80	3	0.038

[a] The plant required 150 workers. However, the plant was divided into two modules: the solid waste processing and the sewage sludge processing modules. According to Mr. N.C. Vasuki, the administrator in charge of the plant, a modern but similar facility would require approximately 50 employees (personal communication, 1999).

Equation A-100

lab_cost = [wage_empl x num_empl] / (mass_1 / oper_hrs)

lab_cost: annual labor cost ($/ton)

wage_empl: hourly salary per operator, default of $8/h

Overhead cost

Overhead costs are calculated as a fraction of labor salaries. Overhead includes overtime, office supplies, insurance, social security, vacation, sick leave, and other services. Overhead is calculated by the following equation:

Equation A-101

overhead_cost = 40% x lab_cost

overhead_cost: in $/ton

40%: default value for overhead cost as a percentage of labor cost

Maintenance costs are provided below for the windrow turner and the shredding equipment. The maintenance costs for front-end loaders and trommel screens are considered negligible compared to the maintenance costs of the turning and shredding equipment and thus are not included.

Windrow turner maintenance cost

Scarab provides an operating cost range of $43.38 to $71.68 per hour of operation of the compost turner (capital cost not included). These costs comprise operators' salary, diesel fuel, flail replacement, hydraulic filters replacement, other replacement parts, and routine maintenance. Removing labor and diesel fuel costs, as calculated separately, the average hourly costs for maintenance to be used below is expected to range from $12.12 to $22.93 per operational hour. A default value of $22 per hour will be used. This includes flail replacement, hydraulic filter replacement, other replacement parts, and routine maintenance. The following equations calculate the annual windrow turner maintenance costs:

Equation A-102

turner_maint = turner_maint_hr x turner_hours / (mass_1 x days_week)

turner_maint: annual cost of windrow turner maintenance ($/ton)
turner_hours: hours of operation of windrow turner per week (h/week)
turner_maint_hr: average hourly cost for windrow turner operation; default $22/h (1993 $)
days_week: operating days per week; default 5

Hammermill maintenance cost

Hammermill maintenance costs have been estimated by Diaz et al. (1982, p. 59). They compared maintenance cost for three options (i.e., hammer buildup once per week, daily hammer buildup, and the "wear and scrap" option). They concluded that the "wear and scrap" option was the most expensive, and the buildup once per week was the least expensive. The cheapest option will be used (buildup of worn hammers once per week), and the equation is as follows:

Equation A-103

hammer_maint = hammer_unit_maint x mass_3 / mass_1

hammer_maint: annual maintenance cost for hammermills ($/ton)
hammer_unit_maint: cost of hammer maintenance per ton of waste; default of $0.435/ton (in 1978 $)

Tub grinder maintenance cost

Data similar to those presented for hammermills are not available for tub grinders. It is assumed that the hammermill maintenance data apply to the tub grinder as well.

Fuel cost

Diesel fuel is consumed during operation of the windrow turner(s), the tub grinder, and the front-end loaders. The total annual fuel consumption is calculated in the following equation:

Equation A-104

fuel_cons = turner_diesel + tubgrinder_diesel + FEL_diesel

fuel_cons: hourly facility diesel requirements due to diesel-fueled engine operation (gph)

The annual fuel cost is calculated as follows:

Equation A-105

fuel_cost = fuel_cons x diesel_cost / (mass_1 / oper_hrs)

fuel_cost: annual facility diesel cost ($/ton)
diesel_cost: cost of diesel per gallon, default $1.2/gallon

Utilities cost
The main utility cost to be accounted for is electricity. Electricity is consumed by certain equipment and during operation of the odor-control system and buildings. Precombustion environmental emissions and precombustion energies associated with the generation of one unit of electricity will be applied to calculate the corresponding coefficients. Other utilities, such as water consumption, are not accounted for in the present models.

The annual electricity costs from the operation of hammermills and trommel screens are calculated below. Note that hammermill and trommel screens are assumed to operate for a defined number of operating hours daily (a default of 8 h/day has been used), and the odor control system is assumed to operate 24 h/day.

Equation A-106
util_cost = electr_hp x 0.746 x electr_unit_cost / (mass_1 / oper_hrs)

util_cost:	electricity cost coefficient ($/ton)
electr_unit_cost:	cost per kWh; default $0.075/kWh

Compost value
It was assumed that the compost as produced has no market value.

Appendix B

AERATED STATIC PILE COMPOSTING

Aerated static pile composting is an alternative for the processing of the MSW and YW compost streams. The decision support tool allows users to choose between windrow and aerated static pile composting facility designs. The default design option is windrow, and the user can select the aerated static pile design option by entering binary variables to specified input cells. Mostly "if statements" will be used for the differentiation between these two composting operations. "MSW_Comp_wind" stands for windrow composting and "MSW_Comp_aerated" stands for aerated static pile composting.

In the aerated static pile design option, the incoming MSW or YW stream is assumed to be preprocessed using the same equipment and process as in the windrow design option. After preprocessing, piles will be formed using a front-end loader. The aerated static pile design option assumes, as a default, that a grid of piping lies out beneath the preprocessed stream to aerate the pile. Through blowers, sufficient air is supplied to the composting pad to aid the mixing, temperature control, and water vapor control. This type of aeration is called active aeration. Some aerated static pile designs rely on passive aeration and do not require piping or blowers. (Note: if passive aeration is used, the user should zero out the cost for environmental aspects for the piping and blowers.) Finally, a layer of screened compost is often placed on top of the newly formed pile for insulation and odor control.

The following residence times will be used as default during composting and curing stages of the waste stream:

- For the low quality MSW stream, a 51-day compost residence time without curing will be used.
- For the high quality MSW stream, a 51-day compost residence time with a curing period of 30 days will be used.
- Approximately 51 days of combined composting and curing time will be used for the yardwaste compost facilities.

The above information was developed based on communication with the North Carolina Division of Pollution Prevention.

Blower and Piping

Blowers and pipes are essential elements of the aerated static pile composting operation; therefore, the appropriate and efficient design must be implemented for the best results. For 1 dry ton of MSW and/or yard waste, 100-CFM capacity blowers are suitable for aerated static pile designs. According to the operational control systems, power requirements are identified based on information from *Grainger's 1995 General catalogue for Industrial and commercial Equipment and Suppliers*. Two types of control options, time-control or temperature-control, can be chosen. In the time-controlled operation, the blowers are operated for certain times during the day, according to the prescheduled plan, such as blowers turn on for 5 minutes and turn off for 20 minutes. Typically one-third to one-half hp blowers are used. In the temperature-controlled option, which is more sophisticated and expensive, blowers are connected to temperature probes. When the temperature within the pile reaches a predetermined value, the blower turns on, cools the pile, and removes water vapor. Typical blower size used for this type of operation is 3 to 5 hp. Note that as default, a time-controlled operation has been chosen so that blowers with one-half hp will be operated for only 1.58 hours during the day. In order to find the number of equipment units, the capacity of the compost facility is related to aeration requirement for 1 dry ton of compost. Equation A-93 is modified for this purpose. The information about blower system design is based on communication with the North Carolina Division of Pollution Prevention.

The default blowers used in this model are taken from Grainger's Catalogue, 1995, pp 2913, having a general capacity of 2000 CFM and one-half hp. The required data, such as dimensions and cost, can be referred from there.

For each windrow in the facility, a grid of 3 in. black plastic drainage or PVC pipes are laid out underneath each windrow and are connected to the blowers. Note that the life-cycle inventory association with the production of the PVC pipes is not included in the aerated static pile compost model.

For aerated static pile composting, pile dimensions are chosen according to default ranges, as follows:

Base width:	10 -16 ft
Height:	5 – 8 ft
Length:	90 – 100 ft

The same dimension ranges apply to MSW and YW composting.

Modified Model Equations

Many of the cost and LCI equations for the aerated static pile compost design option are the same as those used for the windrow design option. The following equations include those that were modified for the aerated static pile composting option. The equations are shown for only the yard waste but are implement for mixed MSW facilities as well.

<u>Mass balance</u>

Equation A-10

comp_vol = vol_3 x comp_res

comp_vol:	maximum volume of wastes existing in composting pad in the form of windrows or piles (yd^3)
comp_res:	residence time in composting pad (days); default values shown in Table 5

According to the selection of user (aerated static pile or windrow turning), residence time in composting pad will be tracked using an “if statement.”

comp_vol =if (YW_Comp_wind=1, vol_3 x comp_res_wind, vol_3 x comp_res_aerated)

Equation A-21
comp_mass = (mass_3 + water_3) x comp_res
comp_mass: maximum mass of wastes in composting pad (tn); this is the mass to be aerated by the windrow turner at each turning time

The wet bulk density of cured compost (end of curing stage) is taken to be similar to the density of the produced composts (end of composting stage). A 5 percent dry mass reduction during curing is also assumed.

According to the selection of user (aerated static pile or windrow turning), residence time in composting pad will be tracked using an “if statement.”

comp_vol =if (YW_Comp_wind=1, (mass_3 + water_3) x comp_res_wind, (mass_3 + water_3) x comp_res_aerated)

<u>Fuel combustion power requirements</u>

Equation A-48
fuel_hp = turner_hp + grinder_hp + fel_hp
fuel_energy: power requirements supplied by fuel combustion (hp)

According to the selection of user (aerated static pile or windrow turning), turner hp will be included or not using an “if statement.”

fuel_hp = if(YW_Comp_wind=1, turner_hp + grinder_hp + fel_hp, grinder_hp + fel_hp)

<u>Electrical equipment power requirements</u>

Equation A-49
electr_hp = hammer_hp + trommel_hp + odor_hp + build_hp
electr_hp: electrical power requirements due to equipment operation (hp)

According to the selection of user (aerated static pile or windrow turning), blower hp will be included or not using an “if statement.”

electr_equip = if(YW_Comp_wind=1, hammer_hp + trommel_hp + odor_hp + build_hp, hammer_hp + trommel_hp + blower_hp + odor_hp + build_hp

<u>Combustion and precombustion energy requirements</u>

Equation A-51

fuel_engr = (coefffuelprec + coefffuelcomb) x (turner_diesel + FEL_diesel + tubgrinder_diesel) / (mass_1 / oper_hrs)

fuel_engr:	combustion and precombustion energy requirements per ton of waste (Btu/ton)
coefffuelprec:	precombustion fuel related energy; default 25,900 Btu/gal
coefffuelcomb:	combustion fuel related energy; default 137,000 Btu/gal

According to the selection of user (aerated static pile or windrow turning), windrow turner's fuel requirement will be tracked using an "if statement."

fuel_energy = if(YW_Comp_wind=1, (coefffuelprec + coefffuelcomb) x (turner_diesel + FEL_diesel + tubgrinder_diesel) / (mass_1 / oper_hrs), (coefffuelprec + coefffuelcomb) x (FEL_diesel + tubgrinder_diesel) / (mass_1 / oper_hrs))

<u>Composting pad area</u>

Equation A-63

compost_pad = windrow_area x pile_mnv

compost_pad:	area required for the composting and turning of yard waste compost piles (yd^2)
pile_mnv:	front end loader maneuverability factor for turning of piles; default of 2.25; range of 2 to 2.5 (Diaz et al., 1993)

According to the selection of user (aerated static pile or windrow turning), front-end loader maneuverability factor for turning of piles is chosen as either 1 or 2.25 using an "if statement."

compost_pad = if(YW_Comp_wind=1, windrow_area x pile_mnv, windrow_area x 1)

<u>Environmental emissions</u>

Equation A-79

$diesel\_poll_{1...6} = [(turner\_hp \times coeff\_poll_{1...6} + tubgrinder\_hp \times coeff\_poll_{1...6} + fel\_hp \times coeff\_poll_{1...6} + bobcat\_hp \times coeff\_poll_{1...6}) / (1{,}000 \times 0.454)]/(mass\_1 / oper\_hrs)$

$diesel\_poll_{1...6}$:	Annual environmental pollutants for each of the 6 pollutants produced due to the direct combustion of diesel fuel for that type of equipment (gr/year)
$coeff\_poll_{1..6}$:	Pollution coefficients (in gr/hp-hr) for each contaminant (1 to 6) due to combustion of diesel fuel as shown in table 16.
oper_hrs:	operating hours per day; default of 8
oper_days:	operating days per year; default of 262

According to the selection of user (aerated static pile or windrow turning), windrow turner's emissions are included or not using an "if statement."

$diesel\_poll_{1...6}$ = if(YW_Comp_wind=1, [(turner_hp x $coeff\_poll_{1...6}$ + tubgrinder_hp x $coeff\_poll_{1...6}$ + fel_hp x $coeff\_poll_{1...6}$ + bobcat_hp x $coeff\_poll_{1...6}$) / (1,000 x 0.454)]/(mass_1 / oper_hrs), [(tubgrinder_hp x $coeff\_poll_{1...6}$ + fel_hp x $coeff\_poll_{1...6}$ + bobcat_hp x $coeff\_poll_{1...6}$) / (1,000 x 0.454)]/(mass_1 / oper_hrs)

Equation A-81

$fuel\_precomb_{1...i}$ = ($lbgalcf_{1...i}$ / 1,000) x (turner_diesel + FEL_diesel + tubgrinder_diesel) x 0.746 / (mass_1 / oper_hrs)

$fuel\_precomb_{1...i}$: precombustion emissions due to diesel use lb/ton; applies to 23 pollutants (Table 3)
$lbgalcf_{1...i}$: diesel related precombustion emissions (Table 3) (lb/1000 gal)
0.746: kW/hp
Leachable emissions after land application

According to the selection of user (aerated static pile or windrow turning), windrow turner's emissions are included or not using an "if statement."

$fuel\_precomb_{1...i}$ = if(YW_Comp_wind=1, ($lbgalcf_{1...i}$ / 1,000) x (turner_diesel + FEL_diesel + tubgrinder_diesel) x 0.746 / (mass_1 / oper_hrs), ($lbgalcf_{1...i}$ / 1,000) x (FEL_diesel + tubgrinder_diesel) x 0.746 / (mass_1 / oper_hrs))

Equipment cost

Equation(s) A-93

Num_blower = 0.05 * dry_mass
0.05: ratio of air reqirement per dry mass to typical blower capacity of ½ hp blower.
Dry_mass: dry mass of compost entering the compost pad.

blower_cost = num_blower x unit_blower_cost

blower_cost: cost of blowers ($)
unit_blower_cost: unit cost of blower, default $237.75/unit for year 1995.

Above equations are added to Equations A-93 set.

Equation A-95

eqp_cost = turner_cost + hammer_cost + grinder_cost + trommel_cost + FEL_cost + bobcat_cost + odor_cap_cost

eqp_cost: equipment capital cost; ($)

According to the selection of user (aerated static pile or windrow turning), blowers or windrow turners are included in the system using an "if statement."

eqp_cost = if(YW_Comp_wind=1, turner_cost + hammer_cost + grinder_cost + trommel_cost + FEL_cost + bobcat_cost + odor_cap_cost, blower_cost + hammer_cost + grinder_cost + trommel_cost + FEL_cost + bobcat_cost + odor_cap_cost)

<u>Blower maintenance cost</u>

Blower_maint = 0.1 * PMT (interest rate, lifetime, capital cost) * operating hours / 24

Blower_maint:	blower maintenance cost per year; $/yr
PMT ():	present value amortization function
Interest rate:	8%
Lifetime:	lifetime of blowers, 5 years
0.1:	yearly maintenance cost is assumed as 10% of the amortized capital cost of the blowers.

<u>Labor Cost</u>

Equation(s) A-99
num_empl = 0.1 x mass_1

num_empl:	total number of employees working in the facility
0.1:	coefficient that correlates number of employees with initial waste flowrate (#employees/tpd); derived based on regression from actual data

According to the selection of user (aerated static pile or windrow turning) blowers or windrow turners are included in the system using an “if statement.”

num_empl = if(YW_Comp_wind=1, 0.1 x mass_1, 0.05 x mass_1)