CHAPTER 4

PHYSICAL, CHEMICAL, AND BIOLOGICAL PROPERTIES OF MUNICIPAL SOLID WASTE

The purpose of this chapter is to introduce the reader to the physical, chemical, and biological properties of MSW and to the transformations that can affect the form and composition of MSW. These properties must be known to develop and design integrated solid waste management systems. Further, the physical, chemical, and biological properties and transformations introduced in this chapter form the basis for topics discussed in the remaining portions of this book.

4-1 PHYSICAL PROPERTIES OF MSW

Important physical characteristics of MSW include specific weight, moisture content, particle size and size distribution, field capacity, and compacted waste porosity. The discussion is limited to an analysis of residential, commercial, and some industrial solid wastes. The hazardous wastes found in MSW are addressed separately in Chapter 5. Note, however, that the fundamentals of analysis presented in this and the following chapter are applicable to all types of solid wastes. Additional details on the various physical, chemical, and microbiological methods of testing for solid wastes may be found in the various publications of the American Society for Testing and Materials (ASTM).

Specific Weight

Specific weight is defined as the weight of a material per unit volume (e.g., lb/ft^3, lb/yd^3). (It should be noted that specific weight expressed as lb/yd^3 is commonly referred to in the solid waste literature incorrectly as density. In U.S. customary units density is expressed correctly as slug/ft^3.) Because the specific weight of MSW is often reported as *loose, as found in containers, uncompacted, compacted,* and the like, the basis used for the reported values should always be noted. Specific weight data are often needed to assess the total mass and volume of waste that must be managed. Unfortunately, there is little or no uniformity in the way solid waste specific weights have been reported in the literature. Frequently, no distinction has been made between uncompacted or compacted specific weights. Typical specific weights for various wastes as found in containers, compacted, or uncompacted are reported in Table 4-1.

TABLE 4-1
Typical specific weight and moisture content data for residential, commercial, industrial, and agricultural wastes

	Specific weight, lb/yd^3		Moisture content, % by weight	
Type of waste	**Range**	**Typical**	**Range**	**Typical**
Residential (uncompacted)				
Food wastes (mixed)	220–810	490	50–80	70
Paper	70–220	150	4–10	6
Cardboard	70–135	85	4–8	5
Plastics	70–220	110	1–4	2
Textiles	70–170	110	6–15	10
Rubber	170–340	220	1–4	2
Leather	170–440	270	8–12	10
Yard wastes	100–380	170	30–80	60
Wood	220–540	400	15–40	20
Glass	270–810	330	1–4	2
Tin cans	85–270	150	2–4	3
Aluminum	110–405	270	2–4	2
Other metals	220–1940	540	2–4	3
Dirt, ashes, etc.	540–1685	810	6–12	8
Ashes	1095–1400	1255	6–12	6
Rubbish	150–305	220	5–20	15
Residential yard wastes				
Leaves (loose and dry)	50–250	100	20–40	30
Green grass (loose and moist)	350–500	400	40–80	60
Green grass (wet and compacted)	1000–1400	1000	50–90	80
Yard waste (shredded)	450–600	500	20–70	50
Yard waste (composted)	450–650	550	40–60	50
Municipal				
In compactor truck	300–760	500	15–40	20
In landfill				
Normally compacted	610–840	760	15–40	25
Well compacted	995–1250	1010	15–40	25
Commercial				
Food wastes (wet)	800–1600	910	50–80	70
Appliances	250–340	305	0–2	1

(continued)

Because the specific weights of solid wastes vary markedly with geographic location, season of the year, and length of time in storage, great care should be used in selecting typical values. Municipal solid wastes as delivered in compaction vehicles have been found to vary from 300 to 700 lb/yd^3; a typical value is about 500 lb/yd^3.

Moisture Content

The moisture content of solid wastes usually is expressed in one of two ways. In the wet-weight method of measurement, the moisture in a sample is expressed

TABLE 4-1 (*continued*)

	Specific weight, lb/yd^3		Moisture content, % by weight	
Type of waste	**Range**	**Typical**	**Range**	**Typical**
Commercial (*cont.*)				
Wooden crates	185–270	185	10–30	20
Tree trimmings	170–305	250	20–80	5
Rubbish (combustible)	85–305	200	10–30	15
Rubbish (noncombustible)	305–610	505	5–15	10
Rubbish (mixed)	235–305	270	10–25	15
Construction and demolition				
Mixed demolition (noncombustible)	1685–2695	2395	2–10	4
Mixed demolition (combustible)	505–675	605	4–15	8
Mixed construction (combustible)	305–605	440	4–15	8
Broken concrete	2020–3035	2595	0–5	—
Industrial				
Chemical sludges (wet)	1350–1855	1685	75–99	80
Fly ash	1180–1515	1350	2–10	4
Leather scraps	170–420	270	6–15	10
Metal scrap (heavy)	2530–3370	3000	0–5	—
Metal scrap (light)	840–1515	1245	0–5	—
Metal scrap (mixed)	1180–2530	1515	0–5	—
Oils, tars, asphalts	1350–1685	1600	0–5	2
Sawdust	170–590	490	10–40	20
Textile wastes	170–370	305	6–15	10
Wood (mixed)	675–1140	840	30–60	25
Agricultural				
Agricultural (mixed)	675–1265	945	40–80	50
Dead animals	340–840	605	—	—
Fruit wastes (mixed)	420–1265	605	60–90	75
Manure (wet)	1515–1770	1685	75–96	94
Vegetable wastes (mixed)	340–1180	605	60–90	75

Adapted in part from Refs. 6 and 8.

Note: lb/yd^3 × 0.5933 = kg/m^3

as a percentage of the wet weight of the material; in the dry-weight method, it is expressed as a percentage of the dry weight of the material. The wet-weight method is used most commonly in the field of solid waste management. In equation form, the wet-weight moisture content is expressed as follows:

$$M = \left(\frac{w - d}{w}\right)100 \tag{4-1}$$

where M = moisture content, %
w = initial weight of sample as delivered, lb (kg)
d = weight of sample after drying at 105°C, lb (kg)

Typical data on the moisture content for the solid waste components given in Table 3-3 as well as other materials are given in Table 4-1. For most MSW in the United States, the moisture content will vary from 15 to 40 percent, depending on the composition of the wastes, the season of the year, and the humidity and weather conditions, particularly rain. The use of data in Table 4-1 to estimate the overall moisture content of solid wastes is illustrated in Example 4-1.

EXAMPLE 4-1 Estimation of moisture content of typical residential MSW. Estimate the overall moisture content of a sample of *as collected* residential MSW with the typical composition given in Table 3-4.

Solution

1. Set up the computation table to determine dry weights of the solid waste components using the data given in Table 4-1.

Component	Percent by weight	Moisture content, %	Dry weight,[a] lb
Organic			
Food wastes	9.0	70	2.7
Paper	34.0	6	32.0
Cardboard	6.0	5	5.7
Plastics	7.0	2	6.9
Textiles	2.0	10	1.8
Rubber	0.5	2	0.5
Leather	0.5	10	0.4
Yard wastes	18.5	60	7.4
Wood	2.0	20	1.6
Misc. organics	—	—	—
Inorganic			
Glass	8.0	2	7.8
Tin cans	6.0	3	5.8
Aluminum	0.5	2	0.5
Other metal	3.0	3	2.9
Dirt, ash, etc.	3.0	8	2.8
Total	100.0		78.8

[a] Based on an *as delivered* sample weight of 100 lb.

2. Determine the moisture content of the solid waste sample using Eq. (4-1).

$$\text{Moisture content(\%)} = \left(\frac{100 - 78.8}{100}\right)100 = 21.2\%$$

Particle Size and Size Distribution

The size and size distribution of the component materials in solid wastes are an important consideration in the recovery of materials, especially with mechanical means such as trommel screens and magnetic separators. The size of a waste component may be defined by one or more of the following measures:

$$S_c = l \tag{4-2}$$

$$S_c = \left(\frac{l + w}{2}\right) \tag{4-3}$$

$$S_c = \left(\frac{l + w + h}{3}\right) \tag{4-4}$$

$$S_c = (l \times w)^{1/2} \tag{4-5}$$

$$S_c = (l \times w \times h)^{1/3} \tag{4-6}$$

where S_c = size of component, in (mm)
l = length, in (mm)
w = width, in (mm)
h = height, in (mm)

A general indication of the particle size distribution (by longest dimension and ability to pass a sieve) may be obtained from the data presented in Figs. 4-1 and 4-2. Typical data on the size distribution of the individual components in MSW are presented in Fig. 4-3. Based on single linear measurement as defined by Eq. (4-2), the average size of the individual components found in residential MSW is between 7 and 8 in. Typical data on the size distribution of aluminum cans, tin cans, and glass, based on Eq. (4-5), are presented in Fig. 4-4. Because there are significant differences among the various measures on size, individual measurements should be made on the waste in question using a measure of size that will provide the information needed for the specific application.

Field Capacity

The field capacity of solid waste is the total amount of moisture that can be retained in a waste sample subject to the downward pull of gravity. The field capacity of waste materials is of critical importance in determining the formation of leachate in landfills. Water in excess of the field capacity will be released as leachate. The field capacity varies with the degree of applied pressure and the state of decomposition of the waste. A field capacity of 30 percent by volume

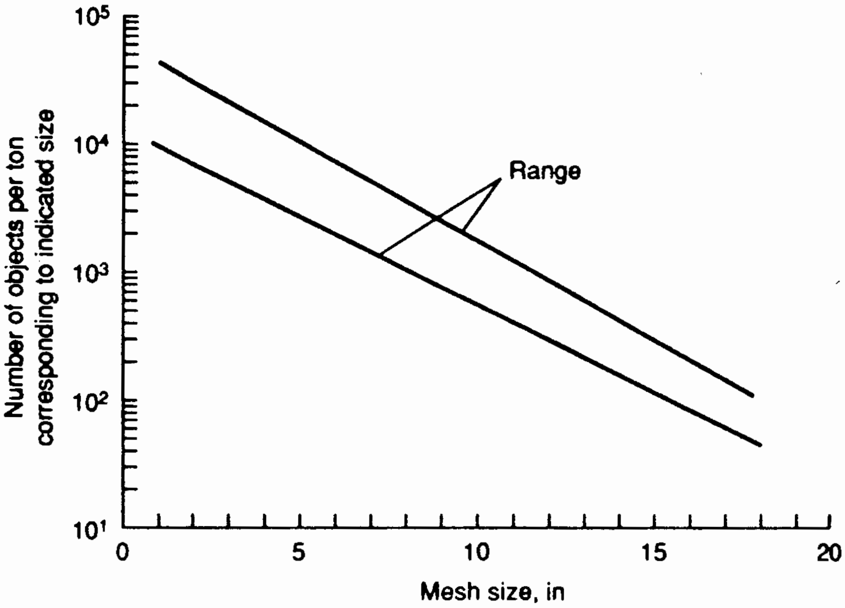


FIGURE 4-1
Typical sizes of individual components comprising residential and commercial MSW [4, 12].

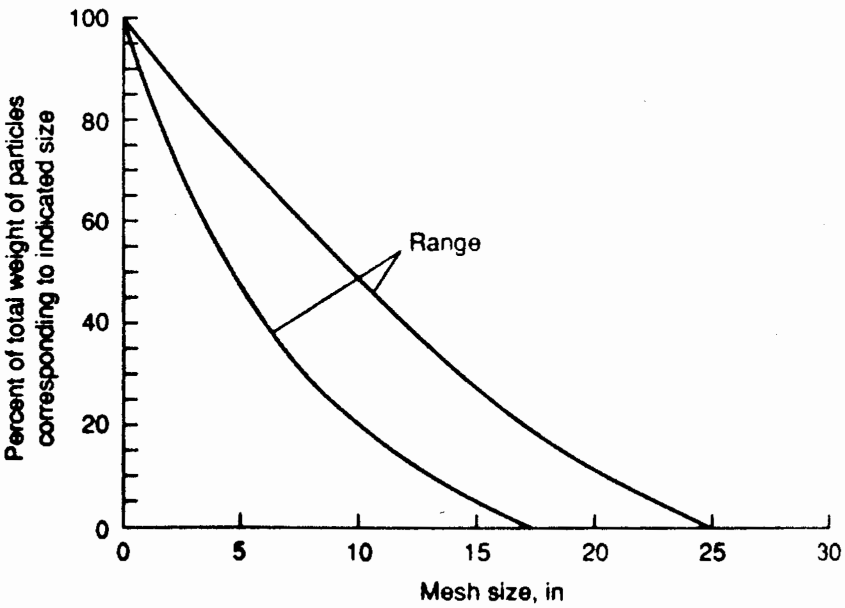


FIGURE 4-2
Percentage of total mass of residential and commercial MSW as a function of mesh size [4, 12].

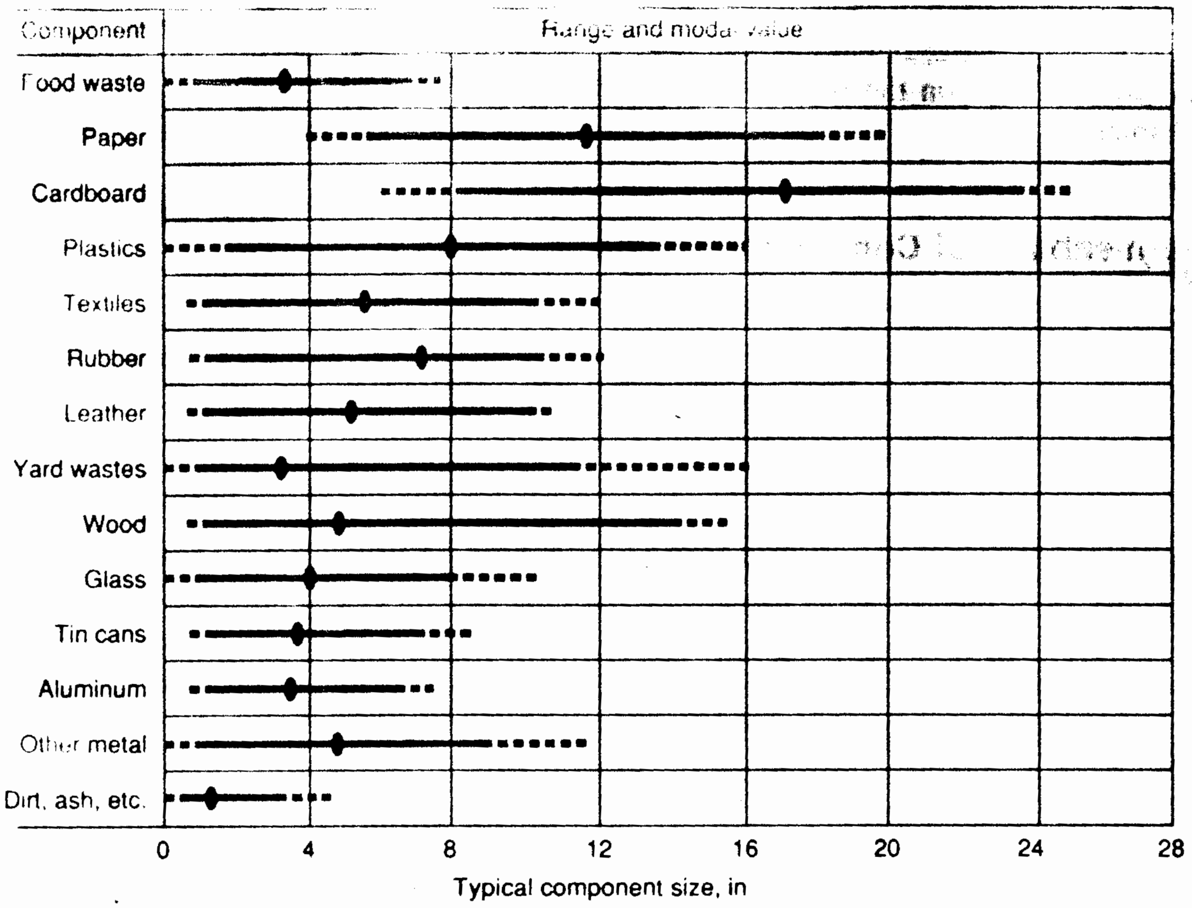


FIGURE 4-3
Typical size distribution of the components found in residential MSW (adapted, in part, from Ref. 4).

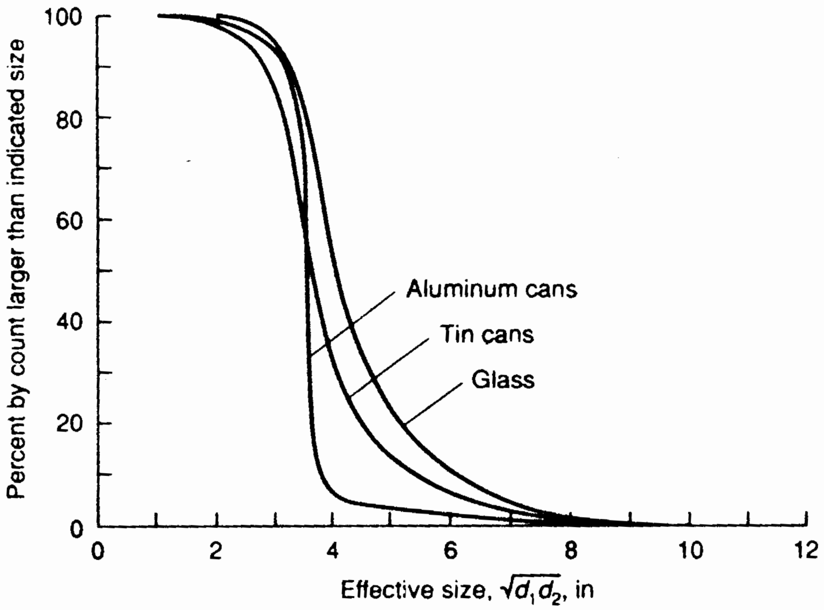


FIGURE 4-4
Typical distribution by count of effective sizes $(l \times w)^{1/2}$ of aluminum cans, tin cans, and glass containers found in residential MSW as delivered to a landfill.

corresponds to 30 in/100 in. The field capacity of uncompacted commingled wastes from residential and commercial sources is in the range of 50 to 60 percent. (Additional data on the field capacity of solid wastes and soils may be found in Chapter 11.)

Permeability of Compacted Waste

The hydraulic conductivity of compacted wastes is an important physical property that, to a large extent, governs the movement of liquids and gases in a landfill. The coefficient of permeability is normally written as [2]:

$$K = Cd^2 \frac{\gamma}{\mu} = k \frac{\gamma}{\mu} \tag{4-7}$$

where K = coefficient of permeability
C = dimensionless constant or shape factor
d = average size of pores
γ = specific weight of water
μ = dynamic viscosity of water
k = intrinsic permeability

The term Cd^2 is known as the intrinsic (or specific) permeability. The intrinsic permeability depends solely on the properties of the solid material, including pore size distribution, tortuosity, specific surface, and porosity. Typical values for the intrinsic permeability for compacted solid waste in a landfill are in the range between about 10^{-11} and 10^{-12} m^2 in the vertical direction and about 10^{-10} m^2 in the horizontal direction.

4-2 CHEMICAL PROPERTIES OF MSW

Information on the chemical composition of the components that constitute MSW is important in evaluating alternative processing and recovery options. For example, the feasibility of combustion depends on the chemical composition of the solid wastes. Typically, wastes can be thought of as a combination of semimoist combustible and noncombustible materials. If solid wastes are to be used as fuel, the four most important properties to be known are:

1. Proximate analysis
2. Fusing point of ash
3. Ultimate analysis (major elements)
4. Energy content

Where the organic fraction of MSW is to be composted or is to be used as feedstock for the production of other biological conversion products, not only will information on the major elements (ultimate analysis) that compose the waste be important, but also information will be required on the trace elements in the waste materials.

Proximate Analysis

Proximate analysis for the combustible components of MSW includes the following tests [3, 10]:

1. Moisture (loss of moisture when heated to 105°C for 1 h)
2. Volatile combustible matter (additional loss of weight on ignition at 950°C in a covered crucible)
3. Fixed carbon (combustible residue left after volatile matter is removed)
4. Ash (weight of residue after combustion in an open crucible)

Proximate analysis data for the combustible components of MSW *as discarded* are presented in Table 4-2. It is important to note that the test used to determine volatile combustible matter in a proximate analysis is different from the volatile solids test used in biological determinations (see Section 4-3).

Fusing Point of Ash

The fusing point of ash is defined as that temperature at which the ash resulting from the burning of waste will form a solid (clinker) by fusion and agglomeration. Typical fusing temperatures for the formation of clinker from solid waste range from 2000 to 2200°F (1100 to 1200°C).

Ultimate Analysis of Solid Waste Components

The ultimate analysis of a waste component typically involves the determination of the percent C (carbon), H (hydrogen), O (oxygen), N (nitrogen), S (sulfur), and ash. Because of the concern over the emission of chlorinated compounds during combustion, the determination of halogens is often included in an ultimate analysis. The results of the ultimate analysis are used to characterize the chemical composition of the organic matter in MSW. They are also used to define the proper mix of waste materials to achieve suitable C/N ratios for biological conversion processes. Data on the ultimate analysis of individual combustible materials are presented in Table 4-3. Representative data for the typical MSW components given in Table 3-4 are presented in Table 4-4. Estimation of the average chemical composition of solid waste materials using the data given in Tables 4-1 and 4-2 is illustrated in Example 4-2.

TABLE 4-2
Typical proximate analysis and energy data for materials found in residential, commercial, and industrial solid wastes[a]

Type of waste	Proximate analysis, % by weight: Moisture	Volatile matter	Fixed carbon	Non-combustible	Energy content, Btu/lb: *As collected*	Dry	Dry ash-free
Food and food products							
Fats	2.0	95.3	2.5	0.2	16,135	16,466	16,836
Food wastes (mixed)	70.0	21.4	3.6	5.0	1,797	5,983	7,180
Fruit wastes	78.7	16.6	4.0	0.7	1,707	8,013	8,285
Meat wastes	38.8	56.4	1.8	3.1	7,623	12,455	13,120
Paper products							
Cardboard	5.2	77.5	12.3	5.0	7,042	7,428	7,842
Magazines	4.1	66.4	7.0	22.5	5,254	5,478	7,157
Newsprint	6.0	81.1	11.5	1.4	7,975	8,484	8,612
Paper (mixed)	10.2	75.9	8.4	5.4	6,799	7,571	8,056
Waxed cartons	3.4	90.9	4.5	1.2	11,326	11,724	11,872
Plastics							
Plastics (mixed)	0.2	95.8	2.0	2.0	14,101	14,390	16,024
Polyethylene	0.2	98.5	<0.1	1.2	18,687	18,724	18,952
Polystyrene	0.2	98.7	0.7	0.5	16,419	16,451	16,430
Polyurethane	0.2	87.1	8.3	4.4	11,204	11,226	11,744
Polyvinyl chloride	0.2	86.9	10.8	2.1	9,755	9,774	9,985
Textiles, rubber, leather							
Textiles	10.0	66.0	17.5	6.5	7,960	8,844	9,827
Rubber	1.2	83.9	4.9	9.9	10,890	11,022	12,250
Leather	10.0	68.5	12.5	9.0	7,500	8,040	8,982

Wood, trees, etc.							
Yard wastes	60.0	30.0	9.5	0.5	2,601	6,503	6,58[illegible]
Wood (green timber)	50.0	42.3	7.3	0.4	2,100	4,200	4,234
Hardwood	12.0	75.1	12.4	0.5	7,352	8,354	8,402
Wood (mixed)	20.0	68.1	11.3	0.6	6,640	8,316	8,383
Glass, Metals, etc.							
Glass and mineral	2.0	—	—	96–99+	84[b]	86	60
Metal, tin cans	5.0	—	—	94–99+	301[b]	319	317
Metal, ferrous	2.0	—	—	96–99+	—	—	—
Metal, nonferrous	2.0	—	—	94–99+	—	—	—
Miscellaneous							
Office sweepings	3.2	20.5	6.3	70.0	3,669	3,791	13,692
Residential MSW	21.0 (15–40)	52.0 (40–60)	7.0 (4–15)	20.0 (10–30)	5,000	6,250	8,333
Commercial MSW	15.0 (10–30)	—	—		5,500	6,470	
MSW	20.0 (10–30)	—	—		4,600	5,750	

[a] Adapted in part from Refs. 6–8.

[b] Energy content is from coatings, labels, and attached materials.

Note: Btu × 1.0551 = kJ

TABLE 4-3

Typical data on the ultimate analysis of the combustible materials found in residential, commercial, and industrial solid wastes[a]

	Percent by weight (dry basis)					
Type of waste	**Carbon**	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulfur**	**Ash**
Food and food products						
Fats	73.0	11.5	14.8	0.4	0.1	0.2
Food wastes (mixed)	48.0	6.4	37.6	2.6	0.4	5.0
Fruit wastes	48.5	6.2	39.5	1.4	0.2	4.2
Meat wastes	59.6	9.4	24.7	1.2	0.2	4.9
Paper products						
Cardboard	43.0	5.9	44.8	0.3	0.2	5.0
Magazines	32.9	5.0	38.6	0.1	0.1	23.3
Newsprint	49.1	6.1	43.0	<0.1	0.2	1.5
Paper (mixed)	43.4	5.8	44.3	0.3	0.2	6.0
Waxed cartons	59.2	9.3	30.1	0.1	0.1	1.2
Plastics						
Plastics (mixed)	60.0	7.2	22.8	—	—	10.0
Polyethylene	85.2	14.2	—	<0.1	<0.1	0.4
Polystyrene	87.1	8.4	4.0	0.2	—	0.3
Polyurethane[b]	63.3	6.3	17.6	6.0	<0.1	4.3
Polyvinyl chloride[b]	45.2	5.6	1.6	0.1	0.1	2.0
Textiles, rubber, leather						
Textiles	48.0	6.4	40.0	2.2	0.2	3.2
Rubber	69.7	8.7	—	—	1.6	20.0
Leather	60.0	8.0	11.6	10.0	0.4	10.0
Wood, trees, etc.						
Yard wastes	46.0	6.0	38.0	3.4	0.3	6.3
Wood (green timber)	50.1	6.4	42.3	0.1	0.1	1.0
Hardwood	49.6	6.1	43.2	0.1	<0.1	0.9
Wood (mixed)	49.5	6.0	42.7	0.2	<0.1	1.5
Wood chips (mixed)	48.1	5.8	45.5	0.1	<0.1	0.4
Glass, metals, etc.						
Glass and mineral[c]	0.5	0.1	0.4	<0.1	—	98.9
Metals (mixed)[c]	4.5	0.6	4.3	<0.1	—	90.5
Miscellaneous						
Office sweepings	24.3	3.0	4.0	0.5	0.2	68.0
Oils, paints	66.9	9.6	5.2	2.0	—	16.3
Refuse-derived fuel (RDF)	44.7	6.2	38.4	0.7	<0.1	9.9

[a] Adapted in part from Ref. 6.

[b] Remainder is chlorine.

[c] Organic content is from coatings, labels, and other attached materials.

TABLE 4-4

Typical data on the ultimate analysis of the combustile components in residential MSW[a]

Component	Percent by weight (dry basis)					
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Organic						
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0
Plastics	60.0	7.2	22.8	—	—	10.0
Textiles	55.0	6.6	31.2	4.6	0.15	2.5
Rubber	78.0	10.0	—	2.0	—	10.0
Leather	60.0	8.0	11.6	10.0	0.4	10.0
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5
Wood	49.5	6.0	42.7	0.2	0.1	1.5
Inorganic						
Glass[b]	0.5	0.1	0.4	<0.1	—	98.9
Metals[b]	4.5	0.6	4.3	<0.1	—	90.5
Dirt, ash, etc.	26.3	3.0	2.0	0.5	0.2	68.0

[a] Adapted in part from Ref 6.

[b] Organic content is from coatings, labels, and other attached materials.

EXAMPLE 4-2 Estimation of the chemical composition of a solid waste sample. Determine the chemical composition of the organic fraction, without and with sulfur and without and with water, of a residential MSW with the typical composition shown in Table 3-4.

Solution

1. Set up a computation table to determine the percentage distribution of the major elements composing the waste. The necessary computations are presented below:

Component	Wet weight, lb	Dry weight, lb	Composition, lb					
			C	H	O	N	S	Ash
Food wastes	9.0	2.7	1.30	0.17	1.02	0.07	0.01	0.14
Paper	34.0	32.0	13.92	1.92	14.08	0.10	0.06	1.92
Cardboard	6.0	5.7	2.51	0.34	2.54	0.02	0.01	0.28
Plastics	7.0	6.9	4.14	0.50	1.57	—	—	0.69
Textiles	2.0	1.8	0.99	0.12	0.56	0.08	—	0.05
Rubber	0.5	0.5	0.39	0.05	—	0.01	—	0.05
Leather	0.5	0.4	0.24	0.03	0.05	0.04	—	0.04
Yard wastes	18.5	6.5	3.11	0.39	2.47	0.22	0.02	0.29
Wood	2.0	1.6	0.79	0.10	0.68	—	—	0.02
Total	79.5	58.1	27.39	3.62	22.97	0.54	0.10	3.48

Moisture content = 21.4 lb (79.5 lb − 58.1 lb)

2. Prepare a summary table of the percentage distribution of the elements without and with the water contained in the waste.

	Weight, lb	
Component	Without H_2O	With H_2O
Carbon	27.39	27.39
Hydrogen	3.62	6.00
Oxygen	22.97	41.99
Nitrogen	0.54	0.54
Sulfur	0.10	0.10
Ash	3.48	3.48

3. Compute the molar composition of the elements neglecting the ash.

		Moles	
Component	Atomic weight, lb/mole	Without H_2O	With H_2O
Carbon	12.01	2.280	2.280
Hydrogen	1.01	3.584	5.940
Oxygen	16.00	1.436	2.624
Nitrogen	14.01	0.038	0.038
Sulfur	32.07	0.003	0.003

4. Determine an approximate chemical formula without and with sulfur and without and with water. Set up a computation table to determine normalized mole ratios.

	Mole ratio (Nitrogen = 1)		Mole ratio (Sulfur = 1)	
Component	Without H_2O	With H_2O	Without H_2O	With H_2O
Carbon	60.0	60.0	760.0	760.0
Hydrogen	94.3	156.3	1194.7	1980.0
Oxygen	37.8	69.1	478.7	874.7
Nitrogen	1.0	1.0	12.7	12.7
Sulfur	0.1	0.1	1.0	1.0

(*a*) The chemical formulas without sulfur are:

1. Without water $C_{60.0}H_{94.3}O_{37.8}N$
2. With water $C_{60.0}H_{156.3}O_{69.1}N$

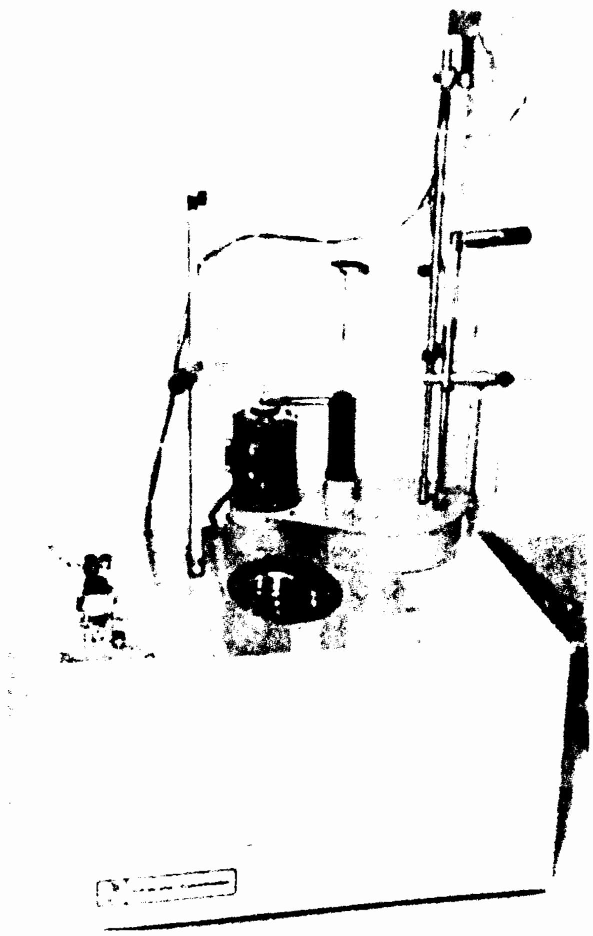
(*b*) The chemical formulas with sulfur are:

1. Without water $C_{760.0}H_{1194.7}O_{478.7}N_{12.7}S$
2. With water $C_{760.0}H_{1980.0}O_{874.7}N_{12.7}S$

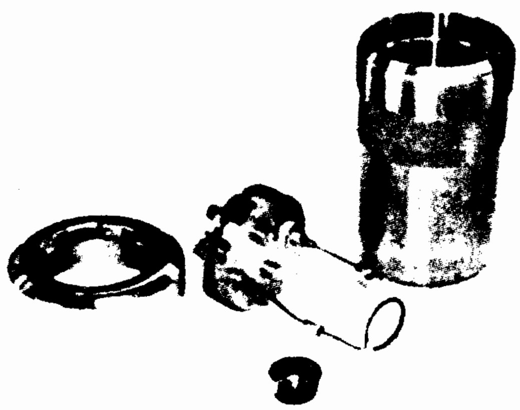
Comment. The fractional coefficients reported in these formulas are usually rounded off, as the original data do not warrant such precision.

Energy Content of Solid Waste Components

The energy content of the organic components in MSW can be determined (1) by using a full scale boiler as a calorimeter, (2) by using a laboratory bomb calorimeter (see Fig. 4-5), and (3) by calculation, if the elemental composition is known. Because of the difficulty in instrumenting a full-scale boiler, most of the data on the energy content of the organic components of MSW are based on the results of bomb calorimeter tests. Typical data for energy content and inert residue for the



(a)



(b)

FIGURE 4-5
Laboratory bomb calorimeter used to determine the energy content of solid waste materials: (a) calorimeter with access cover opened for loading oxygen bomb and (b) disassembled oxygen bomb with sample cup in foreground.

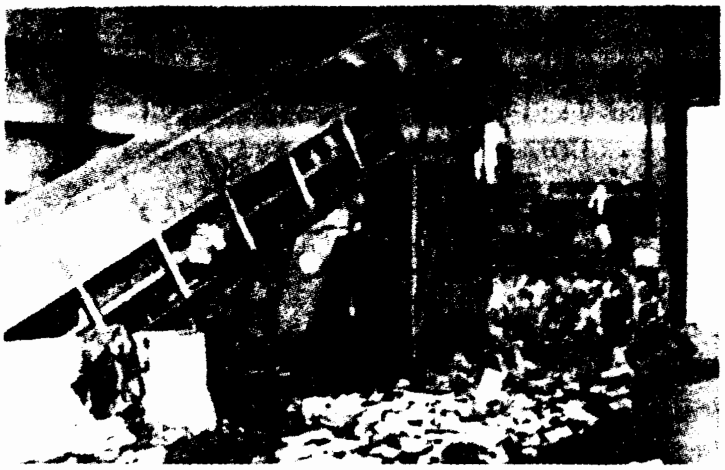


FIGURE 4-6
Baler used at materials recovery facility to bale paper, cardboard, plastic, and aluminum cans.

processing centers (see Fig. 4-6). Recently, high-pressure compaction systems have been developed to produce materials suitable for various alternative uses such as production of fireplace logs from paper and cardboard. To decrease the costs associated with the transport of waste materials to landfill disposal sites, municipalities also may use transfer stations equipped with compaction facilities. To increase the useful life of landfills, wastes are usually compacted before being covered (see Fig. 4-7).

Mechanical Size Reduction. *Size reduction* is the term applied to the transformation processes used to reduce the size of the waste materials. The objective of size reduction is to obtain a final product that is reasonably uniform and considerably reduced in size in comparison with its original form (see Fig. 4-8). Note that size reduction does not necessarily imply volume reduction. In some situations, the total volume of the material after size reduction may be greater than that of the original volume (e.g., the shredding of office paper). In practice, the terms *shredding*, *grinding*, and *milling* are used to describe mechanical size-reduction operations.

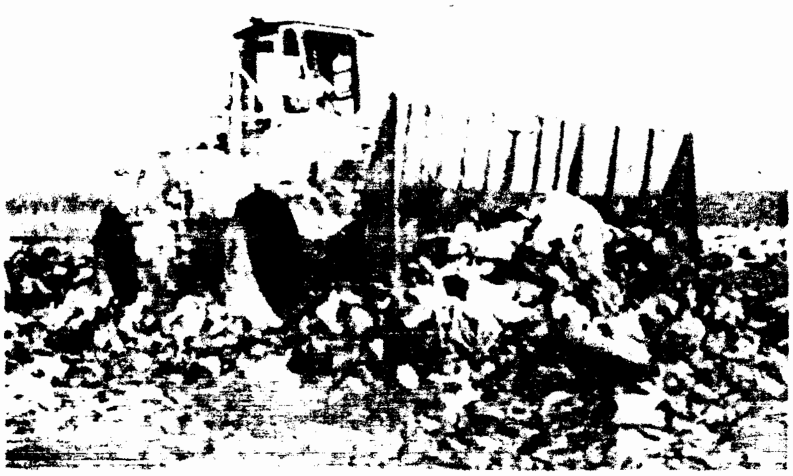


FIGURE 4-7
Compaction of waste at a landfill before daily cover is applied.

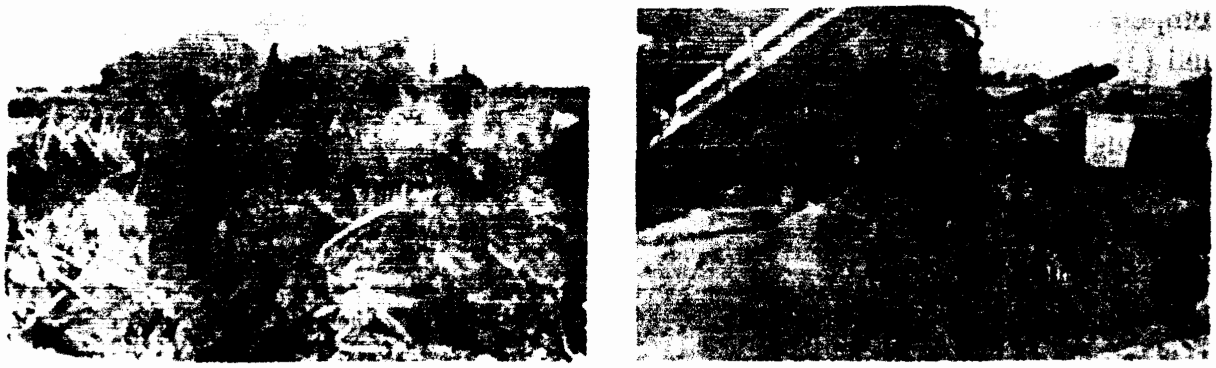


FIGURE 4-8
Yard trimmings before and after mechanical size reduction in a tub grinder.

Chemical Transformations

Chemical transformations of solid waste typically involve a change of phase (e.g., solid to liquid, solid to gas, etc.). To reduce the volume and/or to recover conversion products, the principal chemical processes used to transform MSW include (1) combustion (chemical oxidation), (2) pyrolysis, and (3) gasification. All three of these processes are often classified as thermal processes.

Combustion (Chemical Oxidation). *Combustion* is defined as the chemical reaction of oxygen with organic materials, to produce oxidized compounds accompanied by the emission of light and rapid generation of heat. In the presence of excess air and under ideal conditions, the combustion of the organic fraction of MSW can be represented by the following equation:

$$\text{Organic matter} + \text{excess air} \rightarrow N_2 + CO_2 + H_2O + O_2 + \text{ash} + \text{heat} \quad (4\text{-}18)$$

Excess air is used to ensure complete combustion. The end products derived from the combustion of MSW, Eq. (4-18), include hot combustion gases—composed primarily of nitrogen (N_2), carbon dioxide (CO_2), water (H_2O, flue gas), and oxygen (O_2)—and noncombustible residue. In practice, small amounts of ammonia (NH_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other trace gases will also be present, depending on the nature of the waste materials.

Pyrolysis. Because most organic substances are thermally unstable, they can be split, through a combination of thermal cracking and condensation reactions in an oxygen-free atmosphere, into gaseous, liquid, and solid fractions. *Pyrolysis* is the term used to describe the process. In contrast with the combustion process, which is highly exothermic, the pyrolytic process is highly endothermic. For this reason, *destructive distillation* is often used as an alternative term for pyrolysis.

The characteristics of the three major component fractions resulting from the pyrolysis of the organic portion of MSW are (1) a gas stream containing primarily hydrogen (H_2), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), and various other gases, depending on the organic characteristics of the waste material being pyrolyzed; (2) a tar and/or oil stream that is liquid at room temperature and contains chemicals such as acetic acid, acetone, and methanol; and (3) a char consisting of almost pure carbon plus any inert material that may have entered the process. For cellulose ($C_6H_{10}O_5$) the following expression has been suggested as being representative of the pyrolysis reaction [3]:

$$3(C_6H_{10}O_5) \rightarrow 8H_2O + C_6H_8O + 2CO + 2CO_2 + CH_4 + H_2 + 7C \quad (4\text{-}19)$$

In Eq. (4-19), the liquid tar and/or oil compounds normally obtained are represented by the expression C_6H_8O.

Gasification. The gasification process involves partial combustion of a carbonaceous fuel so as to generate a combustible fuel gas rich in carbon monoxide, hydrogen, and some saturated hydrocarbons, principally methane. The combustible fuel gas can then be combusted in an internal combustion engine or boiler. When a gasifier is operated at atmospheric pressure with air as the oxidant, the end products of the gasification process are (1) a low-Btu gas typically containing carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and nitrogen (N_2); (2) a char containing carbon and the inerts originally in the fuel, and (3) condensible liquids resembling pyrolytic oil.

Other Chemical Transformation Processes. In addition to the various combustion, pyrolysis, and gasification processes under investigation and/or construction, a variety of other public and proprietary processes are being developed and evaluated for the transformation of solid waste. The hydrolytic conversion of cellulose to glucose, followed by the fermentation of glucose to ethyl alcohol, is an example of such a process (see Chapter 14).

Biological Transformations

The biological transformations of the organic fraction of MSW may be used to reduce the volume and weight of the material; to produce compost, a humus-like material that can be used as a soil conditioner; and to produce methane. The principal organisms involved in the biological transformations of organic wastes are bacteria, fungi, yeasts, and actinomycetes. These transformations may be accomplished either *aerobically* or *anaerobically*, depending on the availability of oxygen. The principal differences between the aerobic and anaerobic conversion reactions are the nature of the end products and the fact oxygen must be provided to accomplish the aerobic conversion. Biological processes that have been used for the conversion of the organic fraction of MSW include aerobic composting, anaerobic digestion, and high-solids anaerobic digestion.

Aerobic Composting. Left unattended, the organic fraction of MSW will undergo biological decomposition. The extent and the period of time over which the decomposition occurs will depend on the nature of the waste, the moisture content, the available nutrients, and other environmental factors. Under controlled conditions, yard wastes and the organic fraction of MSW can be converted to

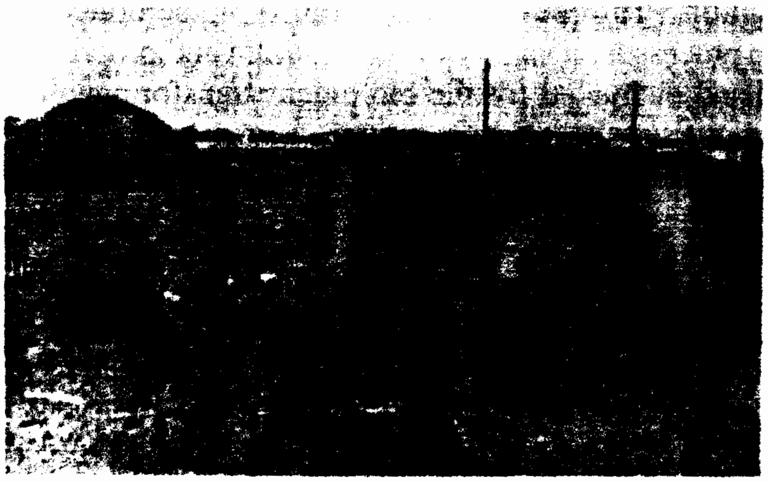


FIGURE 4-9
Compost produced from processed (see Fig. 4-8) yard wastes.

a stable organic residue known as *compost* (see Fig. 4-9) in a reasonably short period of time (four to six weeks).

Composting the organic fraction of MSW under aerobic conditions can be represented by the following equation:

$$\text{Organic matter} + O_2 + \text{nutrients} \rightarrow \text{new cells} + \begin{matrix}\text{resistant}\\ \text{organic}\\ \text{matter}\end{matrix} + CO_2 + H_2O$$
$$+ NH_3 + SO_2^{2-} + \text{heat} \qquad (4\text{-}20)$$

In Eq. (4-20), the principal end products are new cells, resistant organic matter, carbon dioxide, water, ammonia, and sulfate. Compost is the resistant organic matter that remains. The resistant organic matter usually contains a high percentage of lignin, which is difficult to convert biologically in a relatively short time. Lignin, found most commonly in newsprint, is the organic polymer that holds together the cellulose fibers in trees and certain plants.

Anaerobic Digestion. The biodegradable portion of the organic fraction of MSW can be converted biologically under anaerobic conditions to a gas containing carbon dioxide and methane (CH_4). This conversion can be represented by the following equation:

$$\text{Organic matter} + H_2O + \text{nutrients} \rightarrow \text{new cells} + \begin{matrix}\text{resistant}\\ \text{organic}\\ \text{matter}\end{matrix} + CO_2 + CH_4$$
$$+ NH_3 + H_2S + \text{heat} \qquad (4\text{-}21)$$

Thus, the principal end products are carbon dioxide, methane, ammonia, hydrogen sulfide, and resistant organic matter. In most anaerobic conversion processes carbon dioxide and methane constitute over 99 percent of the total gas produced. The resistant organic matter (or digested sludge) must be dewatered before it can be disposed of by land spreading or landfilling. Dewatered sludge is often composted aerobically to stabilize it further before application.

Other Biological Transformation Processes. In addition to the aerobic composting and anaerobic digestion processes, a variety of other public and proprietary processes are being developed and evaluated for the biological transformation of solid waste. The high-solids anaerobic digestion process discussed in Chapter 14 is one such example.

Importance of Waste Transformations in Solid Waste Management

Typically, physical, chemical, and biological transformations are used (1) to improve the efficiency of solid waste management operations and systems, (2) to recover reusable and recyclable materials, and (3) to recover conversion products and energy. The implications of waste transformation in the design of integrated solid waste management systems can be illustrated by the following example. If composting is to be an element of a solid waste management plan, the organic fraction of the MSW must be separated from the commingled MSW. If the organic fraction must be separated, should it be done at the source of generation or at a materials recovery facility? If separation of wastes is to occur at the source, what components should be separated to produce an optimum compost?

Improving Efficiency of Solid Waste Management Systems. To improve the efficiency of solid waste management operations and to reduce storage volume requirements at medium- and high-rise apartment buildings, wastes are often baled. For example, waste paper, recovered for recycling, is baled to reduce storage volume requirements and shipping costs. In some cases, waste materials are baled to reduce haul costs to the disposal site. At disposal sites, solid wastes are compacted to use the available landfill capacity effectively. If solid wastes are to be transported hydraulically or pneumatically, some form of shredding is normally required. Mechanical size reduction (shredding) has also been used to improve the efficiency of disposal sites. Hand separation at the point of generation is now considered an efficient way to remove small quantities of hazardous waste from MSW, thereby making landfills safer. Chemical and biological processes can be used to reduce the volume and weight of waste requiring disposal and to produce useful products.

Recovery of Materials for Reuse and Recycling. As a practical matter, components that are most amenable to recovery are those for which markets exist and which are present in the wastes in sufficient quantity to justify their separation. Materials most often recovered from MSW include paper, cardboard, plastic, garden trimmings, glass, ferrous metal, aluminum, and other nonferrous metal.

Recovery of Conversion Products and Energy. The organic fraction of MSW can be converted to usable products and ultimately to energy in a number of ways, including (1) combustion to produce steam and electricity; (2) pyrolysis to produce a synthetic gas, liquid or solid fuel, and solids; (3) gasification to produce a synthetic fuel; (4) biological conversion to produce compost; and (5) biodigestion to generate methane and to produce a stabilized organic humus.

4-5 DISCUSSION TOPICS AND PROBLEMS

4-1. Using the data in Table 4-1, determine the *as discarded* specific weight of typical residential MSW. Use the typical distribution of waste components given in column 3 of Table 3-4.

4-2. Using the data in Table 4-1, estimate the specific weight of two wastes (to be selected by instructor) with the composition given in the following table:

	Percent by weight		
Component	**A**	**B**	**C**
Food wastes	15	45	70
Paper	35	25	10
Cardboard	7	4	3
Plastics	5	5	6
Textiles	3	0	0
Rubber	3	0	0
Leather	2	0	0
Yard wastes	20	18	11
Wood	10	3	0

4-3. Estimate the overall moisture content of wastes (to be selected by instructor) given in Problem 4-2.

4-4. Using the data in Problem 4-2, estimate the overall moisture content of wastes C.

4-5. Using the data in Table 4-3, derive an approximate chemical formula for waste A given in Problem 4-2.

4-6. Estimate the *as discarded* energy content for waste A in Problem 4-2. Use the typical values in Table 4-5. What is the energy content on a dry and dry ash-free basis?

4-7. Compare the *as discarded* energy content for wastes A and C in Problem 4-2. Use the typical data given in Table 4-5. What are the implications of this comparison?

4-8. Estimate the energy content of waste A in Problem 4-2 based on the chemical composition of the individual waste components. Use the data given in Table 4-3.

4-9. Hydrogen sulfide has an odor recognition threshold concentration of 0.47 ppb. Based on Eqs. (4-12) and (4-14), determine the minimum concentration of both lactate and sulfate that would lead to the recognition of H_2S. Assume that both reactions convert 100% of the starting material.

4-10. Obtain data on the breeding time for flies from your local vector control agency. How do the values you obtained compare with the values given in Section 4-3? Explain any differences.

4-11. Identify (*a*) the physical, chemical, and biological transformations that can be applied to solid waste with which you have first-hand experience and (*b*) the context of your experience—for example, the combustion of paper in a fireplace.

4-12. Identify the physical, chemical, and biological transformations that are used by the waste management agency in your community and the context (volume reduction, energy production) in which they are used.

4-13. What waste materials do you now separate where you live? What waste materials do your parents separate at their home?

4-14. What is the difference between compaction and consolidation? What effect will consolidation have in baled material that has a specific weight of 1800 lb/yd^3? *Hint:* What is the weight of one cubic yard of water?

4-15. Although compaction of waste increases the amount of solid waste that can be collected per collection trip, what are the disadvantages of compaction with respect to the separation of waste components at a materials recovery facility?

4-16. Combustion of solid waste involves a chemical transformation in which solid matter is transformed to gas. However, there will always be some undesirable products. Describe which factors and process variables affect the conversion products.

4-17. Steam and carbon dioxide are two main products of the combustion process. Is the following ratio constant for all solid wastes? Explain.

$$R = \frac{\text{moles } H_2O}{\text{moles } CO_2}$$

4-18. Explain how the nature of the waste affects the aerobic decomposition of solid waste.

4-6 REFERENCES

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