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Solid Wastes

CHAPTER

TEN

SOLID WASTE: DEFINITIONS, CHARACTERISTICS, AND PERSPECTIVES

H.S. Peavy, D.R. Rowe and G. Tchobanoglous, "Environmental Engineering", McGraw-Hill, New York, 1988.

Solid wastes are all the wastes arising from human and animal activities that are normally solid and that are discarded as useless or unwanted. The term as used in this chapter is all-inclusive, and it encompasses the heterogeneous mass of throwaways from residences and commercial activities as well as the more homogeneous accumulations of a single industrial activity. To avoid confusion, the term *refuse*, often used interchangeably with the term *solid wastes*, is not used in this chapter.

The purpose of this chapter is threefold: (1) to identify the various types of solid wastes and their sources, (2) to examine the physical and chemical composition of wastes, and (3) to consider in general terms the elements involved in the management of these wastes. Engineering aspects of solid-waste management are considered in Chap. 11. The recovery of materials and energy from solid wastes is discussed in Chap. 12.

Types of Solid Wastes

The types and sources of solid wastes and the physical and chemical composition of solid wastes are considered in this section. The term *solid wastes* is all-inclusive and encompasses all sources, types of classifications, composition, and properties. As a basis for subsequent discussions, it will be helpful to define the various types of solid wastes that are generated. Three general categories are considered: (1) municipal wastes, (2) industrial wastes, and (3) hazardous wastes.

Table 10-1 Classification of materials comprising municipal solid waste

Component	Description
Food wastes	The animal, fruit, or vegetable residues (also called garbage) resulting from the handling, preparation, cooking, and eating of foods. Because food wastes are putrescible, they will decompose rapidly, especially in warm weather.
Rubbish	Combustible and noncombustible solid wastes, excluding food wastes or other putrescible materials. Typically, combustible rubbish consists of materials such as paper, cardboard, plastics, textiles, rubber, leather, wood, furniture, and garden trimmings. Noncombustible rubbish consists of items such as glass, crockery, tin cans, aluminum cans, ferrous and nonferrous metals, dirt, and construction wastes.
Ashes and residues	Materials remaining from the burning of wood, coal, coke, and other combustible wastes. Residues from power plants normally are not included in this category. Ashes and residues are normally composed of fine, powdery materials, cinders, clinkers, and small amounts of burned and partially burned materials.
Demolition and construction wastes	Wastes from razed buildings and other structures are classified as demolition wastes. Wastes from the construction, remodeling, and repairing of residential, commercial, and industrial buildings and similar structures are classified as construction wastes. These wastes may include dirt, stones, concrete, bricks, plaster, lumber, shingles, and plumbing, heating, and electrical parts.
Special wastes	Wastes such as street sweepings, roadside litter, catch-basin debris, dead animals, and abandoned vehicles are classified as special wastes.
Treatment-plant wastes	The solid and semisolid wastes from water, wastewater, and industrial-waste treatment facilities are included in this classification.

10-1 MUNICIPAL WASTES

It is important to note that the definitions of terms and the classifications used to describe the components of solid waste vary greatly in practice and in the literature. Consequently, the use of published data requires considerable care, judgment, and common sense. The definitions presented in Table 10-1 are intended to serve as a guide for municipal solid wastes.

10-2 INDUSTRIAL WASTES

Industrial wastes are those wastes arising from industrial activities and typically include rubbish, ashes, demolition and construction wastes, special wastes, and hazardous wastes.

10-3 HAZARDOUS WASTES

Wastes that pose a substantial danger immediately or over a period of time to human, plant, or animal life are classified as hazardous wastes. A waste is classified as hazardous if it exhibits any of the following characteristics: (1) ignitability, (2) corrosivity, (3) reactivity, or (4) toxicity. A detailed definition of these terms was first published in the *Federal Register* on May 19, 1980 (pp. 33, 121–122).

In the past, hazardous wastes were often grouped into the following categories: (1) radioactive substances, (2) chemicals, (3) biological wastes, (4) flammable wastes, and (5) explosives. The chemical category includes wastes that are corrosive, reactive, or toxic. The principal sources of hazardous biological wastes are hospitals and biological research facilities.

Sources of Solid Wastes

Knowledge of the sources and types of solid wastes, along with data on the composition and rates of generation, is basic to the engineering management of solid wastes.

10-4 MUNICIPAL WASTES

Sources and types of municipal solid wastes are reported in Table 10-2. In evaluating the sources of solid waste as reported in Table 10-2 it can be concluded that they are, for the most part, related to land use and zoning. The most difficult

Table 10-2 General sources of municipal solid wastes

Source	Typical facilities, activities, or locations where wastes are generated	Types of solid wastes
Residential	Single-family and multifamily dwellings, low-, medium-, and high-rise apartments, etc.	Food wastes, rubbish, ashes, special wastes
Commercial	Stores, restaurants, markets, office buildings, hotels, motels, print shops, auto repair shops, medical facilities and institutions, etc.	Food wastes, rubbish, ashes, demolition and construction wastes, special wastes, occasionally hazardous wastes
Open areas	Streets, alleys, parks, vacant lots, playgrounds, beaches, highways, recreational areas, etc.	Special wastes, rubbish
Treatment plant sites	Water, wastewater, and industrial treatment processes, etc.	Treatment-plant wastes, principally composed of residual sludges

source to deal with is open areas because in these locations the generation of wastes is a diffuse process.

10-5 HAZARDOUS WASTES

Hazardous wastes are generated in limited amounts throughout most industrial activities. In terms of generation, the concern is with the identification of the amounts and types of hazardous wastes developed at each source, with emphasis on those sources where significant waste quantities are generated. Unfortunately, very little information is available on the quantities of hazardous wastes generated in various industries.

The spreading of hazardous wastes by spillage must also be considered. The quantities of hazardous wastes that are involved in spillages usually are not known. After a spill, the wastes requiring collection and disposal are often significantly greater than the amount of spilled wastes, especially where an absorbing material, such as straw, is used to soak up liquid hazardous wastes or where the soil into which a hazardous liquid waste has percolated must be excavated. Both the straw and the liquid and the soil and the liquid are classified as hazardous wastes.

Properties of Solid Wastes

Information on the properties of solid wastes is important in evaluating alternative equipment needs, systems, and management programs and plans, especially with respect to the implementation of disposal and resource- and energy-recovery options.

10-6 PHYSICAL COMPOSITION

Information and data on the physical composition of solid wastes including (1) identification of the individual components that make up municipal solid wastes, (2) analysis of particle size, (3) moisture content, and (4) density of solid wastes are presented below. Sampling techniques used to obtain data on solid wastes are also discussed in this section.

Individual Components

Components that typically make up most municipal solid wastes and their relative distribution are reported in Table 10-3. Although any number of components could be selected, those listed in Table 10-3 have been selected because they are readily identifiable, are consistent with component categories reported in the literature, and are adequate for the characterization of solid wastes for most applications.

Table 10-3 Typical composition of municipal solid wastes

	Percent by mass			
Component	Range	Typical	Davis California*	Merida, Venezuela†
Food wastes	6–26	14	8.3	27.4
Paper	15–45	34	35.8	15.5
Cardboard	3–15	7	10.9	13.0
Plastics	2–8	5	6.9	4.6
Textiles	0–4	2	2.5	2.3
Rubber	0–2	0.5	2.5	0.4
Leather	0–2	0.5	0.7	1.3
Garden trimmings	0–20	12	10.8	5.8
Wood	1–4	2	1.9	3.6
Misc. organics	0–5	2	2.0	0.6
Glass	4–16	8	7.5	10.3
Tin cans	2–8	6	5.1	8.3
Nonferrous metals	0–1	1	1.6	0.1
Ferrous metals	1–4	2	2.2	1.2
Dirt, ashes, brick, etc.	0–10	4	1.3	5.6

* Based on measurements made during the month of October over a 5-year period (1978 through 1982).

† Based on measurements made during the month of July over a 3-year period (1978 through 1980).

Particle Size

The size of the component materials in solid wastes is of importance in the recovery of materials, especially with mechanical means such as trommel screens and magnetic separators. 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. 10-1 and 10-2.

Moisture Content

The moisture content of solid wastes usually is expressed as the mass of moisture per unit mass of wet or dry material. In the wet-mass method of measurement, the moisture in a sample is expressed as a percentage of the wet mass of the material; in the dry-mass method, it is expressed as a percentage of the dry mass of the material. In equation form, the wet-mass moisture content is expressed as follows:

$$\text{Moisture content } (\%) = \left(\frac{a-b}{a}\right) 100 \qquad (10\text{-}1)$$

where a = initial mass of sample as delivered
b = mass of sample after drying

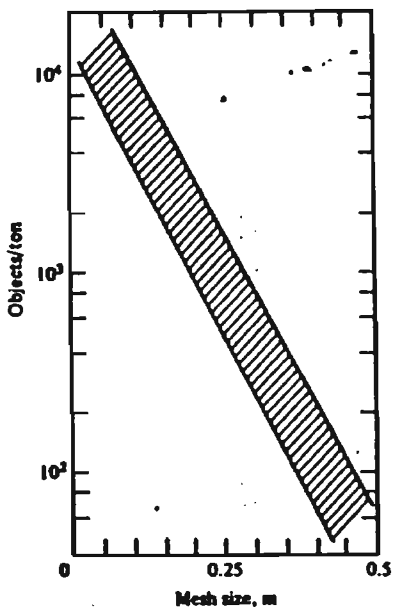

Figure 10-1 Typical sizes of individual components comprising solid wastes. (*Adapted from Winkler and Wilson [10-7].*)

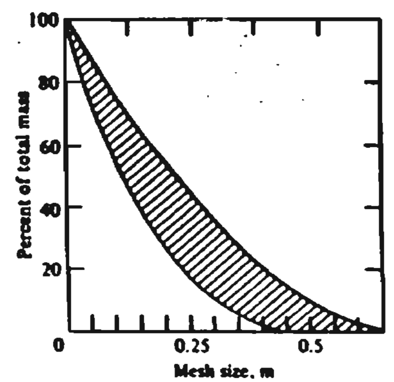

Figure 10-2 Number of individual components of a given size per tonne of municipal solid wastes. (*Adapted from Winkler and Wilson [10-7].*)

Table 10-4 Typical data on moisture content of municipal solid waste components

Component	Moisture, percent: Range	Moisture, percent: Typical
Food wastes	50–80	70
Paper	4–10	6
Cardboard	4–8	5
Plastics	1–4	2
Textiles	6–15	10
Rubber	1–4	2
Leather	8–12	10
Garden trimmings	30–80	60
Wood	15–40	20
Misc. organics	10–60	25
Glass	1–4	2
Tin cans	2–4	3
Nonferrous metals	2–4	2
Ferrous metals	2–6	3
Dirt, ashes, brick, etc.	6–12	8
Municipal solid wastes	15–40	20

Source: From Tchobanoglous et al. [10-5]

To obtain the dry mass, the solid-waste material is dried in an oven at 77°C (170°F) for 24 h. This temperature and time is used to dehydrate the material completely and to limit the vaporization of volatile materials.

Typical data on the moisture content for the solid-waste components are given in Table 10-4. For most industrial solid wastes, the moisture content will vary from 10 to 35 percent. The use of Eq. (10-1) is illustrated in Example 10-1.

Example 10-1: Estimating the moisture content of a solid-waste sample Estimate the moisture content of a solid-waste sample with the following composition:

Component	Percent by mass
Food wastes	15
Paper	45
Cardboard	10
Plastics	10
Garden trimmings	10
Wood	5
Tin cans	5

SOLUTION

1. Set up a computation table to determine the dry mass of the solid-waste sample using the data given in Table 10-4.

Component	Percent by mass	Moisture content, %	Dry mass,* kg
Food waste	15	70	4.5
Paper	45	6	42.3
Cardboard	10	5	9.5
Plastics	10	2	9.8
Garden trimmings	10	60	4.0
Wood	5	20	4.0
Tin cans	5	3	4.9
			79.0

* Based on 100-kg sample of waste.

2. Determine the moisture content using Eq. (10-1) and the data from step 1.

$$\text{Moisture content} = \left(\frac{100 - 79.0}{100}\right)100 = 21.0\%$$

COMMENT The composition of the solid-waste sample used in this example will be used in all of the examples in this chapter. By using the same composition throughout, the interrelationship of the various parameters can be established more clearly.

Density

Typical densities for various wastes as found in containers are reported by source in Table 10-5. Because the densities 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. Estimation of the density of a waste sample is illustrated in Example 10-2.

Example 10-2: Estimating the density of a solid-waste sample Estimate the "as-discarded" density of a solid-waste sample with the composition given in Example 10-1.

SOLUTION

1. Set up a computation table to determine the as-discarded volume of the solid waste sample using the data reported in Table 10-5.

Component	Percent by mass	Typical density, kg/m^3	Volume,* m^3
Food waste	15	290	0.52
Paper	45	85	5.29
Cardboard	10	50	2.00
Plastics	10	65	1.54
Garden trimmings	10	105	0.95
Wood	5	240	0.21
Tin cans	5	90	0.56
			11.07

* Based on a 1000-kg sample of waste.

2. Compute the density of a waste sample using the data from step 1.

$$\text{Density} = \frac{1000\ \text{kg}}{11.07\ \text{m}^3} = 90.33\ \text{kg/m}^3$$

Table 10-5 Typical densities for solid wastes components and mixtures

Item	Density, kg/m^3 Range	Typical
Component*		
Food wastes	120–480	290
Paper	30–130	85
Cardboard	30–80	50
Plastics	30–130	65
Textiles	30–100	65
Rubber	90–200	130
Leather	90–260	160
Garden trimmings	60–225	105
Wood	120–320	240
Misc. organics	90–360	240
Glass	160–480	195
Tin cans	45–160	90
Nonferrous metals	60–240	160
Ferrous metals	120–1200	320
Dirt, ashes, brick, etc.	320–960	480
Municipal solid wastes		
Uncompacted	90–180	130
Compacted (in compactor truck)	180–450	300
In landfill (compacted normally)	350–550	475
In landfill (well-compacted)	600–750	600

* Data for components is on an as-discarded basis.

Sampling Procedures

Perhaps the most difficult task facing anyone concerned with the design and operation of solid-waste management systems is to predict the composition of solid wastes that will be collected now and in the future. The problem is complicated because of the heterogeneous nature of waste materials and the fact that unpredictable externalities such as world oil prices can affect the long-term abundance of the individual waste components.

To assess the total mix of wastes components such as those listed in Table 10-1, the load-count and the mass-volume methods of analysis are recommended. These methods are considered in Sec. 11-3. The following technique is recommended where it is desired to assess the individual components within a given waste category (e.g., domestic wastes).

1. Unload a truckload of wastes in a controlled area away from other operations.
2. Quarter the wasteload.
3. Select one of the quarters and quarter that quarter.
4. Select one of the quartered quarters and separate all of the individual components of the waste into preselected components such as those listed in Table 10-3.
5. Place the separated components in a container of known volume and tare mass and measure the volume and mass of each component. The separated components should be compacted tightly to simulate the conditions in the storage containers from which they were collected.
6. Determine the percentage distribution of each component by mass and the as-discarded density (see Table 10-5). Typically, from 100 to 200 kg (200 to 400 lb) of waste should be sorted to obtain a representative sample. To obtain a more representative distribution of components, samples should be collected during each season of the year. Clearly, no matter how many samples are analyzed, common sense is needed in selecting the loads to be sorted, in analyzing the data, and in preparing projections.

10-7 CHEMICAL COMPOSITION

Information on the chemical composition of solid wastes is important in evaluating alternative processing and energy recovery options. If solid wastes are to be used as fuel, the four most important properties to be known are:

1. Proximate analysis
   a. Moisture (loss at 105°C for 1 h)
   b. Volatile matter (additional loss on ignition at 950°C)
   c. Ash (residue after burning)
   d. Fixed carbon (remainder)
2. Fusing point of ash

3. Ultimate analysis, percent of C (carbon), H (hydrogen), O (oxygen), N (nitrogen), S (sulfur), and ash
4. Heating value (energy value)

Typical proximate analysis data for the components in municipal solid wastes are presented in Table 10-6.

Energy Content

Typical data on the energy content and inert residue for solid wastes are reported in Table 10-7. Energy values may be converted to a dry basis by using Eq. (10-2).

$$\text{kJ/kg (dry basis)} = \text{kJ/kg (as discarded)} \frac{100}{100 - \%\ \text{moisture}} \qquad (10\text{-}2)$$

The corresponding equation on an ash-free dry basis is:

$$\text{kJ/kg (ash-free dry basis)} = \text{kJ/kg (as discarded)} \frac{100}{100 - \%\ \text{ash} - \%\ \text{moisture}} \qquad (10\text{-}3)$$

Application of the data in Table 10-7 and Eqs. (10-2) and (10-3) is illustrated in Example 10-3.

Table 10-6 Proximate and ultimate chemical analysis of municipal solid waste

	Value, percent*	
	Range	Typical
Proximate analysis		
Moisture	15–40	20
Volatile matter	40–60	53
Fixed carbon	5–12	7
Noncombustibles	15–30	20
Ultimate analysis (combustible components)		
Carbon	40–60	47.0
Hydrogen	4–8	6.0
Oxygen	30–50	40.0
Nitrogen	0.2–1.0	0.8
Sulfur	0.05–0.3	0.2
Ash	1–10	6.0
Heating value†		
Organic fraction, kJ/kg	12,000–16,000	14,000
Total, kJ/kg	8,000–12,000	10,500

* By mass.
† As-discarded basis.

Table 10-7 Typical data on inert residue and energy content of municipal solid wastes

	Inert residue,* percent		Energy,† kJ/kg	
Component	Range	Typical	Range	Typical
Food wastes	2-8	5	3,500-7,000	4,650
Paper	4-8	6	11,600-18,600	16,750
Cardboard	3-6	5	13,950-17,450	16,300
Plastics	6-20	10	27,900-37,200	32,600
Textiles	2-4	2.5	15,100-18,600	17,450
Rubber	8-20	10	20,900-27,900	23,250
Leather	8-20	10	15,100-19,800	17,450
Garden trimmings	2-6	4.5	2,300-18,600	6,500
Wood	0.6-2	1.5	17,450-19,800	18,600
Misc. organics	2-8	6	11,000-26,000	18,000
Glass	96-99†	98	100-250	150
Tin cans	96-99+	98	250-1,200	700
Nonferrous metals	90-99+	96		
Ferrous metals	94-99+	98	250-1,200	700
Dirt, ashes, brick, etc.	60-80	70	2,300-11,650	7,000
Municipal solid wastes			9,300-12,800	10,500

* After combustion.
† As-discarded basis.

Example 10-3: Estimating the energy content of a solid-waste sample Estimate the energy content of a solid-waste sample with the composition given in Example 10-1. What is the content on a dry basis and on an ash-free dry basis?

SOLUTION

1. Set up a computation table to determine the total as-discarded energy content of the solid-waste sample using the data in Table 10-7.

Component	Percent by mass	Energy,* kJ/kg	Total energy,† kJ
Food waste	15	4,650	69,750
Paper	45	16,750	753,750
Cardboard	10	16,300	163,000
Plastics	10	32,600	326,000
Garden trimmings	10	6,500	65,000
Wood	5	18,600	93,000
Tin cans	5	700	3,500
			1,474,000

* From Table 10-7, as-discarded basis.
† Based on 100-kg sample of waste.

2. Compute the unit energy content.

$$\text{Energy content} = \frac{1{,}474{,}000\ \text{kJ}}{100\ \text{kg}} = 14{,}740\ \frac{\text{kJ}}{\text{kg}}$$

3. Determine the energy content on a dry basis.
   a. From Example 10-1, the moisture content of the waste is 21.0 percent.
   b. Using Eq. (10-2), the energy on a dry basis is

$$\text{kJ/kg (dry basis)} = 14{,}740\ \frac{100}{100 - 21.0} = 18{,}658$$

4. Determine the energy content on an ash-free dry basis.
   a. Assume the ash content is equal to 5.0 percent.
   b. Using Eq. (10-3) the energy content on an ash-free dry basis is

$$\text{kJ/kg (ash-free dry basis)} = 14{,}740\ \frac{100}{100 - 5 - 21} = 19{,}919$$

Chemical Content

Representative data on the ultimate analysis of typical municipal waste components are presented in Table 10-8. If energy values are not available, approximate values may be determined by using Eq. (10-4), known as the *modified Dulong formula*, and the data in Table 10-8.

$$\text{kJ/kg} = 337C + 1428\left(H - \frac{O}{8}\right) + 9S \qquad (10\text{-}4)$$

where C = carbon, percent
H = hydrogen, percent
O = oxygen, percent
S = sulfur, percent

Table 10-8 Typical data on ultimate analysis of the combustible components in municipal solid wastes

	Percent by mass (dry basis)					
Component	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
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
Plastic	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
Garden trimmings	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
Misc. organics	48.5	6.5	37.5	2.2	0.3	5.0
Dirt, ashes, brick, etc.	26.3	3.0	2.0	0.5	0.2	68.0

Source: From Tchobanoglous et al. [10-5]

Use of the data in Table 10-8 and Eq. (10-4) is illustrated in Example 10-4.

Example 10-4: Estimating the overall chemical composition of a solid-waste sample Derive an approximate chemical formula for the organic portion of a solid-waste sample with the composition given in Example 10-1. Use the resulting chemical composition to estimate the energy content.

SOLUTION

1. Set up a computation table to determine the overall composition of the waste based on a 100-kg sample (see accompanying table).

Computation of the chemical composition of a waste sample

Component	Wet mass, kg	Dry mass, kg	Composition, kg					
			C	H	O	N	S	Ash
Food wastes	15	4.5	2.16	0.29	1.69	0.12	0.02	0.23
Paper	45	42.3	18.40	2.54	18.61	0.13	0.08	2.54
Cardboard	10	9.5	4.18	0.56	4.24	0.03	0.02	0.48
Plastics	10	9.8	5.88	0.71	2.23	—	—	0.98
Garden trimmings	10	4.0	1.91	0.24	1.52	0.14	0.01	0.18
Wood	5	4.0	1.98	0.24	1.71	0.01	—	0.06
Totals	95	74.1	34.51	4.58	30.00	0.43	0.13	4.47

2. Prepare a summary table of the above data.

Component	Mass, kg
Moisture	20.9*
Carbon	34.51
Hydrogen	4.58
Oxygen	30.00
Nitrogen	0.43
Sulfur	0.13
Ash	4.47

* (95.0 − 74.1).

3. Convert the moisture content reported in step 2 to hydrogen and oxygen.
   a. Hydrogen = $\frac{2}{18}$20.9 kg = 2.32 kg
   b. Oxygen = $\frac{16}{18}$20.9 kg = 18.58 kg

4. Prepare a revised summary table similar to the one prepared in step 2 using the data from step 3.

Component	Mass, kg	Percent by mass
Carbon	34.51	36.3
Hydrogen	6.90	7.3
Oxygen	48.58	51.1
Nitrogen	0.43	0.5
Sulfur	0.13	0.1
Ash	4.47	4.7
Total	95.02	100.0

5. Compute molar composition of the elements.

Element	Mass, kg	kg/mol	Moles
Carbon	34.51	12.01	2.873
Hydrogen	6.90	1.01	6.832
Oxygen	48.58	16.00	3.036
Nitrogen	0.43	14.01	0.031
Sulfur	0.13	32.06	0.004

6. Determine an approximate chemical formula with and without sulfur.
   a. Compute normalized mole ratios.

Element	Mol ratios	
	Sulfur = 1	Nitrogen = 1
Carbon	718.2	92.7
Hydrogen	1708.0	220.4
Oxygen	759.0	97.9
Nitrogen	7.8	1.0
Sulfur	1.0	0

   b. Chemical formula with sulfur:

$$C_{718.2}H_{1708.0}O_{759.0}N_{7.8}S$$

   c. Chemical formula without sulfur:

$$C_{92.7}H_{220.4}O_{97.9}N$$

7. Estimate the energy content of the waste using Eq. (10-4) and the data from step 4.

$$\text{kJ/kg} \doteq 337(36.3) + 1428\left(7.3 - \frac{51.1}{8}\right) + 95(0.1)$$

$$= 12{,}233 + 1{,}303 + 9.5 = 13{,}546$$

COMMENT Computations such as the above are especially important where the recovery of energy from solid wastes is being considered. The recovery of energy is considered in more detail in Chap. 12.

10-8 CHANGES IN COMPOSITION

To plan effectively for solid waste management, information and data on the expected future composition of the solid wastes are important. In addition to technological changes in areas such as food processing and packaging, changes in the world economy have also affected the composition of solid wastes. For example, prior to the energy crisis of 1974, the amount of ash in solid waste had all but disappeared. Yet today in many parts of the country there is an increase in the amount of ash present in solid waste. With tight economic conditions there is also an increase in the amount of waste oils in solid waste as more people begin to change their own automobile oil.

Solid-Waste Management: An Overview

Recognizing that our world is finite and that the continued pollution of our environment will, if uncontrolled, be difficult to rectify in the future, the subject of solid-waste management is both timely and important. The overall objective of solid-waste management is to minimize the adverse environmental effects caused by the indiscriminate disposal of solid wastes, especially of hazardous wastes. To assess the management possibilities it is important to consider (1) materials flow in society, (2) reduction in raw materials usage, (3) reduction in solid-waste quantities, (4) reuse of materials, (5) materials recovery, (6) energy recovery, and (7) day-to-day solid-waste management.

10-9 MATERIALS FLOW IN SOCIETY

An indication of how and where solid wastes are generated in a technological society is shown in the simplified materials-flow diagram presented in Fig. 10-3. Solid wastes (debris) are generated at the start of the process, beginning with the mining of raw material. Thereafter, solid wastes are generated at every step in the process as raw materials are converted to goods for consumption. It is apparent from Fig. 10-3 that one of the best ways to reduce the amount of solid wastes to be disposed is to reduce the consumption of raw materials and to increase the rate of recovery and reuse of waste materials. Although the concept is simple, effecting this change in a modern technological society has proved extremely difficult.

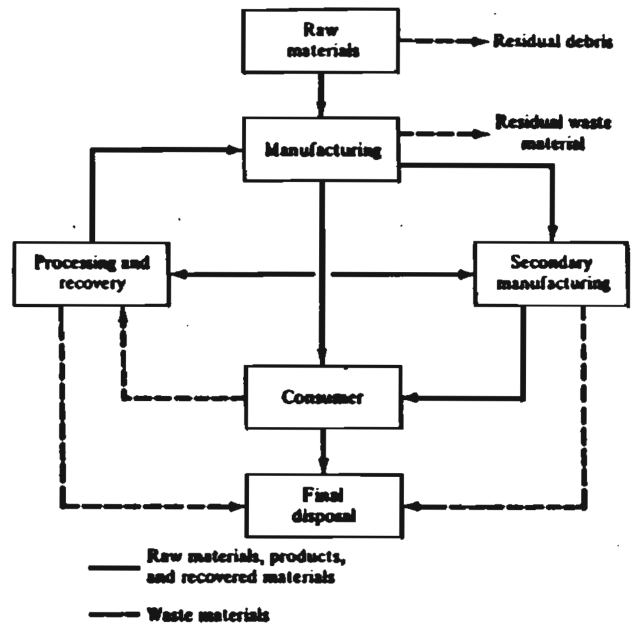

Figure 10-3 Generalized flow of materials and the generation of solid wastes in society. (*From Tchobanoglous et al.* [10-5].)

10-10 REDUCTION IN RAW MATERIALS USAGE

The general relationships shown in Fig. 10-3 can be quantified relatively, as shown in Fig. 10-4. To satisfy the principle of conservation of mass the input must equal the output. Clearly, if a reduction in the usage of raw materials is to occur either the input or output must be reduced. Raw materials usage can be reduced most effectively by reducing the quantity of municipal and industrial wastes. For example, to meet EPA mileage restrictions American cars are now (1984) on the average, 20 percent smaller than they were in the late 1950s and early 1960s. This reduction in size has also reduced the demand for steel by about 20 percent. The reduced demand for steel has in turn resulted in less mining for the iron ore used to make steel. While most people would agree that it is desirable to reduce the usage of raw materials, others would argue that as the usage of raw materials is decreased jobs in those industries also are decreased.

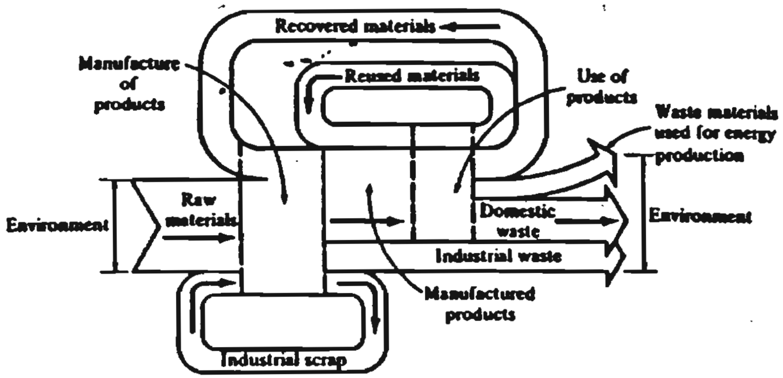

Figure 10-4 Flow of materials in a technological society. (*From Vesilind and Rimer* [10-6].)

Clearly, the question of reduced raw materials usage is closely related to national policies. In more recent times, it has become clear that such usage is also related to the world economy. For example, the increase in oil prices has led to more usage of wood as an alternative source of energy.

10-11 REDUCTION IN SOLID-WASTE QUANTITIES

Reductions in the quantities of waste can occur in several ways: (1) the amount of material used in the manufacture of a product can be reduced, (2) the useful life of a product can be increased, and (3) the amount of materials used for packaging and marketing of consumer goods can be reduced. For example, the quantity of automobile tires now disposed of on an annual basis could be cut almost in half if their useful life (or mileage) were doubled.

The many opportunities to reduce the quantities of municipal and industrial wastes aside, major reductions will occur with changes in our national priorities or as a result of the effects of external economic forces beyond our control. Although this view is somewhat pessimistic it adequately reflects the current situation with respect to the reduction of solid wastes. Further, this view is not meant to minimize the important efforts of individuals and concerned citizen groups.

10-12 REUSE OF SOLID-WASTE MATERIALS

Reuse (recycling) of waste materials now occurs most commonly in those situations where a product has utility in more than one application. For example, the paper bags used to bring home groceries are used to store household wastes prior to placing them in the containers used for their storage for collection. Soup and vegetable containers are used to store used cooking grease. Newspapers are used to start fires in fireplaces; they are also tightly rolled and used as logs for burning.

While all of the above uses are important, their impact on the generation of solid wastes is minimal. A much larger impact would occur if beverage containers were to be recycled. It has been estimated that about 60 billion beer and soft-drink containers are sold annually in the United States. Referring to Table 10-3 it can be seen that glass and nonferrous metals (mostly aluminum cans) consitute 9 percent of the total waste stream. Recycling of these containers would have a major impact on the quantity of wastes that must be disposed on an annual basis.

10-13 MATERIALS RECOVERY

A number of materials present in municipal and industrial solid wastes are suitable for recovery and reuse. Referring to the percentage distribution of the waste components reported in Table 10-3, it would appear that paper, cardboard, plastics, glass, nonferrous metals, and ferrous metals are the most likely candidates. With the exception of plastics, the above materials are those most commonly recovered from solid wastes. The estimated recovery of these materials is reported in Table 10-9. The opportunity for the further recovery of these materials is considered in Chaps. 11 and 12. Impediments to the recovery of energy and materials are examined in Ref. [10-40].

Table 10-9 Materials recovery in the United States in 1975 by category

Material category	Gross discards*	Material recycled: Quantity*	Material recycled: Percent
Paper	44.1	6.8	15.4
Glass	13.7	0.4	2.9
Metals	12.7	0.6	4.7
Ferrous	(11.3)	(0.5)	(4.4)†
Aluminum	(1.0)	(0.1)	(10.0)
Other nonferrous	(0.4)	(0.0)	(0.0)
Plastics	4.4	0.0	0.0
Rubber	2.8	0.2	7.1
Leather	0.7	0.0	0.0
Textiles	2.1	0.0	0.0
Wood	4.8	0.0	0.0
Other	0.1	0.0	0.0
Total nonfood product waste	85.4	8.0	9.3
Food waste	22.8	0.0	0.0
Yard waste	26.0	0.0	0.0
Miscellaneous inorganic wastes	1.9	0.0	0.0
Total	136.1	8.0	5.9

* Million tons per year (metric table unavailable).
† $4.4 = (0.5/11.3) \times 100$
Note: 1.0 ton = 0.907 tonnes.
Source: From U.S. EPA. [10-2]

10-14 ENERGY RECOVERY

Because about 70 percent of the components that comprise solid waste are organic, the potential for the recovery of energy is high. The energy contained in the organic matter must be converted to a form that can be used more easily. The recovery of heat by burning the organic material in solid waste is the option that is spoken of most frequently. In Chap. 12 several alternative energy-recovery technologies are examined.

10-15 DAY-TO-DAY SOLID-WASTE MANAGEMENT

While the issues that have been discussed previously are of great importance and provide a perspective on the waste problem in general, the fact remains that the day-to-day management of the municipal solid wastes is a complex and costly undertaking. Direct activities that must be considered and coordinated on a daily basis include waste generation rates, on-site storage, collection, transfer and transport, processing, and disposal. These activities are associated directly with the management of solid wastes. Indirect activities that are also an important part of a solid-waste management program include: financing; operations; equipment; personnel; cost accounting and budgeting; contract administration; ordinances and guidelines; and public communications. [10-1] The direct activities involved in the management of solid wastes are considered in Chap. 11. The indirect activities are beyond the scope of this text.

DISCUSSION TOPICS AND PROBLEMS

10-1 Obtain data on the percentage distribution of solid-waste components for your community or a nearby community. How do the values compare with the values in Table 10-3? Explain any differences.

10-2 Weigh and sort through a bag of solid waste at your residence and estimate the sizes of the various components. Determine the number of objects per tonne for several size categories (e.g., 51–100, 101–150, 151–200 mm, etc.). How do the values you obtained compare with the data in Fig. 10-1? Explain any major differences.

10-3 Estimate the moisture content for a waste sample (*a*) with the following composition:

Component	Percent by mass			
	(*a*)	(*b*)	(*c*)	(*d*)
Food waste	12	15	10	20
Paper	40	45	40	50
Cardboard	8	5	6	8
Plastic	4	5	6	6
Garden trimming	15	10	15	6
Wood	5	5	5	5
Inerts	16	15	18	5

10-4 Estimate the as-discarded density for a waste (*a*) with the composition given in Prob. 10-3.

10-5 Estimate the as-discarded energy content for a waste (*a*) with the composition given in Prob. 10-3.

10-6 Derive an approximate chemical formula for a waste (*a*) with the composition given in Prob. 10-3.

10-7 Assess what is being done on your campus to reduce the quantities of solid wastes collected for disposal. Have these efforts reduced the quantity of solid wastes generated?

10-8 Assess and discuss what is being done in your own or a nearby community to encourage the reuse of materials.

10-9 Has the recovery of materials been attempted in your community? What have been the results?

10-10 Discuss the merits of trying to pass mandatory recycling legislation.

REFERENCES

10-1 American Public Works Association: *Municipal Refuse Disposal*, 3d ed., Public Administration Service, Chicago, 1970.

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CHAPTER

ELEVEN

ENGINEERED SYSTEMS FOR SOLID-WASTE MANAGEMENT

The analysis of the activities associated with the management of solid waste from the point of waste generation to final disposal is the subject of this chapter. Following a brief overview of the activities involved in the management of solid waste, each activity is considered separately.

11-1 FUNCTIONAL ELEMENTS

The activities involved with the management of solid wastes from the point of generation to final disposal have been grouped into six functional elements: (1) waste generation; (2) on-site handling, storage, and processing; (3) collection; (4) transfer and transport; (5) processing and recovery; and (6) disposal. The functional elements are described in Table 11-1 and illustrated pictorially in Fig. 11-1. The interrelationship between the functional elements is shown in Fig. 11-2. By considering each functional element separately it is possible to identify the fundamental aspects and relationships involved in each element and to develop, where possible, quantifiable relationships for the purposes of making engineering comparisons, analyses, and evaluations.

Solid Waste Generation

Solid wastes, as noted previously, include all solid or semisolid material that is no longer considered of sufficient value to retain in a given setting. It should be noted that the wastes that are discharged may be of significant value in another setting. The types and sources and the physical and chemical composition of solid wastes have been considered previously in Chap. 10. Representative data on the quantities of solid wastes, the estimation of quantities, and the factors affecting the generation rates are considered below.

Table 11-1 Description of the functional elements of a solid waste management system

Functional element	Description
Waste generation	Those activities in which materials are identified as no longer being of value and are either thrown away or gathered together for disposal
On-site handling, storage, and processing	Those activities associated with the handling, storage, and processing of solid wastes at or near the point of generation
Collection	Those activities associated with the gathering of solid wastes and the hauling of wastes after collection to the location where the collection vehicle is emptied
Transfer and transport	Those activities associated with (1) the transfer of wastes from the smaller collection vehicle to the larger transport equipment and (2) the subsequent transport of the wastes, usually over long distance, to the disposal site
Processing and recovery	Those techniques, equipment, and facilities used both to improve the efficiency of the other functional elements and to recover usable materials, conversion products, or energy from solid wastes
Disposal	Those activities associated with ultimate disposal of solid wastes, including those wastes collected and transported directly to a landfill site, semisolid wastes (sludge) from wastewater treatment plants, incinerator residue, compost, or other substances from the various solid-waste processing plants that are of no further use

11-2 TYPICAL GENERATION RATES

Typical unit waste-generation rates for municipal and selected commercial and industrial sources are reported in Tables 11-2 and 11-3, respectively. Because waste-generation practices are changing so rapidly, the presentation of site-specific waste-generation data is meaningless. Where waste-generation data are not available, the data presented in Table 11-2 can be used for purposes of estimation with reasonable confidence.

Table 11-2 Typical per capita solid-waste generation rates in the United States

	Unit rate, kg/capita · d	
Source	Range	Typical
Municipal*	0.75–2.50	1.6
Industrial	0.4–1.60	0.9
Demolition	0.05–0.4	0.3
Other municipal	0.05–0.3	0.2
		3.0

* Includes residential and commercial.

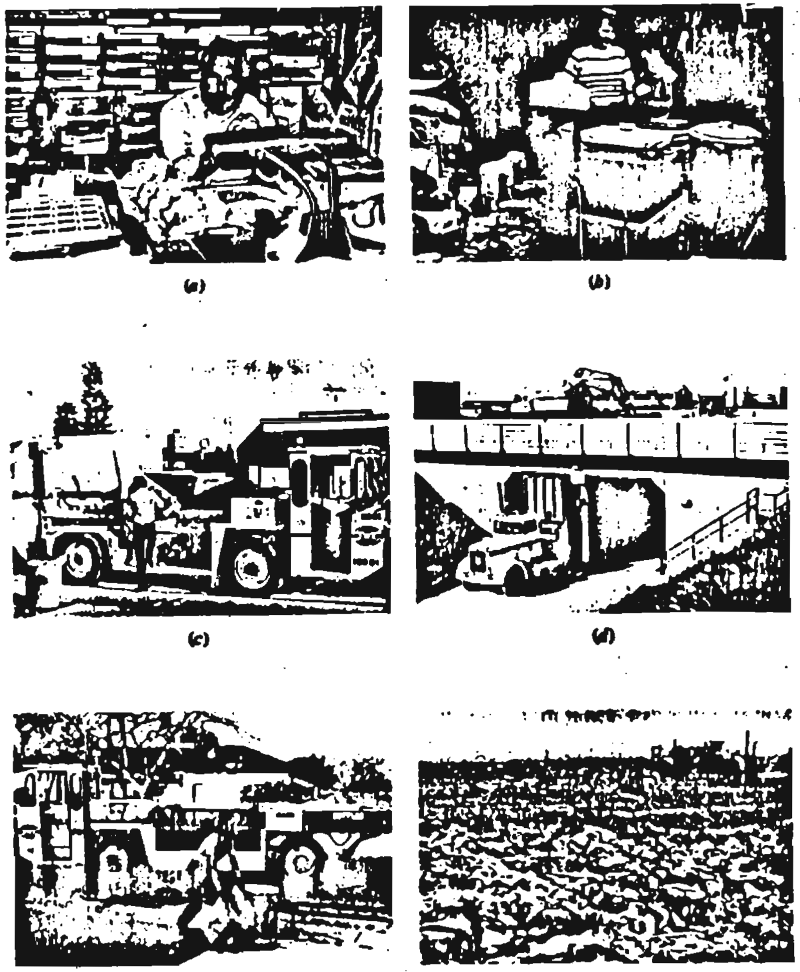


Figure 11-1 Pictorial elements: (a) waste generation, (b) on-site storage, (c) collection, (d) transfer and transport, (e) on-site processing and (f) disposal.

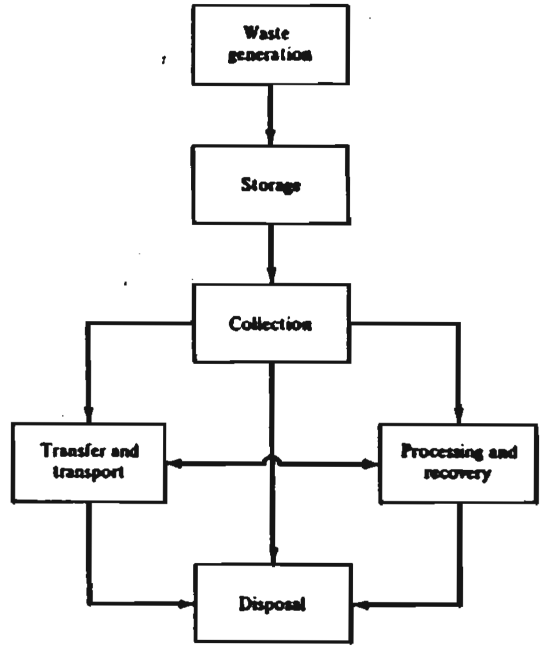


Figure 11-2 Interrelationship of functional elements comprising a solid-waste management system.

Table 11-3 Typical commercial and industrial unit waste-generation rates

Source	Unit	Range
Office buildings	kg/employee · d	0.5–1.1
Restaurants	kg/customer · d	0.2–0.8
Canned and frozen foods	tonnes/tonne of raw product	0.04–0.06
Printing and publishing	tonnes/tonne of raw paper	0.08–0.10
Automotive	tonnes/vehicle produced	0.6–0.8
Petroleum refining	tonnes/employee · d	0.04–0.05
Rubber	tonnes/tonne of raw rubber	0.01–0.3

11-3 ESTIMATION OF SOLID-WASTE QUANTITIES

The quantity and general composition of the waste material that is generated is of critical importance in the design and operation of solid waste management systems. Unfortunately, reliable quantity and composition data are difficult to obtain because most measurements are of the quantities collected or disposed of at a landfill. Although any method of estimation is subject to limitations, the following are recommended.

Load-Count Analysis

In this method, the quantity and composition of solid wastes are determined by recording the estimated volume and general composition of each load of waste delivered to a landfill or transfer station during a specified period of time. The total mass and mass distribution by composition is determined using average density data for each waste category (see Table 10-5).

Mass-Volume Analysis

This method of analysis is similar to the above method with the added feature that the mass of each load is also recorded. Unless the density of each waste category is determined separately, the mass distribution by composition must be derived using average density values (see Table 10-5).

11-4 FACTORS THAT AFFECT GENERATION RATES

Factors that influence the quantity of municipal wastes generated include (1) geographic location, (2) season of the year, (3) collection frequency (affects amount collected), (4) use of kitchen waste grinders, (5) characteristics of populace, (6) extent of salvaging and recycling, (7) public attitudes, and (8) legislation. The existence of salvage and recycling operations within a community definitely affects the quantities of wastes collected for disposal. Whether such operations affect the quantities generated is another question. Until more information is available, no definite statement can be made on this issue. Significant reductions in the quantities of solid wastes that are generated will occur when and if the public and consumer-oriented companies are willing to change—on their own volition—to conserve national resources and to reduce the economic burdens associated with the management of solid wastes.

On-Site Handling, Storage, and Processing

The handling, storage, and processing of solid wastes at the source before they are collected is the second of the six functional elements in a solid-waste management system.

11-5 ON-SITE HANDLING

On-site handling refers to the activities associated with the handling of solid wastes until they are placed in the containers used for their storage before collection. Depending on the type of collection service, handling may also be required to move loaded containers to the collection point and to return the empty containers to the point where they are stored between collections.

Domestic Solid Wastes

Typically, domestic wastes accumulated at several locations in and around low- and medium-rise residential dwellings are placed in larger storage containers to await removal by the waste-collection agency. Where curb collection is used, the resident is also responsible for placing the loaded larger storage container(s) at the curb and for returning the empty container(s) to their storage location next to or in the dwelling.

In high-rise apartments wastes are (1) picked up by building maintenance personnel or porters from each floor and taken to the basement service area, (2) taken to the basement service area by the tenants, or (3) bagged and placed by the tenants in specially designed chutes with openings located at each floor.

Commercial and Industrial Solid Wastes

In most office, commercial, and industrial buildings, solid wastes that accumulate in the offices or work locations usually are collected in relatively large containers mounted on rollers. Once filled, these containers are removed by means of the service elevator, if there is one, and emptied into (1) large storage containers, (2) compactors used in conjunction with the storage containers, (3) stationary compactors that can compress the material into bales or into specially designed containers, or (4) other processing equipment such as incinerators.

11-6 ON-SITE STORAGE

Factors that must be considered in the on-site storage of solid wastes include (1) the type of container to be used, (2) the container location, (3) public health and aesthetics, and (4) the collection methods to be used.

Containers

To a large extent, the types and capacities of the containers used depend on the characteristics of the solid wastes to be collected, the collection frequency, and the space available for the placement of containers. The types and capacities of containers now commonly used for on-site storage of solid wastes are summarized in Table 11-4.

Table 11-4 Data on the types and sizes of containers used for the on-site storage of solid wastes

Container type	Capacity		
	Unit	Range	Typical
Small capacity			
Plastic or metal (office type)	L	16–40	28
Plastic or galvanized metal	L	75–150	120
Barrel: plastic, aluminum, or fiber	L	75–250	120
Plastic containers with wheels (see Fig. 11-5)	L	300–380	340
Disposable paper bags standard leak-resistant and leak-proof	L	75–210	120
Disposable plastic bag	L	50–150	120
Medium capacity			
Side or top loading	m^3	0.75–9	3
Large capacity			
Open top, roll off (also called *debris boxes*)	m^3	9–38	27
Used with stationary compactor	m^3	15–30	23
Equipped with self-contained compaction mechanism	m^3	15–30	23
Trailer-mounted, open top	m^3	15–38	27
Enclosed, equipped with self-contained compaction mechanism	m^3	15–30	27

Because of increasing costs (including the cost of labor, workers' compensation, and fuel and equipment costs) there is a strong movement in the waste-collection field toward the use of large containers that can be emptied mechanically using a vehicle equipped with an articulated pickup mechanism (see Sec. 11-9). Where mechanical collection is to be used, the containers at the individual residences must be standardized to be compatible with the collection equipment.

Container Locations

In newer residential areas, containers for solid waste usually are placed by the side or rear of the house (see Fig. 11-1*b*). In older residential areas containers are located in alleys. In low-rise multifamily apartments large containers are often placed in specially designed and designated enclosures (see Fig. 11-3). In high-rise apartments storage containers are located in a basement or ground-floor service area.

The location of containers at existing commercial and industrial facilities depends on both the location of available space and service-access conditions. In newer facilities, specific service areas have been included for this purpose. Often, because the containers are not owned by the commercial or industrial activity, the locations and types of containers to be used for on-site storage must be worked out jointly between the industry and the public or private collection agency.

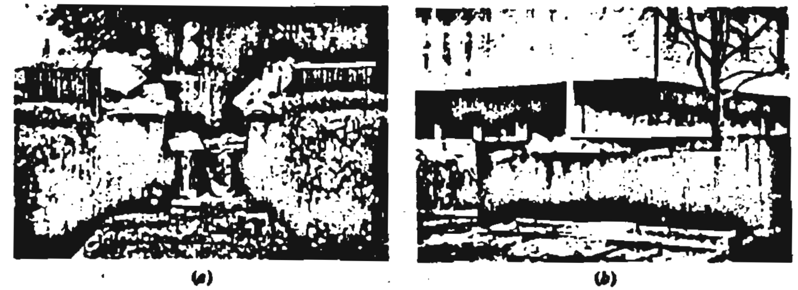


Figure 11-3 Typical storage locations for on-site containers for an apartment complex.

11-7 ON-SITE PROCESSING OF SOLID WASTES

On-site processing methods are used to recover usable materials from solid wastes, to reduce the volume, or to alter the physical form. The most common on-site processing operations include manual sorting, compaction, and incineration. These and other processing operations are considered later in this Chapter.

Collection of Solid Wastes

Information on collection, one of the most costly functional elements, is presented in four parts dealing with (1) the types of collection services, (2) the types of collection systems, (3) an analysis of collection systems, and (4) the general methodology involved in setting up collection routes.

11-8 COLLECTION SERVICES

The various types of collection services now used for municipal and commercial-industrial sources are described in this section.

Municipal Collection Services

Although a variety of collection services are used throughout the United States, the three most common are curb, alley, and backyard collection. Curb collection has gained popularity because labor costs for collection can be minimized (see Fig. 11-4). In the future, it appears that the use of large containers which can be emptied mechanically with an articulated container pickup mechanism (see Fig. 11-5) will be the most common method used for the collection of municipal wastes.

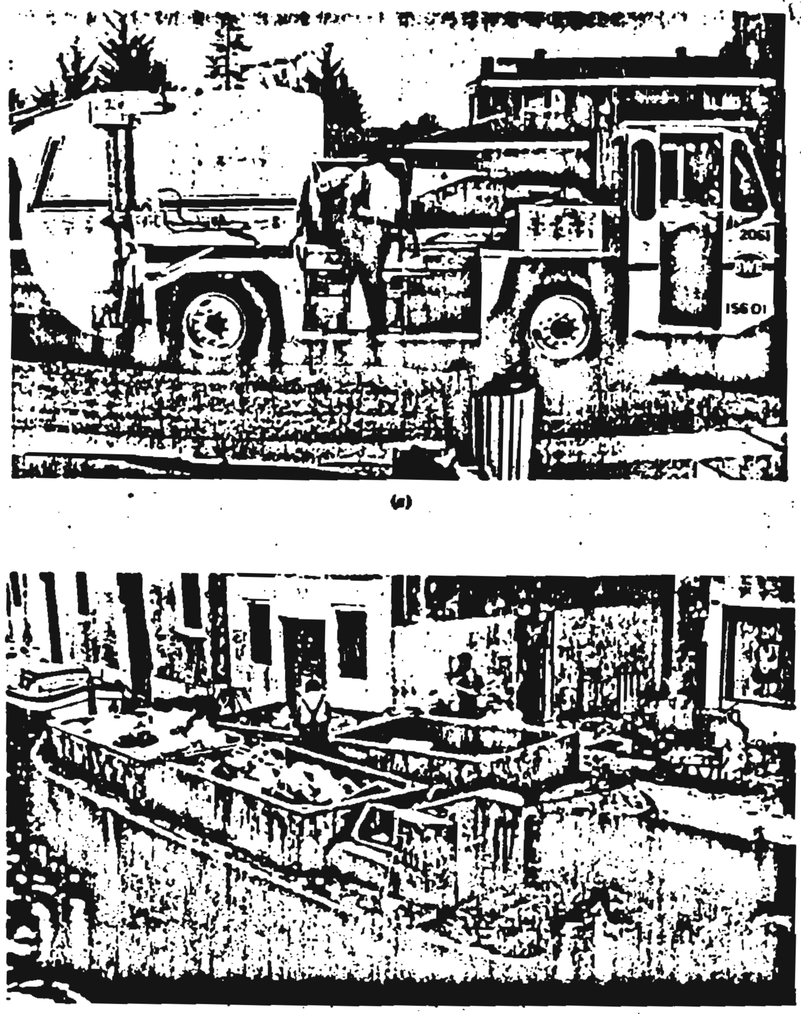


Figure 11-4 Collection of wastes placed at curb by homeowner. (*a*) Davis, California, (*b*) Venice, Italy.

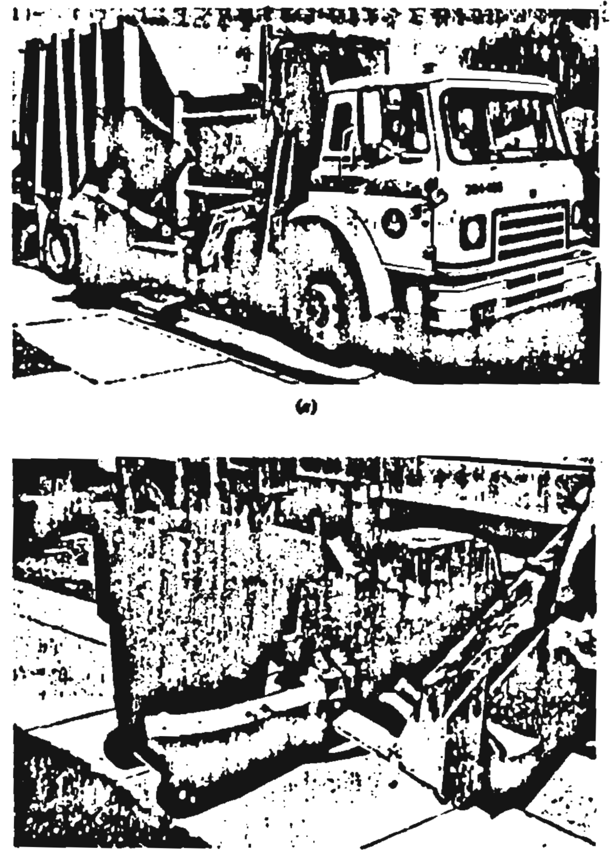


Figure 11-5 (*a*) Collection of domestic wastes placed in large containers (340 L) with mechanical articulated pickup mechanism. (*b*) Close up of pickup mechanism. Containers are brought to the curb by the homeowner.

Commercial-Industrial Collection Services

The collection service provided to large apartment buildings, residential complexes, and commercial and industrial activities typically is centered around the use of large movable and stationary containers (see Fig. 11-6) and large stationary compactors (see Fig. 11-7). Compactors are of the type that can be used to compress material directly into large containers or to form bales that are then placed in large containers.

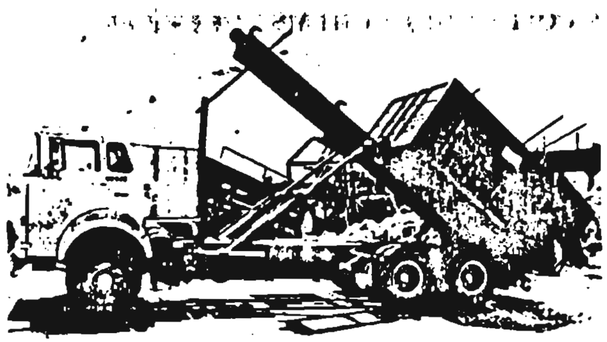


Figure 11-8 Typical tilt-frame collection vehicle loading large container.

are common at commercial and industrial services and at transfer stations. Because of the large volume that can be hauled, the use of tilt-frame hauled-container systems has become widespread, especially among private collectors servicing industrial accounts.

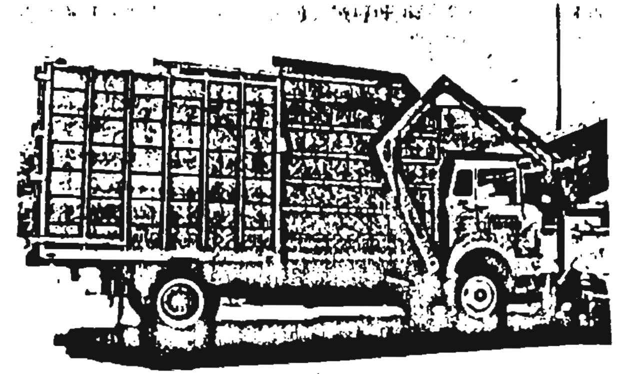
The application of trash-trailers is similar to that of tilt-frame container systems. Trash-trailers are better for the collection of especially heavy rubbish, such as sand, timber, and metal scrap, and often are used for the collection of demolition wastes at construction sites.

Stationary-Container Systems (SCS)

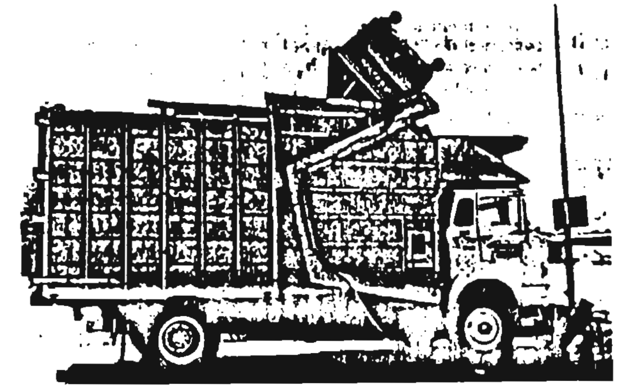
Collection systems in which the containers used for the storage of wastes remain at the point of waste generation, except when moved for collection are defined as *stationary-container systems.* Labor requirements for mechanically loaded stationary-container systems are essentially the same as for hauled-container systems. There are two main types of stationary-container systems: (1) those in which self-loading compactors are used and (2) those in which manually loaded vehicles are used.

Container size and utilization are not as critical in stationary-container systems using self-loading collection vehicles equipped with a compaction mechanism (see Fig. 11-9) as they are in the hauled-container system. Trips to the disposal site, transfer station, or processing station are made after the contents of a number of containers have been collected and compacted and the collection vehicle is full. Because a variety of container sizes and types are available, these systems may be used for the collection of all types of wastes.

The major application of manual transfer and loading methods is in the collection of residential wastes and litter. Manual methods are used for the collection of industrial wastes where pickup points are inaccessible to the collection vehicle.



(a)



(b)

Figure 11-9 Self-loading vehicle equipped with internal compactor.

11-10 DETERMINATION OF VEHICLE AND LABOR REQUIREMENTS

By separating the collection activities into unit operations, it is possible to develop design data and relationships that can be used to establish vehicle and labor requirements for the various collection systems.

Definition of Terms

The operational tasks for the hauled-container and stationary-container systems are shown schematically in Fig. 11-10. The activities involved in the collection of

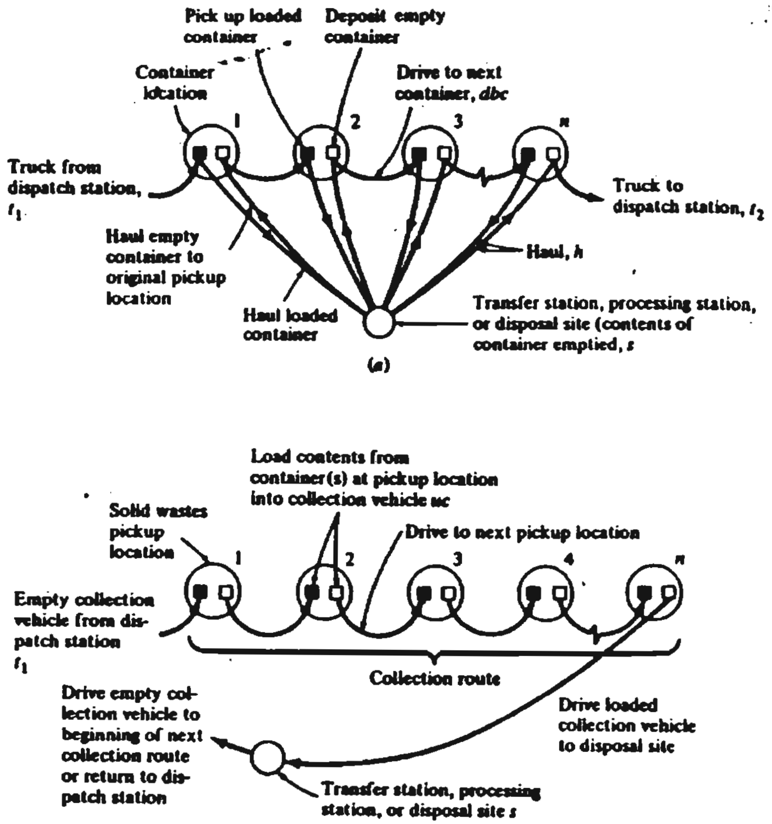


Figure 11-10 Definition sketch for waste collection systems: (*a*) hauled-container and (*b*) stationary-container.

solid wastes can be resolved into four unit operations: pickup, haul, at-site, and off-route. These unit operations are defined in Table 11-6.

Hauled-Container Systems

The time required per trip, which also corresponds to the time required per container, is equal to the sum of pick-up, at-site, and haul times and given by the following equation:

$$T_{hcs} = (P_{hcs} + s + a + bx) \qquad (11\text{-}1)$$

Table 11-6 Definition of terms for the activities involved in the collection of solid wastes

Term	Definition
Pickup (P)	
Hauled-container system, P_{hcs}	The time spent picking up the loaded container, the time required to redeposit the container after its contents have been emptied, and the time spent driving to the next container.
Stationary-container system, P_{scs}	The time spent loading the collection vehicle, beginning with the stopping of the vehicle prior to loading the contents of the first container and ending when the contents of the last container to be emptied have been loaded.
Haul (h)	
Hauled-container system, h_{hcs}	The time required to reach the disposal site, starting after a container whose contents are to be emptied has been loaded on the truck, plus the time after leaving the disposal site until the truck arrives at the location where the empty container is to be redeposited. Time spent at the disposal site is not included.
Stationary-container system, h_{scs}	The time required to reach the disposal site, starting after the last container on the route has been emptied or the collection vehicle is filled, plus the time after leaving the disposal site until the truck arrives at the location of the first container to be emptied on the next collection route. Time spent at the disposal site is not included.
At-site (s)	The time spent at the disposal site, including the time spent waiting to unload as well as the time spent unloading.
Off-route (W)	All time spent on activities that are nonproductive from the point of view of the overall collection operation. Necessary off-route time includes (1) time spent checking in and out in the morning and at the end of the day, (2) time lost due to unavoidable congestion, and (3) time spent on equipment repairs and maintenance. Unnecessary off-route time includes time spent for lunch in excess of the stated lunch period and time spent on taking unauthorized coffee breaks, talking to friends, etc.

where T_{hcs} = time per trip for hauled-container system, h/trip
P_{hcs} = pickup time per trip for hauled-container system, h/trip
s = at-site time per trip, h/trip
a = empirical haul constant, h/trip
b = empirical haul constant, h/km
x = round-trip haul distance, km/trip

The pickup time per trip P_{hcs} is equal to:

$$P_{hcs} = pc + uc + dbc \qquad (11\text{-}2)$$

where P_{hcs} = pickup time per trip, h/trip
pc = time required to pick up loaded container, h/trip
uc = time required to unload empty container, h/trip
dbc = average time spent driving between container locations, h/trip (determined locally)

Table 11-7 Typical values for haul constant coefficients *a* and *b* in Eqs. (11-1), (11-3), (11-4), and (11-8)

Speed limit, km/h	(mi/h)	*a*, h/trip	*b*, h/km	(h/mi)
88	(55)	0.016	0.011	(0.018)
72	(45)	0.022	0.014	(0.022)
56	(35)	0.034	0.018	(0.029)
40	(25)	0.050	0.025	(0.040)

The number of trips that can be made per vehicle per day with a hauled-container system, including a factor to account for off-route activities, is determined using Eq. (11-3):

$$N_d = [(1 - W)H - (t_1 + t_2)]/(P_{hcs} + s + a + bx) \tag{11-3}$$

where N_d = number of trips per day, trip/d
W = off-route factor, expressed as a fraction
H = length of workday, h/d
t_1 = time from garage to first container location, h
t_2 = time from last container location to garage, h

In deriving Eq. (11-3), it is assumed that off-route activities can occur at any time. Data that can be used in the solution of Eqs. (11-2) and (11-3) for various types of hauled-container systems are given in Tables 11-7 and 11-8. The off-route factor

Table 11-8 Typical data for computing equipment and labor requirements for hauled- and stationary-container collection systems

Collection: Vehicle	Loading method	Compaction ratio *r*	Pick up loaded container and deposit empty container, h/trip*	Empty contents of loaded container, h/container†	At-site time *s*, h/trip
Hauled-container systems					
Tilt-frame	Mechanical		0.40		0.127
Tilt-frame	Mechanical	2.0–4.0‡	0.40		0.133
Stationary-container systems					
Compactor	Mechanical	2.0-4.0		0.050	0.10
Compactor	Manual	2.0-4.0			0.10

* $pc + uc$ in Eq. (11-2).
† uc in Eq. (11-5).
‡ Containers used in conjunction with stationary compactor (see Fig. 11-7).

in Eq. 11-3 varies from 0.10 to 0.25; a factor of 0.15 is representative for most operations. Application of Eq. (11-3) is illustrated in Example 11-1.

Example 11-1: Analyzing a hauled-container collection system Solid waste from a new industrial park is to be collected in large containers (drop boxes), some of which will be used in conjunction with stationary compactors. Based on traffic studies at similar parks, it is estimated that the average time to drive from the garage to the first container (t_1) and from the last container (t_2) to the garage each day will be 15 and 20 min, respectively. If the average time required to drive between containers is 6 min and the one-way distance to the disposal site is 25 km (speed limit: 88 km/h), determine the number of containers that can be emptied per day, based on an 8-h workday.

SOLUTION

1. Determine the pickup time per trip using Eq. (11-2).

$$P_{hcs} = pc + uc + dbc$$

Use: $pc + uc = 0.4$ h/trip (see Table 11-8)
$dbc = 0.1$ h/trip (given)
$P_{hcs} = (0.4 + 0.1)$ h/trip
$= 0.5$ h/trip

2. Determine the time per trip using Eq. (11-1).

$$T_{hcs} = (P_{hcs} + s + a + bx)$$

Use: $P_{hcs} = 0.5$ h/trip (from step 1)
$s = 0.133$ (see Table 11-8)
$a = 0.016$ (see Table 11-7)
$b = 0.011$ (see Table 11-7)
$T_{hcs} = [0.5 + 0.133 + 0.016 + 0.011(50)]$ h/trip
$= 1.20$ h/trip

3. Determine the number of trips that can be made per day using Eq. (11-3).

$$N_d = [(1 - W)H - (t_1 + t_2)]/(P_{hcs} + s + a + bx)$$

Use: $W = 0.15$ (assumed)
$H = 8$ (given)
$t_1 = 0.25$ h (given)
$t_2 = 0.33$ h (given)
$N_d = [(1 - 0.15)8 - (0.25 + 0.33)]/1.20$ h/trip
$= (6.8 - 0.58)/1.20$
$= 5.18$ trips/d
N_d(actual) $= 5$ trips/d

4. Determine the actual length of the workday.

$$5 \text{ trips} = (1 - 0.15)H - 0.58/1.2$$
$$H = [(5 \times 1.2) + 0.58]/0.85$$
$$= 7.74 \text{ h (essentially 8 h)}$$

COMMENT If it is assumed that no off-route activities occur during times t_1 and t_2, then theoretically 5.26 trips/d could be made. Again, only 5 trips/d would be made in an actual operation. If, however, the number of trips per day that could be made were 5.8, for example, it may be cost-effective to pay the driver for the overtime and make 6 trips/d.

Stationary-Container Systems

For systems using mechanically self-loading compactors, the time per trip is:

$$T_{scs} = (P_{scs} + s + a + bx) \qquad (11\text{-}4)$$

where T_{scs} = time per trip for stationary-container systems, h/trip
P_{scs} = pickup time per trip for stationary-container systems, h/trip

The pickup time for the stationary-container system is given by:

$$P_{scs} = C_t uc + (n_p - 1)(dbc) \qquad (11\text{-}5)$$

where P_{scs} = pickup time per trip for stationary-container systems, h/trip
C_t = number of containers emptied per trip, container/trip
uc = average unloading time per container for stationary-container systems, h/container
n_p = number of container pickup locations per trip, locations/trip
dbc = average time spent driving between container locations, h/location (determined locally)

The term $n_p - 1$ accounts for the fact that the number of times the collection vehicle will have to be driven between container locations is equal to the number of containers less 1.

The number of containers that can be emptied per collection trip is related directly to the volume of the collection vehicle and the compaction ratio that can be achieved. This number is given by:

$$C_t = vr/cf \qquad (11\text{-}6)$$

where C_t = number of containers emptied per trip, container/trip
v = volume of collection vehicle, m^3/trip
r = compaction ratio
c = container volume, m^3/container
f = weighted container utilization factor

The number of trips required per day is given by:

$$N_d = V_d/vr \qquad (11\text{-}7)$$

where N_d = number of collection trips required per day, trips/d
V_d = daily waste generation rate, m^3/d

Where an integer number of trips are to be made each day, the proper combination of trips per day and the size of the vehicle can be determined by using Eq. (11-8) in conjunction with an economic analysis:

$$H = [(t_1 + t_2) + N_d(P_{scs} + s + a + bx)]/(1 - W) \qquad (11\text{-}8)$$

To determine the required truck volume, two or three different values for N_d are substituted in Eq. (11-8) and the available pickup times per trip are determined. Then, by trial and error, the truck volume required for each value of N_d is determined using Eqs. (11-5) and (11-6). From the available truck sizes, select the ones that most nearly correspond to the computed values. If the available truck sizes are smaller than the required values, compute the actual times per day that will be required using these sizes. The most cost-effective combination then can be selected. The application of the above equations is illustrated in Example 11-2.

Example 11-2: Analysing a stationary-container collection system Solid wastes from a commercial area are to be collected using a stationary-container collection system having 4-m^3 containers. Determine the appropriate truck capacity for the following conditions:

(a) Container size = 4 m^3
(b) Container utilization factor = 0.75
(c) Average number of containers at each location = 2
(d) Collection-vehicle compaction ratio = 2.5
(e) Container unloading time = 0.1 h/container
(f) Average drive time between container locations = 0.1 h
(g) One-way haul distance = 30 km
(h) Speed limit = 88 km/h (55 mi/h)
(i) Time from garage to first container location = 0.33 h
(j) Time from last container location to garage = 0.25 h
(k) Number of trips to disposal site per day = 2
(l) Length of workday = 8 h

SOLUTION

1. Using Eq. (11-8) determine the time available for each trip.

$$H = [(t_1 + t_2) + N_d(T_{scs})]/(1 - W)$$

where T_{scs} = time per trip
Use: H = 8 h
t_1 = 0.33 (given)
t_2 = 0.25 (given)
N_d = 2.0 (given)
W = 0.15 (assumed)
$T_{scs} = [(1 - 0.15)8 - (0.33 + 0.25)]/2$
$= 3.1$ h

2. Determine the pickup time per trip using Eq. (11-4).

$$T_{scs} = (P_{scs} + s + a + bx)$$

Use: $T_{scs} = 3.1$ hr
$s = 0.1$ h/trip (see Table 11-8)
$a = 0.016$ (see Table 11-7)
$b = 0.011$ (see Table 11-7)
$x = 60$ km (given)
$P_{scs} = T_{scs} - (s + a + bx)$
$= 3.1 - [0.1 + 0.016 + 0.011(60)]$
$= 2.32$ h/trip

3. Using Eq. (11-5), determine the number of containers that can be emptied per trip.

$$P_{scs} = C_t uc + (n_p - 1)dbc$$

Use: $P_{scs} = 2.32$ h/trip
$uc = 0.1$ h/container (given)
$n_p = C_t/2$ (2 containers/location)
$dbc = 0.1$ h

$$C_t 0.1 + (0.5C_t - 1)0.1 = 2.32$$

$$0.15C_t = 2.42$$

$$C_t = 16.13, \text{ use } 16$$

4. Using Eq. (11-6), determine the required capacity of the collection truck.

$$C_t = vr/cf$$

Use: $C_t = 16$
$r = 2.5$ (given)
$c = 4\ m^3$ (given)
$f = 0.75$ (given)

$$v = \frac{16(4\ m^3)0.74}{2.5} = 19.2\ m^3$$

Use 20.0 m^3 or nearest larger standard size.

COMMENT The above analysis is exactly the same as would be used for the collection of domestic wastes using the collection system shown in Fig. 11-5.

Stationary-Container Systems (Manually Loaded)

The analysis and design of residential collection systems using manually loaded vehicles may be outlined as follows. If H hours are worked per day and the number of trips to be made per day is known or fixed, the time available for the pickup operation can be computed by using Eq. (11-8) because either all the factors are known or they can be assumed. Once the pickup time per trip is known, the number of pickup locations from which wastes can be collected per trip can be estimated as follows:

$$N_p = 60\ P_{scs} n/t_p \qquad (11\text{-}9)$$

where N_p = number of pickup locations per trip, locations/trip
60 = conversion factor from hours to minutes, 60 min/h
P_{scs} = pickup time per trip, h/trip
n = number of collectors
t_p = pick up time per pickup location, collection · min/location

The pickup time for a two-person collection crew can be estimated using Eq. (11-10).

$$t_p = 0.72 + 0.18C_n + 0.014PRH \qquad (11\text{-}10)$$

where t_p = average pickup time per pickup location, collection · min/location
C_n = average number of containers at each pickup location
PRH = rear-of-house pickup locations, percent

Equation (11-10) is typical of the types of equations derived from field observations for the pickup time per location. Usually, the first term in such equations represents the time spent driving between pickup locations. This value will, of course, depend on the characteristics of the residential area. Values for a one-person crew should be obtained from the field observations. Typically, the time per service is about 0.9 min/service where unlimited service is provided.

Once the number of pickup locations per trip is known, the proper size of collection vehicle can then be estimated as follows:

$$v = \frac{V_p N_p}{r} \qquad (11\text{-}11)$$

where v = volume of collection vehicle, m^3/trip
V_p = volume of solid wastes collected per pickup location, m^3/location
N_p = number of pickup locations per trip, locations/trip
r = compaction ratio

In many housing areas, the collection frequency is twice per week. In terms of labor requirements, it has been found that the requirements for the second weekly collection are about 0.9 to 0.95 times those for the first weekly collection. In general, the labor requirements are not significantly different because container handling time is about the same for both full and partially full containers. Often this difference is neglected in computing the labor requirements.

11-11 COLLECTION ROUTES

Once the equipment and labor requirements have been determined, collection routes must be laid out so both the work force and equipment are used effectively. In general, the layout of collection routes is a trial-and-error process. There are no fixed rules that can be applied to all situations.

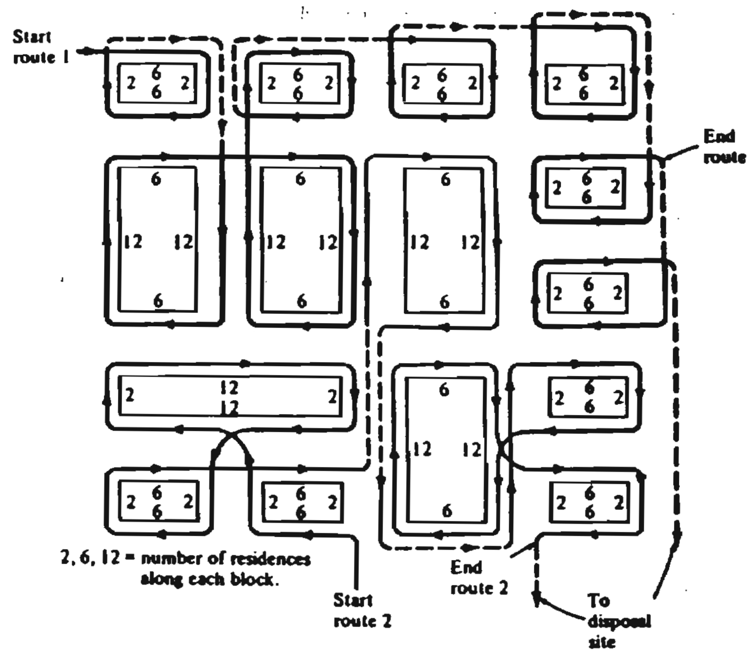
Some of the factors that should be taken into consideration when laying out routes are as follows: (1) existing company policies and regulations related to such items as the point of collection and frequency of collection must be identified, (2) existing system conditions such as crew size and vehicle types must be coordinated, (3) wastes generated at traffic-congested locations should be collected as early in the day as possible, (4) sources at which extremely large quantities of wastes are generated should be serviced during the first part of the day, and (5) scattered pickup points where small quantities of solid wastes are generated should, if possible, be serviced during one trip or on the same day, if they receive the same collection frequency.

Layout of Routes

The layout of collection routes is a four-step process. First, prepare location maps. On a relatively large-scale map of the area to be serviced, the following data should be plotted for each solid-waste pickup point: location, number of containers, collection frequency, and, if a stationary-container system with self-loading compactors is used, the estimated quantity of wastes to be collected at each pickup location. Second, prepare data summaries. Estimate the quantity of wastes to be collected from pickup locations serviced each day that the collection operation is to be conducted. Where a stationary-container system is used, the number of locations that will be serviced during each pickup cycle must also be determined. Third, lay out preliminary collection routes starting from the dispatch station or where the collection vehicles are parked. A route should be laid out that connects all the pickup locations to be serviced during each collection day. The route should be laid out so that the last location is nearest the disposal site. Fourth, develop balanced routes. After the preliminary collection routes have been laid out, the haul distance for each route should be determined. Next, determine the labor requirements per day and check against the available work times per day. In some cases it may be necessary to readjust the collection routes to balance the work load and the distance traveled. After the balanced routes have been established, they should be drawn on the master map. The layout of collection routes is illustrated in Example 11-3.

Example 11-3: Laying collection routes Lay out collection routes for the residential area shown in the accompanying figure. Assume the following data are applicable.

1. General
   - *a*. Occupants per resident = 3.5
   - *b*. Solid-waste generation rate = 1.6 kg/person · d
   - *c*. Collection frequency
   - *d*. Type of collection service = curb
   - *e*. Collection crew size = one person
   - *f*. Collection vehicle capacity = 20 m^3
   - *g*. Compacted density of solid wastes in collection vehicle = 325 kg/m^3
2. Route constraints
   - *a*. No U-turns in streets
   - *b*. Collection from each side of street with stand-up right-hand-drive collection vehicle



SOLUTION

1. Determine total number of residences from which wastes are to be collected.

$$\text{Residences} = 10(16) + 4(36) + 1(28) = 332$$

2. Determine the compacted volume of solid waste to be collected per week.

$$\text{Vol/wk} = (332 \text{ residences} \times 3.5 \text{ persons/residence} \times 1.6 \text{ kg/person} \cdot \text{d} \times 7 \text{ d} \cdot \text{wk})/325 \text{ kg/m}^3 = 40.0 \text{ m}^3\text{/wk}$$

3. Determine the number of trips/wk.

$$\text{Trip/wk} = \frac{40.0 \text{ m}^3\text{/wk}}{20 \text{ m}^3\text{/trip}} = 2$$

4. Determine the average number of residences from which wastes are to be collected each day.

$$\text{Residences/trip} = \frac{332}{2} = 166$$

5. Lay out collection routes by trial and error using the route constraints cited above as a guide. The two routes are shown in the figure.

COMMENT It should be noted that there is no single correct solution to this problem. It just works out that some solutions are better than others when they are implemented. It is only with experience that an intuitive sense can be developed about the layout of collection routes.

Schedules

A master schedule for each collection route should be prepared for use by the engineering department and the transportation dispatcher. A schedule for each route, on which can be found the location and order of each pickup point to be serviced, should be prepared for the driver. In addition, a route book should be maintained by each truck driver.

Transfer and Transport

The functional element of transfer and transport refers to the means, facilities, and appurtenances used to effect the transfer of wastes from relatively small collection vehicles to larger vehicles and to transport them over extended distances to either processing centers or disposal sites. Transfer and transport operations become a necessity when haul distances to available disposal sites or processing centers increase to the point that direct hauling is no longer economically feasible. See Example 11-4.

Example 11-4: Economic comparison of transport alternatives Determine the break-even time for a stationary-container system and a separate transfer and transport system for transporting wastes collected from a metropolitan area to a landfill disposal site. Assume the following cost and system data are applicable.

1. Transportation costs:
   a. Stationary-container system using an 18-m^3 compactor = \$20/h
   b. Tractor-trailer transport unit with a capacity of 120 m^3 = \$25/h
2. Other costs:
   a. Transfer station operating cost, including amortization = \$0.40/m^3
   b. Extra cost for unloading facilities for tractor-trailer transport unit = \$0.05/m^3
3. Other data:
   a. Density of wastes in compactor = 325 kg/m^3
   b. Density of wastes in transport units = 150 kg/m^3

SOLUTION

1. Convert cost data to units of dollars/tonne · min.
   a. Stationary-container system:

$$\text{Operating cost} = (\$20.00/\text{h})/(60\ \text{min/h}) = \$0.33/\text{min}$$

$$\text{Tonnes/load} = \frac{18\ \text{m}^3 \times 325\ \text{kg/m}^3}{1000\ \text{kg/tonne}} = 5.85$$

$$\text{Operating cost} = (\$0.33/\text{min})/5.85\ \text{tonne} = \$0.0564/\text{tonne}\cdot\text{min}$$

   b. Transfer-transport system:

$$\text{Operating cost} = (\$25.00/\text{h})/(60\ \text{min/h}) = \$0.42/\text{min}$$

$$\text{Tonnes/load} = \frac{120 \times 150}{1000} = 18$$

$$\text{Operating cost} = (\$0.42/\text{min})/18\ \text{tonnes} = \$0.0233/\text{tonne}\cdot\text{min}$$

   c. Transfer station cost:

$$\text{Operating cost} = (\$0.40/\text{m}^3)/(0.150/\text{tonne}) = \$2.47/\text{tonne}$$

   d. Unloading cost:

$$\text{Operating cost} = (\$0.05/\text{m}^3)/(0.150/\text{tonne}) = \$0.33/\text{tonne}$$

2. Prepare a plot of cost versus haul time in minutes and determine break-even time.
   a. Fixed cost for transfer and transport system:

$$\text{Cost/tonne} = \$2.67 + \$0.33 = \$3.00$$

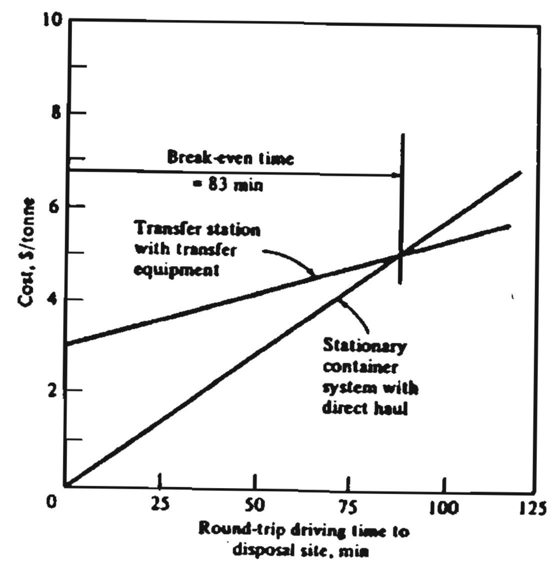
   b. Variable costs at 100 min:
   (1) Stationary-container system

$$\text{Cost/ton} = (\$0.0564/\text{tonne}\cdot\text{min})100\ \text{min} = \$5.64$$

   (2) Transport system

$$\text{Cost/ton} = (\$0.0233/\text{tonne}\cdot\text{min})\ 100\ \text{min} = \$2.33$$

   c. The above data are plotted in the accompanying figure. As shown, the break-even time is equal to 83 min.



11-12 TRANSFER STATIONS

Important factors that must be considered in the design of transfer stations include: (1) type of transfer operation to be used, (2) capacity requirements, (3) equipment and accessory requirements, and (4) environmental requirements. Depending on the method used to load the transport vehicles, transfer stations may be classified into three types: (1) direct discharge, (2) storage discharge, and (3) combined direct and storage discharge.

Direct Discharge

In a direct-discharge transfer station, wastes from the collection vehicles usually are emptied directly into the vehicle to be used to transport them to a place of final disposition. To accomplish this, these transfer stations usually are constructed in a two-level arrangement. The unloading dock or platform from which wastes from collection vehicles are discharged into the transport trailers is elevated, or the transport trailers are located in a depressed ramp. Direct-discharge transfer stations employing stationary compactors are also popular (see Fig. 11-11).

Storage Discharge

In the storage-discharge transfer station, wastes are emptied either into a storage pit or onto a platform from which they are loaded into transport vehicles by various types of auxiliary equipment. In a storage-discharge transfer station, the storage volume varies from about one-half to two days' volume of wastes (see Fig. 11-12).

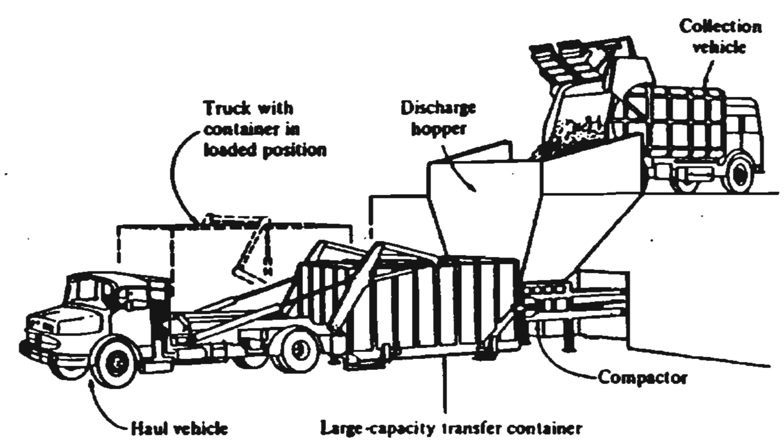


Figure 11-11 Typical direct-discharge transfer station. (*Courtesy Schindler Waggon AG, Pratteln.*)

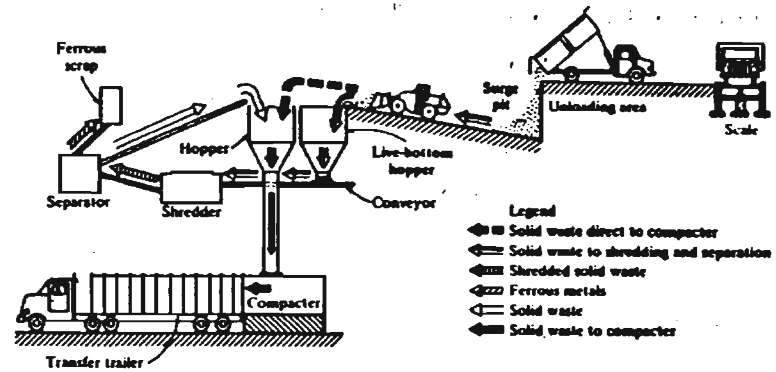


Figure 11-12 Typical storage-discharge transfer station. (*Courtesy of Municipality of Metropolitan Toronto, Department of Public Works.*)

Combined Direct and Storage Discharge

In some transfer stations, both direct-discharge and storage-discharge methods are used. Usually, these are multipurpose facilities designed to service a broader range of users than a single-purpose facility. In addition to serving a broader range of users, a multipurpose transfer station can also house a materials-salvage operation.

Capacity Requirements

The operational capacity of a transfer station must be such that the collection vehicles do not have to wait too long to unload. In most cases, it will not be cost-effective to design the station to handle the ultimate peak number of hourly loads. An economic trade-off analysis should be made between the annual cost for the time spent by the collection vehicles waiting to unload against the incremental annual cost of a larger transfer station and/or the use of more transport equipment. Because of the increased cost of transport equipment, a trade-off analysis must also be made between the capacity of the transfer station and the cost of the transport operation, including both equipment and labor components.

Equipment and Accessory Requirements

The types and amounts of equipment required vary with the capacity of the station and its function in the waste-management system. Specifically, scales should be provided at all medium and large transfer stations both to monitor the operation and to develop meaningful management and engineering data.

Environmental Requirements

Most of the large, modern transfer stations are enclosed and are constructed of materials that can be maintained and cleaned easily. For direct-discharge transfer stations with open loading areas, special attention must be given to the problem of blowing papers. Wind screens or other barriers are commonly used. Regardless of the type of station, the design and construction should be such that all accessible areas where rubbish or paper can accumulate are eliminated.

11-13 LOCATION OF TRANSFER STATIONS

Whenever possible, transfer stations should be located (1) as near as possible to the weighted center of the individual solid-waste production areas to be served, (2) within easy access of major arterial highway routes as well as near secondary or supplemental means of transportation, (3) where there will be a minimum of public and environmental objection to the transfer operations, and (4) where construction and operation will be most economical. Additionally, if the transfer-station site is to be used for processing operations involving materials recovery and/or energy production, the requirements for those operations must be considered.

11-14 TRANSFER MEANS AND METHODS

Motor vehicles, railroads, and ocean-going vessels are the principal means now used to transport solid wastes. Pneumatic and hydraulic systems have also been used. Still other systems have been suggested, but most have not been tested.

Motor Vehicle Transport

Motor vehicles used to transport solid wastes on highways should satisfy the following requirements: (1) the vehicles must transport wastes at minimum cost, (2) wastes must be covered during the haul operation, (3) vehicles must be designed for highway traffic, (4) vehicle capacity must be such that allowable weight limits are not exceeded, and (5) methods used for unloading must be simple and dependable. The maximum volume that can be hauled in highway transport vehicles depends on the regulations in force in the state in which they are operated.

In recent years, because of their simplicity and dependability, open-top trailers and semitrailers have found wide acceptance (see Table 11-9 and Fig. 11-13) for the transport of wastes. Some trailers are equipped with sumps to collect any liquids that accumulate from the solid wastes. The sumps are equipped with drains so that they can be emptied at the disposal site.

Methods used to unload the transport trailers may be classified according to whether they are self-emptying or require the aid of auxiliary equipment. Self-emptying transport trailers are equipped with mechanisms such as hydraulic

Table 11-9 Typical data on haul vehicles used at transfer stations

Type	Capacity per trailer, m^3	Capacity per trailer, Tonnes	Length of tractor and trailer units, m*
Tractor-trailer-trailer	54	11.4	19.8
	54	10.0	
Tractor-trailer	74	17.3	18.3
Tractor-compactor trailer	58	18	14.0

* Overall length will vary with the type of tractor (e.g., conventional or cab-over) and the turning radius of the trailers.

dump beds, powered diaphragms or moving floors that are part of the vehicle (see Fig. 11-14). Moving-floor trailers are an adaptation of equipment used in the construction industry. An advantage of the moving-floor trailer is the rapid turnaround time (typically 6 to 10 min) achieved at the disposal site without the need for auxiliary equipment. Unloading systems that require auxiliary equipment are usually of the "pull-off" type, in which the wastes are pulled out of the truck by either a movable bulkhead or wire-cable slings placed forward of the load. The disadvantage of requiring auxiliary equipment and work force to unload at the disposal site is relatively minor in view of the simplicity and reliability of these methods.

Another auxiliary unloading system that has proved very effective and efficient involves the use of movable, hydraulically operated tipping ramps located at the

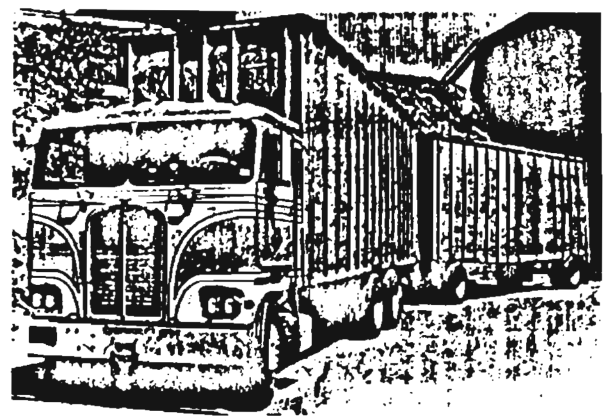


Figure 11-13 Typical large vehicles used for the transport of solid wastes for disposal.

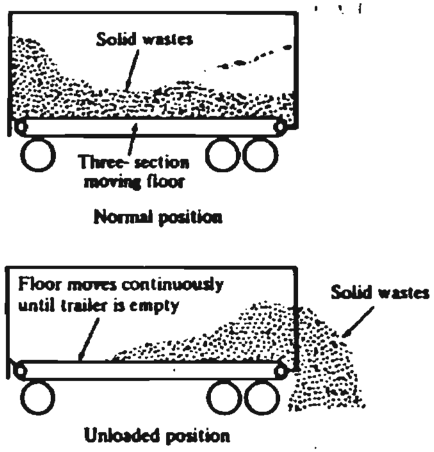


Figure 11-14 Typical self-emptying transport trailer.

disposal site (see Fig. 11-15). Operationally, the semitrailer of a tractor-trailer-trailer combination is backed up onto one of the tipping ramps; the tractor-trailer combination is backed up onto a second tipping ramp. The backs of the trailers are opened, and the units are then tilted upward until the wastes fall out by gravity. The time required for the entire unloading operation typically is about 5 min/trip.

Large-capacity containers and container trailers are used in conjunction with stationary compactors at transfer stations. In some cases, the compaction mechanism is an integral part of the container. When containers are equipped with a self-contained compaction mechanism, the movable bulkhead used to compress the wastes is also used to discharge the compacted wastes.

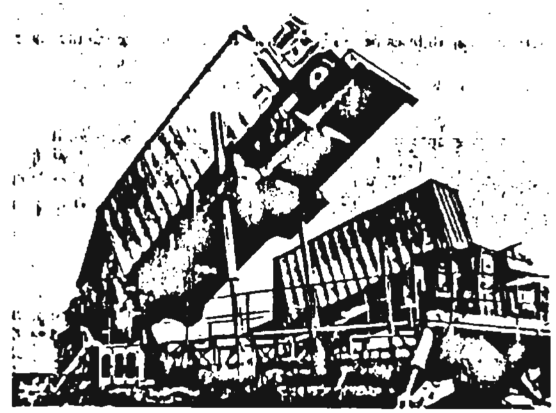
Railroad Transport

Although railroads were commonly used for the transport of solid wastes in the past, they are now used by only a few communities. However, renewed interest is again developing in the use of railroads for hauling solid wastes, especially to remote areas where highway travel is difficult and railroad lines now exist.

Water Transport

Barges, scows, and special boats have been used in the past to transport solid wastes to processing locations and to seaside and ocean disposal sites, but ocean disposal is no longer practiced by the United States. Although some self-propelled vessels (such as United States Navy garbage scows and other special boats) were once used, the most common practice was to use vessels towed by tugs or other special boats.

(a)



(b)

Figure 11-15 Hydraulically operated tipping platforms for unloading transport vehicles.

Pneumatic Transport

Both low-pressure air and vacuum conduit transport systems have been used to transport solid wastes. The most common application is the transport of wastes from high-density apartments or commercial activities to a central location for processing or for loading into transport vehicles. The largest pneumatic system now in use in the United States is at the Walt Disney World amusement park in Orlando, Florida.

Processing Techniques

Processing techniques are used in solid waste management systems to (1) improve the efficiency of solid-waste disposal systems, (2) to recover resources (usable materials), and (3) to prepare materials for the recovery of conversion products and energy. Processes used routinely to improve the efficiency of solid-waste systems and to recover materials manually are considered in this section. Mechanical systems used for the recovery of materials are considered in Chap. 12. Important processing techniques used routinely in municipal solid-waste systems include: compaction, thermal volume reduction (incineration), and manual separation of waste components. Factors that should be considered in evaluating on-site processing equipment are summarized in Table 11-10.

Table 11-10 Factors that should be considered in evaluating on-site processing equipment

Factor	Evaluation
Capabilities	What will the device or mechanism do? Will its use be an improvement over conventional practices?
Reliability	Will the equipment perform its designated functions with little attention beyond preventive maintenance? Has the effectiveness of the equipment been demonstrated in use over a reasonable period of time or merely predicted?
Service	Will servicing capabilities beyond those of the local building maintenance staff be required occasionally? Are properly trained service personnel available through the equipment manufacturer or the local distributor?
Safety of operation	Is the proposed equipment reasonably foolproof so that it may be operated by tenants or building personnel with limited mechanical knowledge or abilities? Does it have adequate safeguards to discourage careless use?
Ease of operation	Is the equipment easy to operate by a tenant or by building personnel? Unless functions and actual operations of equipment can be carried out easily, they may be ignored or "short-circuited" by paid personnel or by tenants.
Efficiency	Does the equipment perform efficiently and with a minimum of attention? Under most conditions, equipment that completes an operational cycle each time it is used should be selected.
Environmental effects	Does the equipment pollute or contaminate the environment? Where possible, equipment should reduce environmental pollution presently associated with conventional functions.
Health hazards	Does the device, mechanism, or equipment create or amplify health hazards?
Aesthetics	Does the equipment and its arrangement offend the senses? Every effort should be made to reduce or eliminate offending sights, odors, and noises.
Economics	What are the economics involved? Both first and annual costs must be considered. Future operation and maintenance costs must be assessed carefully. All factors being equal, equipment produced by well-established companies, having a proven history of satisfactory operation, should be given appropriate consideration.

Source: From Tchobanoglous et al. [11-8]

11-15 MECHANICAL VOLUME REDUCTION

Mechanical volume reduction is perhaps the most important factor in the development and operation of solid-waste management systems. Vehicles equipped with compaction mechanisms are used for the collection of most municipal solid wastes. To increase the useful life of landfills, wastes are compacted. Paper for recycling is baled for shipping to processing centers. When compacting a broad range of municipal solid wastes, it has been found that the final density (typically about 1100 kg/m^3) is essentially the same regardless of the starting density and applied pressure. This fact is important in evaluating the claims made by manufacturers of compacting equipment.

11-16 THERMAL VOLUME REDUCTION

The volume of municipal wastes can be reduced by more than 90 percent by incineration. In the past, incineration was quite common. However, with more restrictive air-pollution control requirements necessitating the use of expensive cleanup equipment only a limited number of municipal incinerators are currently in operation. More recently, increased haul distances to available landfill sites and increased fuel costs have brought about a renewed interest in incineration, and a number of new incinerator projects are now on the drawing boards. Incineration is considered further in Chap. 12.

11-17 MANUAL COMPONENT SEPARATION

The manual separation of solid waste components can be accomplished at the source where solid wastes are generated, at a transfer station, at a centralized processing station, or at the disposal site. Manual sorting at the source of generation is the most positive way to achieve the recovery and reuse of materials. The number and types of components salvaged or sorted (e.g., cardboard and high-quality paper, metals, and wood) depend on the location, the opportunities for recycling, and the resale market.

In Davis, California, residents, on a voluntary basis, manually separate newsprint, aluminum cans, and glass. The separated components are placed at the curb for collection with a special vehicle. The vehicle used for the collection of source-separated waste components is shown in Fig. 11-16. Waste paper is sold to an insulation manufacturer.

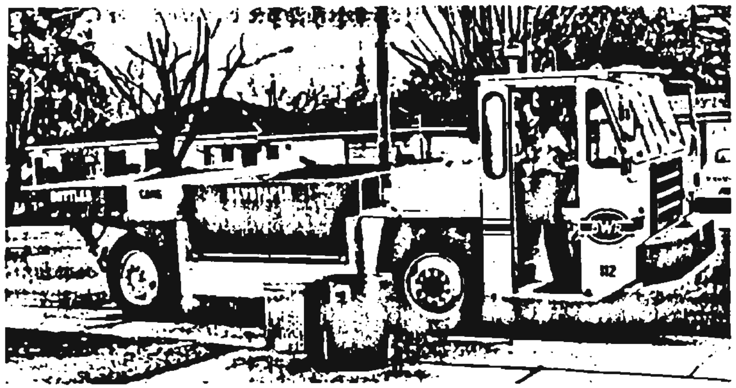


Figure 11-16 Collection of source-separated wastes with a special collection vehicle.

Ultimate Disposal

Disposal on or in the earth's mantle is, at present, the only viable method for the long-term handling of: (1) solid wastes that are collected and are of no further use, (2) the residual matter remaining after solid wastes have been processed, and (3) the residual matter remaining after the recovery of conversion products and/or energy has been accomplished. Landfilling is the method of disposal used most commonly for municipal wastes; landfarming and deep-well injection have been used for industrial wastes. Although incineration is often considered a disposal method, it is, in reality, a processing method (see Chap. 12).

11-18 LANDFILLING WITH SOLID WASTES

Landfilling involves the controlled disposal of solid wastes on or in the upper layer of the earth's mantle. Important aspects in the implementation of sanitary landfills include: (1) site selection, (2) landfilling methods and operations, (3) occurrence of gases and leachate in landfills, and (4) movement and control of landfill gases and leachate.

Site Selection

Factors that must be considered in evaluating potential solid-waste disposal sites are summarized in Table 11-11. Final selection of a disposal site usually is based on the results of a preliminary site survey, results of engineering design and cost studies, and an environmental impact assessment.

Table 11-11 Factors that must be considered in evaluating potential landfill sites

Factor	Remarks
Available land area	Site should have a useful life greater than 1 yr (minimum value).
Haul distance	Will have significant impact on operating costs.
Soil conditions and topography	Cover material must be available at or near the site.
Surface water hydrology	Impacts drainage requirements.
Geologic and hydrogeologic conditions	Probably most important factors in establishment of landfill site, especially with respect to site preparation.
Climatologic conditions	Provisions must be made for wet-weather operation.
Local environmental conditions	Noise, odor, dust, vector, and aesthetic factors control requirements.
Ultimate use of site	Affects long-term management for site.

Landfilling Methods and Operations

To use the available area at a landfill site effectively, a plan of operation for the placement of solid wastes must be prepared. Various operational methods have been developed, primarily on the basis of field experience. The principal methods used for landfilling dry areas may be classified as (1) area, (2) trench, and (3) depression.

The *area method* is used when the terrain is unsuitable for the excavation of trenches in which to place the solid wastes. The filling operation usually is started by building an earthen levee against which wastes are placed in thin layers and compacted (see Fig. 11-17). Each layer is compacted as the filling progresses until the thickness of the compacted wastes reaches a height varying from 2 to 3 m (6 to 10 ft). At that time, and at the end of each day's operation, a 150- to 300-mm (6- to 12-in) layer of cover material is placed over the completed fill. The cover material must be hauled in by truck or earth-moving equipment from adjacent land or from borrow-pit areas. In some newer landfill operations, the daily cover material is omitted. A completed lift, including the cover material, is called a *cell*. Successive lifts are placed on top of one another until the final grade called for in the ultimate development plan is reached. A final layer of cover material is used when the fill reaches the final design height.

The *trench method* of landfilling is ideally suited to areas where an adequate depth of cover material is available at the site and where the water table is well below the surface. To start the process (for a small landfill), a portion of the trench is dug with a bulldozer and the dirt is stockpiled to form an embankment behind the first trench. Wastes are then placed in the trench, spread into thin layers and compacted. The operation (depicted in Fig. 11-18) continues until the desired height is reached. Cover material is obtained by excavating an adjacent trench

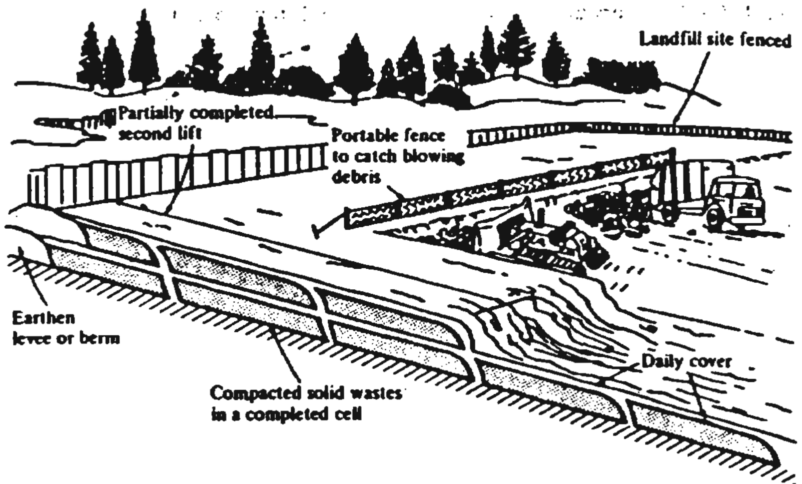


Figure 11-17 Area method of landfilling solid wastes.

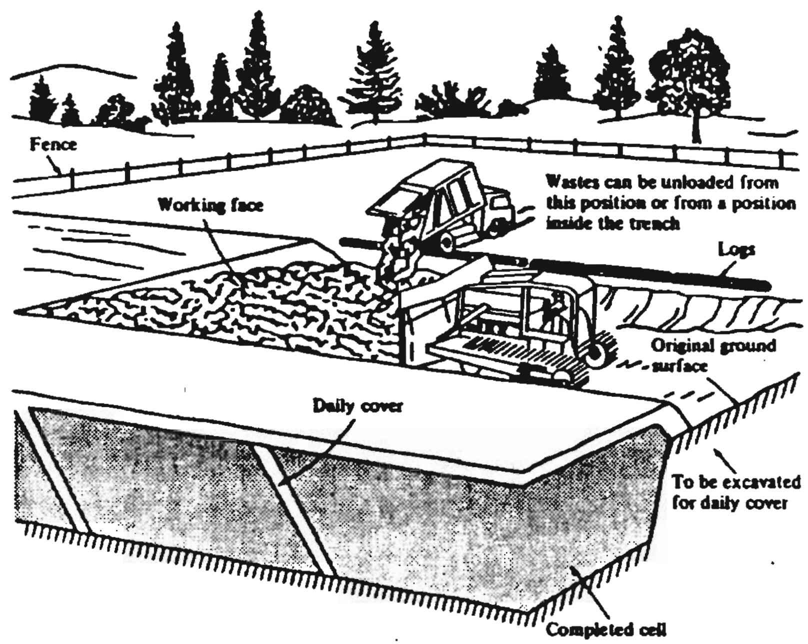


Figure 11-18 Trench method of landfilling solid wastes for small landfills.

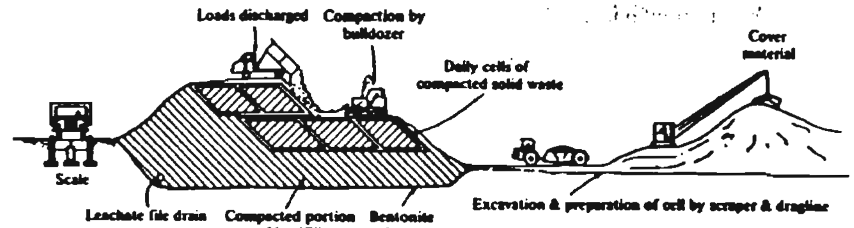


Figure 11-19 Pit method of landfilling solid wastes for large landfills. (*Courtesy of Municipality of Metropolitan Toronto, Department of Public Works.*)

or continuing the trench that is being filled. In large landfills, a dragline and one or more scrapers are used to excavate a deep rectangular pit (see Fig. 11-19).

At locations where natural or artificial depressions exist, it is often possible to use them effectively for landfilling operations. Canyons, ravines, dry borrow pits, and quarries have all been used for this purpose. The techniques to place and compact solid wastes in *depression landfills* vary with the geometry of the site, the characteristics of the cover material, the hydrology and geology of the site, and the access to the site. In a canyon site, filling starts at the head end of the canyon and ends at the mouth. This practice prevents the accumulation of water behind the landfill. Wastes usually are deposited on the canyon floor and from there are pushed up against the canyon face at a slope of about 2 to 1. In this way, a high degree of compaction can be achieved.

Because of the problems associated with contamination of local groundwaters, the development of odors, and structural stability, landfills in wet areas are seldom used. If wet areas such as swamps and marshes, tidal areas, and ponds, pits, or quarries must be used as landfill sites, special provisions must be made to contain or to eliminate the movement of leachate and gases from completed cells. Usually this is accomplished by first draining the site and then lining the bottom with a clay liner or other appropriate sealants. If a clay liner is used, it is important to continue operation of the drainage facility until the site is filled to avoid the creation of uplift pressures that could cause the liner to rupture from heaving.

Occurrence of Gases and Leachate in Landfills

The following biological, physical, and chemical events occur when solid wastes are placed in a sanitary landfill: (1) biological decay of organic materials, either aerobically of anaerobically, with the evolution of gases and liquids; (2) chemical oxidation of waste materials; (3) escape of gases from the fill; (4) movement of liquids caused by differential heads; (5) dissolving and leaching of organic and inorganic materials by water and leachate moving through the fill; (6) movement of dissolved material by concentration gradients and osmosis; and (7) uneven settlement caused by consolidation of material into voids.

With respect to item 1, bacterial decomposition initially occurs under aerobic conditions because a certain amount of air is trapped within the landfill. However, the oxygen in the trapped air is soon exhausted (within days), and the long-term decomposition occurs under anaerobic conditions.

Gases in landfills Gases found in landfills include air, ammonia, carbon dioxide, carbon monoxide, hydrogen, hydrogen sulfide, methane, nitrogen, and oxygen. Carbon dioxide and methane are the principal gases produced from the anaerobic decomposition of the organic solid-waste components.

The anaerobic conversion of organic compounds is thought to occur in three steps: the first involves the enzyme-mediated transformation (*liquefaction*) of higher-weight molecular compounds into compounds suitable for use as a source of energy and cell carbon; the second is associated with the bacterial conversion of the compounds resulting from the first step into identifiable lower-molecular-weight intermediate compounds; and the third step involves the bacterial conversion of the intermediate compounds into simpler end products, such as carbon dioxide (CO_2) and methane (CH_4). The overall anaerobic conversion of organic industrial wastes can be presented with the following equation:

$$C_aH_bO_cN_d \longrightarrow nC_wH_xO_yN_z + mCH_4 + sCO_2 + rH_2O + (d - nz)NH_3 \qquad (11\text{-}12)$$

where $s = a - nw - m$

$r = c - ny - 2s$

The terms $C_aH_bO_cN_d$ and $C_wH_xO_yN_z$ are used to represent on a molar basis the composition of the material present at the start and the end of the process. If it is assumed that the organic wastes are stabilized completely, the corresponding expression is

$$C_aH_bO_cN_d + \left(\frac{4a - b - 2c + 3d}{4}\right)H_2O \longrightarrow \left(\frac{4a + b - 2c - 3d}{8}\right)CH_4 + \left(\frac{4a - b + 2c + 3d}{8}\right)CO_2 + dNH_3 \qquad (11\text{-}13)$$

The rate of decomposition in unmanaged landfills, as measured by gas production, reaches a peak within the first 2 years and then slowly tapers off, continuing, in many cases, for periods up to 25 years or more. The total volume of the gases released during anaerobic decomposition can be estimated in a number of ways. If all the organic constituents in the wastes (with the exception of plastics, rubber, and leather) are represented with a generalized formula of the form $C_aH_bO_cN_d$, the total volume of gas can be estimated by using Eq. (11-13), with the assumption of complete conversion to carbon dioxide and methane.

Leachate in landfills Leachate may be defined as liquid that has percolated through solid waste and has extracted dissolved or suspended materials from it. In most landfills, the liquid portion of the leachate is composed of the liquid produced from the decomposition of the wastes and liquid that has entered the landfill from external sources, such as surface drainage, rainfall, groundwater, and water from underground springs. Representative data on the chemical characteristics of leachate are reported in Table 11-12. The leachate should be either contained within the landfill or removed for treatment.

Gas Movement

Under ideal conditions, the gases generated from a landfill should be either vented to the atmosphere or, in larger landfills, collected for the production of energy. In most cases, over 90 percent of the gas volume produced from the decomposition of solid wastes consists of methane and carbon dioxide. Although most of the methane escapes to the atmosphere, both methane and carbon dioxide have been found in concentrations of up to 40 percent at lateral distances of up to 120 m (400 ft) from the edges of landfills. If vented into the atmosphere in an uncontrolled

Table 11-12 Data on the composition of leachate from landfills

	Value, mg/L*	
Constituent	Range†	Typical
BOD_5 (5-day biochemical oxygen demand)	2000–30,000	10,000
TOC (total organic carbon)	1500–20,000	6,000
COD (chemical oxygen demand)	3000–45,000	18,000
Total suspended solids	200–1000	500
Organic nitrogen	10–600	200
Ammonia nitrogen	10–800	200
Nitrate	5–40	25
Total phosphorus	1–70	30
Orthophosphorus	1–50	20
Alkalinity as $CaCO_3$	1000–10,000	3,000
pH	5.3–8.5	6
Total hardness as $CaCO_3$	300–10,000	3,500
Calcium	200–3000	1,000
Magnesium	50–1500	250
Potassium	200–2000	300
Sodium	200–2000	500
Chloride	100–3000	500
Sulfate	100–1500	300
Total iron	50–600	60

* Except pH.

† Representative range of values. Higher maximum values have been reported in the literature for some of the constituents.

Source: From Tchobanoglous et al. [11-8]

manner, methane can accumulate (because its specific gravity is less than that of air) below buildings or in other enclosed spaces on, or close to, a sanitary landfill. With proper venting, methane should not pose a problem.

Because carbon dioxide is about 1.5 times as dense as air and 2.8 times as dense as methane, it tends to move toward the bottom of the landfill. As a result, the concentration of carbon dioxide in the lower portions of landfills may be high for years. Ultimately, because of its density, carbon dioxide will also move downward through the underlying formation until it reaches the groundwater. Because carbon dioxide is readily soluble in water, it usually lowers the pH, which in turn can increase the hardness and mineral content of the groundwater through the solubilization of calcium and magnesium carbonates.

Control of Gas Movement

The movement of gases in landfills can be controlled by constructing vents and barriers and by gas recovery.

Control of gas movement with vents and barriers The lateral movement of gases produced in a landfill can be controlled by installing vents made of materials that are more permeable than the surrounding soil. Typically, as shown in Fig. 11-20*a*, gas vents are constructed of gravel. The spacing of cell vents depends on the width of the waste cells but usually varies from 18 to 60 m (60 to 200 ft). The thickness of the gravel layer should be such that it will remain continuous even though there may be differential settling; 0.30 to 0.45 m (12 to 18 in) is recommended. Barrier or well vents (see Fig. 11-20*b*) also can be used to control the lateral movement of gases. Well vents (see Fig. 11-20*c*) are often used in conjunction with lateral-surface vents buried below grade in a gravel trench. Control of the downward movement of gases can be accomplished by installing perforated pipes in a gravel layer at the bottom of the landfill. If the gases cannot be vented laterally, it may be necessary to install gas wells and to vent the pumped gas to the atmosphere.

The movement of landfill gases through adjacent soil formations can be controlled by constructing barriers of materials that are more impermeable than the soil (Fig. 11-21). Some of the landfill sealants that are available for this use are identified in Table 11-13. Of these, the use of compacted clays is most common. The thickness will vary depending on the type of clay and the degree of control required; thicknesses ranging from 0.15 to 1.25 m (6 to 48 in) have been used.

Control of gas movement by recovery The movement of gases in landfills can also be controlled by installing gas recovery wells in complete landfills (see Fig. 11-22). Clay and other liners are used where landfill gas is to be recovered. In some gas-recovery systems, leachate is collected and recycled to the top of the landfill and reinjected through perforated lines located in drainage trenches. Typically, the rate of gas production is greater in leachate recirculation systems or where water is added.

Although gas-recovery systems have been installed in some large municipal landfills, the economics of such operations are, at present, not well defined. The cost of the gas cleanup and processing equipment may limit the recovery of landfill gases, especially from small landfills.

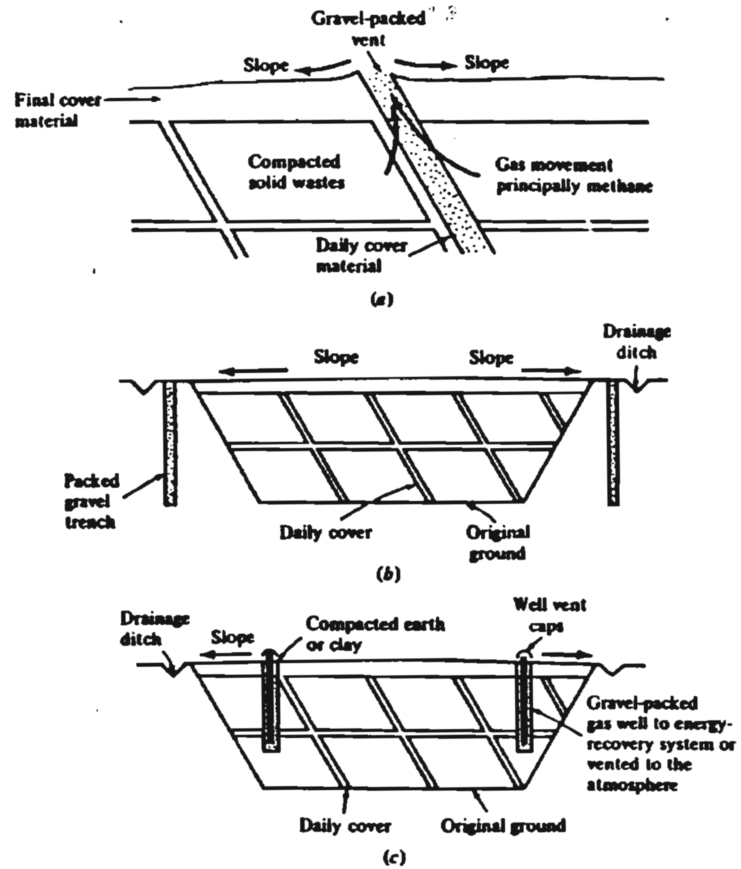


Figure 11-20 Typical methods for venting landfill gases: (*a*) cell; (*b*) barrier; (*c*) well.

Leachate Movement

Under normal conditions, leachate is found in the bottom of landfills. From there, its movement is through the underlying strata, although some lateral movement may also occur, depending on the characteristics of the surrounding material. The rate of seepage of leachate from the bottom of a landfill can be estimated by Darcy's law by assuming that the material below the landfill to the top of the water table is saturated and that a small layer of leachate exists at the bottom of the fill. Under these conditions the leachate discharge rate per unit area is equal to the

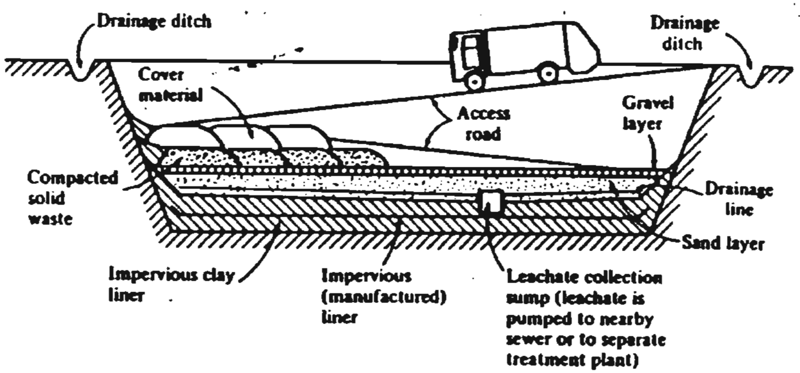


Figure 11-21 Landfill designed to prevent the movement of gases and leachate.

Table 11-13 Landfill sealants for the control of gas and leachate movement

Sealant		
Classification	Representative types	Remarks
Compacted soil		Should contain some clay or fine silt.
Compacted clay	Bentonites, illites, kaolinites	Most commonly used sealant for landfills; layer thickness varies from 6 to 48 in; layer must be continuous and not allowed to dry out and crack.
Inorganic chemicals	Sodium carbonate, silicate, or pyrophosphate	Use depends on local soil characteristics.
Synthetic chemicals	Polymers, rubber latex	Experimental, use not well established.
Synthetic membrane liners	Polyvinyl chloride, butyl rubber, hypalon, polyethylene, nylon-reinforced liners	Expensive, may be justified where gas is to be recovered.
Asphalt	Modified asphalt, asphalt-covered polypropylene fabric, asphalt concrete	Layer must be thick enough to maintain continuity under differential settling conditions.
Others	Gunite concrete, soil cement, plastic soil cement	

Source: From Tchobanoglous et al. [11-8]

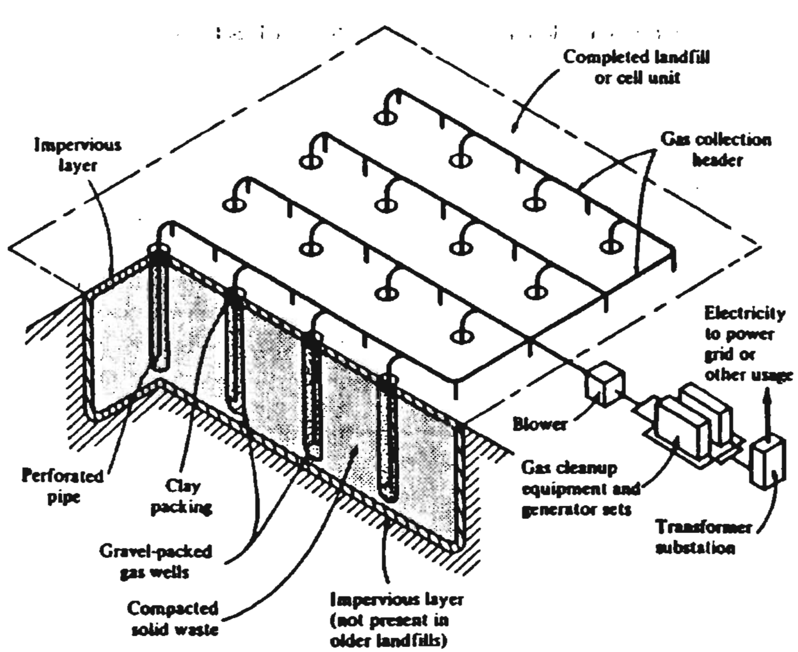


Figure 11-22 Well system used for the recovery of gases from landfills.

value of the coefficient of permeability K expressed in meters per day. The computed value represents the maximum amount of seepage that would be expected, and this value should be used for design purposes. Under normal conditions, the actual rate would be less than this value because the soil column below the landfill would not be saturated.

Control of leachate movement

As leachate percolates through the underlying strata, many of the chemical and biological constituents originally contained in it will be removed by the filtering and adsorptive action of the material composing the strata. In general, the extent of this action depends on the characteristics of the soil, especially the clay content. Because of the potential risk involved in allowing leachate to percolate to the groundwater, best practice calls for its elimination or containment. Ultimately, it may be necessary to collect and treat the leachate.

The use of clay has been the favored method of reducing or eliminating the percolation of leachate (see Fig. 11-21 and Table 11-13). Membrane liners have also been used, but they are expensive and require care so that they will not be damaged during the filling operations. Equally important in controlling the movement of leachate is the elimination of surface-water infiltration, which is the major

Table 11-14 Generalized ratings of the suitability of various types of soils for use as landfill cover material

	General soil type*					
Function	Clean gravel	Clayey-silty gravel	Clean sand	Clayey-silty sand	Silt	Clay
Prevents rodents from burrowing or tunneling	G	F–G	G	P	P	P
Keeps flies from emerging	P	F	P	G	G	E†
Minimizes moisture entering fill	P	F–G	P	G–E	G–E	E†
Minimizes landfill gas venting through cover	P	F–G	P	G–E	G–E	E†
Provides pleasing appearance and controls blowing paper	E	E	E	E	E	E
Supports vegetation	P	G	P–F	E	G–E	F–G
Vents decomposition gas‡	E	P	G	P	P	P

* E, excellent; G, good; F, fair; P, poor.
† Except when cracks extend through the entire cover.
‡ Only if well drained.
Source: From Tchobanoglous et al. [11-8]

contributor to the total volume of leachate. With the use of an impermeable clay layer, and appropriate surface slope (1 to 2 percent) and adequate drainage, surface infiltration can be controlled effectively. Generalized ratings for the suitability of various types of soil for use as a landfill cover are reported in Table 11-14.

Settlement and Structural Characteristics of Landfills

The settlement of landfills depends on the initial compaction, characteristics of wastes, degree of decomposition, and effects of consolidation when the leachate and gases are formed in the landfill. The height of the completed fill will also influence the initial compaction and degree of consolidation. The degree of consolidation can be modeled with a first-order equation.

11-19 DESIGN AND OPERATION OF LANDFILLS

Important design considerations in the design and operation of landfills include: (1) land requirements, (2) types of wastes that must be handled, (3) evaluation of seepage potential, (4) design of drainage and seepage control facilities, (5) development of a general operation plan, (6) design of solid-waste filling plan, and (7) determination of equipment requirements. The more important individual factors that must be considered in the design of a landfill are reported in Table 11-15. The last three items are considered further in the following discussion.

Table 11-15 Important factors that must be considered in the design and operation of solid-waste landfills

Factor	Remarks
Design	
Access	Paved all-weather access roads to landfill site; temporary roads to unloading areas.
Cell design and construction	Will vary depending on terrain, landfilling method, and whether gas is to be recovered.
Cover material	Maximize use of on-site earth materials; approximately 1 m^3 of cover material will be required for every 4 to 6 m^3 of solid wastes; mix with sealants to control surface infiltration. In some designs, intermediate cover is not used.
Drainage	Install drainage ditches to divert surface-water runoff; maintain 1 to 2 percent grade on finished fill to prevent ponding.
Equipment requirements	Vary with size of landfills.
Fire prevention	Water on-site; if nonpotable, outlets must be marked clearly; proper cell separation prevents continuous burn-through if combustion occurs.
Groundwater protection	Divert any underground springs; if required, install sealants for leachate control; install wells for gas and groundwater monitoring.
Land area	Area should be large enough to hold all wastes for a minimum of 1 yr but preferably 5 to 10 yr.
Landfilling method	Selection of method will vary with terrain and available cover.
Litter control	Use movable fences at unloading areas; crews should pick up litter at least once per month or as required.
Operation plan	With or without the codisposal of treatment plant sludges and the recovery of gas.
Spread and compaction	Spread and compact waste in 0.6-m (2-ft) layers.
Unloading area	Keep small, generally under 30 m (100 ft).
Operation	
Communications	Telephone for emergencies.
Days and hours of operation	Usual practice is 5 to 6d/wk and 8 to 10 h/d.
Employee facilities	Restrooms and drinking water should be provided.
Equipment maintenance	A covered shed should be provided for field maintenance of equipment.
Operational records	Tonnage, transactions, and billing if a disposal fee is charged.
Salvage	No scavenging; salvage should occur away from the unloading area; no salvage storage on-site.
Scales	Essential for record keeping.

Source: From Tchobanoglous et al. [11-8]

Landfill Operation Plan

The layout of the site and the development of a workable operating schedule are the main features of a landfill operation plan. In planning the layout of a landfill site, the location of the following must be determined: (1) access roads, (2) equipment shelters, (3) scales, if used, (4) storage sites for special wastes, (5) topsoil stockpile sites, (6) the landfill areas, and (7) plantings. A typical landfill operation plan is shown in Fig. 11-23.

Solid-Waste Filling Plan

The specific method of filling will depend on the characteristics of the site, such as the amount of available cover material, the topography, and the local hydrology and geology. To assess future development plans, it will be necessary to prepare a detailed plan for the layout of the individual solid-waste cells (see Fig. 11-24). On the basis of the characteristics of the site or the method of operation (e.g., gas recovery), it may be necessary to incorporate special features for the control of the movement of gases and leachate from the landfill. Estimation of the capacity of a landfill is illustrated in Example 11-5.

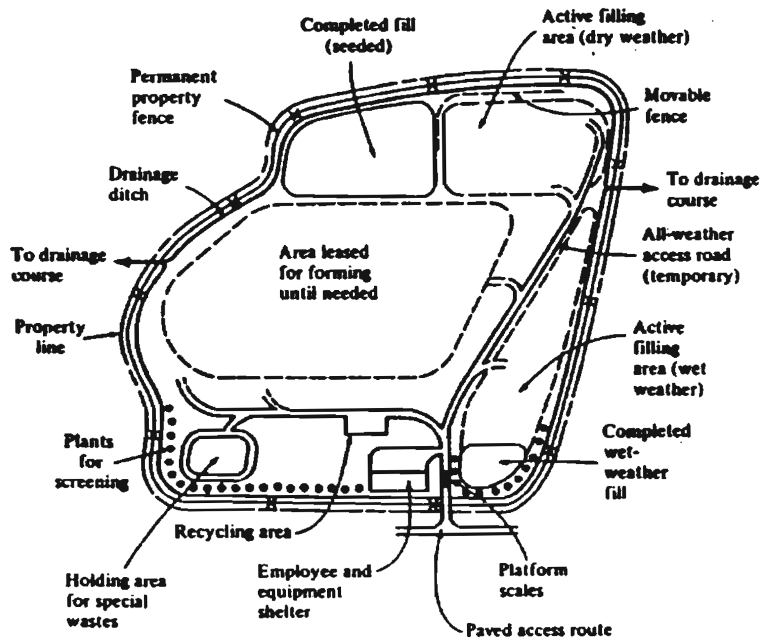


Figure 11-23 Typical landfill operation plan.

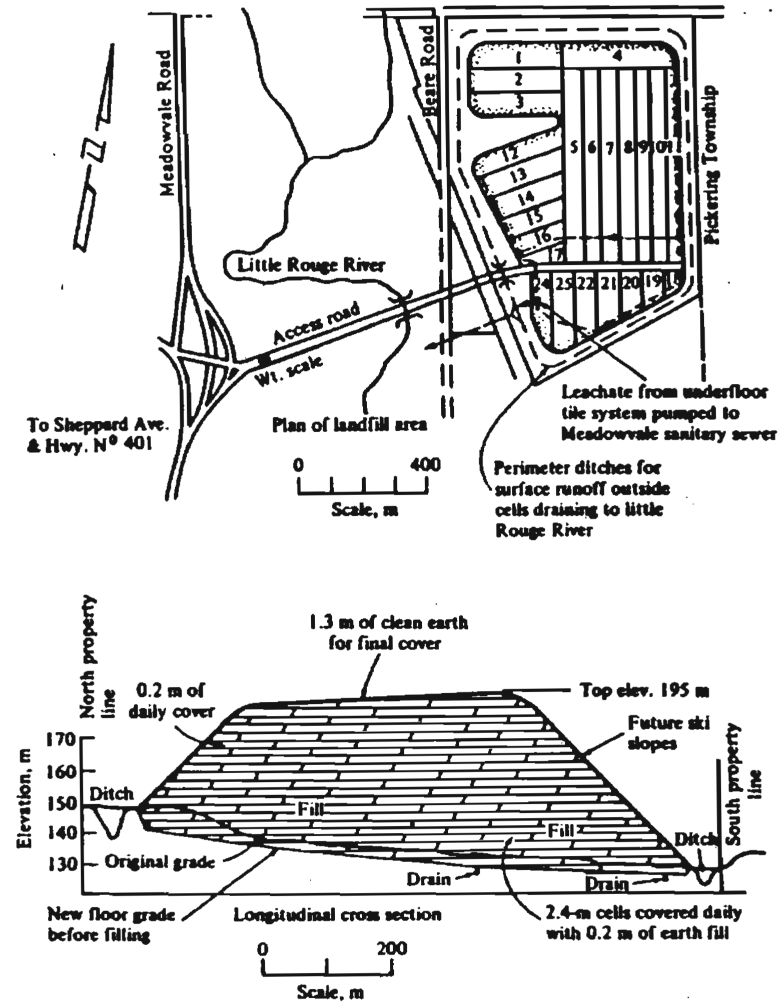
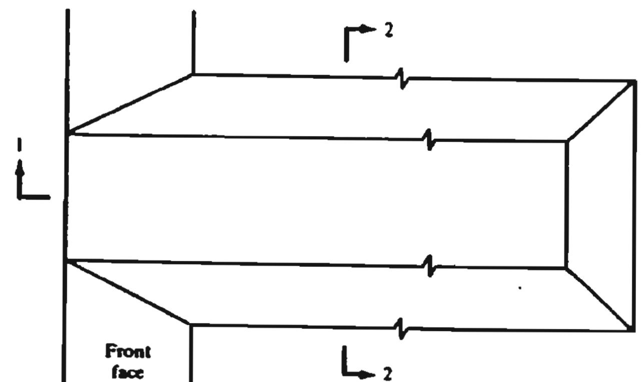


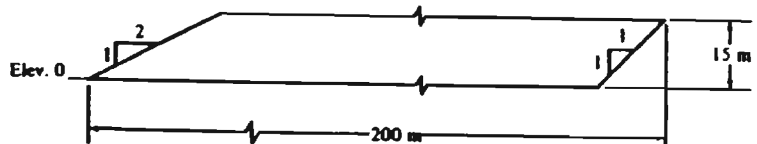
Figure 11-24 Typical plan for filling landfill. (*Courtesy of Municipality of Metropolitan Toronto, Department of Public Works.*)

Example 11-5: Determining the capacity of a disposal site Determine the capacity of the solid-waste disposal site shown in the accompanying figure (*a*), (*b*), and (*c*). Also determine the amount of cover material that must be cut from the sides and rear slope of the disposal site to meet the specified cover requirements. Prepare a sketch showing the final cut limits of the disposal site. Assume the following conditions are applicable:

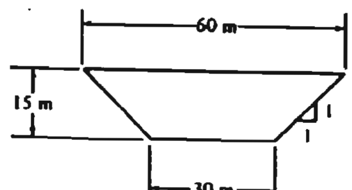
a. Total lift height is 3.0 m.
b. Front face of completed landfill will have a slope of 2 to 1 and will be coincident with the front face of the existing site.
c. The ratio of solid waste to cover material is 5 to 1.
d. Vertical excavation is possible without bank collapse (for the purpose of illustration only).



Plan view
(*a*)



Section 1-1
(*b*)



Section 2-2
(*c*)

SOLUTION

1. Determine the capacity of the disposal site and the amount of cover material required. Because the site will be excavated to obtain the necessary cover material, the capacity of the site is equal to the volume of the site. Because cover material will have to be excavated from the sides of the site, it will be useful to compute the volume of each lift separately. The necessary computations are summarized in the table.

Estimation of capacity of landfill

Lift number	Elevation, m	Area, m² At contour interval	Area, m² Average between intervals	Capacity between contours, m³	Cover material required, m³
	0	5,550*			
1			6,015	18,045†	3,609‡
	3	6,480			
2			6,945	20,835	4,167
	6	7,410			
3			7,875	23,625	4,725
	9	8,340			
4			8,805	26,415	5,283
	12	9,270			
5			9,735	29,205	5,841
	15	10,200			
Total capacity, m³				118,125	
Total cover, m³					23,625

* Referring to the figure, the area at elevation zero is computed as 5550 m² = (200 m − 15 m) × 30 m.
† 18,045 m³ = 6015 m² × 3 m (lift height).
‡ 3609 m³ = 18,045 m³ × (1/5), ratio of cover material to solid waste.

2. Determine the limits of excavation that will be needed to obtain the required cover material (see the table assuming that a triangular wedge of material will be excavated (see figure (*d*) all around the disposal site.

a. Develop a relationship that can be used to determine the volume.

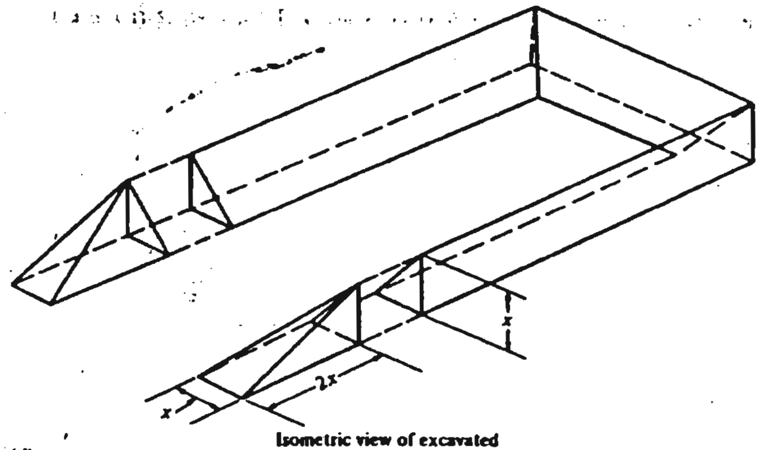
$$\text{Vol} = 2\,(\text{volume of truncated excavated wedge sections}) + L\,(\text{area of continuous triangular wedge})$$
$$= 2[\tfrac{1}{2}(2x \times x)x] + L(\tfrac{1}{2}x^2)$$

where L = length of wedge measured along a line drawn on a horizontal plane of a distance $\tfrac{2}{3}x$ in from the bottom perimeter of the disposal site. Thus

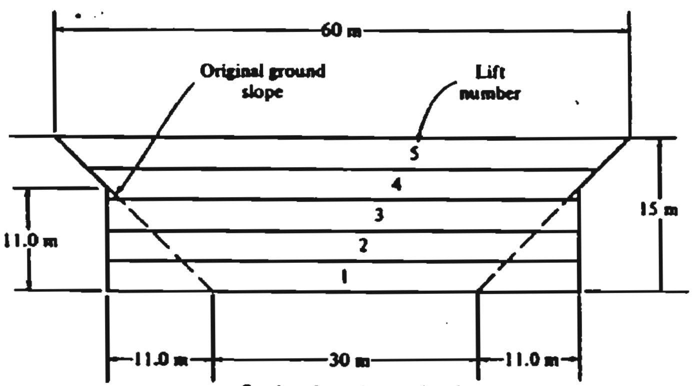
$$L = 2(155\text{ m}) + 30\text{ m} + 4(\tfrac{2}{3}x)$$
$$= 340 + 2.67x$$

Hence

$$\text{Vol} = 1.33x^3 + (340 + 2.67x)(\tfrac{1}{2}x^2)$$
$$= 170x^2 + 2.67x^3$$



(*d*) Isometric view of excavated wedge of cover material



(*e*) Section through completed landfill

b. Equate above expression to require cover volume and solve for x by trial and error.
Try $x = 10$ m.

$$23{,}625 = 170(10^3) + 2.67(10^3)$$
$$23{,}625 \neq 19{,}670 \qquad \text{unacceptable}$$

Try $x = 11.0$ m

$$23{,}625 \approx 24.123 \qquad \text{O.K.}$$

3. Prepare a sketch showing the final cut limits of the disposal site. A section through completed landfill is shown in figure (*e*).

COMMENT An alternative solution would be to excavate the cover material in a stepped (staircase) fashion. In this situation, only enough material is excavated to meet the cover requirements for each lift (see the table). This solution is left to the reader as Prob. 11-15.

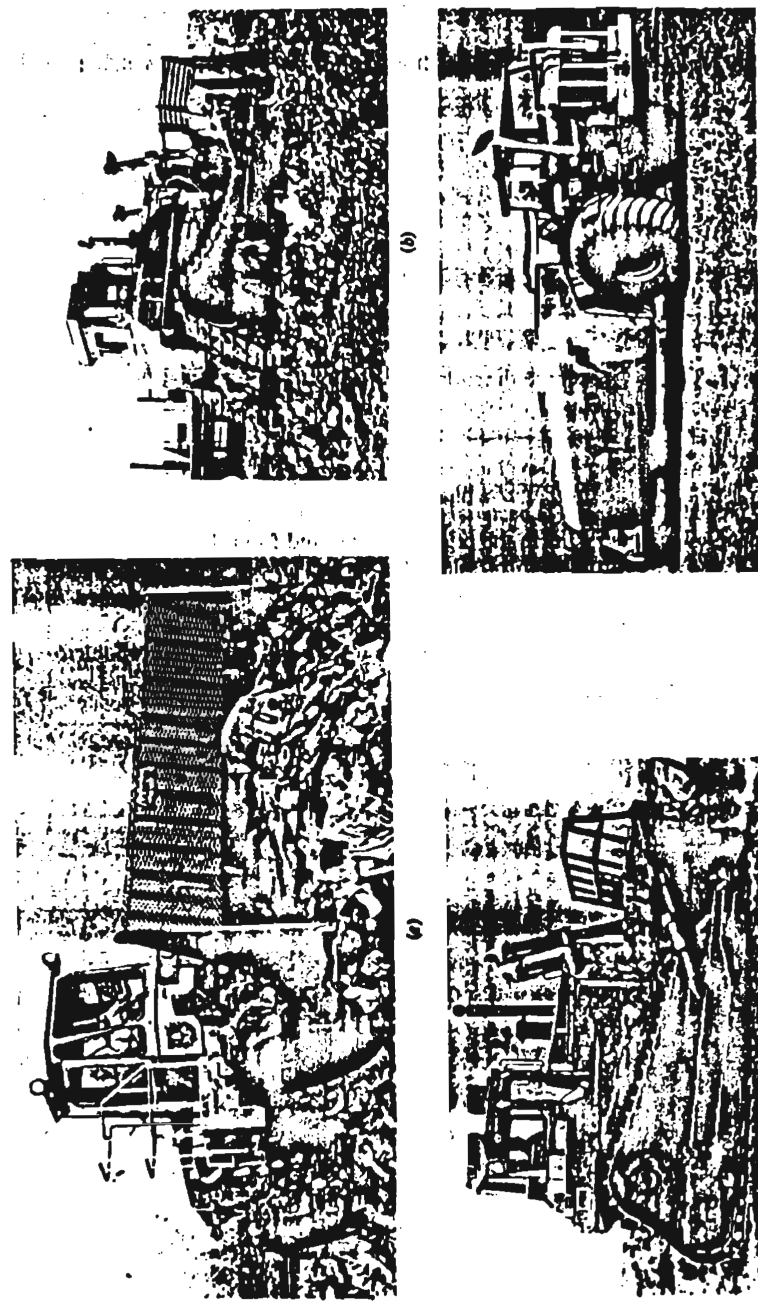


Figure 11-25 Typical equipment used at sanitary landfills.

Equipment Requirements

The types of equipment that have been used at sanitary landfills include both crawler and rubber-tired tractors, scrapers, compactors, draglines, and motor graders (see Fig. 11-25). The size and amount of equipment required will depend primarily on local site conditions, the size of the landfill operation, and the method of operation.

11-20 LANDFARMING

Landfarming is a waste-disposal method in which the biological, chemical, and physical processes that occur in the surface of the soil are used to treat biodegradable industrial wastes. Wastes to be treated are either applied on top of the land, which has been prepared to receive the wastes, or injected below the surface of the soil (see Fig. 11-26).

When organic wastes are added to the soil, they are subjected simultaneously to the following processes: (1) bacterial and chemical decomposition, (2) leaching of water-soluble components in the original wastes and from the decomposition products, and (3) volatilization of selected components in the original wastes and from the products of decomposition. Factors that must be considered in evaluating the biodegradability of organic wastes in a landfarming application include (1) composition of the waste; (2) compatibility of wastes and soil microflora; (3) environmental requirements including oxygen, temperature, pH, and inorganic nutrients, and (4) moisture content of solid-waste mixture.

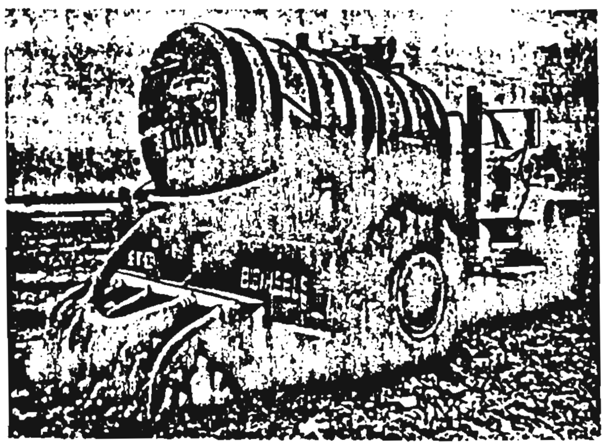


Figure 11-26 Equipment used for the landfarming of liquid solid waste such as those from a wastewater treatment plant.

Landfarming is suitable for wastes that contain organic constituents that are biodegradable and are not subject to significant leaching while the bioconversion process is occurring. For example, petroleum wastes and oily sludges are ideally suited for disposal by landfarming. A variety of other organic wastes with similar characteristics are also suitable. Properly managed landfarming sites can be reused at frequent intervals with no adverse affects.

11-21 DEEP-WELL INJECTION

Deep-well injection for the disposal of liquid solid wastes involves injecting the wastes deep in the ground into permeable rock formations (typically limestone or dolomite) or underground caverns. The installation of deep wells for the injection of wastes closely follows the practices used for the drilling and completion of oil and gas wells. To isolate and protect potential water supply aquifers, the surface casing must be set well below such aquifers and cemented to the surface of the well (see Fig. 11-27). The drilling fluid should not be allowed to penetrate

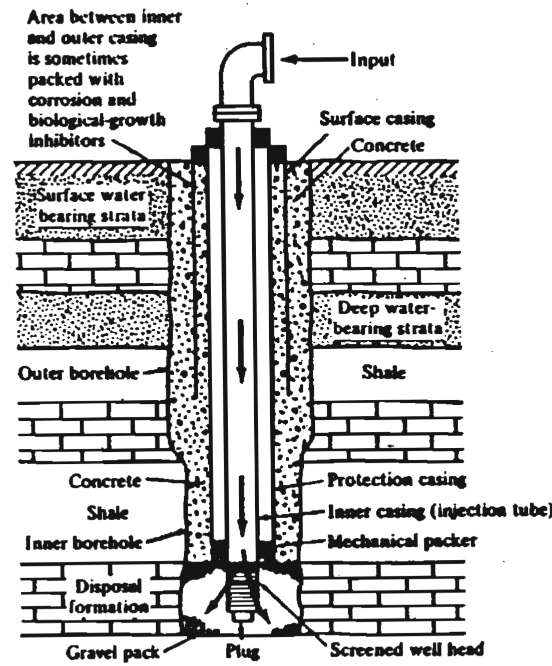


Figure 11-27 Well used for injection of liquid solid wastes.

the formation that is to be used for waste disposal. To prevent clogging of the formation, the drilling fluid is replaced with a compatible solution. Also, in some cases, it may be necessary to acid-treat the formation before injection of wastes is initiated.

Deep-well injection has been used principally for liquid wastes that are difficult to treat and dispose of by more conventional methods and for hazardous wastes. Chemical, petrochemical, and parmaceutical wastes are those most commonly disposed of with this method. The waste may be liquid, gases, or solids. The gases and solids are either dissolved in the liquid or are carried along with the liquid.

DISCUSSION TOPICS AND PROBLEMS

11-1 Obtain data on the solid-waste generation rates for your community. How do they compare with the values reported in the text? Explain any differences.

11-2 If you were asked to determine the solid-waste generation rates for your community, how would you assess the seasonal effects if the only data available had been collected during the month of December?

11-3 Plot a histogram of the following generation rates obtained at a commercial establishment over a period of a year. What conclusions can be drawn from histograms? What can you say about the histogram you have plotted?

Generation rate, m^3/wk	Frequency
100–199	1
200–299	3
300–399	7
400–499	10
500–599	6
600–699	2
700–799	1
800–899	1
900–999	0
1000–1099	1
1100–1199	4
1200–1299	7
1300–1399	5
1400–1499	3
1500–1599	1

11-4 Drive around your community and make a brief survey of the types of containers that are used for the outside storage of solid wastes.

11-5 Prepare an estimate of the volume and mass of solid wastes that would be generated by a family of four with and without the use of a kitchen garbage grinder.

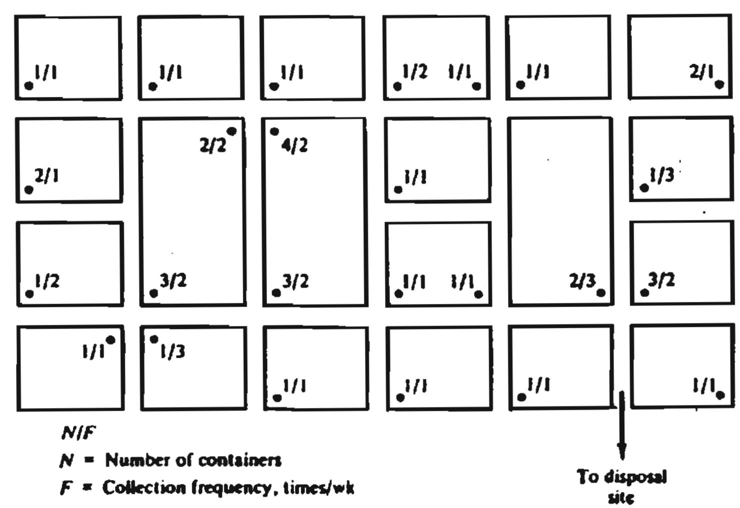
11-6 Drive around your community and identify the principal types of solid-waste collection systems that are in use. Select two of the systems and obtain some field data on the times required for the various activities associated with the collection of solid wastes. How do the values compare with those reported in the text? Explain any differences in the values.

11-7 A new residential area composed of 600 single-family dwellings is being developed. Assuming that either two or three trips per day will be made to the disposal site, select an appropriate truck size and determine the number of trips that must be made.

1. Solid waste generation rate = 5.0 kg/residence · d
2. Containers per service = 2
3. Type of service = 80 percent curbside and 20 percent rear of house
4. Collection frequency = once per week
5. Collection vehicle compaction ratio = 2.5
6. Size of collection crew = two persons
7. Length of workday = 8 h
8. Off-route factor = 0.15
9. Round-trip haul distance = 34 km
10. Haul route constants: a = 0.016 h/trip; b = 0.011 h/km
11. At-site time per trip = 0.083 h/trip

11-8 Layout the collection routes for the commercial area shown in the accompanying figure. Assume the following data are applicable:

1. Collection system = stationary container
2. Container size = 4 m^3
3. Container utilization factor = 0.80
4. Collection frequency = as shown
5. Collection vehicle capacity = 26 m^3

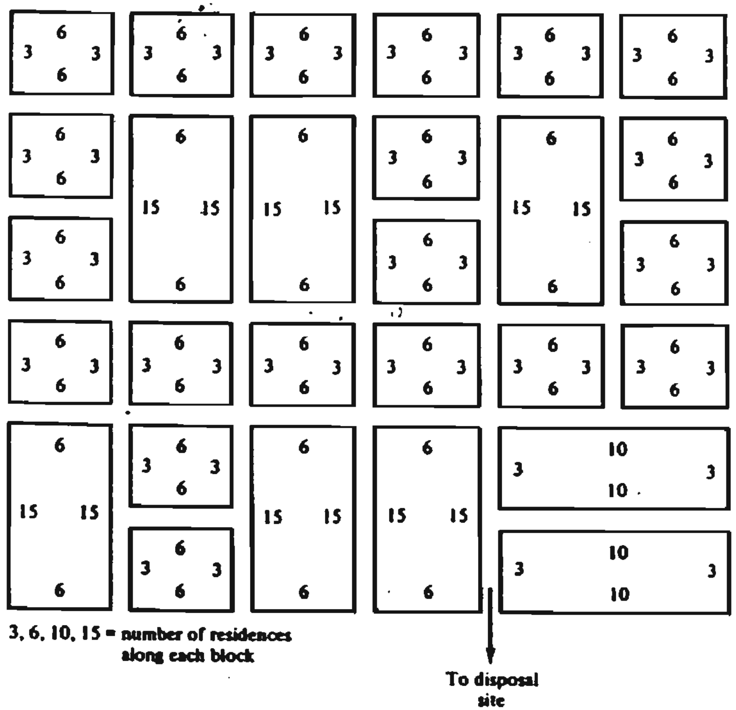


N/F

N = Number of containers

F = Collection frequency, times/wk

11-9 Lay out collection routes for the residential area shown in the accompanying figure. Assume the same conditions as specified in Example 11-3 are applicable.



3, 6, 10, 15 = number of residences along each block

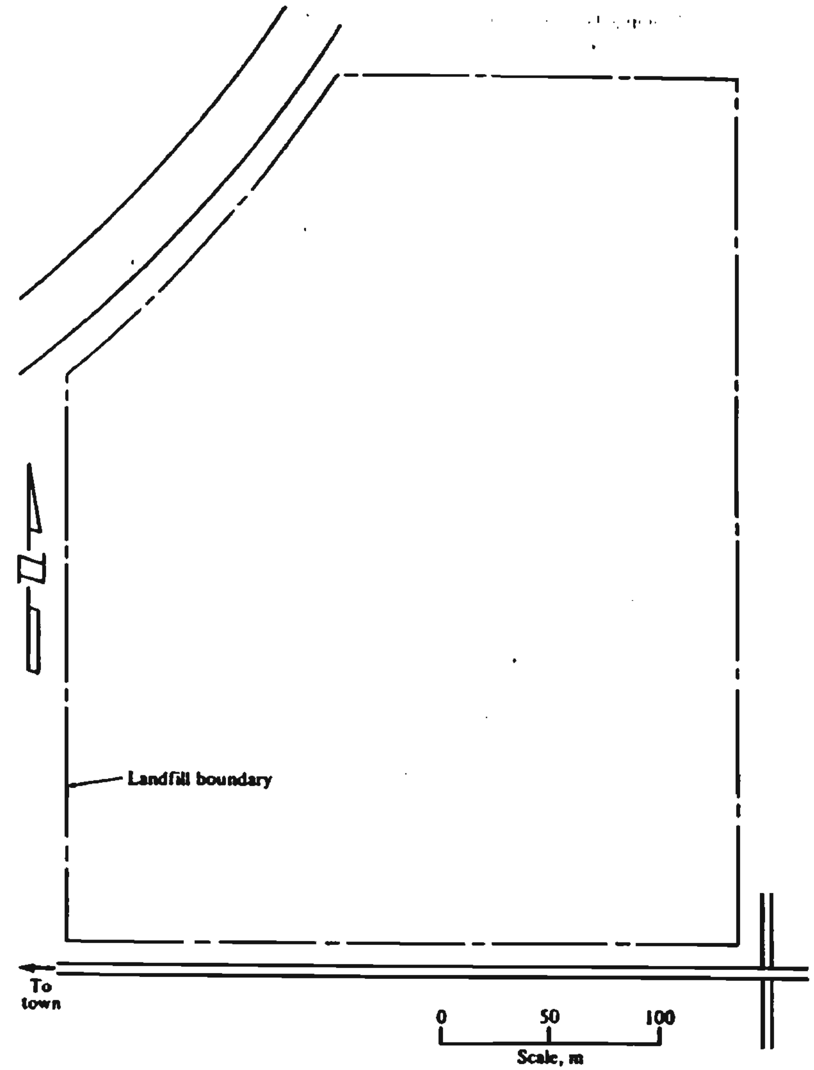
11-10 If your community does not have a transfer station (if it does, do Prob. 11-11) estimate the break-even time at which a transfer station operation would become feasible. How does this value compare to the actual time now spent by the collection vehicles in the haul operation? State all of your assumptions clearly.

11-11 If your community has a transfer station, estimate what the break-even time would be for a direct-haul operation. How does this value compare to the actual time now spent by the transport vehicles in the transport operation? State all of your assumptions clearly.

11-12 Estimate the maximum amount of gas that can be produced per kilogram, under anaerobic conditions, from a waste with the same chemical composition as the waste in Example 10-4.

11-13 Prepare an operating plan, including equipment requirements, and estimate the capacity of a landfill to be placed in the area shown in the accompanying figure. Assume the following data are applicable:

1. Number of collection services = 3000 (average over 20 yr)
2. Amount of wastes generated per service = 6.5 kg/d



3. Compacted density of solid wastes in landfill = 475 kg/m^3
4. Maximum allowable finished grade above surrounding ground = 20 ft
5. Ratio of solid wastes to cover material = 6 to 1

11-14 Estimate the capacity of the landfill shown in Fig. 11-24. If the in-place density is 714 kg/m^3, how many tonnes have been placed in the landfill?

11-15 Solve Example 11-5 in a stepped fashion where only the amount of cover material needed for each lift is excavated. Prepare a sketch showing the final cut limits of the disposal site.

REFERENCES

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CHAPTER

TWELVE

ENGINEERED SYSTEMS FOR RESOURCE AND ENERGY RECOVERY

The purpose of this chapter is to introduce the reader to the techniques and methods used to recover materials, conversion products, and energy from solid wastes. Topics to be considered include (1) processing techniques, (2) materials-recovery systems, (3) recovery of biological conversion products, (4) recovery of chemical conversion products, (5) recovery of energy from conversion products, and (6) materials and energy recovery systems.

Because many of the techniques to be considered are in a state of flux with respect to application and design criteria, the objective here is only to introduce them to the reader. If these techniques are to be considered in the development of waste-management systems, current engineering design and performance data must be obtained from the records of operating installations, from field tests, from equipment manufacturers, and from the literature. References [12-3, 12-6, and 12-8] are recommended as a starting point.

Processing Techniques

Processing techniques, as noted previously in Chap. 11, are used in solid-waste management systems to improve the efficiency of solid-waste management systems, to recover resources (usable materials), and to prepare materials for the recovery of conversion products and energy. Processing techniques used to improve the efficiency of solid-waste systems and to recover materials manually were considered previously in Chap. 11. The more important techniques used for processing solid wastes to recover materials and to prepare the waste for subsequent processing are summarized in Table 12-1.