CHAPTER 11

SOLID WASTE MANAGEMENT

11-1 PERSPECTIVE

Solid waste is a generic term used to describe the things we throw away. It includes things we commonly describe as garbage, refuse, and trash. The U.S. Environmental Protection Agency's (EPA) regulatory definition is broader in scope. It includes any discarded item; things destined for reuse, recycle, or reclamation; sludges; and hazardous wastes. The regulatory definition specifically excludes radioactive wastes and *in situ* mining wastes. The Resource Conservation and Recovery Act (RCRA) is the federal act that regulates the disposal of solid waste. The act has two subtitles that have become a shorthand means of identifying the type of solid waste. "Subtitle C" wastes are hazardous wastes. "Subtitle D" wastes are all other solid wastes that are not hazardous or radioactive.

We have limited the discussion in this chapter to solid wastes generated from residential and commercial sources. Sludges were discussed in Chapters 6 and 8. Hazardous waste will be discussed in Chapter 12, and radioactive waste will be discussed in Chapter 14, which can be found at the text's website: www.mhhe.com/davis.

Magnitude of the Problem

Solid waste disposal creates a problem primarily in highly populated areas. The more concentrated the population, the greater the problem becomes. Various estimates have been made of the quantity of solid waste generated and collected per person per day. In 2009, the EPA estimated that the national average rate of solid waste generated was 2.0 kg/capita · day (U.S. EPA, 2010). On this basis, in 2009, the U.S. produced 221 teragrams (Tg) of solid waste.* This is a 60 percent increase over the 1980 estimate of 137.8 Tg and a nearly 175 percent increase over the 1960 estimate of 80.1 Tg. The EPA estimates that between 55 and 65 percent of the waste stream comes from residential sources, and the remainder is from commercial sources. Individual cities may vary greatly from these estimates. For example, Los Angeles, California, generates about 3.18 kg/capita · day while the rural community of Wilson, Wisconsin, generates about 1.0 kg/capita · day.

Figure 11-1 shows solid waste production rates. Averages are subject to adjustment depending on many local factors. Studies show there are wide differences in amounts collected by municipalities because of differences in climate, living standards, time of year, education, location, and collection and disposal practices.

Recycling Trends in Waste Management

While the amount of solid waste produced in the United States has increased, the recycling rate has also increased. In 1980, less than 10 percent of the solid waste produced was recycled. In 2009, the percentage of waste recycled increased to 34 percent. An additional 12 percent of the solid waste produced in 2009 was combusted with energy recovery, resulting in 54 percent of the solid waste generated in the United States in 2009 discarded in landfills. Therefore, although the amount of solid waste

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*In keeping with correct SI notation, we use teragrams (1×10^{12} grams). One Tg is equivalent to 1×10^{9} kilograms (kg) or 1×10^{6} megagrams (Mg). The megagram is often referred to as the "metric ton."

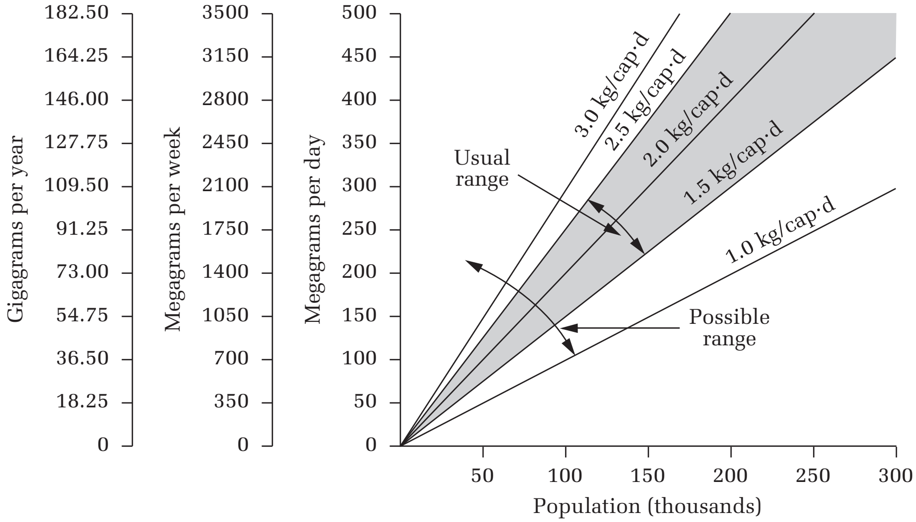

FIGURE 11-1
Solid waste produced: varying per capita figures.

produced each year from 1980 to 2009 increased by 60 percent, the amount of waste discarded in landfills remained about the same because of combustion and recycle of solid waste.

EPA also estimates the percentage of certain types of solid waste recycled. In 2009, for example, 74 percent of office paper was recycled, as were 96 percent of auto batteries, 88 percent of newspapers, 63 percent of junk mail, and 54 percent of magazines. Large percentages of aluminum and steel cans, yard trimmings, tires, and glass containers were also recycled.

Characteristics of Solid Waste

The terms *refuse* and *solid waste* are used more or less synonymously, although the latter term is preferred. The common materials of solid waste can be classified in several different ways. The point of origin is important in some cases, so classification as domestic, institutional, commercial, industrial, street, demolition, or construction may be useful. The nature of the material may be important, so classification can be made on the basis of organic, inorganic, combustible, noncombustible, putrescible, and nonputrescible fractions. One of the most useful classifications is based on the kinds of materials as shown in Table 11-1. Another classification system that is similar to this is the one used by the Incinerator Institute of America (Table 11-2). This is based primarily on the heat content of the waste.

Garbage is the animal and vegetable waste resulting from the handling, preparation, cooking, and serving of food. It is composed largely of putrescible organic matter and moisture; it includes a minimum of free liquids. The term does not include food processing wastes from canneries, slaughterhouses, packing plants, and similar facilities, or large quantities of condemned food products. Garbage originates primarily in home kitchens, stores, markets, restaurants, and other places where food is stored,

TABLE 11-1
Refuse materials by kind, composition, and sources

Kind	Composition	Sources
Garbage	Wastes from preparation, cooking, and serving of food; market wastes; wastes from handling, storage, and sale of produce	Households, restaurants, institutions, stores, markets
Rubbish	Combustible: paper, cartons, boxes, barrels, wood, excelsior, tree branches, yard trimmings, wood furniture, bedding, dunnage	
	Noncombustible: metals, tin cans, metal furniture, dirt, glass, crockery, minerals	
Ashes	Residue from fires used for cooking and heating and from on-site incineration	
Street refuse	Sweepings, dirt, leaves, catch basin dirt, contents of litter receptacles	Streets, sidewalks, alleys, vacant lots
Dead animals	Cats, dogs, squirrels, deer	
Abandoned vehicles	Unwanted cars and trucks left on public property	
Industrial wastes	Food-processing wastes, boiler house cinders, lumber scraps, metal scraps, shavings	Factories, power plants
Demolition wastes	Lumber, pipes, brick, masonry, and other construction materials from razed buildings and other structures	Demolition sites to be used for new buildings, renewal projects, expressways
Construction wastes	Scrap lumber, pipe, other construction materials	New construction, remodeling
Special wastes	Hazardous solids and liquids; explosives, pathological wastes, radioactive materials	Households, hotels, hospitals, institutions, stores, industry
Sewage treatment residue	Solids from coarse screening and from grit chambers; septic tank sludge	Sewage treatment plants, septic tanks

(*Source:* ISW, 1970.)

TABLE 11-2
Incinerator Institute of America waste classification

Classification of wastes to be incinerated						
Classification of Wastes						
Type	Description	Principal components	Approximate composition % by weight	Moisture content %	Incombustible solids %	MJ heat value/kg of refuse as fired
[a]0	Trash	Highly combustible waste, paper, wood, cardboard cartons, including up to 10% treated papers, plastic or rubber scraps; commercial and industrial sources	Trash 100%	10%	5%	19.8
[a]1	Rubbish	Combustible waste, paper, cartons, rags, wood scraps, combustible floor sweepings; domestic, commercial, and industrial sources	Rubbish 80% Garbage 20%	25%	10%	15.1
[a]2	Refuse	Rubbish and garbage; residential sources	Rubbish 50% Garbage 50%	50%	7%	10.0
[a]3	Garbage	Animal and vegetable wastes; restaurants, hotels, markets; institutional, commercial, and club sources	Garbage 65% Rubbish 35%	70%	5%	5.8
4	Animal solids and organic wastes	Carcasses, organs, solid organic wastes; hospital, laboratory, abattoirs, animal pounds, and similar sources	100% Animal and human tissue	85%	5%	2.3
5	Gaseous, liquid, or semi-liquid wastes	Industrial process wastes	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey
6	Semi-solid and solid wastes	Combustibles requiring hearth, retort, or grate burning equipment	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey

[a]The above figures on moisture content, ash, and MJ as fired have been determined by analysis of many samples. They are recommended for use in computing heat release, burning rate, velocity, and other details of incinerator designs. Any design based on these calculations can accomodate minor variations. (*Data Source:* IIA, 1968.)

prepared, or served. Garbage decomposes rapidly, particularly in warm weather, and may quickly produce disagreeable odors. There is some commercial value in garbage as animal food and as a base for commercial feeds. However, this use may be precluded by health considerations.

Rubbish consists of a variety of both combustible and noncombustible solid wastes from homes, stores, and institutions, but does not include garbage. Trash is synonymous with rubbish in some parts of the country, but trash is technically a subcomponent of rubbish. Combustible rubbish (the "trash" component of rubbish) consists of paper, rags, cartons, boxes, wood, furniture, tree branches, yard trimmings,

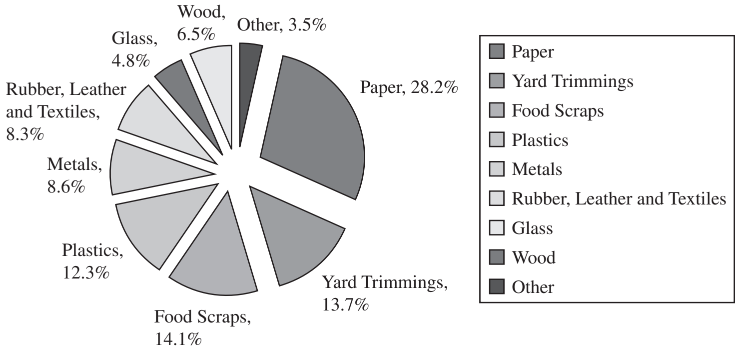

FIGURE 11-2
Materials generated in municipal solid waste (percent by mass), 2009. (*Source:* U.S. EPA, 2010.)

and so on. Some cities have separate designations for yard wastes. Combustible rubbish is not putrescible and may be stored for long periods of time. Noncombustible rubbish is material that cannot be burned at ordinary incinerator temperatures of 700 to 1,100°C. It is the inorganic portion of refuse, such as tin cans, heavy metals, glass, ashes, and so on.

The average municipal solid waste composition in the United States in 2003 is shown in Figure 11-2.

The density of loose combustible refuse is approximately 115 kg/m^3, while the density of collected solid waste is 235 to 300 kg/m^3.

Solid Waste Management Overview

The first objective of solid waste management is to remove discarded materials from inhabited places in a timely manner to prevent the spread of disease, to minimize the likelihood of fires, and to reduce aesthetic insults arising from putrifying organic matter. The second objective, which is equally important, is to dispose of the discarded materials in a manner that is environmentally responsible.

Policy Making. Solid waste system policy making is primarily a function of the public sector rather than the private sector. The goal of a private firm is to minimize a well-defined cost function or to maximize profits. These are generally not the only, or even the primary, constraints of the public sector. The public objective function is more vague and difficult to express formally.

Constraints on the public sector, especially those of a political or a social nature, are difficult to measure, and criteria of effectiveness may not exist in units that can be quantified. Criteria of effectiveness against which public efficiency might be measured include such things as the frequency of collection, types of waste collected, location from which waste is collected, method of disposal, location of disposal site, environmental acceptability of disposal system, and the level of satisfaction of the customers. Public receptivity of a solid waste management system also depends on even less quantifiable parameters, which we group under the term *institutional factors.* Institutional factors include such things as political feasibility of the system, legislative constraints, and administrative simplicity.

Additional constraints on decision making in the public sector are environmental factors and resource conservation. Environmental factors are most important in the areas of waste storage and disposal because these functions represent prolonged exposure of wastes to the environment. Resource conservation is considered seriously by local governments as we become increasingly conscious of the limits of our natural resources.

Decisions in solid waste management policy formulation must be made in four basic areas: collection, transport, processing, and disposal. The flowchart in Figure 11-3 illustrates the decisions that must be made from the point of generation to the ultimate disposal of residential solid waste.

In designing a solid waste collection system, one of the first decisions to be made is where the waste will be picked up: the curb or the backyard. This is an important decision because it affects many other collection variables, including choice of storage containers, crew size, and the selection of collection trucks. Backyard service, once the predominant method of pickup, is still used by some communities. It is generally more costly, but it eliminates the need for scheduled pickups.

Another key decision is frequency of collection. Both point of collection and frequency of collection should be evaluated in terms of their impact on collection costs. Because collection costs generally account for 70 to 85 percent of total solid waste management costs, and labor represents 60 to 75 percent of collection costs, increases in the productivity of collection personnel can dramatically reduce overall costs. Most communities offer collection once or twice a week, with once per week being the most common schedule (U.S. EPA, 1995).

Systems with once-a-week curbside collection help maximize labor productivity and result in significantly lower costs than systems with more frequent collection and/or backyard pickup. The main reason many communities retain twice-a-week backyard service is that the citizens demand this convenience and are willing to pay for it. In warmer regions of the country, twice-a-week service may be deemed essential to prevent gross odors and to break the fly-breeding cycle. The egg-larvae-adult cycle is about 4–5 days.

The choice of solid waste storage containers must be evaluated in terms of both environmental effects and costs. From the environmental standpoint, some storage containers can present health and safety problems to the collectors, as well as to the general public. Therefore, the decision facing a community is which storage system is both environmentally sound and most economical, given the collection system characteristics. For example, paper and plastic bags are superior to many other containers from a health and esthetic standpoint and can increase productivity when used in conjunction with curbside collection. However, with backyard collection systems, bags have little effect on productivity.

The type of container used may also be dictated by the type of collection. If solid waste is collected manually, then plastic bags or cans can be used. Some communities have recently begun to sell special plastic bags or stickers to put on plastic bags that include the cost of the bag as well as the disposal fee. If the system is

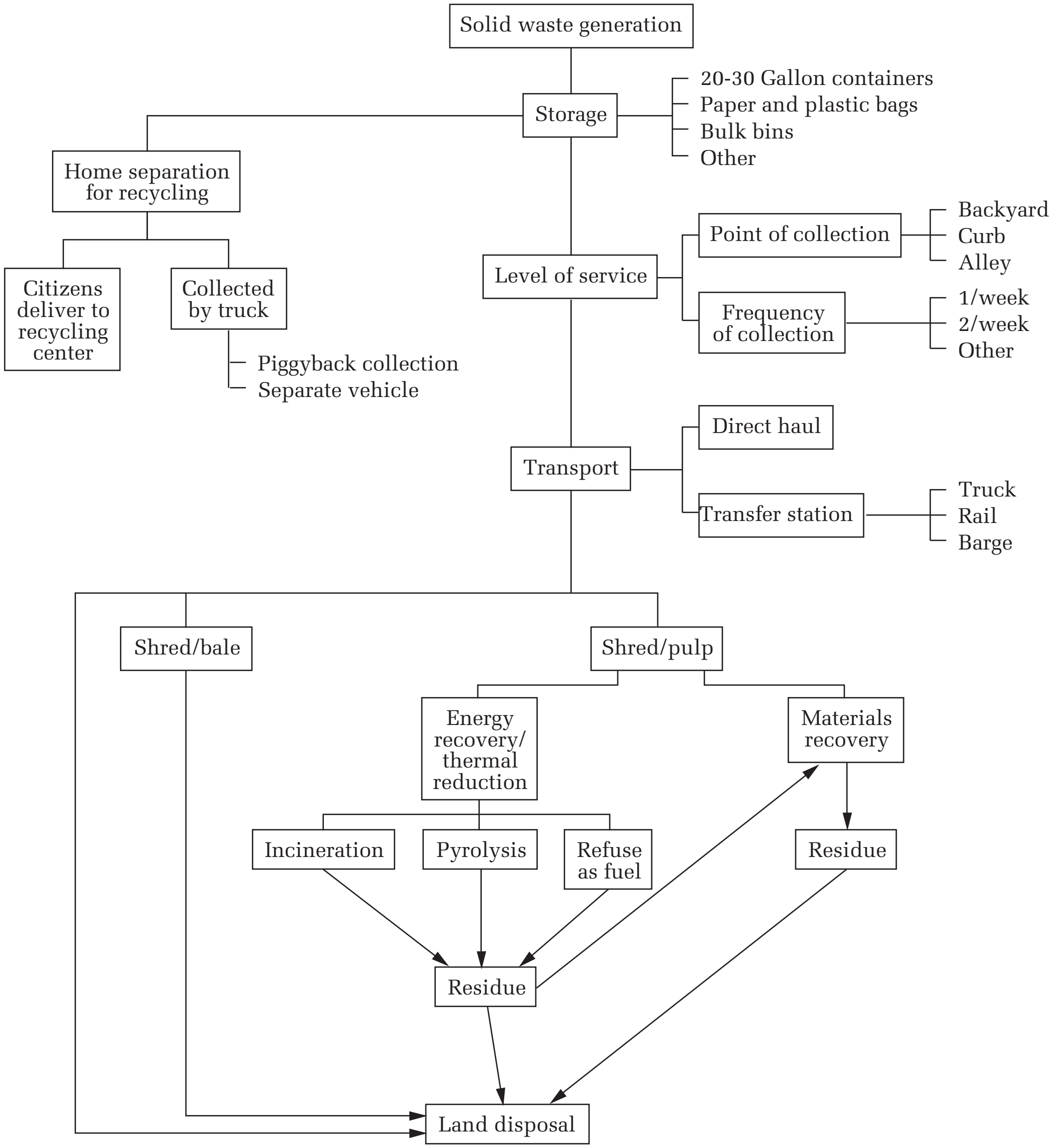

FIGURE 11-3
Solid waste management decision alternatives. (*Source:* U.S. EPA, 1974.)

automated or semiautomated, then the container must be specifically designed to fit the truck-mounted loading system. The containers typically hold from 1 to 20 cubic meters of waste.

Another factor to be considered in examining storage alternatives is home separation of various materials for recovery. The collection of materials for recovery/recycle is a growing practice that many cities are implementing. The technique of greatest interest to municipal decision makers is home separation and collection by either the regular collection truck equipped with special bins or by separate trucks.

One of the primary factors to consider in implementing a separate collection system is whether the benefits of recovery outweigh the costs involved. The economic viability of separate collection depends primarily on the local market price for the material and the degree of participation by the citizens. If these factors are positive, it may be possible to implement a recovery system with no increase, and possibly a savings, in collection operating costs; often no additional capital expenditure is required. Another factor to be considered is the expectation of the community that the municipality be actively involved in recycling. Most people perceive recycling as an environmentally friendly practice and so expect municipalities to provide the opportunity.

The distance between the disposal site and the center of the city will determine the advisability of including a *transfer station* in the transport system.* In addition to distance traveled to the disposal site, the time required for the transport is a key factor, especially in traffic-congested large cities.

The tradeoffs involved in transfer station operations are the capital and operating costs of the transfer station as compared to the cost (mostly labor) of having route collection vehicles travel excessive distances to the disposal site. These tradeoffs can be computed to find the point at which transfer becomes economically advantageous.

The sheer quantities of solid waste to be disposed of daily makes the problem of what to do with the waste, once it has been collected, among the most difficult problems confronting community officials. A crisis situation can develop very quickly, for example, in the case of an incinerator or land disposal site forced to shut down because of failure to meet newly passed environmental regulations. Alternatively, a crisis can build gradually over a period of time if needed new facilities are not properly planned for and put into service.

There are three basic alternatives for disposal. Some have subalternatives. The major alternatives are: (1) direct disposal of unprocessed waste in a municipal solid waste landfill, (2) processing of waste followed by land disposal, and (3) processing of waste to recover resources (materials and/or energy) with subsequent disposal of the residues. Most municipal solid waste is landfilled, but the amount landfilled declined from 73 percent in 1988 to 56 percent in 2003. Fourteen percent of the waste was incinerated in 2003 and 30 percent was recycled or composted. EPA projects the increase in waste incineration and recycling to continue.

Direct haul to a sanitary landfill (with or without transfer and long haul) is usually the cheapest disposal alternative in terms of both operating and capital costs. In 1988, it was estimated that about 8,000 landfills were in operation, but by 2002 the number had decreased to about 1,800. Many were closed as a result of regulatory restrictions. Municipalities own 75 percent of the sites (Wolpin, 1994). With rising *tipping fees* (the cost to dump solid waste at a disposal facility), a surplus of disposal capacity has replaced the late 1980s predictions of lack of landfill space.

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*A transfer station is a place where trucks dump their loads into a larger vehicle where it is compacted. By combining loads, the cost per Mg · km for transport to the landfill is reduced.

With the second alternative, processing prior to land disposal, the primary objective is to reduce the volume of wastes. Such volume reduction has definite advantages because it reduces hauling costs and ultimate disposal cost, both of which are, to some extent, a function of waste volume. However, the capital and operating cost to achieve this volume reduction are significant and must be balanced against the savings achieved.

An additional consideration is the environmental benefit that might be derived from the volume reduction process. In some cases, shredding and baling may reduce the chances for water pollution from leachate. This alternative is more conserving of land than sanitary landfilling of unprocessed wastes, but by itself provides no opportunity for material or energy recovery.

The third category of disposal alternatives includes those processes that recover energy or materials from solid waste and leave only a residue for ultimate land disposal. There are significant capital and operating costs associated with all these energy and/or materials recovery systems. However, if markets are available, both energy and materials can be sold to reduce the net costs of recovery.

While resource recovery techniques may be more costly than other disposal alternatives, they do achieve the goal of resource conservation while enhancing sustainability and the residuals of the processes require much less space for land disposal than unprocessed wastes.

Affecting all four major functions are basic decisions regarding how the solid waste system will be managed and operated. This includes how the system will be financed, which level of government will administer it, and whether a public agency or private firm will operate the collection, transport, processing, and disposal functions. The criteria most relevant for making these decisions are the institutional factors of political feasibility and legislative constraints.

Integrated Solid Waste Management (ISWM). The selection of a combination of techniques, technologies, and management programs to achieve waste management objectives is called *integrated solid waste management* (ISWM). This approach has made major strides in recent years. The EPA proposed a hierarchy of actions to implement ISWM: source reduction (including reuse and waste reduction), recycling and composting, and disposal in combustion facilities and landfills (U.S. EPA, 1995). The most obvious effect of the integrated approach is to reduce the size of the incineration facility. This reduces the capital cost of the incineration facility. Although the energy output is also reduced, the waste that remains has a higher energy content so that the reduction in energy output is less than the reduction in plant size. Recycling also reduces waste elements that can damage the boilers and removes those components that slag in the furnace and foul it (Shortsleeve and Roche, 1990).

11-2 COLLECTION

The solid waste collection policies of a city begin with decisions made by elected representatives about whether collection is to be made by: (1) city employees (municipal collection), (2) private firms that contract with city government (contract collection), or (3) private firms that contract with private residents (private collection). Many communities have moved away from exclusive municipal collection and toward a combined system.

More and more communities are moving toward mandatory recycling of materials such as paper, plastic, and glass. In these situations, separation of waste is required.

Elected officials may also determine what type of solid wastes are to be collected and from whom. In some municipalities broad classes of solid wastes (such as rubbish) are not accepted for collection. In others, certain materials (such as tires, grass trimmings, furniture, or dead animals) may be excluded. Hazardous wastes are generally excluded from regular collections because of disposal and collection dangers. The nature of the service may be governed by limitations of disposal facilities or by the opinion of the legislative body as to what service should be performed. A city may collect garbage only or it may collect everything but garbage. Almost all municipal systems collect residential waste, but only about one-third collect industrial waste.

The final decision concerning collection, which is made by the elected officials, is the frequency of collection. The proper frequency for the most satisfactory and economical service is governed by the amount of solid waste that must be collected and by climate, cost, and public requests. For the collection of solid waste that contains garbage, the maximum period should not be greater than

1. The normal time for the accumulation of the amount that can be placed in containers of reasonable size.
2. The time it takes for fresh garbage to putrefy and emit foul odors under average storage conditions.
3. The length of the fly-breeding cycle, which, during the hot summer months, is less than seven days.

In the last three decades the prevailing frequency of collection has changed from twice a week pickup to once a week. The increased use of once per week service is due to two factors. First, unit costs are reduced when frequency is cut from twice to once per week. Second, the increased percentage of paper and decreased percentage of garbage in the solid waste permit longer periods of acceptable storage.

Once policy has been set, the actual method of collection is determined by engineers or managers. Major considerations include how the solid waste will be collected, how the crews will be managed, how the trucks will be routed, and the type of equipment to be used.

Collection Methods

The first decision to be made is how the solid waste container will get from the residence to the collection vehicle. The three basic methods are: (1) *curbside* or alley pickup, (2) *set-out, set-back collection,* and (3) *backyard pickup,* or the tote barrel method. Most urban and suburban areas utilize curbside pickup, but a few communities still use backyard pickup. In some less populated areas, municipal waste collection is sometimes accomplished by requiring residents to transport waste to a specified point. This point may be a transfer station or the disposal site. This is the least expensive method for a municipality, but it is the least convenient method for the homeowner.

The quickest and most economical point of collection is from curbs or alleys using standard containers. It is the most common type of collection used. It costs only about one-half as much as backyard collection. Usually the city designates what type of containers are to be used. The crews simply empty the containers into the collection vehicles. Whenever possible the crews collect from both sides of the street at the same time. Municipal ordinances or administrative regulations usually specify when the containers must be placed at the curb or in the alley for pickup and also how long they may remain after pickup. Common limits are out by 7 A.M. and back by 7 P.M. When solid wastes are loaded from curbs or alleys, work progresses rapidly. A typical crew consists of a driver and two collectors. Some crews still have three or even four collectors, but the trend is toward fewer collectors. Recent studies indicate that small crews are more efficient than larger ones, because labor costs are a major element of the total cost. Aside from the cost advantage of this method, it also eliminates the need for the collectors to enter private property, and the amount of service given each homeowner is relatively uniform. However, many citizens dislike having to set their solid wastes out at certain times and object to the unsightly appearance on the streets. Some surveys have shown that many homeowners would prefer to pay more in order to receive backyard service.

When curbside removal is chosen, automatic and semiautomatic collection vehicles can be utilized. In an automated system, residents are provided with large specialized containers (approximately 90 gallons), which they roll to the curb. These containers are then lifted by powerful hydraulic arms that empty the contents of the container into the truck's hopper. The crew, or often just the driver, performs the operation from inside the cab of the collection vehicle. A typical side-loading vehicle with a hydraulic arm is shown in Figure 11-4. A fully automated system can be the most economical for a

FIGURE 11-4
Side-loading refuse collection vehicle with hydraulic lift arm. In this model, the tractor-trailer configuration allows for additional maneuverability. (*Source:* Heil Environmental, 2006.)

community, particularly if the community also uses this single truck to collect recyclables. The city of Los Angeles converted to such a system and in 2000 collected 712 Gg of refuse, recyclables, and yard waste with automated sideloading trucks. The waste is then transported to a waste processing facility where the materials are separated.

However, many communities cannot accommodate these large vehicles in their existing residential neighborhoods. They therefore use some combination of automatic and semiautomatic vehicles. In a semiautomatic system, the crew wheels the cart to the collection vehicle, lines the cart up with the lifting device and activates the lifter. A hydraulic device lifts and tips the cart, allowing the contents to fall into the hopper of the truck.

The existence of cul de sacs, alleys, and narrow streets as well as low-hanging utility lines may dictate the type of vehicle selected. For example, the city of Houston uses three different types of vehicles in its fleet of 200 vehicles. The city uses automated sideloaders to pick up curbside trash as well as recyclables, semiautomatic rear loaders to pick up yard waste, and a combination of rear loaders and a one-operator heavy-duty vehicle equipped with a grapple to pick up heavy trash to deposit in the rear loader (Bader, 2001, and Luken and Bush, 2002).

The set-out, set-back method eliminates most of the disadvantages of the curb method, but it does require the collector to enter private property. This method consists of the following operations: (1) the set-out crew carries the full containers from the residential storage location to the curb or alley before the collection vehicle arrives, (2) the collection crew loads the refuse in the same manner as the curb method, and (3) the set-back crew returns the empty cans. Any of the crew may be required to do more than one step or the homeowner may be required to do one of the steps. This method has not been shown to be more economical or advantageous than the backyard method, and it is more costly and time-consuming than curbside pickup.

Backyard pickup is usually accomplished by the use of tote barrels. In this method, the collector enters the resident's property, dumps the container into a tote barrel, carries it to the truck, and dumps it. The collector may collect refuse from more than one house before returning to the truck to dump. The primary advantage of this system is in the convenience to the homeowner. The major disadvantage is the high cost. Many homeowners object to having the collectors enter their private property. With this collection method, a rear-loading vehicle, such as the one shown in Figure 11-5, is used.

Cost analyses have revealed that 70 to 85 percent of the cost of solid waste collection and disposal can be attributed to the collection phase. For this reason, it would seem that a great deal of municipal effort should be directed to studying collection alternatives to determine the most efficient system. However, many analyses begin their studies assuming that waste loads are already collected and waiting for disposal. There are two major reasons why the collection system is not studied more often. First, the collection system is a complex and expensive system to analyze. The primary reasons for this are that it involves people, equipment, and levels of service, plus the possibility of numerous variations in secondary factors such as collection methodology; quantity, nature, and the method of storage of refuse; location of pickup point; equipment type and characteristics of operation; road factors; service density; route topography; climatic factors; and human factors. Human factors would include morale, incentive, fatigue, and other variables that influence the time required to complete a

FIGURE 11-5
Typical rear-loading refuse collection vehicle. (*Source:* Heil Environmental, 2006.)

given task. Secondly, most cities are already collecting refuse in some manner, and the cliche "leave well enough alone" often prevails. It is generally on the disposal system that the public is placing pressure for improvement, rather than the collection system.

Most changes in collection systems will require a great deal of investigation and testing. Even if the change is an obvious one, often "proof" of some sort is needed to convince the elected officials. The most important thing to realize about the solid waste collection system is that it is too big, complex, and vital to allow actual experimentation except on a very small scale. Coupled with this are all the other problems peculiar to studying large-scale public systems. A relevant database is probably nonexistent. The political implications of control of the system and cost distribution may override an otherwise practical solution. A large investment will have already been made in the existing system and the designer is not allowed the luxury of starting at the beginning, but must start with a system that may be founded on a pyramid of errors.

EPA suggests a method that can be used to estimate the time requirements of a waste collection system in order to evaluate and subsequently optimize the system (U. S. EPA, 1995). The steps included in a time study are shown in Table 11-3.

TABLE 11-3
Steps for conducting a time study

1. Select crew(s) representative of average level and skill level.
2. Determine the best method (series of movements) for conducting the work.
3. Set up a data sheet that can be used to record the following information: date, name of crew members and time recorder, type of collection method and equipment (including loading mechanism), specific area of municipality, and distance between collection points.
4. Divide loading activity into elements that are appropriate for the type of collection service. For example, the following elements might be appropriate for a study of residential collection loading times:
   - Time to travel from last loading point to next one
   - Time to get out of vehicle and carry container to the loading area
   - Time to load vehicle
   - Time to return container to the collection point and return to the vehicle.
5. Using a stop watch, record the time required to complete each element for a representative number of repetitions. Time may be measured using one of the following two methods:
   - *Snapback method:* The time recorder records the time after each element and then resets watch to zero for measurement of the next element.
   - *Continuous method:* The time recorder records the time after each element but does not reset the watch so that it moves continuously until the last elements is completed.

   Because the continuous method requires the time recorder to perform fewer movements and no time is lost for watch resetting, the continuous method is usually recommended.

   The number of repetitions that will be representative depends on the time required to complete the overall activity (cycle). The following numbers of repetitions have been suggested as sufficient:

Number of Repetitions	Minutes Per Cycle	Number of Repetitions	Minutes Per Cycle
60	0.50	20	2.0
40	0.75	15	5.0
30	1.00	10	10.5

6. Determine the average time recorded (T_o) and adjust it for "normal" conditions.

   In the case of waste collection, adjustments should be made for delays and for crew fatigue. These adjustments are typically in terms of the percent of time spent in a workday. The delay allowance (D) should include time for traffic conditions, equipment failures, and other uncontrollable delays. Crew fatigue allowance (F) should include adequate rest time for recovery from heavy lifting, extreme hot and cold weather conditions, and other circumstances encountered in waste collection. The allowance factors (D and F) along with the average observed time (T_o), can be used to estimate the "normal" time (T_n):

$$T_n = (T_o) \times [1 + (F + D)/100]$$

   This "normal" time is the loading time required for the particular area and collection system.

   For other activities, adjustments are also made for personal time (bathroom breaks). In this case, adjustment for personal time is made when calculating the number of loads/crew/day.

(*Source:* U.S. EPA, 1995.)

Waste Collection System Design Calculations

Often, it is desirable to calculate "quick and dirty" estimates of such things as crew size, desired truck capacity, and labor and capital costs. Simple formulas have been developed that enable such calculations. The formulas are based on crude averages regarding collection times, and they make broad assumptions. An example of a not-always-justifiable assumption is that if one collector can collect a house in one minute, then two can do it in one-half minute. Several such equations follow.

Estimating Truck Capacity. Given that you are able to estimate a large number of factors, the following equation will allow you to estimate the volume of solid waste a truck must be able to carry.

$$\forall_T = \frac{\forall_p}{rt_p}\left[\frac{H}{N_d} - \frac{2x}{s} - 2t_d - t_u - \frac{B}{N_d}\right] \tag{11-1}$$

where $\forall_T$ = volume of solid waste carried per trip by truck at a mean density, D_T, m^3
$\forall p$ = volume of solid waste per pickup location or stop, m^3/stop
r = compaction ratio
t_p = mean time per collection stop plus the mean time to reach the next stop, h
H = length of working day,* h
N_d = number of trips to the disposal site per day
x = one-way distance to disposal site, km
s = average haul speed to and from disposal site, km/h
t_d = one-way delay time, h/trip
t_u = unloading time at disposal site, h/trip
B = off route time per day, h

The factor of two in Equation 11-1 accounts for travel both to and from the disposal site. The average haul speed is a function of the total round-trip distance to the disposal site (Figure 11-6). As noted in the definitions, the volume carried presumes a mean density, D_T. This is the density that results after the waste has been compacted in the truck. The compaction ratio (r) is the ratio of the density after compaction to that before compaction. Typical densities "as discarded" are given for several solid waste components in Table 11-4. If, for example, paper waste was compacted to a density of 163.4 kg/m^3, the compaction ratio would be two to one. Compactor trucks can achieve densities ranging from 300 to 600 kg/m^3.

A value for t_p can be estimated from empirical data (U. Calif., 1952; Stone, 1969). The data may be approximated by linear equations of the following form:

$$t'_p = t_{b_p} + a(C_n) + b(PRH) \tag{11-2}$$

*We should note that it is standard practice to allow two fifteen-minute breaks during the day. Because the crew is paid for this, the number of hours in the workday (H) are unchanged. However, some allowance must be made for it. Hence the off route time (B) is included in the equation.

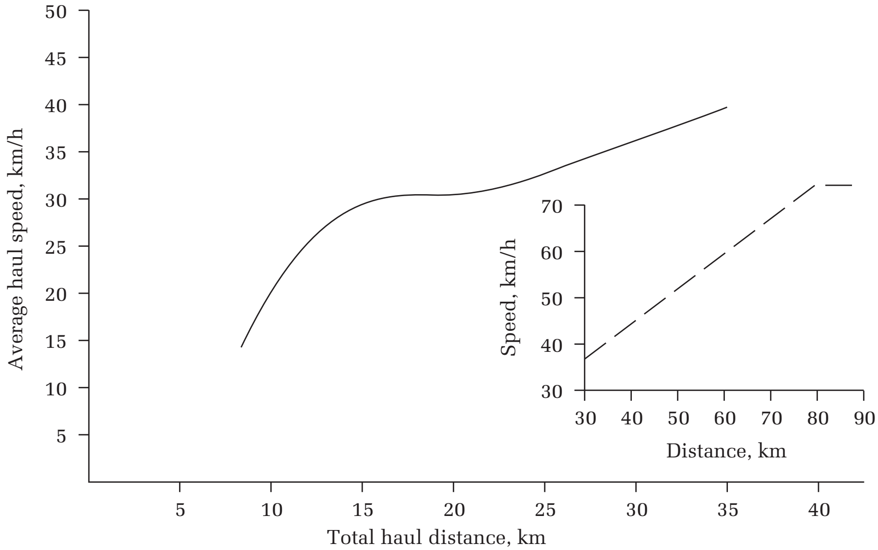

FIGURE 11-6
Effect of haul distance on average haul speed. (Adapted from U. Calif., 1952.)

TABLE 11-4
Typical properties of uncompacted solid waste as discarded in Davis, California

Component	Mass (kg)	Density (kg/m^3)	Volume (m^3)
Food wastes	4.3	288	0.0149
Paper	19.6	81.7	0.240
Cardboard[a]	2.95	99.3	0.0297
Plastics	0.82	64	0.013
Textiles	0.091	64	0.0014
Rubber	—	128	—
Leather	0.68	160	0.0043
Garden trimmings	6.5	104	0.063
Wood	1.59	240	0.00663
Glass	3.4	194	0.018
Tin cans	2.36	88.1	0.0268
Nonferrous metals	0.68	160	0.0043
Ferrous metals	1.95	320	0.00609
Dirt, ashes, brick	0.50	480	0.0010
Total	45.4		0.429

[a]Cardboard partially compressed by hand before being placed in container.
(*Source:* Tchobanoglous et al., 1977.)

where t'_p = mean time per collection stop plus mean time to reach next stop, min/stop
t_{b_p} = mean time between collection stops, min/stop
a, b = coefficients of regression fit to data points
C_n = mean number of containers at each pickup location
PRH = rear of house pickup locations, %

To convert t'_p to t_p, we must divide by 60 min/h.

The number of pickup locations that can be handled by a given crew is simply the available time after haul divided by the mean pickup time:

$$N_p = \frac{\frac{H}{N_d} - \frac{2x}{s} - 2t_d - t_u - \frac{B}{N_d}}{t_p} \tag{11-3}$$

where N_p = number of pickup locations per load

Example 11-1. The solid waste collection vehicle of Watapitae, Michigan, is about to expire, and city officials are in need of advice on the size of truck they should purchase. The compactor trucks available from a local supplier are rated to achieve a density (D_T) of 400 kg/m^3 and a dump time of 6.0 minutes. In order to ensure once-a-week pickup the truck must service 250 locations per day. The disposal site is 6.4 km away from the collection route. From past experience, a delay time of 13 minutes can be expected. The data given in Table 11-4 have been found to be typical for the entire city. Each stop typically has three cans containing 4 kg each. About 10 percent of the stops are backyard pickups. Assume that two trips per day will be made to the disposal site. Also assume that the crew size will be two and that the empirical equation of Tchobanoglous, Theisen, and Eliassen for a two-person crew applies (1977). That equation is given as follows:

$$t'_p = 0.72 + 0.18(C_n) + 0.014(PRH)$$
$$t'_p = 0.72 + 0.54 + 0.14 = 1.40 \text{ min/stop}$$
$$t_p = \frac{1.40 \text{ min}}{60 \text{ min/h}} = 0.0233 \text{ h}$$

Solution. Using Table 11-4 we determine the mean density of the uncompacted solid waste to be

$$D_u = \frac{\text{Total Mass}}{\text{Total Volume}} = \frac{45.4 \text{ kg}}{0.429 \text{ m}^3} = 105.83 \text{ or } 106 \text{ kg/m}^3$$

The volume per pickup is then

$$\forall_p = \frac{(3 \text{ cans})(4 \text{ kg/can})}{106 \text{ kg/m}^3} = 0.11 \text{ m}^3$$

The compaction ratio is determined from the densities:

$$r = \frac{D_T}{D_u} = \frac{400 \text{ kg/m}^3}{106 \text{ kg/m}^3} = 3.77$$

The average haul speed is determined from Figure 11-6. Because the graph is for total haul distance, we enter with (2)(6.4) = 12.8 km and determine that $s = 27$ km/h. All of the other required data were given; thus, we can now use Equation 11-1. The factor of 60 is to convert minutes to hours. For two 15-minute breaks, $B = 0.50$.

$$\mathcal{V}_t = \frac{0.11}{(3.77)(0.0233)}\left[\frac{8}{2} - \frac{(2)(6.4)}{27} - 2\,\frac{13\text{ min}}{60\text{ min/h}} - \frac{6\text{ min}}{60\text{ min/h}} - \frac{0.50}{2}\right]$$
$$= (1.25)(2.74) = 3.43\text{ m}^3$$

The number of stops that can be handled is given by Equation 11-3:

$$N_p = \frac{2.74}{0.0233} = 117.60\text{, or } 118\text{, pickups per load}$$

The smallest compactor truck available is one that will hold 4.0 m^3. Obviously, this will be satisfactory. However, the crew will not be able to reach the required 250 stops per day. Thus, some other alternative must be considered. One would be to extend the workday by 30 minutes.

Estimating Costs. Most of the decisions involved in the collection of solid waste are based on economic considerations rather than technical ones. The costs are considered on the basis of a unit mass of solid waste to facilitate comparison between different size vehicles, crews, and the like. Furthermore, truck costs are considered separately from labor costs.

Truck costs include depreciation of the initial capital investment plus the *operating and maintenance (O & M)* costs.*

The following equation may be used to estimate the annual cost per Mg (U. Calif., 1952):

$$A_T = \frac{1{,}000(F)}{\mathcal{V}_T D_T N_T Y}\left[1 + \frac{i(Y+1)}{2}\right] + \frac{1{,}000(X_t)(OM)}{\mathcal{V}_T D_T} \tag{11-4}$$

where A_T = annual truck cost, \$/Mg
F = initial (first) cost of truck, \$
$\mathcal{V}_T$ = volume of solid waste carried per trip by the truck
D_T = mean density of solid waste in truck, kg/m^3
N_T = number of trips per year
Y = useful life of truck, y
i = interest rate on capital
X_t = distance per trip, pickup plus haul, km
OM = operating and maintenance cost, \$/km

The factor of 1,000 is to convert kg to Mg.

*Government-operated collection systems, by the nature of their operation, do not actually depreciate purchases. First of all, they get no tax credit for doing so and, secondly, they do not save or put aside money in a bank and therefore cannot draw interest. In spite of all this, good engineering economics demands that capital costs be depreciated in order to allow valid comparisons between alternatives.

Labor costs consist of direct wages plus some overhead costs for such things as supervision, secretarial support, phone, utilities, insurance, and fringe benefits. Equation 11-5 can be used to estimate the annual labor cost per Mg:

$$A_L = \frac{1{,}000(CS)(W)(H)}{\mathcal{V}_T D_T N_d}[1 + (OH)] \tag{11-5}$$

where A_L = annual labor cost, \$/Mg
CS = average crew size
W = average hourly wage rate, \$/h
OH = overhead as a fraction of wages*

Again, the factor of 1,000 is to convert kg to Mg.

Example 11-2. Estimate the customer service charge for the situation of Example 11-1. The initial truck cost of a 4.0 m^3 compactor truck is \$104,000, and the average O & M cost over the five-year life of the truck is expected to be \$5.50/km. The interest rate is 8.25 percent. The average route length is 6.3 km. The average hourly wage rate is \$13.50 per hour with time and a half for overtime. The overhead rate is 125 percent of the hourly wage rate.

Solution. Assuming a five-day workweek and ignoring holidays, the number of trips per year would be

$$N_t = N_d(5)(52) = 2(5)(52) = 520$$

Because the average route length is 6.3 km and the average haul distance from Example 11-1 is 2(6.4) = 12.8 km, then

$$X_t = 6.3 + 12.8 = 19.1 \text{ km}$$

For the extended workday proposed at the end of Example 11-1, the volume of solid waste per trip would be

$$\mathcal{V}_T = (1.25)(2.74 + 1/2(0.5)) = 3.74 \text{ m}^3$$

The factor of one-half times the extra half hour was selected because we assumed the time to be equally divided between each of the two trips. Note that we do not use the actual volume of the truck, which is somewhat larger than $\mathcal{V}_T$. (The truck size is the nearest standard size.) Now we may compute the annualized truck cost.

$$A_T = \frac{1{,}000(104{,}000)}{(3.74)(400)(520)(5)}\left[1 + \frac{0.0825(5 + 1)}{2}\right] + \frac{1{,}000(19.1)(5.50)}{(3.74)(400)}$$
$$= (26.74)(1.25) + 70.22 = \$103.65/\text{Mg}$$

---

*OH is not a product. It is shorthand for “overhead”.

Because we have planned for an extra half hour of work each workday, we must adjust the hourly wage rate accordingly before we can use Equation 11-5. The adjustment is simply a determination of the weighted average rate.

$$W = \frac{(\text{reg. shift hours})(\text{wage}) + (\text{overtime hours})(\text{OT rate})(\text{wage})}{\text{total hours}}$$

$$= \frac{8(13.50) + 0.5(1.5)(13.50)}{8.5} = \$13.90/\text{h}$$

Now we may apply Equation 11-5 directly.

$$A_L = \frac{(1{,}000)(2)(13.90)(8.5)}{(3.74)(400)(2)}[1 + 1.25] = \$177.70/\text{Mg}$$

The total annual cost is then

$$A_{\text{tot}} = \$103.65 + \$177.70 = \$281.35/\text{Mg}$$

From Example 11-1, we know that each service stop averages three cans per week at 4 kg per can. Thus, each service stop contributes 3(4)(52) = 624 kg or 0.624 Mg per year. The annual cost per service stop should be ($281.35/Mg)(0.624 Mg) = $175.56. For 52 pickups per year, this is an average cost of about $3.38 per week (that is, $175.56/52).

Truck Routing

The routing of trucks may follow one of four methods. The first possibility is the daily route method. In this method the crew has a definite route that must be finished before going home. When the route is finished the crew can leave, but if necessary, they must work overtime to finish the route. This is the simplest method and the most common. The advantages of this method are as follows:

1. The homeowner knows when the refuse will be picked up.
2. The route sizes can be adjusted for the load to maximize crew and truck utilization.
3. The crew likes the method because it provides an incentive to get done early.

The disadvantages include:

1. If the route is not finished, the crew will work overtime, which will increase the expense.
2. The crew may have a tendency to become careless as they try to finish the job sooner.
3. Frequently the result is underutilization of the crew and equipment due to the increased incentive of the crew.
4. A breakdown seriously affects operations.

5. It is hard to plan routes if the load is variable, because of the disposal of yard wastes and the like.

The next method is the large route method. In this scheme the crew has enough work to last the entire week. The route must be completed in one week. The crew is left on its own to decide when to pick up the route. Usually some time off at the end of the week is the goal of the crew. This method is only good for backyard pickup because the residents don't know when pickup will be. The same advantages and disadvantages apply to this method as to the daily route method.

In the single load method, the routes are planned to get a full truck load. Each crew is assigned as many loads as it can collect per day. The biggest advantage of this method is that it can minimize travel time. The method must consider size of crew, capacity of truck, length of travel, refuse generated, and similar variables. Other advantages include:

1. A full day's work can be provided for maximum utilization of the crew and equipment.
2. It can be used for any type of pickup.

The major disadvantage is that it is hard to predict the number of homes that can be serviced before the truck is filled.

The last method is the definite working day method. As its name implies, the crew works for its assigned number of hours and quits. This method predominates in areas where unions are strong. With this method, the crew and the equipment get maximum utilization. Regularity is sacrificed with this method, and residents have little idea when pickup will occur.

Having determined the method by which the trucks will be managed, it is still necessary to find the actual route the truck will follow through the city. The purpose of routing and districting is to subdivide the community into units that will permit collection crews to work efficiently. No matter what the size of the community, it can be divided into districts, with each district constituting one day's work for the crew. The route is the detailed path of travel for the collection vehicle. The size of each route depends upon various factors as discussed earlier. The Office of Solid Waste Management Programs of the U.S. Environmental Protection Agency has developed a simple, noncomputerized "heuristic" (rule-of-thumb) approach to routing based on logical principles. The goal is to minimize deadheading, delay, and left turns. This method relies on developing, recognizing, and using certain patterns that repeat themselves in every municipality. Routing skills can be quickly acquired by applying the rules and developing experience. The following rules are taken from an EPA publication (Shuster and Schur, 1974).

1. Routes should not be fragmented or overlapped. Each route should be compact, consisting of street segments clustered in the same geographical area.
2. Total collection plus haul times should be reasonably constant for each route in the community (equalized workloads).
3. The collection route should be started as close to the garage or motor pool as possible, taking into account heavily traveled and one-way streets. (See rules 4 and 5.)

4. Heavily traveled streets should not be collected during rush hours.
5. In the case of one-way streets, it is best to start the route near the upper end of the street, working down it through the looping process.
6. Services on dead-end streets can be considered as services on the street segment that they intersect, because they can only be collected by passing down that street segment. To keep left turns at a minimum, collect the dead-end streets when they are to the right of the truck. They must be collected by walking down, backing down, or making a U-turn.
7. When practical, service stops on steep hills should be collected on both sides of the street while the vehicle is moving downhill for safety, ease, speed of collection, wear on vehicle, and conservation of gas and oil.
8. Higher elevations should be at the start of the route.
9. For collection from one side of the street at a time, it is generally best to route with many clockwise turns around blocks. (Authors' note: Heuristic rules 8 and 9 emphasize the development of a series of clockwise loops in order to minimize left turns, which generally are more difficult and time-consuming than right turns. Especially for right-hand-drive vehicles, right turns are safer.)
10. For collection from both sides of the street at the same time, it is generally best to route with long, straight paths across the grid before looping clockwise.
11. For certain block configurations within the route, specific routing patterns should be applied.

See Figure 11-7 for an example of the heuristic routing procedure.

Crew Integration

Another area of consideration is the integration of several crews. There are four ways of managing crews; usually some combination of the four is employed by any given city.

The swing crew method utilizes an extra crew as standby for heavy pickups, breakdown, or illness. Many times this crew will not report until noon to begin its day.

Crew sizes may be varied because of heavy loads, rain, different route sizes, and other factors. This is referred to as the variable crew method.

With the interroute relay method, when a crew member finishes one job, he or she is put on another route that needs additional help. This method requires more administration to operate, but results in better utilization of personnel and helps ensure that all routes will be completed during the day. Some form of this method has found wide acceptance with good results. Management must be sure that the workload is being balanced fairly and that a faster worker doesn't have to carry the load for others.

The last possibility is the reservoir route method. In this method, the crews work around a central core. When they have finished the route, the crews go to the core and begin picking up there. The core is usually an every day pickup, such as a park or a downtown area.

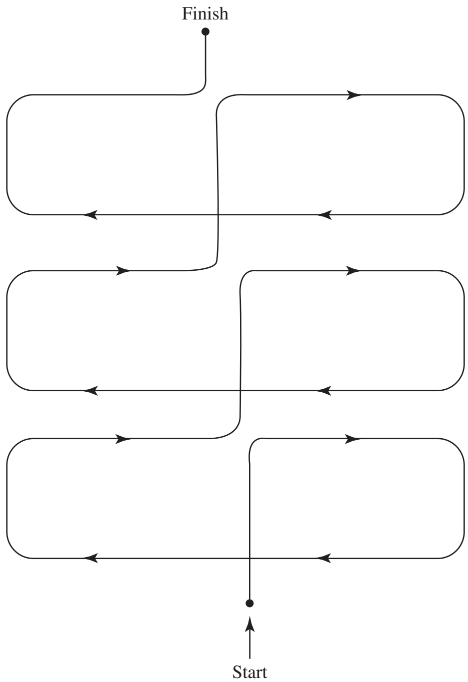

FIGURE 11-7
Arrows show heuristic routing pattern developed for a north-south, one-way street combined with east-west, two-way streets. If both sides of the one-way street cannot be collected in one pass, it is necessary to loop back to the upper end and make a straight pass down the other side.

11-3 INTERROUTE TRANSFER

It is not always economical, or even possible, to haul the solid waste directly to the disposal site in the collection vehicle. In these cases, the solid waste is transferred from several collection vehicles to a larger vehicle, which then carries it to the disposal site. The larger vehicle (*transfer vehicle*) may be a tractor-trailer, railroad car, or barge. A special facility, called a *transfer station,* must be constructed to permit this exchange in a rapid and sanitary fashion.

Among the more important considerations in planning and designing a transfer station are location, type of station, sanitation, access, and accessories such as weighing scales and fences. The use of a transfer station may also provide for present or future resource recovery facilities.

Maximum Haul Time

As in estimating collection times, it is possible to use average values to evaluate tradeoffs in transfer station effectiveness. One such method is to compute the travel time available to the crew to travel to the disposal site and still collect the appointed route. This can be done by rearranging Equation 11-3:

$$T_H = \frac{H}{N_d} - t_p N_p - 2t_d - t_u - \frac{B}{N_d} \qquad (11\text{-}6)$$

where T_H = maximum available haul time, h.

If the maximum available haul time is less than the round trip distance divided by the average route speed ($2x/s$), then you have a problem. Up to a point, changes in t_d, t_u, B, and/or H may alleviate the situation.

Economical Haul Time

The travel time in and of itself is not usually the prime consideration. Cost is usually the prime consideration. Costs are saved when a transfer operation is used because

1. The nonproductive time of collectors is reduced, because they no longer ride to and from the disposal site. It may be possible to reduce the number of collection crews needed because of increased productive collection time.
2. Any reduction in mileage traveled by the collection trucks results in a savings in operating costs.
3. The maintenance requirements for collection trucks can be reduced when these vehicles are no longer required to drive into the landfill site. Much of the damage to suspensions, drive trains, and tires occurs at landfills.
4. The capital cost of collection equipment may be reduced; because the trucks will be traveling only on improved roads, lighter duty, less expensive models can be used (U.S. EPA, 1995).

In order to compare "direct haul" with "transfer" costs, the costs are computed on the basis of $/Mg · km or, preferably, $/Mg · min. The time-based comparison is preferred because the average haul speed of the collection vehicle will often be greater than that of the transfer vehicle. Because it is time, not distance, that costs money, this gives a fairer comparison. In addition to the travel cost of operating the transfer vehicle, there are fixed costs for the construction and operation of the transfer station and for maneuvering and unloading the transfer vehicle. Figure 11-8 may be used to estimate the cost of the transfer station.

Example 11-3. The disposal site for Watapitae will be closed in two years because of the lack of capacity. An alternative disposal site will be available when the present site is closed. It will be a countywide regional system that will be 32.5 km from the collection route. Using the data from Examples 11-1 and 11-2 and the following assumptions, determine the maximum haul time for the collection vehicle and the cost for collection vehicle and transfer vehicle haul: $N_d = 1$, $B = 0.50$ h, and the amortized capital cost and operating cost for the transfer station is approximately $37/Mg.

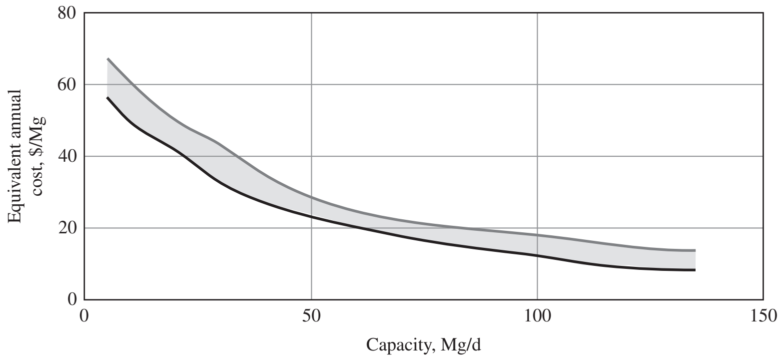

FIGURE 11-8
Transfer station equivalent annual cost as a function of capacity. Costs adjusted to 2006. (*Data Source:* Zuena, 1987.)

Solution. First we must determine whether or not the collection vehicle has the time to get to the disposal site while still making all of its pickups.

$$T_H = \frac{8.5}{1} - (0.0233)(250) - 2\,\frac{13}{60} - \frac{6}{60} - \frac{0.5}{1}$$
$$= 1.64 \text{ h or } 98.5 \text{ min}$$

We now note that the round trip distance is two times the distance from the collection route. The average haul speed can be determined from Figure 11-6. The average haul speed is 64 km/h. Thus, we find the round trip travel time to the regional facility to be

$$\frac{2(32.5 \text{ km})}{64 \text{ km/h}} = 1.02 \text{ h or } 61 \text{ min}$$

The collection vehicle can make it to the disposal site. However, because we have reduced the number of trips to the disposal site, we must either provide an additional vehicle of the same size or replace the existing one with one that is twice as large. Because the existing crew size can handle the 250 pickups per day, the more logical choice would seem to be to choose the larger vehicle. (This is especially true because the existing one is about to expire.) Let us assume the new vehicle will have a capacity of 10.0 m^3.

Now let us examine the comparative haul costs. First we will look at the collection vehicle. We will take the annual cost for a new vehicle exclusive of O & M to be $29,851. Assuming eight hours of operation per day for five days a week for 52 weeks per year, the annual cost per minute of operation is

$$\frac{\$29{,}851}{(8 \text{ h/d})(60 \text{ min/h})(5 \text{ d/w})(52 \text{ wk/y})} = \$0.2392/\text{min}$$

With the effective wage rate of $13.90 per hour from Example 11-2, the cost of wages and 125 percent overhead is

$$\frac{(\$13.90 \times 2.25)}{60 \text{ min/h}} = \$0.5213/\text{min}$$

per worker or \$1.0425/min for the crew. The operating cost will be about \$5.50 per kilometer. For travel to the disposal site, the cost per minute would be

$$\frac{(\$5.50/\text{km})(32.5\text{ km})(2)}{61\text{ min}} = \$5.8607/\text{min}$$

The factor of two is for the round trip to the disposal site. The total haul cost per trip would be

$$61[(\$0.2392) + (\$1.0425) + (\$5.8607)] = \$435.69$$

The mass of solid waste hauled per trip is

$$(\mathcal{V}_T)(D_T) = \text{mass}$$
$$(7.48\text{ m}^3)(400\text{ kg/m}^3) = 2{,}992\text{ kg, or }3.0\text{, Mg}$$

Note that the volume is twice that of a single trip (Example 11-2), but is considerably less than the capacity of the new vehicle. The unit cost of the haul would then be

$$\frac{\$435.69}{3.0\text{ Mg}} = 145.23\text{, or }\$145/\text{Mg}$$

Now let us look at the transfer vehicle. Assume that a tractor-trailer rig having a capacity of 46 m^3 has an annual cost exclusive of O & M of \$37,601. The cost per minute is then

$$\frac{\$37{,}601}{(8\text{ h/d})(60\text{ min/h})(5\text{ d/wk})(52\text{ wk/y})} = \$0.3013/\text{min}$$

Because the tractor-trailer rig requires an operator with higher skill, the wage rate will be higher. Using a rate of \$19.85 per hour and an overhead rate of 125 percent of wages, the cost per minute is

$$\frac{(\$19.85 \times 2.25)}{60\text{ min/h}} = \$0.7444/\text{min}$$

In contrast to the collection vehicle, the crew is comprised of only the operator. Thus, the crew cost is \$0.7444/min.

The operating cost will be about \$6.50 per kilometer. The time for the rig to travel to the disposal site will be about 25 percent more than the collection vehicle. The travel cost would then be

$$\frac{(\$6.50)(32.5)(2)}{61 \times 1.25} = \$5.541/\text{min}$$

The total haul cost per trip would be

$$(1.25)(61)[(\$0.3013) + (\$0.7444) + (\$5.541)] = \$502.23$$

Because the capacity of the rig is four times that of the collection vehicle, the mass hauled per trip is

$$4(3.0) = 12\text{ Mg}$$

The unit cost of the haul, including the cost of building and operating the transfer station (approximately \$37/Mg), would be

$$\frac{\$502.23}{12} + \$37 = 78.83, \text{ or } \$79/\text{Mg}$$

Obviously, consideration should be given to the construction and operation of a transfer station as an alternative to direct haul.

11-4 DISPOSAL BY MUNICIPAL SOLID WASTE LANDFILL

A municipal solid waste (MSW) landfill is defined as a land disposal site employing an engineered method of disposing of solid wastes on land in a manner that minimizes environmental hazards by spreading the solid wastes to the smallest practical volume, and applying and compacting cover material at the end of each day.

Site Selection

Site location is perhaps the most difficult obstacle to overcome in the development of a MSW landfill. Opposition by local citizens eliminates many potential sites. In choosing a location for a landfill, consideration should be given to the following variables:

1. Public opposition
2. Proximity of major roadways
3. Speed limits
4. Load limits on roadways
5. Bridge capacities
6. Underpass limitations
7. Traffic patterns and congestion
8. Haul distance (in time)
9. Detours
10. Hydrology
11. Availability of cover material
12. Climate (for example, floods, mud slides, snow)
13. Zoning requirements
14. Buffer areas around the site (for example, high trees on the site perimeter)
15. Historic buildings, endangered species, wetlands, and similar environmental factors.

In October of 1991, under Subtitle D of the Resource Conservation and Recovery Act (RCRA), the EPA promulgated new federal regulations for landfills. These regulations are known as the Criteria for Municipal Solid Waste Landfills (MSWLF Criteria). EPA also published a companion document to assist owners and municipalities comply with these criteria (U.S. EPA, 1998). These included siting criteria that specify restrictions on distances from airports, flood plains, and fault areas, as well as limitations on construction in wetlands, seismic impact areas, and other areas of unstable geology such as landslide areas and those susceptible to sink holes. Other restrictions may apply. For example, a landfill should be more than:

30 m from streams,

160 m from drinking water wells,

65 m from houses, schools, and parks, and

3,000 m from airport runways.

Site Preparation

The plans and specifications for a MSW landfill should require that certain steps be carried out before operations begin. These steps include grading the site area, constructing access roads and fences, and installing signs, utilities, and operating facilities.

On-site access roads should be of all-weather construction and wide enough to permit two-way truck travel (7.3 m). Grades should not exceed equipment limitations. For loaded vehicles, most uphill grades should be less than 7 percent, and downhill grades should be less than 10 percent.

All MSW landfill sites should have electric, water, and sanitary services. Remote sites may have to use acceptable substitutes, for example, portable chemical toilets, trucked-in drinking water, and electric generators. Water should be available for drinking, fire-fighting, dust control, and sanitation. Telephone or radio communications are desirable.

A small MSW landfill operation will usually require only a small building for storing hand tools and equipment parts and a shelter with sanitary facilities. A single building may serve both purposes. Buildings may be temporary and preferably movable.

Equipment

The size, type, and amount of equipment required at an MSW landfill depends on the size and method of operation, quantities and time of solid waste deliveries, and, to a degree, the experience and preference of the designer and equipment operators. Another factor to be considered is the availability and dependability of service from the equipment.

The most common equipment used on MSW landfills is the crawler or rubber-tired tractor (Figure 11-9). The tractor can be used with a dozer blade, trash blade, or a front-end loader. A tractor is versatile and can perform a variety of operations: spreading,

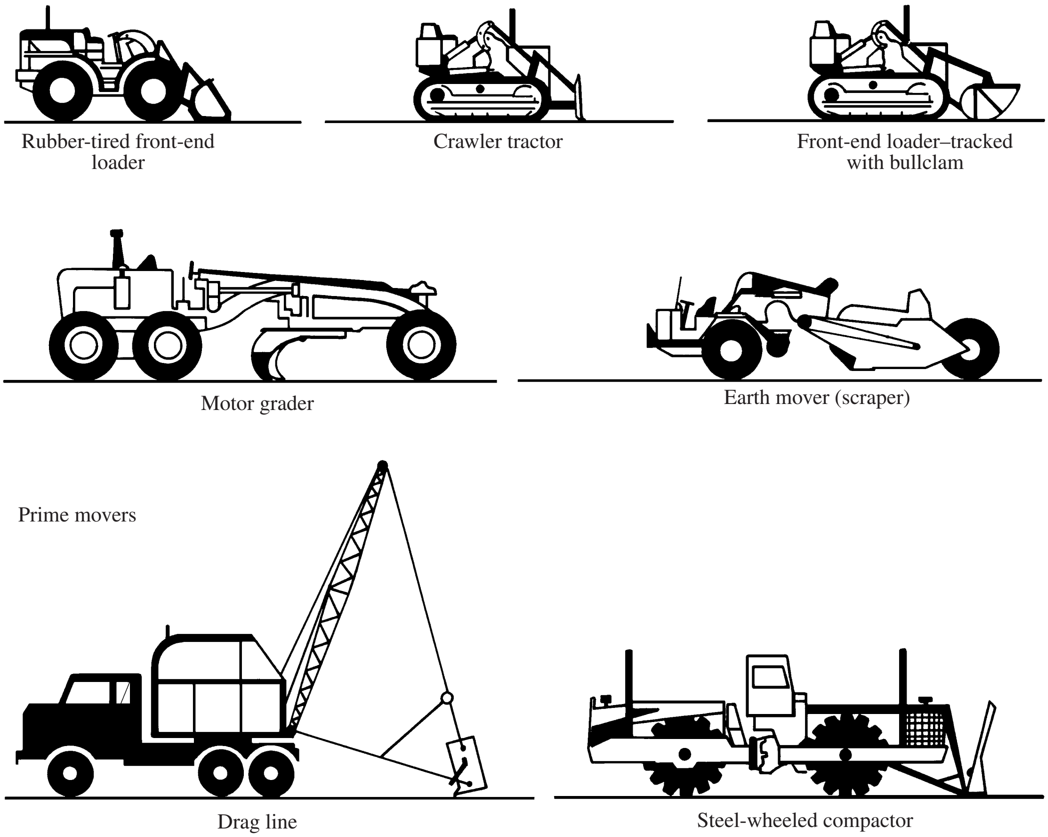

FIGURE 11-9
Municipal solid waste landfill equipment.

compacting, covering, trenching, and even hauling the cover material. The decision on whether to select a rubber-tired or a crawler-type tractor, and a dozer blade, trash blade, or front-end loader must be based on the conditions at each individual site (see Table 11-5).

The crawler dozer is excellent for grading and can be economically used for dozing solid waste or soil over distances up to 100 m. The larger trash or landfill blade can be used in lieu of a straight dozer blade, thereby increasing the volume of solid waste that can be dozed. The crawler loader has the capability to lift materials off the ground for carrying. It is an excellent excavator, well suited for trench operations.

Rubber-tired machines are generally faster than crawler machines. Because their loads are concentrated more, rubber-tired machines have less flotation and traction than crawler machines. Rubber-tired machines can be economically operated at distances of up to 200 m.

Steel-wheeled compactors are finding increased application at MSW landfills. In basic design, compactors are similar to rubber-tired tractors. The unique feature of

TABLE 11-5
Performance characteristics of landfill equipment[a]

Equipment	Spreading	Compacting	Excavating	Spreading	Compacting	Hauling	Density of compacted solid waste (kg/m^3)
Crawler dozer	E	G	E	E	G	NA	750
Crawler loader	G	G	E	G	G	NA	—
Rubber-tired dozer	E	G	F	G	G	G	733
Rubber-tired loader	G	G	F	G	G	G	—
Steel-wheeled compactor	E	E	P	G	E	NA	809
Scraper	NA	NA	G	E	NA	E	NA
Dragline	NA	NA	E	F	NA	NA	NA

[a] *Basis of evaluation:* Easily workable soil and cover material haul distance greater than 300 m.
Rating key: E, excellent; G, good; F, fair; P, poor; NA, not applicable.
Note: Density of "well-compacted" solid waste resulting from four passes over each square meter. Density measured after daily soil cover emplaced but not including soil in volume and weight measurements.
(*Source:* Data from Stone and Conrad, 1969, and O'Leary and Walsh, 2002.)

compactors is the design of their wheels, which are steel and equipped with teeth or lugs of varying shape and configuration. This design is employed to impart greater crushing and demolition forces to the solid waste. Use of compactors should be restricted to solid waste, because their design does not lend them to application of a smooth layer of compacted cover material. Thus, compactors are best used in conjunction with tracked or rubber-tired machines that can be used for cover material application.

Other equipment used at MSW landfills are scrapers, water wagons, drag-lines, dump trucks, and graders. This type of equipment is normally found only at large solid waste landfills where specialized equipment increases the overall efficiency.

Equipment size depends on the size of the operation. Small landfills for communities of 15,000 or less, or landfills handling 50 Mg of solid wastes per day or less, can operate successfully with one tractor in the 20 to 30 Mg range. Heavier equipment in the 30 to 45 Mg range, or larger, can handle more waste and achieve better compaction. Heavy equipment is recommended for MSW landfill sites serving more than 15,000 people or handling more than 50 Mg per day. MSW landfills serving 50,000 people or less or handling no more than about 150 Mg of solid waste per day normally can manage well with one piece of heavy equipment (30 to 45 Mg range).

Operation

Although various titles are used to describe the operating methods employed at MSW landfills, only two basic techniques are involved. They are termed the *area method* (Figure 11-10) and the *trench method* (Figure 11-11). At many sites, both methods are used, either simultaneously or sequentially.

In the area method, the solid waste is deposited on the surface, compacted, then covered with a layer of compacted soil at the end of the working day. Use of the area method is seldom restricted by topography; flat or rolling terrain, canyons, and other types of depressions are all acceptable. The cover material may come from on- or off-site.

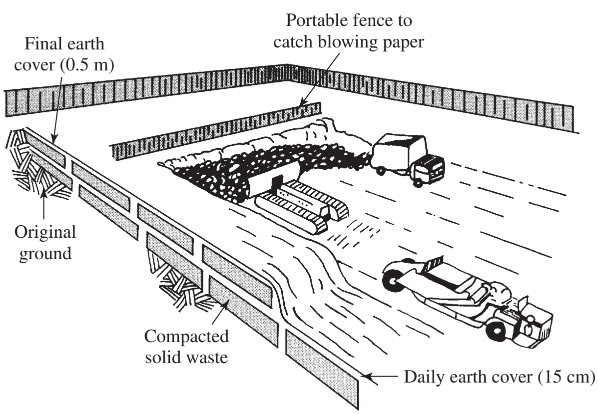

FIGURE 11-10
The area method.

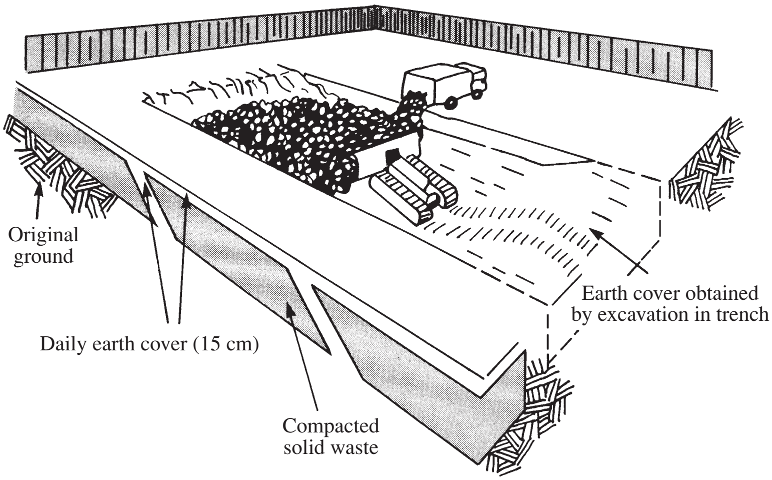

FIGURE 11-11
The trench method.

The trench method is used on level or gently sloping land where the water table is low. In this method a trench is excavated; the solid waste is placed in it and compacted; and the soil that was taken from the trench is then laid on the waste and compacted. The advantage of the trench method is that cover material is readily available as a result of trench excavation. Stockpiles can be created by excavating long trenches, or the material can be dug up daily. The depth depends on the location of the groundwater and/or the character of the soil. Trenches should be at least twice as wide as the compacting equipment so that the treads or wheels can compact all the material on the working area.

A MSW landfill does not need to be operated by using only the area or trench method. Combinations of the two are possible. The methods used can be varied according to the constraints of the particular site.

A profile view of a typical landfill is shown in Figure 11-12. The waste and the daily cover placed in a landfill during one operational period form a *cell*. The operational period is usually one day. The waste is dumped by the collection and transfer vehicles onto the working *face*. It is spread in 0.4 to 0.6 m layers and compacted by driving a crawler tractor or other compaction equipment over it. At the end of each day *cover* material is placed over the cell. The cover material may be native soil or other approved materials. Its purpose is to prevent fires, odors, blowing litter, and scavenging. The federal regulations also permit the state regulatory authority to allow the use of alternative daily covers (ADC) if the owner of the landfill can demonstrate that the alternative material functions as well as the earthen cover without presenting a threat to human health or the environment. Some landfills have successfully demonstrated that diverted wastes such as chipped tires, yard waste, shredded wood waste, and petroleum-contaminated soils can be used effectively as ADCs. Using these waste products as ADCs presents a cost savings for the landfill and also increases the landfill's available space. The use of manufactured ADCs such as colored tarps is also

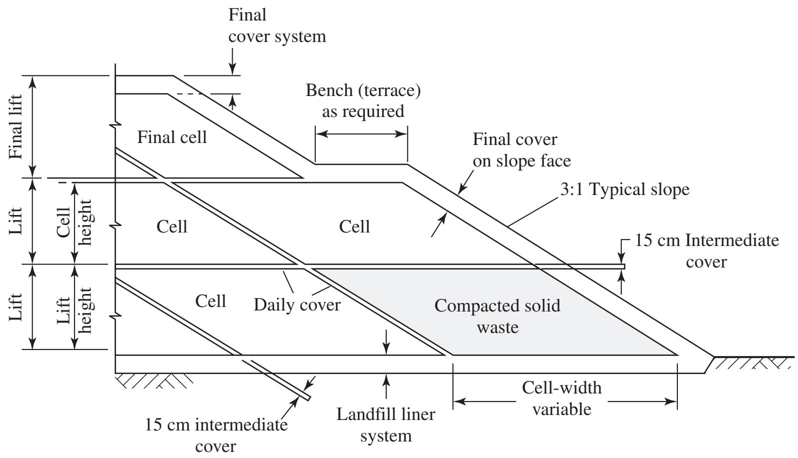

FIGURE 11-12
Sectional view through a MSW landfill. (*Source:* Tchobanoglous et al., 1993.)

being accepted in some localities. Recommended depths of cover for various exposure periods are given in Table 11-6. The dimensions of a cell are determined by the amount of waste and the operational period.

A *lift* may refer to the placement of a layer of waste or the completion of the horizontal active area of the landfill. In Figure 11-12 a lift is shown as the completion of the active area of the landfill. An extra layer of intermediate cover may be provided if the lift is exposed for long periods. The active area may be up to 300 m in length and width. The side slopes typically range from 1.5:1 to 2:1. Trenches vary in length from 30 to 300 m with widths of 5 to 15 m. The trench depth may be 3 to 9 m (Tchobanoglous et al., 1993).

Benches are used where the height of the landfill exceeds 15 to 20 m. They are used to maintain the slope stability of the landfill, for the placement of surface water drainage channels, and for the location of landfill gas collection piping.

Final cover is applied to the entire landfill site after all landfilling operations are complete. A modern final cover will contain several different layers of material to perform different functions. These are discussed more fully in the landfill design section of this chapter.

TABLE 11-6
Recommended depths of cover

Type of cover	Minimum depth (m)	Exposure time (d)
Daily	0.15	< 7
Intermediate	0.30	7 to 365
Final	0.60	> 365

Additional considerations in the operation of the landfill are those required by the 1991 Subtitle D regulations promulgated by EPA. These require exclusion of hazardous waste, use of cover materials, disease vector control, explosive gas control, air quality measurements, access control, runoff and run-on controls, surface water and liquids restrictions, and groundwater monitoring, as well as record keeping (40 CFR 257 and 258; FR 9 OCT 1991).

Environmental Considerations

Vectors (carriers of disease) and water and air pollution should not be a problem in a properly operated and maintained landfill. Good compaction of the waste, daily covering of the solid waste with good compaction of the cover, and good housekeeping are musts for control of flies, rodents, and fires.

Burning, which may cause air pollution, is never permitted at a MSW landfill. If accidental fires should occur, they should be extinguished immediately using soil, water, or chemicals. Odors can be controlled by covering the wastes quickly and carefully, and by sealing any cracks that may develop in the cover.

Landfill Gases. The principal gaseous products emitted from a landfill (methane and carbon dioxide) are the result of microbial decomposition. Typical concentrations of landfill gases and their characteristics are summarized in Table 11-7. During the early life of the landfill, the predominant gas is carbon dioxide. As the landfill matures, the gas is composed almost equally of carbon dioxide and methane. Because the methane is explosive, its movement must be controlled. The heat content of this landfill gas mixture

TABLE 11-7
Typical constituents found in MSW landfill gas

Component	Percent (dry volume basis)
Methane	45–60
Carbon dioxide	40–60
Nitrogen	2–5
Oxygen	0.1–1.0
Sulfides, disulfides, mercaptans, etc.	0–1.0
Ammonia	0.1–1.0
Hydrogen	0–0.2
Carbon monoxide	0–0.2
Trace constituents	0.01–0.06
Characteristic	**Value**
Temperature, °C	35–50
Specific gravity	1.02–1.05
Moisture content	Saturated
High heating value, kJ/m^3	16,000–20,000

(*Source:* G. Tchobanoglous et al., 1993.)

(16,000 to 20,000 kJ/m^3), although not as substantial as methane alone (37,000 kJ/m^3), has sufficient economic value that many landfills have been tapped with wells to collect it. At the end of 2004, there were 378 landfill gas (LFG) recovery projects in the United States. This is a four-fold increase over the 86 LFG projects operating in 1990.

Because of their toxicity, trace gas emissions from landfills are of concern. More than 150 compounds have been measured at various landfills. Many of these may be classified as volatile organic compounds (VOCs). The occurrence of significant VOC concentrations is often associated with older landfills that previously accepted industrial and commercial wastes containing these compounds. The concentrations of 10 compounds measured in landfill gases from several California sites are shown in Table 11-8.

Leachate

Liquid that passes through the landfill and that has extracted dissolved and suspended matter from it is called *leachate.* The liquid enters the landfill from external sources such as rainfall, surface drainage, groundwater, and the liquid in and produced from the decomposition of the waste.

Leachate Quantity. The amount of leachate generated from a landfill site may be estimated using a hydrologic mass balance for the landfill. Those portions of the global hydrologic cycle (see Chapter 4) that typically apply to a landfill site include precipitation, surface runoff, evaporation, transpiration (when the landfill cover is completed), infiltration, and storage. Precipitation may be estimated in the conventional fashion from climatological records. Surface runoff or run-on may be estimated using the rational formula (Equation 4-19 or 4-20). Evaporation and transpiration are often lumped together as *evapotranspiration.* It may be estimated from regional data such as that provided by the U.S. Geologic Service *Water Atlas.* Infiltration (and exfiltration) may be estimated using Darcy's law (Equation 4-27). Until the landfill becomes saturated, some of the water infiltration will be stored in both the cover material and the waste. The quantity of water that can be held against the pull of gravity is referred to as *field capacity* (Figure 11-13 on page 822). Theoretically, when the landfill reaches its field capacity, leachate will begin to be produced. Then, the potential quantity of leachate is the amount of moisture within the landfill in excess of the field capacity. In reality, leachate will begin to be produced almost immediately because of channeling in the waste. The following equation may be used to estimate the field capacity of the waste (Tchobanoglous et al., 1993):

$$FC = 0.6 - 0.55\left(\frac{2.205W}{10{,}000 + 2.205W}\right) \tag{11-7}$$

where FC = field capacity (fraction of water in the waste based on dry weight of the waste)

W = overburden mass of waste calculated at midheight of the lift in question, kg

The EPA and the Waterways Experiment Station of the U.S. Army Corps of Engineers developed a microcomputer model of the hydrologic balance called the Hydrologic Evaluation of Landfill Performance (HELP) (Schroeder et al., 1984). The

TABLE 11-8
Concentrations of specified air contaminants measured in landfill gases (in parts per billion)

	Landfill Site						
Compound	Yolo Co.	City of Sacramento	Yuba Co.	El Dorado Co.	L.A.-Pacific (Ukiah)	City of Clovis	City of Willits
Vinyl chloride	6,900	1,850	4,690	2,200	<2	66,000	7.5
Benzene	1,860	289	963	328	<2	895	<18
Ethylene dibromide	1,270	<10	<50	<1	<1	<1	<0.5
Ethylene dichloride	nr	nr	nr	<20	0.2	<20	4
Methylene chloride	1,400	54	4,500	12,900	<1	41,000	<1
Perchloroethylene	5,150	92	140	233	<0.2	2,850	8.1
Carbon tetrachloride	13	<5	<7	<5	<0.2	<5	<0.2
1,1,1-TCA[1]	1,180	6.8	<60	3,270	0.52	113	0.8
TCE[2]	1,200	470	65	900	<0.6	895	8
Chloroform	350	<10	<5	120	<0.8	1,200	<0.8
Methane	nr	nr	nr	nr	0.11%	17%	0.14%
Carbon dioxide	nr	nr	nr	nr	0.12%	24%	<0.1%
Oxygen	nr	nr	nr	nr	nr	10%	21%

nr: Not reported by operator
[1]1,1,1-TCA: 1,1,1-trichloroethane, methyl chloroform
[2]TCE: Trichloroethene, trichloroethylene
(*Data Source:* CARB, 1988.)

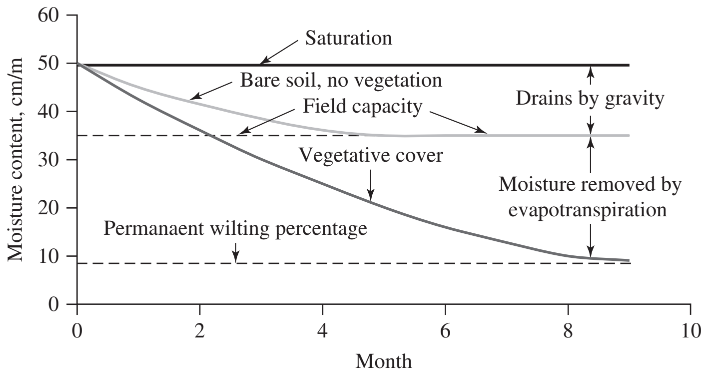

FIGURE 11-13
Soil moisture relationships.

program contains extensive data on the characteristics of various soil types, precipitation patterns, and evapotranspiration-temperature relationships as well as the algorithms to perform a routing of the moisture flow through the landfill.

Leachate Composition. Solid wastes placed in a sanitary landfill may undergo a number of biological, chemical, and physical changes. Aerobic and anaerobic decomposition of the organic matter results in both gaseous and liquid end products. Some materials are chemically oxidized. Some solids are dissolved in water percolating through the fill. A range of leachate compositions is listed in Table 11-9. The VOCs in the landfill gas often contribute to contamination of groundwater because they dissolve in the leachate as it passes through the landfill. Henry's law (see Chapter 5) may be used to estimate the VOC concentrations that might occur in the leachate. Because of the differential heads (slope of the piezometric surface), the water containing dissolved substances moves into the groundwater system. The result is gross pollution of the groundwater.

Bioreactor Landfills

The implementation of RCRA Subtitle D resulted in more stringent protection of the environment, particularly the groundwater resources. The future trend in landfill design appears to be the development of engineered systems that optimize waste degradation and so minimize the amount of land needed for waste disposal. One technology that shows a lot of promise is bioreactor landfills. EPA has initiated a number of studies and partnerships with waste management companies to fully investigate the potential of this technology.

In traditional municipal solid waste landfills, organic waste eventually decomposes and stabilizes. These processes are controlled by microorganisms. In bioreactor landfills, biological decomposition is accelerated by enhancing the conditions necessary for these microorganisms to flourish. This is accomplished by the controlled addition of supplemental air and water. The degradation and stabilization of organic waste is then accelerated.

TABLE 11-9
Typical data of the composition of leachate from new and mature landfills

Constituent	Value, mg/L		
	New landfill (less than 2 years)		Mature landfill (greater than 10 years)
	Range	Typical	
BOD_5 (5-day biochemical oxygen demand)	2,000–30,000	10,000	100–200
TOC (total organic carbon)	1,500–20,000	6,000	80–160
COD (chemical oxygen demand)	3,000–60,000	18,000	100–500
Total suspended solids	200–2,000	500	100–400
Organic nitrogen	10–800	200	80–120
Ammonia nitrogen	10–800	200	20–40
Nitrate	5–40	25	5–10
Total phosphorus	5–100	30	5–10
Ortho phosphorus	4–80	20	4–8
Alkalinity as $CaCO_3$	1,000–10,000	3,000	200–1,000
pH (no units)	4.5–7.5	6	6.6–7.5
Total hardness as $CaCO_3$	300–10,000	3,500	200–500
Calcium	200–3,000	1,000	100–400
Magnesium	50–1,500	250	50–200
Potassium	200–1,000	300	50–400
Sodium	200–2,500	500	100–200
Chloride	200–3,000	500	100–400
Sulfate	50–1,000	300	20–50
Total iron	50–1,200	60	20–200

(*Source:* Tchobanoglous et al., 1993.)

EPA defines a bioreactor landfill as "any permitted Subtitle D landfill (under RCRA) or landfill cell where liquid or air is injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of the waste" (40 CFR 257 and 258, FR, 9 OCT 1991.) In these landfills additional moisture is introduced to the waste, typically by recirculating the leachate and adding additional moisture such as stormwater, wastewater, and wastewater treatment plant sludge. The goal is to provide enough moisture to the waste to maintain the optimal moisture content for microbial decomposition, typically 35 to 65 percent moisture.

One of the benefits of this system is that the decomposition rate is increased, so complete decomposition can occur in years instead of decades. The waste density is increased, so over the life of the landfill, 15 to 30 percent additional space is available. Also, the cost of the leachate disposal is reduced, because it is recirculated. And there is a significant increase in the landfill gas that is generated. If this is captured on-site, then it can be used to produce energy.

These systems have a higher initial cost to build and operate, because extensive recirculation and monitoring is required. Bioreactor landfills can be designed to use aerobic, anaerobic, or facultative microorganisms.

Phases of Bioreaction. Five more or less sequential phases of bioreaction are thought to occur in a landfill. In the *initial adjustment phase,* the organic biodegradable components in the MSW undergo aerobic biodegradation because some air is trapped when the waste is placed in the landfill. In a conventional landfill, the principle source of microorganisms is the soil material that is used as daily and final cover. Digested wastewater treatment plant sludge as well as recycled leachate are also sources of microorganisms. In a bioreactor landfill, the latter sources provide a means of accelerating the decomposition process.

The second phase is called the *transitional phase.* Oxygen is depleted and anoxic and anaerobic conditions begin to develop. As the landfill becomes anaerobic, nitrate and sulfate serve as electron acceptors. Nitrogen, hydrogen, and hydrogen sulfide are products of the decomposition process. As the conversion process proceeds, the microbial community responsible for conversion of organic material to methane and carbon dioxide begin the three-step process described in Chapter 8 (Figure 8-35).

In the *acid phase,* the anaerobic microbial activity initiated in the second phase accelerates. Significant amounts of organic acids are produced and the production of hydrogen decreases. Carbon dioxide is the principle gas produced in this phase. The pH of the leachate will often drop to 5 or lower (Tchobanoglous et al., 1993).

The fourth phase is called the *methane fermentation phase. Methanogens* convert the acetic acid and hydrogen gas produced by the acid formers into methane (CH_4) and CO_2. The pH of the leachate rises to more neutral values in the range 6 to 8.

The *maturation phase* begins after the readily available biodegradable organic matter has been converted to CH_4 and CO_2. The rate of landfill gas generation decreases dramatically.

Volume of Gas Produced. Cossu et al. (1996) present the following reaction representing the overall methane fermentation process:

$$C_aH_bO_cN_d + nH_2O \rightarrow x\,CH_4 + y\,CO_2 + w\,NH_3 = z\,C_5H_7O_2N + \text{energy} \quad (11\text{-}8)$$

where $C_aH_bO_cN_d$ is the empirical formula for the biodegradable organic matter and $C_5H_7O_2N$ is the empirical chemical formula of bacterial cells.

The maximum theoretical landfill gas yield (neglecting bacterial cell conversion) may be estimated as (Tchobanoglous et al., 1993):

$$C_aH_bO_cN_d + \left(\frac{4a - b - 2c + 3d}{4}\right)H_2O \rightarrow \left(\frac{4a + b - 2c - 3d}{8}\right)CH_4 + \left(\frac{4a - b + 2c + 3d}{8}\right)CO_2 + dNH_3 \quad (11\text{-}9)$$

For the purpose of analysis, the MSW may be divided into two classes: rapidly biodegradable and slowly biodegradable. Food waste, newspaper, office paper, cardboard, leaves, and leafy yard trimmings fall into the first category. Textiles, rubber, leather, tree branches, and wood fall into the second category.

Tchobanoglous et al. (1993) developed empirical chemical formulas for typical U.S. MSW as collected in 1990 for each of these categories:

- Rapidly decomposable = $C_{68}H_{111}O_{50}N$
- Slowly decomposable = $C_{20}H_{29}O_9N$

These formulas may be used to estimate the maximum theoretical gas production. Actual quantities of gas will be lower because (1) all of the biodegradable organic matter is not available for decomposition, (2) the biodegradability is less for organic wastes with high lignin content, and (3) moisture may be limiting. The construction and operation of a bioreactor landfill is designed to minimize these limitations. Actual gas production rates from typical MSW landfills ranges from 40 to 400 m^3/Mg of MSW.

The rate of decomposition that is reflected in gas production of MSW is highly variable. Most models use first-order equations in two stages to describe the gas production as it rises to some peak value and then falls (Cossu et al., 1996).

Gas Flux. The rate of evolution of gas from the landfill cover is called the *gas flux*. It may be estimated with the following equation:

$$F_A = \frac{D_A\, \eta^{4/3}\,(C_{A\text{-}atmos} - C_{A\text{-}fill})}{T} \tag{11-10}$$

Where F_A = gas flux of compound A, $g/m^2 \cdot min$
η = landfill cover porosity
D_A = diffusion coefficient of compound A, m^2/min
$C_{A\text{-}atmos}$ = concentration of compound A at surface of landfill cover, g/m^3
$C_{A\text{-}fill}$ = concentration of compound A at bottom of landfill cover, g/m^3
T = depth of landfill cover, m

Landfill Design

The design of the landfill has many components including site preparation, buildings, monitoring wells, size, liners, leachate collection system, final cover, and gas collection system. Figure 11-14 shows a schematic of a typical municipal solid waste landfill with all of these components shown. In the following discussion we will limit ourselves to introductory consideration of the design of the size of the landfill, the selection of a liner system, the design of a leachate collection system, and a discussion of the final cover system.

Volume Required. To estimate the volume required for a landfill, it is necessary to know the amount of refuse being produced and the density of the in-place, compacted refuse. The volume of refuse differs markedly from one city to another because of local conditions.

Salvato recommends a formula of the following form for estimating the annual volume required (Salvato, 1972).

$$\mathcal{V}_{LF} = \frac{PEC}{D_c} \tag{11-11}$$

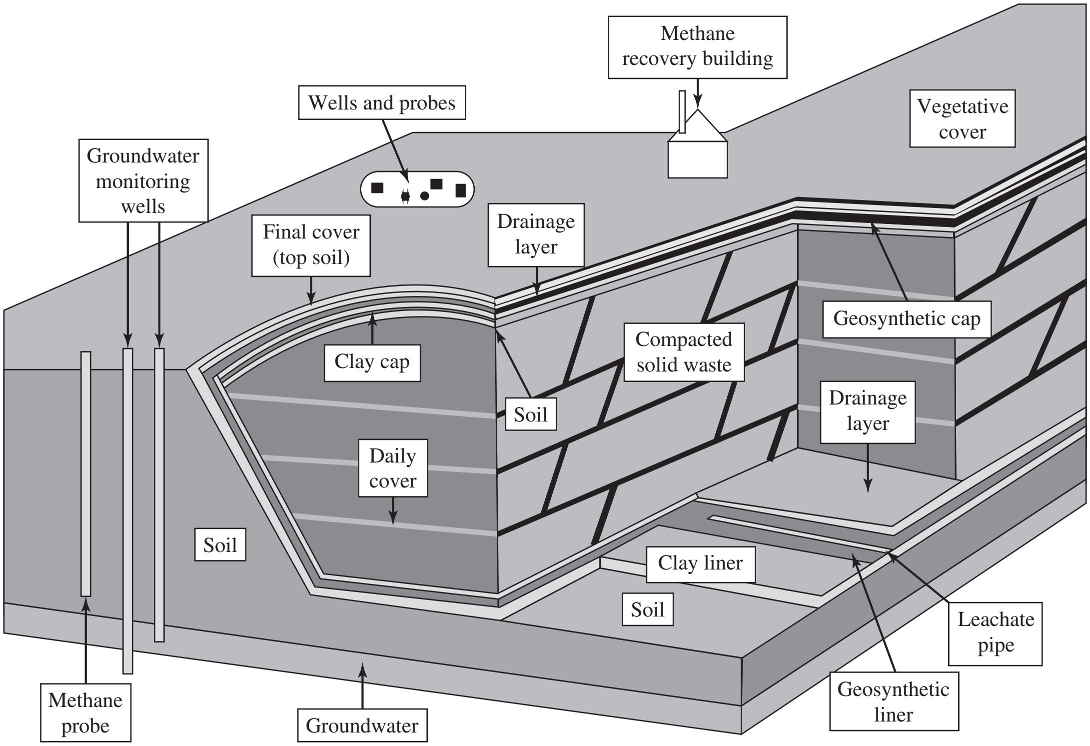

FIGURE 11-14
Schematic of a typical municipal solid waste landfill.
(*Source:* U.S. EPA, 1995.)

where $\forall_{LF}$ = volume of landfill, m^3
P = population
E = ratio of cover (soil) to compacted fill

$$= \frac{\forall_{sw} + \forall_c}{\forall_{sw}}$$

$\forall_{sw}$ = volume of solid waste, m^3
$\forall_c$ = volume of cover, m^3
C = average mass of solid waste collected per capita per year, kg/person
D_c = density of compacted fill, kg/m^3

The density of the compacted fill is somewhat dependent on the equipment used at the landfill site and the moisture content of the waste. Compacted solid waste densities vary from 300 to 700 kg/m^3. Nominal values are generally in the range of 475 to 600 kg/m^3. The compaction ratios given in Table 11-10 may be used for estimating the density of the compacted fill.

TABLE 11-10
Typical compaction ratios[a]

Component	Poorly compacted	Normal compaction	Well-compacted
Food wastes	2.0	2.8	3.0
Paper	2.5	5.0	6.7
Cardboard	2.5	4.0	5.8
Plastics	5.0	6.7	10.0
Textiles	2.5	5.8	6.7
Rubber, leather, wood	2.5	3.3	3.3
Garden trimmings	2.0	4.0	5.0
Glass	1.1	1.7	2.5
Nonferrous metal	3.3	5.6	6.7
Ferrous metal	1.7	2.9	3.3
Ashes, masonry	1.0	1.2	1.3

[a] The ratio of the density after compaction to that as discarded, that is, before pickup by collection vehicle.
(*Source:* Tchobanoglous et al., 1977)

Example 11-4. How much landfill space does Watapitae require for 20 years of operation? Assume that the village will use a cell height of 2.4 m and that it will follow normal practice and use 0.15 m of soil for daily cover; 0.3 m to complete the cell; and a final cover of 0.6 m for every stack of three cells. Assume that compaction will be "normal."

Solution. Although we do not know the population or per capita waste generation rate, we can estimate the mass generated per year from other data. From Example 11-1 we know that 1,250 service stops must be collected each week. From Example 11-2 we know that each service stop contributes an average of 0.624 Mg per year. Then the annual mass generation rate is

$$\text{Mass} = (1{,}250 \text{ stops}) \times (0.624 \text{ Mg/y stop}) = 780 \text{ Mg/y}$$

This is equivalent to the product $(P)(C)$ in Equation 11-11.

In Example 11-1 we determined that the mean density of the uncompacted solid waste was 106 kg/m^3. Using the fractional mass composition of the waste as given in Table 11-4 and the "normal" compaction ratios in Table 11-10, we can determine the weighted compaction ratio by multiplying the fractional mass by the compaction ratio (Table 11-11).

With a compaction ratio of 4.18, the density of the compacted fill is estimated to be

$$D_c = (106 \text{ kg/m}^3) \times (4.18) = 443 \text{ kg/m}^3 \text{ or } 0.443 \text{ Mg/m}^3$$

Note that this implies that waste dumped at the face of the fill in a 1.25-m layer would have to be compressed to a depth of 0.3 m, that is,

$$\left(\frac{1}{4.18}\right)(1.25 \text{ m})$$

TABLE 11-11
Weighted compaction ratios for Example 11-4

Component	Mass fraction	Weighted compaction ratio
Food wastes	0.0947	0.27
Paper	0.4317	2.16
Cardboard	0.0650	0.26
Plastics	0.0181	0.12
Textiles	0.0020	0.01
Rubber	—	—
Leather	0.0150	0.05
Garden trimmings	0.1432	0.57
Wood	0.0350	0.12
Glass	0.0749	0.12
Tin cans	0.0520	0.29
Nonferrous metals	0.0150	0.08
Ferrous metals	0.0430	0.12
Dirt, ashes, brick	0.0110	0.01
Total	1.0006	4.18

Before we can estimate E, we must determine the daily volume of solid waste and the area over which it will be spread. For a five-day week, the daily volume is determined as follows:

$$\forall = \frac{780 \text{ Mg/y}}{0.443 \text{ Mg/m}^3} \times \frac{1}{52 \text{ wk/y}} \times \frac{1}{5 \text{ d/wk}} = 6.77 \text{ m}^3\text{/d}$$

If this is spread in a 0.3-m layer, then the area would be

$$\frac{6.77 \text{ m}^3}{0.3 \text{ m}} = 22.57 \text{ m}^2\text{/d}$$

This is equivalent to a square 4.75 m on each side. This seems reasonable for a small community.

If 0.15 m of soil is used as cover each day, then 0.45 m will be placed each day and it will take

$$\frac{2.4 \text{ m} - 0.15 \text{ m}}{0.45 \text{ m/day}} = 5.00 \text{ days}$$

to complete the cell. (The 0.15 m is the addition to daily cover to complete the cell with 0.3 m of cover.) At this rate we will complete a stack of three cells every three weeks (15 working days).

The soil volume separating a stack of three cells will be about

$$0.3 \text{ m thick} \times 2.4 \text{ m high} \times 4.75 \text{ m long} \times 3 \text{ cells} = 10.26 \text{ m}^3$$

To account for two sides of the cell, this number needs to be multiplied by two.

$$10.26 \text{ m}^3 \times 2 = 20.52 \text{ m}^3$$

If we ignore this volume, E can be calculated as

$$E = \frac{0.3 + (0.15 + 0.03 + 0.02)}{0.3} = 1.67$$

The terms in the brackets account for the daily cover of 0.15 m; the cell cover of an additional 0.15 m each five days or 0.03 m per day; and the final stack cover of an additional 0.3 m to the three-cell cover each 15 days or 0.02 m per day.

If we do not ignore the soil separating the cells, then the soil volume per stack of three cells as shown in Figure 11-15 is calculated as follows:

$$(3 \text{ cells/stack})(5 \text{ lifts/cell})(22.57 \text{ m}^2)(0.15 \text{ m}) = 50.78 \text{ m}^3$$

plus the 0.15 m of additional soil to bring the weekly cell cover to 0.30 m is

$$(3 \text{ cells/stack})(22.57 \text{ m}^2)(0.15 \text{ m}) = 10.16 \text{ m}^3$$

plus the additional 0.3 m to bring the final cover to 0.6 m,

$$(22.57 \text{ m}^2)(0.3 \text{ m}) = 6.77 \text{ m}^3$$

The total soil volume, including the 20.52 m^3 for the sides of the stack, is

$$50.78 + 10.16 + 6.77 + 20.52 = 88.23 \text{ m}^3$$

The value for $\forall_{sw}$ would then be

$$\forall_{sw} = (6.77 \text{ m}^3/\text{d})(15 \text{ d/stack}) = 101.55 \text{ m}^3/\text{stack}$$

The value for E would then be

$$E = \frac{101.55 + 88.23}{101.55} = 1.87$$

Thus, for this landfill, the separation wall will increase the volume by about 12 percent. This is not insignificant!

The estimated volume requirement for 20 years would be

$$\forall_{LF} = \frac{(780 \text{ Mg/y})(1.87)}{0.443 \text{ Mg/m}^3} \times 20 \text{ y} = 6.59 \times 10^4 \text{ m}^3$$

Since the average landfill depth will be three 2.4 m cells plus an additional 0.3 m final cover, the area will be

$$A_{LF} = \frac{6.59 \times 10^4}{(3)(2.4) + 0.3} = 8.78 \times 10^3 \text{ m}^2$$

An area approximately 100 m on a side would do very nicely.

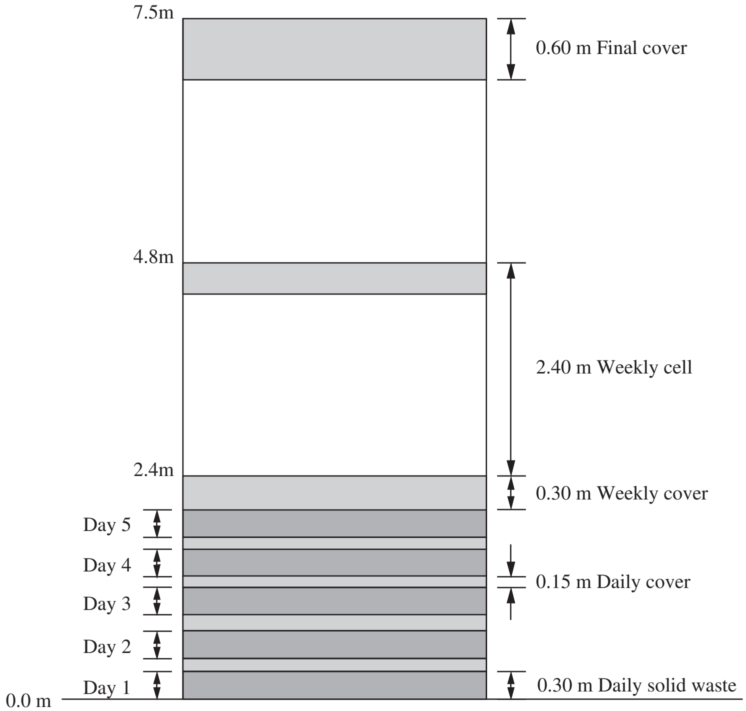

FIGURE 11-15
Schematic diagram of MSW landfill stack of three cells (Example 11-4).

Liner Selection. In order to prevent groundwater contamination, strict leachate control measures are required. Under the 1991 Subtitle D rules promulgated by EPA, new landfills must be lined in a specific manner or meet maximum contaminant levels for the groundwater at the landfill boundary. The specified liner system includes a synthetic membrane (*geomembrane*) at least 30 mils (0.76 mm) thick supported by a compacted soil liner at least 0.6 m thick. The soil liner must have a hydraulic conductivity of no more than 1×10^{-7} cm/s. Flexible membrane liners consisting of high-density polyethylene (HDPE) must be at least 60 mils thick (40 CFR 257 and 258, and FR 9 OCT 1991). A schematic of the EPA specified liner system is shown in Figure 11-16.

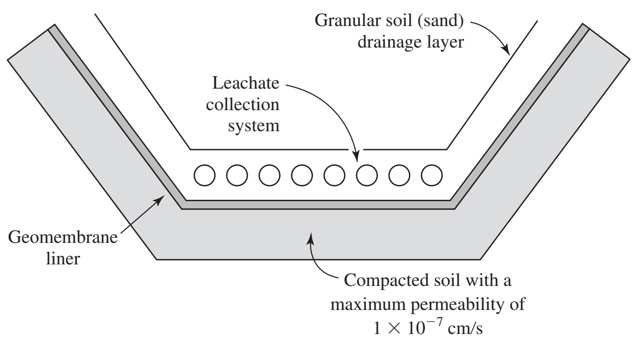

FIGURE 11-16
A composite liner and leachate collection system.

Several geomembrane materials are available. Some examples include polyvinyl chloride (PVC), high-density polyethylene (HDPE), chlorinated polyethylene (CPE), and ethylene propylene diene monomer (EPDM). Designers show a strong preference for PVC and especially for HDPE. Although the geomembranes are highly impermeable (hydraulic conductivities are often less than 1×10^{-12} cm/s), they can be easily damaged or improperly installed. Damage may occur during construction by construction equipment, by failure due to tensile stress generated by the overburden, tearing as a result of differential settling of the supporting soil, puncture from sharp objects in the overburden, puncture from coarse aggregate in the supporting soil, and tearing by landfill equipment during operation. Installation errors primarily occur during seaming when two pieces of geomembrane must be attached or when piping must pass through the liner. A liner placed with adequate quality control should have less than 3 to 5 defects per hectare.

The soil layer under the geomembrane acts as a foundation for the geomembrane and as a backup for control of leachate flow to the groundwater. Compacted clay generally meets the requirement for a hydraulic conductivity of less than 1×10^{-7} cm/s. In addition to having a low permeability, it should be: free of sharp objects greater than 1 cm in diameter, graded evenly without pockets or hillocks, compacted to prevent differential settlement, and free of cracks.

Leachate Breakthrough. Historically, landfill liners were constructed with only a single clay liner. Over time the leachate will pass through the liner. This is called *breakthrough*. The following equation may be used to estimate the time to breakthrough:

$$t = \frac{T^2 \eta}{K(H + T)} \tag{11-12}$$

FE

Where t = breakthrough time, y
T = thickness of the clay liner, m
η = clay liner porosity
K = hydraulic conductivity, m/y
H = depth of leachate above liner (also called "head"), m

Leachate Collection. Under the 1991 Subtitle D rules promulgated by EPA, the leachate collection system must be designed so that the depth of leachate above the liner does not exceed 0.3 m. The leachate collection system is designed by sloping the floor of the landfill to a grid of underdrain pipes* that are placed above the geomembrane. A 0.3-m-deep layer of granular material (for example, sand) with a high hydraulic conductivity (EPA recommends greater than 1×10^{-2} cm/s) is placed over the geomembrane to conduct the leachate to the underdrains. In addition to carrying the leachate, this layer also protects the geomembrane from mechanical damage from equipment and solid waste. In some instances a geonet (a synthetic matrix that resembles a miniature chain link fence), with a geofabric (an open-weave cloth) protective layer to keep out the sand, is placed under the sand and above the geomembrane to increase the flow of leachate to the pipe system.

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*Underdrain pipes are perforated pipes designed to collect the leachate.

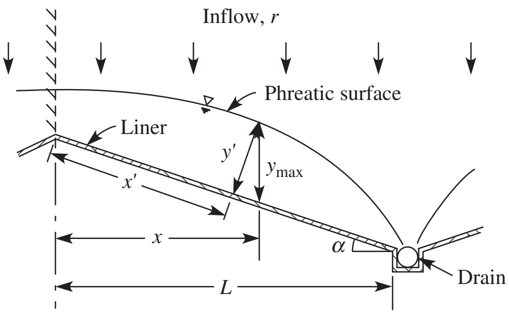

FIGURE 11-17
Geometry and symbols for calculating Y_{max}. (*Source:* McEnroe, 1993.)

Several different methods for estimating the steady-state maximum leachate depth have been proposed. EPA has proposed the following formula (refer to Figure 11-17 for an explanation of the notation) (U.S. EPA, 1989):

$$y_{max} = L\left(\frac{r}{2K}\right)^{0.5}\left[\frac{KS^2}{r} + 1 - \frac{KS}{r}\left(S^2 + \frac{r}{K}\right)^{0.5}\right] \tag{11-13}$$

where y_{max} = maximum saturated depth, m
L = drainage distance, measured horizontal, m
r = vertical flow rate per unit horizontal area, $m^3/s \cdot m^2$
K = hydraulic conductivity of drainage layer, m/s
S = slope of liner (= tan α)

This formula may overestimate the value of y_{max} where the underdrain system has free drainage, that is, it is not undersized or clogged. Because this is commonly the case, McEnroe has proposed the following equations as a better approximation. (McEnroe, 1993):

$$Y_{max} = (R - RS + R^2S^2)^{0.5}\left[\frac{(1 - A - 2R)(1 + A - 2RS)}{(1 + A - 2R)(1 - A - 2RS)}\right]^{0.5A} \tag{11-14}$$

for $R < 1/4$;

$$Y_{max} = \frac{R(1 - 2RS)}{1 - 2R}\exp\left[\frac{2R(S - 1)}{(1 - 2RS)(1 - 2R)}\right] \tag{11-15}$$

for $R = 1/4$;
and

$$Y_{max} = (R - RS + R^2S^2)^{0.5}\exp\left[\frac{1}{B}\tan^{-1}\left(\frac{2RS - 1}{B}\right) - \frac{1}{B}\tan^{-1}\left(\frac{2R - 1}{B}\right)\right] \tag{11-16}$$

for $R > 1/4$;

where $Y_{max} = y_{max}/(L \tan \alpha)$
$R = r/(K \sin^2 \alpha)$
S = slope of liner (= $\tan \alpha$)
$A = (1 - 4R)^{0.5}$
$B = (4R - 1)^{0.5}$

The collected leachate must be treated because of the high concentration of pollutants it contains. In some instances on-site treatment is provided. This frequently is a biological treatment system. In other cases, the leachate may be pumped to a municipal treatment plant. In some recent designs, the leachate is recirculated through the landfilled waste. This provides moisture for the microbial population and accelerates the stabilization process. It also promotes the production of methane and provides some treatment for the biodegradable fraction of the constituents in the leachate.

Final Cover. The major function of the final cover is to prevent moisture from entering the finished landfill. If no moisture enters, then at some point in time the leachate production will reach minimal proportions and the chance of groundwater contamination will be minimized.

Modern final cover design consists of a surface layer, biotic barrier, drainage layer, hydraulic barrier, foundation layer, and gas control. The surface layer is to provide suitable soil for plants to grow. This minimizes erosion. A soil depth of about 0.3 m is appropriate for grass. The biotic barrier is to prevent the roots of the plants from penetrating the hydraulic barrier. At this time, there does not seem to be a suitable material for this barrier. The drainage layer serves the same function here as in the leachate collection system—that is, it provides an easy flow path to a grid of perforated pipes. This collection piping system is subject to differential settling and may fail because of this settling. Some designers do not recommend installing it as they prefer to use the funds to develop a thicker hydraulic barrier. The hydraulic barrier serves the same function as the liner in that it prevents movement of water into the landfill. The EPA recommends a composite liner consisting of a geomembrane and a low hydraulic conductivity soil that also serves as the foundation for the geomembrane. This soil also protects the geomembrane from the rough aggregate in the gas control layer. The gas control layer is constructed of coarse gravel that acts as a vent to carry the gases to the surface. If the gas is to be collected for its energy value, a series of gas recovery wells is installed. A negative pressure is placed on these wells to draw the gas into the system.

Completed MSW Landfills

Completed landfills generally require maintenance because of uneven settling. Maintenance consists primarily of regrading the surface to maintain good drainage and filling in small depressions to prevent ponding and possible subsequent groundwater pollution. The final soil cover should be about 0.6 m deep.

Completed landfills have been used for recreational purposes such as parks, playgrounds, or golf courses. Parking and storage areas or botanical gardens are other final uses. Because of the characteristic uneven settling and gas evolution from landfills, construction of buildings on completed landfills should be avoided.

On occasion, one-story buildings and runways for light aircraft might be constructed. In such cases, it is important to avoid concentrated foundation loading, which can result in uneven settling and cracking of the structure. The designer must provide the means for the gas to dissipate into the atmosphere and not into the structure.

11-5 WASTE TO ENERGY

Utilization of the organic fraction of solid waste for fuel, while simultaneously reducing the volume, may be an important part of an integrated waste management plan. Specially designed power plants known as waste-to-energy facilities can produce energy through the combustion of municipal solid waste. In these facilities, trash volume is reduced by 90 percent and its weight by 75 percent. The remaining residue is disposed of in a MSW landfill. According to a 2004 Integrated Waste Services Association publication, 89 waste-to-energy facilities were in operation as of that time, disposing of 86 Gg of waste each day (IWSA, 2004). This waste was converted to approximately 2,500 megawatts of electric power.

Heating Value of Waste

The heating value of waste is measured in kilojoules per kilogram (kJ/kg), and is determined experimentally using a bomb calorimeter. A dry sample is placed in a chamber and burned. The heat released at a constant temperature of 25°C is calculated from a heat balance. Because the combustion chamber is maintained at 25°C, combustion water produced in the oxidation reaction remains in the liquid state. This condition produces the maximum heat release and is defined as the *higher heating value* (HHV).

In actual combustion processes, the temperature of the combustion gas remains above 100°C until the gas is discharged into the atmosphere. Consequently, the water from actual combustion processes is always in the vapor state. The heating value for actual combustion is termed the *lower heating value* (LHV). The following equation gives the relationship between HHV and LHV:

$$\text{LHV} = \text{HHV} - [(\Delta H_v)(9\ \text{H})] \tag{11-17}$$

where ΔH_v = heat of vaporization of water
= 2,420 kJ/kg
H = hydrogen content of combusted material

The factor of 9 results because one gram mole of hydrogen will produce 9 gram moles of water (that is, 18/2). Note that this water is only that resulting from the combustion reaction. If the waste is wet, the free water must also be evaporated. The energy required to evaporate this water may be substantial. This results in a very inefficient combustion process from the point of view of energy recovery. The ash content also reduces the energy yield because it reduces the proportion of dry organic matter per kilogram of fuel and because it retains some heat when it is removed from the furnace.

Fundamentals of Combustion

Combustion is a chemical reaction where the elements in the fuel are oxidized. In waste-to-energy (WTE) plants, the fuel is, of course, the solid waste. The major oxidizable elements in the fuel are carbon and hydrogen. To a lesser extent sulfur and nitrogen are also present. With complete oxidation, carbon is oxidized to carbon dioxide, hydrogen to water, and sulfur to sulfur dioxide. Some fraction of the nitrogen may be oxidized to nitrogen oxides.

The combustion reactions are a function of oxygen, time, temperature, and turbulence (O, T, T, T). There must be a sufficient excess of oxygen to drive the reaction to completion in a short period of time. The oxygen is most frequently supplied by forcing air into the combustion chamber. Over 100 percent excess air may be provided to ensure a sufficient excess. Sufficient time must be provided for the combustion reactions to proceed. The amount of time is a function of the combustion temperature and the turbulence in the combustion chamber. Some minimum temperature must be exceeded to initiate the combustion reaction (that is, to ignite the waste). Higher temperatures also yield higher quantities of nitrogen oxide emissions, so there is a tradeoff in destroying the solid waste and forming air pollutants. Mixing of the combustion air and the combustion gases is essential for completion of the reaction.

As the solid waste enters the combustion chamber and its temperature increases, volatile materials are driven off as gases. Rising temperatures cause the organic components to thermally "crack" and form gases. When the volatile compounds are driven off, fixed carbon remains. When the temperature reaches the ignition temperature of carbon (700°C), it is ignited. To achieve destruction of all the combustible material (*burnout*), it is necessary to achieve 700°C throughout the bed of waste and ash (Pfeffer, 1992).

The flame zone is that area where the hot volatilized gases mix with oxygen. This reaction is very rapid. It goes to completion within 1 or 2 seconds if there is sufficient excess air and turbulence.

The evolution of solid waste combustion has led to higher temperatures both to destroy toxic compounds and to increase the opportunity to utilize the waste as an energy source by producing steam.

Conventional Incineration

The basic arrangement of the conventional incinerator is shown in Figure 11-18. Although the solid waste may have some heat value, it is normally quite wet and is not *autogenous* (self-sustaining in combustion) until it is dried. Conventionally, auxiliary fuel is provided for the initial drying stages. Because of the large amount of particulate matter generated in the combustion process, some form of air pollution control device is required. Normally, electrostatic precipitators or scrubbers are chosen. Bulk volume reduction in incinerators is about 90 percent. Thus, about 10 percent of the material still must be carried to a landfill.

Recovering Energy from Waste

In order to utilize the heat value of solid waste, most modern combustion devices are designed to recover the energy. The concept is more than 100 years old. The first refuse-to-electricity system was built in Hamburg, Germany, in 1896. In 1903, the first of several solid waste-fired electricity generating plants in the United States was installed in New York City.

There are now many WTE plants operating in the United States. They burn solid waste in a specially designed incinerator furnace jacketed with water-filled tubes to recover the heat as steam. The steam may be used directly for heating or to produce electricity.

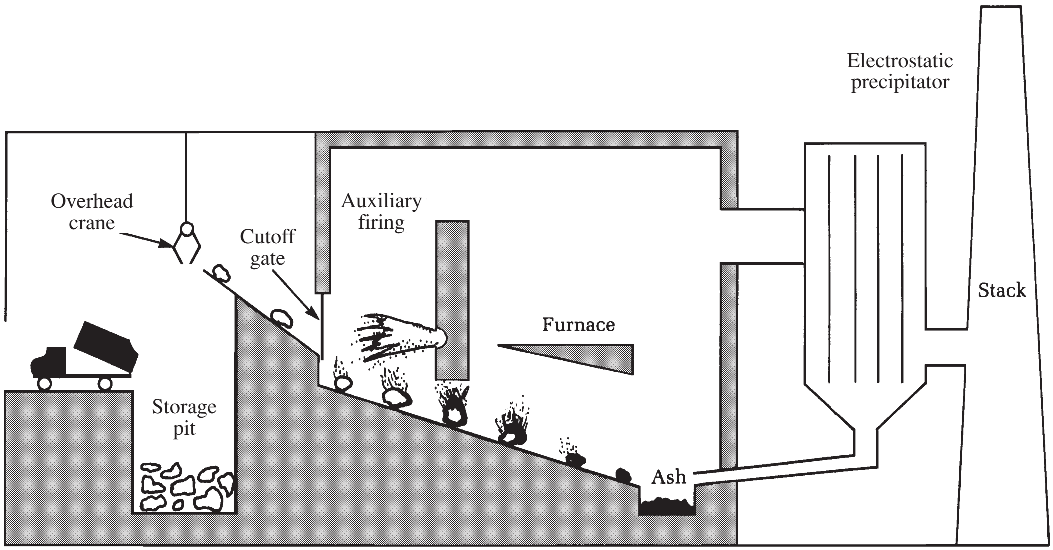

FIGURE 11-18
Schematic of a conventional traveling grate incinerator.

Many states require public utilities to buy the electricity produced at these plants. With efficient heat recovery and electric generators, WTE plants can produce about 600 kWh per mg of waste.

Refuse-Derived Fuel (RDF). Refuse-derived fuel is the combustible portion of solid waste that has been separated from the noncombustible portion through processes such as shredding, screening, and air classifying (Vence and Powers, 1980). By processing municipal solid waste (MSW), refuse-derived fuel containing 12 to 16 MJ/kg can be produced from between 55 and 85 percent of the refuse received. This system is also called a supplemental fuel system because the combustible fraction is typically marketed as a fuel to outside users (utilities or industries) as a supplement to coal or other solid fuels in their existing boilers.

In a typical system, MSW is fed into a trommel or rotating screen to remove glass and dirt, and the remaining fraction is conveyed to a shredder for size reduction. Shredded wastes may then pass through an air classifier to separate the "light fraction" (plastics, paper, wood, textiles, food wastes, and smaller amounts of light metals) from the "heavy fraction" (metals, aluminum, and small amounts of glass and ceramics).

The light fraction, after being routed through a magnetic system to remove ferrous metals, is ready for fuel use. The heavy fraction is conveyed to another magnetic removal system for recovery of ferrous metals. Aluminum may also be recovered. The remaining glass, ceramics, and other nonmagnetic materials from the heavy fraction are then sent to the landfill.

The first full-scale plant to prepare RDF has been in operation in Ames, Iowa, since 1975. Subsequently, other plants using similar technology have been designed and constructed. Figure 11-19 shows the process flow diagram for the Southeastern Virginia Public Service Authority's RDF plant.

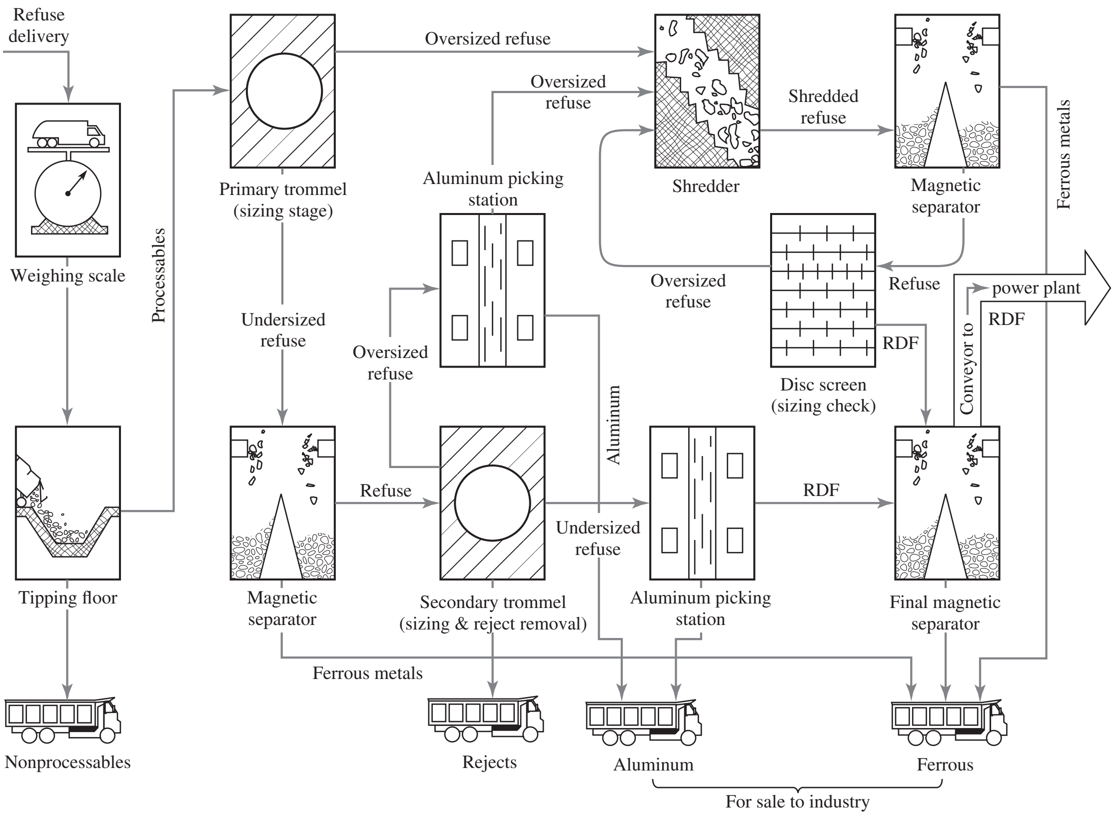

FIGURE 11-19
Southeastern Virginia Public Service Authority's refuse-derived fuel (RDF) plant.

Although there are a number of RDF production systems operating or starting up, they are still developmental in terms of process, equipment, and application. Data still are being gathered for prediction of performance and maintenance requirements.

Modular Incinerators. These units are available in various sizes. Their modularity enables them to be coupled with similar units to process available tonnage.

Most modular incinerators that produce energy incorporate a controlled air principle, use unprocessed MSW, and require a small amount of auxiliary fuel for startup. The waste is fed into a primary chamber where it is burned in the absence of sufficient oxygen for complete combustion. The resulting combustible gas passes through a second chamber, where excess air is injected, completing combustion. Auxiliary fuel may also be required in minimal quantities to maintain proper combustion temperatures.

After most of the particulate matter burns off, the hot effluent passes through a waste heat boiler to produce steam. The ash is water-quenched and disposed of at a landfill. The steam can be used directly or can be converted to electricity with the addition of a turbine generator.

The newer waste-to-energy plants are not without their problems. Serious concern has been raised about emissions of dioxins that result from the combustion process.

Two approaches are used to reduce the dioxin emission. Because the dioxin is formed as a combustion by-product from chlorinated plastics, it can be minimized by reducing the plastic in the feed stream. The second approach is to utilize sophisticated air pollution control equipment.

A second problem is associated with the ash from the combustion process. There are two categories of ash generated: fly ash from the air pollution control equipment and bottom ash from the furnace. Fly ash is of greater concern because the metals are adsorbed on particulates and are easily leached with water. When fly ash is mixed with bottom ash, the leachability of the metals is reduced. In 1994, the Supreme Court ruled that ash from municipal incinerators is not excluded from being considered as a hazardous waste (Chicago vs. EDF, 1994). It must be tested before it can be landfilled and must be treated if it fails the tests.

11-6 RESOURCE CONSERVATION AND RECOVERY FOR SUSTAINABILITY

Background and Perspective

The earth's prime mineral deposits are limited. As high-quality ores are depleted, lower-grade ores must be used. Lower-grade ores require proportionately greater amounts of energy and capital investment to extract. In a broad economic context, we should view with concern the long-term reasonableness of a market-accounting system that applies only current development costs to our use of depletable, nonrenewable natural resources such as aluminum, copper, iron, and petroleum. High rates of solid waste production imply high rates of virgin raw material extraction. In the United States, blatant mispricing—including the "depletion allowance" on minerals and unreasonably low rail rate fares on ores in contrast to scrap—is in no small way responsible for this state of affairs. Furthermore, our high-waste, low-recycle lifestyle is inherently wasteful of a bountiful endowment of natural resources.

Our renewable resources, primarily timber, are also under siege. Our prepackaged society, in combination with a wanton lack of care in our forests, has strained nature's capacity for growth and replenishment. Europe, India, and Japan have long been faced with a want of timber. We in the United States should learn from their predicaments.

The prevention of waste generation (resource conservation) and the productive use of waste material (resource recovery) represent means of alleviating some of the problems of solid waste management. At one time in our history, resource recovery played an important role in our industrial production. Until the mid-twentieth century, salvage (recovery and recycling) from household wastes was an important source of materials. In the five years preceding 1939, recycled copper, lead, aluminum, and paper supplied 44, 39, 28, and 30 percent, respectively, of the total raw materials shipments to fabricators in the United States (NCRR, 1974). Ultimately, it became more economical to process virgin materials than to use recovered materials.

In principle, processable municipal solid waste could provide 95 percent and 73 percent of our nation's needs in glass and paper, respectively. EPA estimates that overall, 30 percent of municipal solid waste was recovered in 2003. This represents an increasing trend. Table 11-12 shows the trend in recycling and reuse from 1960 to

TABLE 11-12
Generation, materials recovery, composting, and discards of municipal solid waste, 1960–2003[a, b]

	1960	1970	1980	1990	2000	2003
Generation	80.1	110.1	137.8	186.6	212.8	214.8
Recovery for recycling	5.1	7.3	13.2	26.4	47.6	50.4
Recovery for composting[c]				3.8	15.0	15.4
Total materials recovery	**5.1**	**7.3**	**13.2**	**30.2**	**62.6**	**65.7**
Discards after recovery	75.0	102.7	124.7	156.4	150.1	149.0

[a]*Source:* U.S. EPA, 2003. [b]In teragrams (Tg).
[c]Composting of yard trimmings, food scraps, and other MSW organic material. Does not include backyard composting. Details may not add because of rounding.

2003 in millions of tons of waste. In 2003, 65.7 Tg million tons of waste were diverted from landfills by recycling and composting.

Table 11-13 shows a breakdown of recovered waste by 1=1 product in 2003. EPA estimates that during 2003, nearly 39 percent of containers and packaging were recycled. About 44 percent of aluminum beverage cans were recycled, as well as 48 percent of paper and paperboard, 22 percent of glass containers, and 8 percent of plastic packaging and containers. Newspapers, the most recycled product, were recycled at a rate of about 82 percent, while used telephone books were recycled at a rate of only 16 percent.

Recycling of municipal solid waste for profit or for energy recovery is rarely cost-effective. However, many communities have initiated recycling programs as a means of protecting the environment. Citizens have become increasingly aware of their role in protecting the natural environment, and so demand that communities offer recycling services. EPA has also set national goals to encourage active resource conservation and recovery programs.

Most states and the District of Columbia have enacted laws on recycling ranging from purchasing preferences to comprehensive recycling goals. Over 8,000 curbside recycling programs, 3,000 composting programs, and 200 municipal recycling facilities are in operation (Wolpin, 1994, and U.S. EPA, 2003). The recyclable market continues to fluctuate dramatically. For example, the price of old newsprint fell from \$50/Mg in 1988 to less than \$10/Mg in 1993 (Rogoff and Williams, 1995). It rose to over \$100/Mg in 1995 (Paul, 1995).

The remainder of our discussion will be devoted to the technical details of several of the more promising resource conservation and recovery (RC & R) techniques. We have divided these into three broad categories entitled low technology, medium technology, and high technology. These categories refer to increasing degrees of sophistication in terms of implementation, equipment, and capital investment. No municipal government should be enticed into any one of these schemes with the hope of making money. The best that can be hoped for is defraying the additional costs over conventional landfilling and extending the life of the landfill by some modest amount. In some cases, even these modest goals may not be achieved.

TABLE 11-13
Generation and recovery of products in MSW by material 2003[a,b]

	Mass generated[c]	Mass recovered[c]	Recovery as a percent of generation
Durable goods			
Steel	10.16	3.06	30.2
Aluminum	0.96	Neg.[f]	Neg.
Other nonferrous metals[d]	1.44	0.96	66.7
Total metals	12.52	4.02	32.1
Glass	1.61	Neg.	Neg.
Plastics	7.61	0.30	3.9
Rubber and leather	5.36	1.00	18.6
Wood	4.78	Neg.	Neg.
Textiles	2.75	0.29	10.6
Other materials	1.18	0.89	75.4
Total durable goods	35.83	6.50	18.1
Nondurable goods			
Paper and paperboard	40.19	16.42	40.8
Plastics	5.76	Neg.	Neg.
Rubber and leather	0.80	Neg.	Neg.
Textiles	6.69	1.09	16.3
Other materials	2.96	Neg.	Neg.
Total nondurable goods	56.34	17.51	31.0
Containers and packaging			
Steel	2.58	1.56	60.6
Aluminum	1.76	0.63	35.6
Total metals	4.34	2.19	50.4
Glass	9.71	2.13	22.0
Paper and paperboard	35.20	19.87	56.4
Plastics	10.80	0.96	8.9
Wood	7.58	1.16	15.3
Other materials	0.20	Neg.	Neg.
Total containers and packaging	67.86	26.31	38.8
Other wastes			
Food, other[e]	25.04	0.68	2.7
Yard trimmings	25.95	14.61	56.3
Miscellaneous inorganic wastes	3.28	Neg.	Neg.
Total other wastes	54.25	15.33	28.2
Total MSW	214.28	65.59	30.6

[a]*Source:* U.S. EPA, 2003.
[b]Includes waste from residential, commercial, and institutional sources.
[c]In teragrams (Tg).
[d]Includes lead from lead-acid batteries.
[e]Includes recovery of other MSW organic material for composting.
[f]Neg. = negligible.

Low Technology RC & R

Returnable Beverage Containers. The substitution of reusable products for single-use "disposable" products is a workable means of conserving natural resources. Legislation requiring mandatory refunds and/or deposits on both returnable and nonreturnable beverage containers has been and will continue to be hotly contested by the beverage and beverage container industries. States that have enacted mandatory refund and/or deposit legislation include California, Connecticut, Delaware, Hawaii, Maine, Massachusetts, Michigan, New York, Oregon, and Vermont as of 2002. The programs are successful in encouraging recycling of containers. Between 90 and 95 percent of the bottles are returned and between 80 and 85 percent of the cans are returned. In Oregon, a reduction in total roadside litter of 39 percent by item count and 47 percent by volume was reported after the second year of implementation of its law. Furthermore, for glass containers there is a significant energy savings in that a glass bottle reused 10 times consumes less than one-third of the energy of a single-use container. Average reuse cycles vary from 10 to 20 times per container.

Recycling. The reprocessing of wastes to recover an original raw material was formerly called *salvage* and is now called *recycling.* At its lowest and most appropriate technological level, the materials are separated at the source by the consumer (*source-separation*). This is the most appropriate level because it requires the minimum expenditure of energy. With stringent goals for recycling, municipalities are looking at detailed recycling options.

Generally, the recycling options available to a municipality for residential use include:

Curbside collection

Drop-off centers

Material processing facility

Material transfer stations

Leaf/yard waste compost

Bulky waste collection and processing

Tire recovery

The primary method of recycling in the United States today is curbside collection. This has the advantage of being easier on the resident than having to drive to a recycling center. There are two basic types of curbside collection for recycling. In the first, the homeowner is given a number of bins or bags. The homeowner separates the refuse as it is used, placing it in the appropriate bin. On collection day the container is placed on the curb. The primary disadvantage of supplying home storage containers is the cost, which can represent a significant investment. A second method of curbside recycling is to provide the homeowner with only one bin, into which is placed all the recyclable materials. Curbside personnel then separate material as it is being picked up, placing each type of material into a separate compartment in the vehicle.

A second alternative is a drop-off center. Because recycling is a community-specific operation, a drop-off system must be designed around and in consideration of conditions particular to the area of involvement. To evaluate and select the most appropriate drop-off system, we must consider critical factors such as location, materials handled, population, number of centers, operation, and public information. When drop-offs are used to supplement curbside programs, fewer and smaller drop-off sites may be required. When drop-off sites are the only, or primary, recycling system in a community, the system must provide for increased capacity. Careful planning to accommodate traffic flow, as well as storage and collection of materials, must be part of the siting activity.

The convenience of a drop-off center will directly affect the amount of citizen participation. Strategically locating a drop-off center in an area of high traffic flow, where the center is highly visible, will encourage a greater level of participation. Even rural areas with widely scattered populations provide good locations for drop-offs. Rural homeowners have certain common travel patterns that bring them to a few locations at regular intervals—to a grocery store, church, or post office, to name a few. Figure 11-20 shows an example of a drive-through material recycling center.

A third major type of recycling is a materials recovery facility. In this case the recyclable material is taken by the municipality to a central facility where the material is separated via mechanical and labor-intensive means. Figure 11-21 shows an example layout of a separation facility and Figure 11-22 shows a mass balance of what can be expected at such a facility.

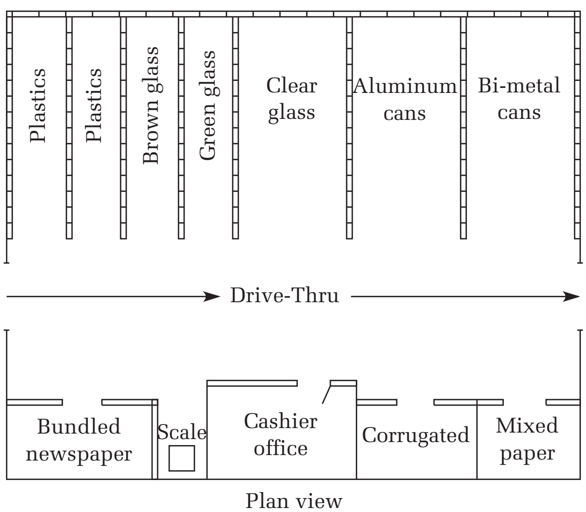

FIGURE 11-20
Enclosed drive-through drop-off center.

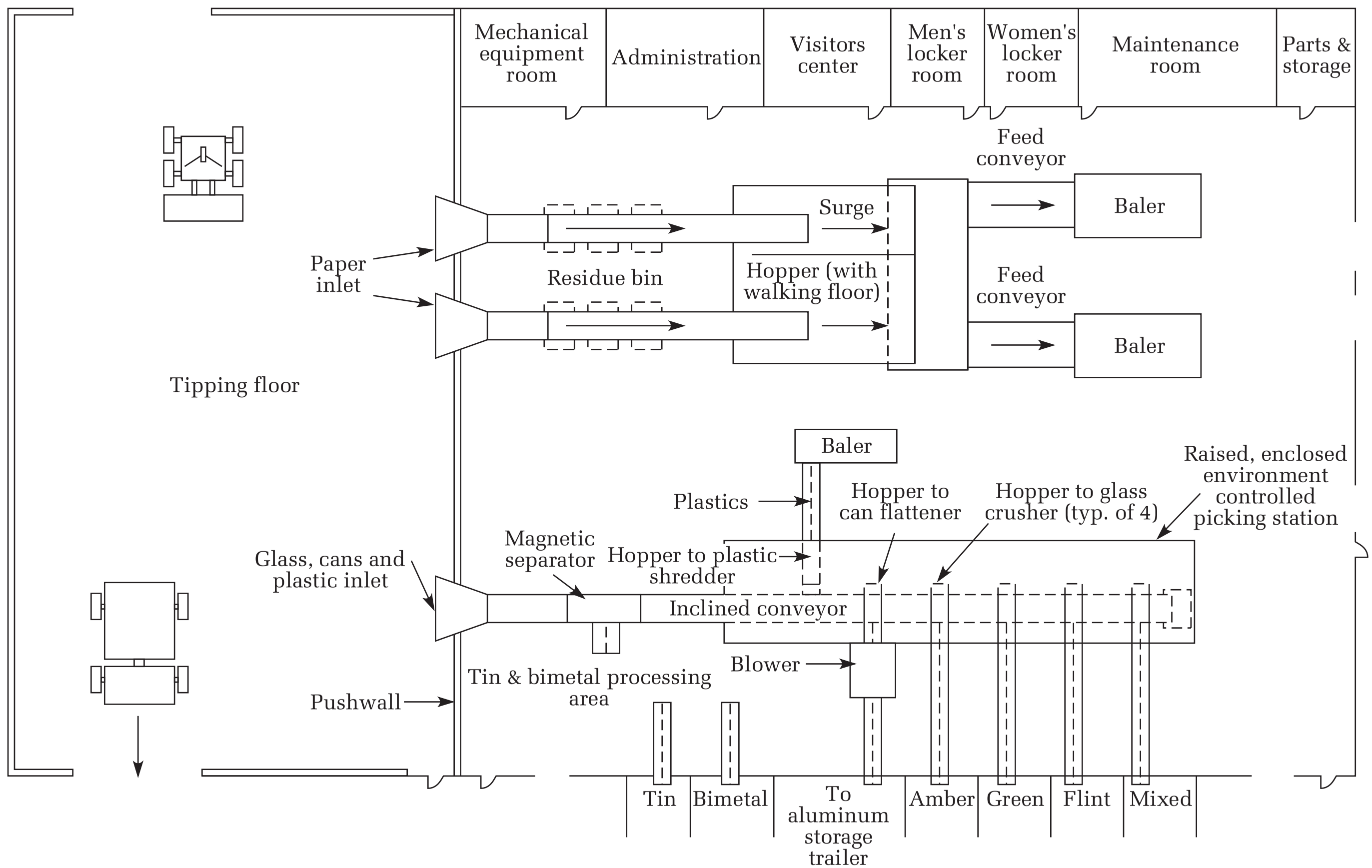

FIGURE 11-21
Material processing conceptual floor plan.

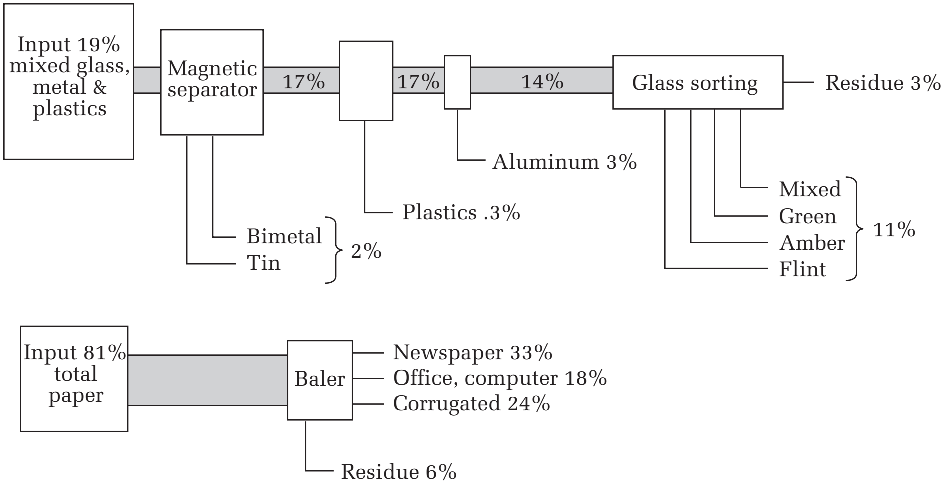

FIGURE 11-22
Material recovery facility process mass flow.

Medium Technology RC & R

Product Design. Simple changes in product configuration or packaging can result in conservation of resources. Three examples will suffice to illustrate the concept. In the mid-1970s several newspapers (for example, *Los Angeles Times, Washington Post,* and *New York Times*) switched from a traditional eight-column format to a new six-column format for news and nine-column format for advertising. This shift resulted in a 5 percent reduction in the amount of newsprint consumed. A large retail grocery store found that it could eliminate the custom of double bagging groceries by using a slightly heavier-weight bag with a reinforced bottom. This resulted in a 30 percent savings in the amount of fiber consumed. Many fast-food restaurants eliminated styrofoam containers for their sandwiches and now use paper wrapping, which is more readily biodegraded.

These kinds of changes are generally beyond the scope of the environmental engineer. However, their use can be encouraged, and purchases can be made that support those who use environmentally conservative packages and products.

Shredding and Separation. As a first step in a medium technology system or as an add-on to a landfill volume enhancement program, some materials may be reclaimed at a central processing point. The most likely candidates for recycling are paper, nonferrous metals (for example, aluminum), and ferrous metals. Paper generally is removed by hand as the MSW passes along on a conveyor belt.* After passing through a shredder, ferrous metals can be removed using a magnetic separator. In large communities, where more than 1,000 Mg/wk of MSW is collected, some consideration may

*Depending upon the economy, hand sorting may be a losing proposition. An average worker can pick about 2.0 Mg of newspaper in an eight-hour day. At a wage of $5.50/h, a day's wages amount to $44.00, exclusive of overhead and fringe benefits. Using an overhead rate of 100 percent, the cost of sorting is $44.00/Mg. If the price for No. 6 newsprint (a grade of paper) is $22/Mg as it was in 1994, this is a loss of $22/Mg before transportation costs are deducted. Of course, in 1995, when the price was $116/Mg, it was a winning proposition.

be given to the separation and shredding of auto and truck tires. Asphaltic concrete plants may be able to use the shredded tires in their raw material feedstock. Because tires are troublesome at landfills (because no matter how deep they are buried, they often pop up to the surface), their recovery as a resource is doubly beneficial.

Composting. Compost is a humus-like material that results from the aerobic biological stabilization of the organic materials in solid waste. The most effective composting occurs when the waste stream is free of inorganic materials. Frequently, this makes source-separated yard waste ideal. For the biological process to be effective, the following conditions must be met (Tchobanoglous et al., 1993).

1. Particle size must be small (< 5 cm).
2. Aerobic conditions must be maintained by turning the compost pile or forcing air through it.
3. Adequate, but not excessive, moisture must be present (50 to 60 percent).
4. An adequate population of acclimated microorganisms must be present.
5. The carbon-to-nitrogen ratio must be in the range of 20–25 to 1.

The biodegradation process is exothermic and a well-operating compost will have a temperature between 55 and 60°C during the period of active degradation. These temperatures are effective in destroying pathogens. The processing cycle for composting is about 20 to 25 days with active degradation taking place over a 10- to 15-day period. One of the major drawbacks of composting is odors. Maintenance of aerobic conditions and a proper cure time minimize odor problems.

Compost is useful as a soil conditioner. In this role compost will: (1) improve soil structure, (2) increase moisture-holding capacity, (3) reduce leaching of soluble nitrogen, and (4) increase the buffer capacity of the soil. It should be emphasized that compost is not a valuable fertilizer. It contains only 1 percent or less of the major nutrients, such as nitrogen, phosphorus, and potash.

Composting is one of the fastest-growing aspects of ISWM. The driving force is legislation enacted to extend the life of landfills by removing yard waste from the waste stream. According to the EPA, recovery by composting was negligible in 1988. By 1990, EPA estimated that 2 percent of the nation's solid waste was being composted. The 2000 estimate was that 7 percent of the solid waste was being composted. In 1994, over 3,000 composting facilities were operating in the United States. Sludge composting facilities numbered over 180, and municipal solid waste composting was being practiced by 21 cities (Monk, 1994).

Methane Recovery. Methane is produced in sanitary landfills as a result of anaerobic decomposition of the organic fraction of the waste. In addition to gas extraction wells and a collection system, some gas processing equipment is employed. The minimum processing consists of dehydration, gas cooling, and, perhaps, removal of heavy hydrocarbons. The gas produced is a low-Joule gas having heating value of 18.6 MJ/m^3. In high-Joule processing systems, carbon dioxide and some hydrocarbons are removed to yield essentially pure methane. The resulting gas is of pipeline quality and has a heating value of approximately 37.3 MJ/m^3. The anticipated quantity of landfill gas (LFG) varies between 0.6 and 8.7 liters per kilogram of solid waste present per year (L/kg · y). The average production rate is 5 L/kg · y.

Although landfill sites as small as 11 ha have yielded substantial quantities of recoverable methane, the capital investment and complexity of the gas processing equipment will limit this technique to the larger sites (>65 ha). Otherwise, the technology is readily available and can make use of a resource that otherwise would dissipate into the atmosphere. According to EPA data, in 1999, 360 LFG-recovery projects nationwide produced the equivalent of 1,200 MW of power (Skinner, 1999).

High Technology RC & R

In the mid-1970s, under the auspices of the U.S. Environmental Protection Agency and with federal financing, several innovative high technologies for resource recovery were examined. At the end of the decade, a few workable systems and a large number of unworkable systems were identified.

Because the successful high technology systems depend, to a large measure, on the recovery of energy for their success, we will consider the worth of solid waste as a fuel. As illustrated in Table 11-14, MSW is not a very good fuel. On the other hand, its cost of $0.00/Mg may seem quite attractive. This is especially so when the price of anthracite coal may be $50/Mg and the price of No. 2 fuel oil is $250/Mg. Unfortunately, solid

TABLE 11-14
Net heating value of various materials

Material	Net heating value (MJ/kg)
Charcoal	26.3
Coal, anthracite	25.8
Coal, bituminous (hi volatile B)	28.5
Fuel oil, no. 2 (home heating)	45.5
Fuel oil, no. 6 (bunker C)	42.5
Garbage	4.2
Gasoline (regular, 84 octane)	48.1
Methane[a]	55.5
Municipal solid waste (MSW)	10.5
Natural gas[a]	53.0
Newsprint	18.6
Refuse derived fuel (RDF)	18.3
Rubber	25.6
Sewage gas[a]	21.3 to 26.6
Sewage sludge (dry solids)	23.3
Trash	19.8
Wood, oak	13.3 to 19.3
Wood, pine	14.9 to 22.3

[a]Densities taken as follows (all in kg/m^3): CH_4 = 0.680; natural gas = 0.756; sewage gas = 1.05.

waste, as a fuel, has a hidden cost. Unless the physical characteristics are upgraded by removing metals and glass and by reducing the particle size, MSW cannot be burned in conventional coal-fired power plants. The alternative is the construction of a special power plant that can handle the MSW as it is received. In either case, some cost is imposed.

It appears that if a high technology resource recovery facility is to be successful, it must meet the following criteria (Serper, 1980):

1. High technology resource recovery can only be economical in large metropolitan areas where landfill sites are unavailable or are very expensive, above $25/Mg, or in geographic locations where the water table makes safe landfilling impossible, as, for example, the city of New Orleans and its surrounding suburbs.
2. There must be an adequate refuse supply committed to the facility (a minimum of 1.8 Gg/d is needed). In general, this implies a population of 250,000 or more.
3. A customer must be obtained for the steam or the power generated by the plant and must be located close by. Firm contracts must be obtained for both the refuse supply and the sale of energy.
4. If the customer is totally dependent on the energy supplied by the facility, the combustion facility must be designed with the capacity to burn fossil fuel when refuse is unavailable or when the plant cannot process the raw refuse due to malfunctions of the processing equipment.
5. The logistics of delivering refuse to the resource recovery facility should be planned long in advance. It may be necessary to establish transfer stations and storage locations that will operate in conjunction with the resource recovery plant.
6. Systems that can dispose of both municipal refuse and sewage sludge will have economic advantages over systems that dispose of refuse only. With the ban of ocean dumping now in effect, local sewage districts are being forced to spend astronomical amounts of money to incinerate sludge. A co-disposal plant should reduce both the refuse and sludge disposal costs. In order to be economically competitive, sewage sludge must be dewatered to the maximum practical extent. A number of co-disposal plants are now in operation in Europe. Except for large installations, there will not be sufficient excess energy to warrant exporting it.

Many of the high technology systems have, as a common starting point, the medium technology materials recovery systems as their first process steps. These were discussed in a previous section.

11-7 CHAPTER REVIEW

When you have completed studying this chapter, you should be able to do the following without the aid of your textbook or notes:

1. State the average mass of solid waste produced per capita per day in the United States in 2003.

2. Differentiate between garbage, rubbish, refuse, and trash, based on their composition and source.
3. Compare the advantages and disadvantages of public and private solid waste collection systems.
4. List the three pickup methods (backyard, set-out/set-back, and curbside) and explain the advantages and disadvantages of each.
5. List the components of a time study for a waste collection system.
6. Compare the advantages and disadvantages of the four methods of collection truck routing.
7. Explain the four methods of integrating several crews.
8. Explain what a transfer station is and what purpose it serves.
9. List and discuss the factors pertinent to the selection of a landfill site.
10. Describe the two methods of constructing a MSW landfill.
11. Explain the purpose of daily cover in a MSW landfill and state the minimum desirable depth of daily cover.
12. Define leachate and explain why it occurs.
13. Sketch a MSW landfill that includes proper cover and a leachate collection system.
14. Define or explain the following terms: WTE, autogenous, HHV, LHV, RDF, source-separation.
15. Explain the relationship between oxygen, time, temperature, and turbulence in establishing efficient combustion reactions.
16. Explain the effect of source-separation on the heating value of solid waste and on the potential for hazardous air pollution emissions.
17. List two highly feasible methods of resource conservation and/or recovery in low technology and medium technology RC & R.
18. Describe and explain, in a basic manner, each of the two methods listed in number 17 above such that the average citizen could understand the method.

With the aid of this text, you should be able to do the following:

19. Determine the volume and mass of solid waste from various establishments.
20. Determine the required volume capacity of a solid waste collection truck, or conversely, determine the number of stops possible for a given truck volume, or the allowable mean time per collection.
21. Estimate the annual truck and labor cost for solid waste collection and the cost per service stop.

22. Lay out a truck route using the heuristic routing technique.

23. Determine the necessity and/or advisability of constructing a transfer station.

24. Estimate the volume and area requirements for a landfill.

25. Compute the LHV given the HHV and the chemical formula for a compound to be burned.

11-8 PROBLEMS

11-1. The student population of Metuchen High School is 881. The school has 30 standard classrooms. Assuming a 5-day school week with solid waste pickups on Wednesday and Friday before school starts in the morning, determine the size of storage container (dumpster) required. Assume waste is generated at a rate of 0.11 kg/cap · d plus 3.6 kg per room and that the density of uncompacted solid waste is 120.0 kg/m^3. Standard container sizes are as follows (all in m^3): 1.5, 2.3, 3.0, and 4.6.

Answer: Select one 1.5-m^3 and one 4.6-m^3 container.

11-2. The Bailey Stone Works employs six people. Assuming that the density of uncompacted waste is 480 kg/m^3, determine the annual volume of solid waste produced by the stone works assuming a waste generation rate of 1 kg/cap · d.

11-3. As the supply of high-grade ores is used up, lower grade ores are used to produce minerals. Assuming that you are producing 100 kg of metal, use the mass balance method to calculate the kilograms of waste rock per kilogram of metal for ore containing 50, 25, 10, 5, and 2.5 percent metal.

11-4. Professor Green has made measurements of her household solid waste, shown in the table below. If the container volume is 0.0757 m^3, what is the average density of the solid waste produced in her household? Assume that the mass of each empty container is 3.63 kg.

Date	Can no.	Gross mass[a] (kg)
March 18	1	7.26
	2	7.72
March 25	1	10.89
	2	7.26
	3	8.17
April 8	1	6.35
	2	8.17
	3	8.62

[a]Container plus solid waste.

Answer: Average density = 58.4 kg/m^3