CHAPTER 9

SEPARATION AND PROCESSING AND TRANSFORMATION OF SOLID WASTE

The purpose of this chapter is to introduce the reader to the topics of the recovery of separated materials, the separation and processing of solid waste components, and the transformation processes used to alter the form of the waste and to recover useful products. The separation and processing and transformation of waste materials make up the fourth of the functional elements. Because the many details associated with the design and implementation of the unit operations and facilities used for the separation, processing, and transformation of waste materials would impede the introduction to these important subjects, design details have been grouped together and are presented in Part IV in Chapters 12 through 15.

The methods now used to recover source-separated waste materials include curbside collection and homeowner delivery of separated materials to drop-off and buy-back centers. The further separation and processing of wastes that have been source-separated, as well as the separation of commingled wastes, usually occur at *materials recovery facilities* (MRFs) or at large integrated *materials recovery/transfer facilities* (MR/TFs). Integrated MR/TFs may include the functions of a drop-off center for separated wastes, a materials separation facility, a facility for the composting and bioconversion of wastes, a facility for the production of refuse-derived fuel, and a transfer and transport facility.

Chemical and biological transformation processes are used to reduce the volume and weight of waste requiring disposal and to recover conversion products and energy. The most commonly used chemical transformation process is combustion, which is used in conjunction with the recovery of energy in the form of heat. The most commonly used biological transformation process is aerobic composting. Technical details on these processes and descriptions of other chemical and biological processes that have been applied to the transformation of solid waste are considered in Chapters 13 and 14, respectively. Issues that must be addressed in the implementation of MRFs and MR/TFs, combustion facilities, and composting facilities are also discussed in this chapter and in Chapters 18 and 19.

9-1 REUSE AND RECYCLING OPPORTUNITIES FOR WASTE MATERIALS

Materials that have been recovered from MSW for reuse and recycling have been discussed earlier (see Tables 3-10 and 6-7). Materials separated from MSW can be used directly, as a raw material for remanufacturing (see Fig. 9-1) and reprocessing, as feedstock for the production of compost and other chemical and biological conversion products, as a fuel source for the production of energy, and for land reclamation. Reuse opportunities for the materials separated from MSW are reported in Table 9-1.

In assessing the opportunities for recycling, the available options for the separation and processing of waste materials, the economics of materials recovery, and materials specifications are critical. For example, even though it may be possible to separate the various components, finding buyers for the materials may be difficult if they do not meet the buyers' specifications. Some typical materials specification items that can affect the components separated from MSW are presented in Table 9-2.

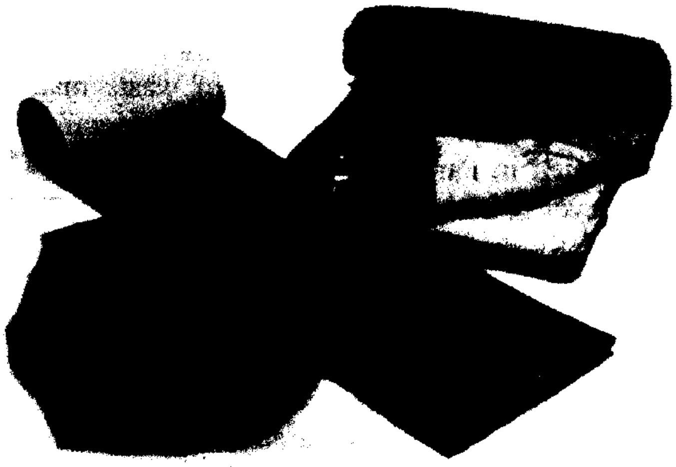


FIGURE 9-1
Representative products manufactured from recycled plastics. (Courtesy of National Association for Plastic Container Recovery.)

TABLE 9-1
Uses for materials that have been recovered from MSW

Use/application	Remarks
Direct reuse	Many of the materials separated from MSW can be reused directly. Examples of such materials include lumber, wooden pallets, 55-gal drums, furniture, etc. Whenever possible, direct reuse should be encouraged.
Raw materials for remanufacturing and reprocessing	Typical specifications for eight different materials derived from municipal wastes are presented in Table 9-2. Specific details, such as product purity, density, and shipping conditions, must be worked out with each potential buyer. Whenever possible, it is beneficial to develop a range of product specifications and product prices. In this way, processing costs to achieve a higher-quality product can be evaluated with respect to the higher market price obtainable for the higher-quality product.
Feedstock for production of biological and chemical conversion products.	Many communities have elected to meet their diversion goals by producing compost that can be marketed directly, given to the residents of the community, used on city property (e.g., greenbelts, highway dividers, etc.), or used as intermediate landfill cover. Each of these uses requires a different quality of compost, especially with respect to the type and amount of contaminant materials that may be present (e.g., plastic, pieces of metal, etc.). The production of methane in controlled reactors, ethanol, and other organic compounds will require that the materials that make up the organic fraction of the MSW be separated from the commingled MSW.
Fuel source	Energy can be derived from municipal wastes in two forms: (1) by combusting (burning) the organic fraction of MSW and/or yard wastes and recovering the heat that is given off and (2) by converting the wastes to some type of fuel (oil, gas, pellets, etc.) that can be stored and used locally or transported to distant energy markets. Specifications for direct use of wastes for the production of steam are usually not so restrictive as those for the production of a fuel. However, as firing and storage techniques improve, specifications for direct use may become more stringent. Note that in many states the use of waste materials as a fuel source is not considered an appropriate means of waste diversion or recycling.
Land reclamation	Applying wastes to land is one of the oldest and most used techniques in solid waste management. Land disposal technology has developed to the point that communities can now plan land reclamation projects without fear of the development of health problems. Typically, land reclamation will be accomplished with clean or processed demolition wastes (see Fig. 9-30). Land reclamation using wastes should not be started until a final land use has been designated.

TABLE 9-2
Typical materials specifications that affect the selection and design of processing operations for MSW[a]

Reuse category and materials components	Typical specification items
Direct reuse	Must be usable for original or related function. Degree of cleanliness (e.g., bicycles, processesd construction and demolition wastes)
Raw material for remanufacturing and reprocessing	
Aluminum	Particle size; degree of cleanliness; moisture content; density; quantity, shipment means, and delivery point
Paper and cardboard	Source; grade; no magazines; no adhesives; moisture content; quantity; storage; and delivery point
Plastics	Type (e.g., PETE/1, HDPE/2, PVC/3, LDPE/4, PP/5, PS/6, and multilayer/7); degree of cleanliness, moisture content
Glass	Amount of cullet material; color, no labels or metal; degree of cleanliness; freedom from metallic contamination; no noncontainer glass; no broken crockery; quantity, storage and delivery point
Ferrous metals	Source (domestic, industrial, etc.); specific weight; degree of cleanliness; degree of contamination with tin, aluminum, and lead; quantity; shipment means; and delivery point
Nonferrous metals	Vary with local needs and markets
Rubber (e.g., waste tires)	Recapping standards; specifications for other uses not well defined
Textiles	Type of material; degree of cleanliness
Feedstock for bioconversion products	
Yard wastes	Composition of material, particle sizes, particle size distribution, degree of contamination
Organic fraction of MSW	Composition of material, degree of contamination
Fuel source	
Yard wastes	Composition, particle size, moisture content
Organic fraction of MSW	Composition, Btu content; moisture content; storage limits; firm quantities; sale and distribution of energy and/or by-products
Plastics	Depends on application and design of combustion equipment
Wastepaper	Use as fuel will vary with local needs and markets
Wood	Composition, degree of contamination
Tires	Tire-to-energy plants; or pulp and paper mills and cement manufacturing facilities that use tire fuel
Waste oil	Depends on application and design of combustion equipment
Land reclamation	
Construction and demolition waste	Composition; degree of contamination. Local and state regulations; final land-use designation

[a] Detailed specifications on the individual materials may be found in Chapter 15.

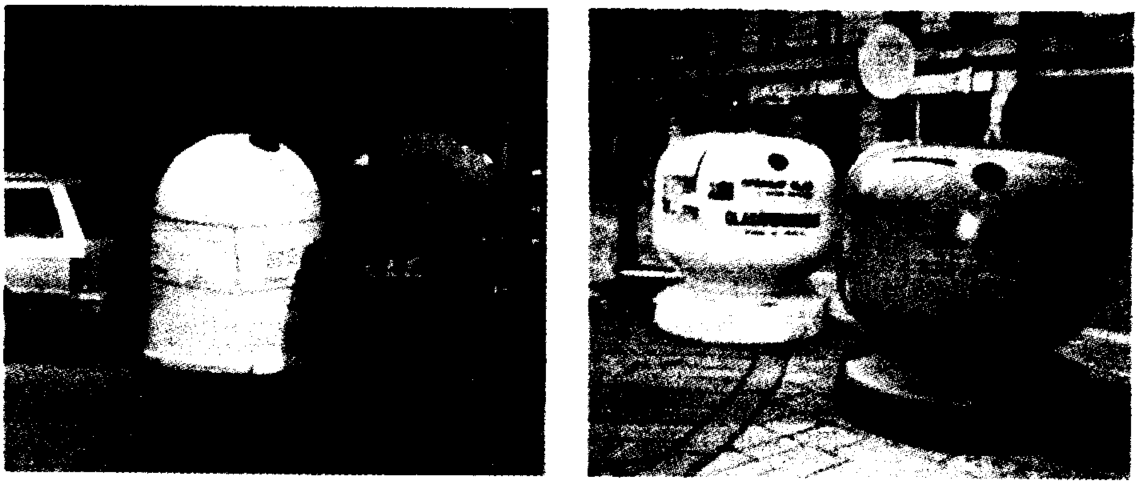
9-2 MATERIALS RECOVERED AT DROP-OFF AND BUY-BACK CENTERS

Waste materials that have been source-separated must be collected or gathered together before they can be recycled. The principal methods now used for the collection of these materials include curbside collection using specially designed collection vehicles (see Section 8-2) and delivery by homeowners to drop-off and buy-back centers.

Drop-Off Centers

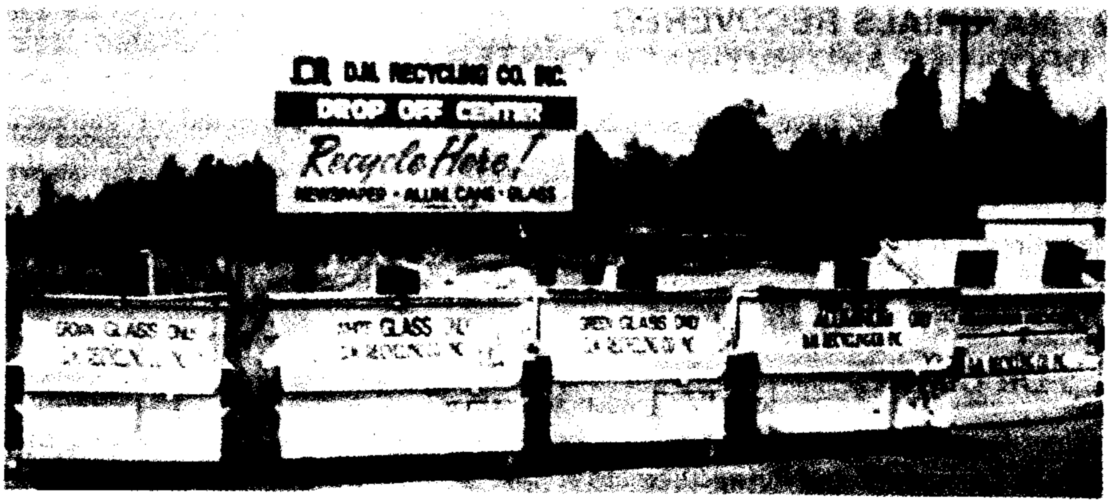
A drop-off program requires residents or businesses to separate recyclable materials at the source and bring them to a specified drop-off or collection center. Drop-off centers range from single material collection points (e.g., easy-access "igloo" containers such as shown in Fig. 9-2) to staffed, multimaterial collection centers. Because residents and businesses are responsible for not only separating their recyclable materials but also taking them to a drop-off center, low participation can be a problem in achieving the diversion rates desired from these programs. Drop-off centers also require residents and businesses to store the materials until sufficient material is collected to warrant a trip to the drop-off center. The storage of multiple material types is a problem in densely populated areas, where residences typically do not have much storage space available.

To encourage participation, most successful programs have made drop-off centers as convenient to use as possible. For example, drop-off points at shopping centers and supermarkets (see Fig. 9-3) or other convenient locations are common. In many communities, combination drop-off and buy-back centers are located at the MRF (see Fig. 9-4). Mobile collection centers, which can be moved to new locations periodically, also increase convenience. Other incentives, such as donating portions of proceeds to a local charity, can also foster greater participation.



(a) (b)

FIGURE 9-2
Typical drop-off containers: (a) igloo type, Davis, CA and (b) pedestal type, Stockholm, Sweden.



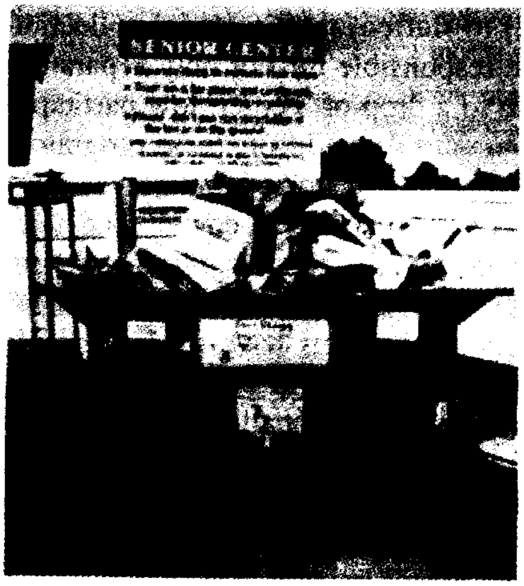


FIGURE 9-3
Typical drop-off centers located at shopping centers with grocery stores. As shown in photo on left, drop-off centers are often operated to benefit charities.

FIGURE 9-4
Typical drop-off and buy-back centers for recyclable materials located at supermarkets and shopping centers. Trailer is used for the storage of recyclable materials to minimize transportation costs. In many communities, drop-off and buyback centers are also located at materials recovery facilities, transfer stations, and at disposal sites.

Example 9-1 Home separation and delivery to drop-off centers. A community of 1200 homes cannot pay for the initial and operating costs of the recycling collection vehicles that were to be used. Instead, residents are to haul recycling containers to a drop-off center operated by the community. Calculate the number of vehicles from which recyclable materials must be unloaded per hour at the recycling drop-off center. Assume the center is open for eight hours per day, two days per week, and that 40 percent of the residents will deliver recycling containers. Also assume that 75 percent of the participants will take their separated materials to the drop-off center once per week and that the remaining 25 percent of the participants will bring their separated materials to the drop-off center once every two weeks.

Solution

1. Determine the average number of trips per week.

$$\begin{aligned}\text{Trips/wk} &= [1200 \text{ homes } \times 0.40 \text{ (participation rate)} \times 0.75 \times 1 \text{ trip/home} \cdot \text{wk} \\ &\quad + 1200 \text{ homes } \times 0.40 \text{ (participation rate)} \times 0.25 \times 0.5 \text{ trip/home} \cdot \text{wk} \\ &= 420 \text{ trips/wk}\end{aligned}$$

2. Determine the average number of cars per hour.

$$\text{Cars/hr} = [420 \text{ trips (cars)/wk}]/[(2 \text{ d/wk}) \times (8 \text{ hr/d})] = 27 \text{ cars/hr}$$

Comment. Clearly, a small drop-off center cannot accommodate 27 cars/hr (equivalent to one car unloading every 2.2 minutes). Also, it is unlikely that the cars would arrive at a uniform rate. The most viable solution is to increase the number of hours per week that the drop-off center will be open.

Buy-Back Centers

Buy-back refers to a drop-off program that provides a monetary incentive to participate (see Fig. 9-4). In this type of program, the residents are paid for their recyclables either directly (e.g., price per pound) or indirectly through a reduction in monthly collection and disposal fees. Other incentive systems include contests or lotteries.

9-3 OPTIONS FOR THE SEPARATION OF WASTE MATERIALS

Separation is a necessary operation in the recovery of reusable and recyclable materials from MSW. Separation can be accomplished either at the source of generation or at MRFs. Depending on the separation objectives, a variety of MRFs or MR/TFs can be developed. The reuse and recycling opportunities and the options available for the separation of materials will affect the type of waste management program implemented by a community. Various waste management options for meeting diversion goals are considered in Chapter 18.

Waste Separation at the Source of Generation

Waste separation at the source is usually accomplished by manual means. The number and types of components separated will depend on the waste diversion goals established for the program. Even though waste materials have been separated at the source, additional separation and processing will usually be required before these materials can be reused or recycled.

Waste Separation at MRFs and MR/TFs

MRFs and MR/TFs are used for (1) the further processing of source-separated wastes obtained from curbside collection programs and drop-off and buy-back centers without processing facilities, (2) the separation and recovery of reusable and recyclable materials from commingled MSW, and (3) improvements in the quality (specifications) of the recovered waste materials. In the simplest terms, a MRF can function as a centralized facility for the separation, cleaning, packaging, and shipping of large volumes of materials recovered from MSW.

Manual versus Mechanical Separation. The separation of waste materials from MSW can be accomplished manually or mechanically. Manual separation is used almost exclusively for the separation of wastes at the source of generation. Many of the early MRFs built in the 1970s were designed to separate the waste components mechanically. Unfortunately, none of these early facilities is currently in operation, primarily because of mechanical problems. The current trend is to design MRFs based on the integration of both manual and mechanical separation functions.

MRFs for Source-Separated Wastes. The types of source-separated materials that are separated further at MRFs may include paper and cardboard from mixed paper and cardboard; aluminum from commingled aluminum and tin cans; plastics by class from commingled plastics; aluminum cans, tin cans, plastics, and glass from a mixture of these materials; glass by color (clear, amber, and green). The processing of wastes that have been separated at the source is considered in Section 9-6.

MRFs for Commingled MSW. All types of waste components can be separated from commingled MSW. Wastes are typically separated both manually and mechanically. The sophistication of the MRF will depend on (1) the number and types of components to be separated, (2) the waste diversion goals established for the waste recovery program, and (3) the specifications to which the separated product must conform (see Chapter 15).

9-4 INTRODUCTION TO THE UNIT OPERATIONS USED FOR THE SEPARATION AND PROCESSING OF WASTE MATERIALS

The unit operations and facilities used for the separation and processing of waste materials at MRFs are introduced in this section. Unit operations used for the separation and processing of separated and commingled wastes are designed (1) to modify the physical characteristics of the waste so that waste components can be removed more easily, (2) to remove specific components and contaminants from the waste stream, and (3) to process and prepare the separated materials for subsequent uses. Commonly used unit operations for the processing of MSW are summarized in Table 9-3. Facilities used for the handling, moving, and storage of waste materials are considered further in Section 9-5. Application of the unit operations introduced in this section is illustrated in Section 9-6, which deals with MRFs for processing MSW. Technical details on the unit operations described in this section are presented in Chapter 12. Additional details may be found in Refs. 2, 5, 6, 9, 12, and 14. Cost information for the equipment and facilities described in this section is outlined in Appendix E.

Size Reduction

Size reduction is the unit operation in which *as collected* waste materials are mechanically reduced in size. In practice, the terms shredding, grinding, and milling are used interchangeably to describe mechanical size-reduction operations. The objective of size reduction is to obtain a final product that is reasonably uniform and considerably reduced in size in comparison with its original form (see Fig. 9-5). Note that size reduction does not necessarily imply volume reduction. In some situations, the total volume of the material after size reduction may be greater than that of the original volume. Size reduction equipment used for the processing of wastes includes shredders, glass crushers, and wood grinders.

Shredders. The three most common types of shredding devices used to reduce the size of MSW are the hammer mill, the flail mill or shredder, and the shear shredder (see Fig. 9-6). Other examples of shredding devices include cutters, cage disintegrators, drum pulverizers, and wet pulpers. In operation, the hammers in the hammer mill (see Fig. 9-6*a*), attached to a rotating element, strike the waste material as it enters and eventually force the shredded material through the discharge of the unit, which may or may not be equipped with bottom grates of varying sizes. The flail mill (see Fig. 9-6*b*) is similar to the hammer mill, but provides only coarse shredding, as the hammers are spaced further apart. Operationally, flail mills are single-pass devices, whereas material remains in a hammer mill until it will pass through the openings in the bottom grate. Flail mills are often used as bag breakers. The shear shredder (see Fig. 9-6*c*) is composed of two parallel counterrotating shafts with a series of discs mounted perpendicularly that serve as cutters. The waste material to be shredded is directed to the center

TABLE 9-3
Commonly used unit operations and facilities for the separation and processing of separated and commingled MSW

Item	Function/material processed	Preprocessing
	Unit operations	
Shredding		
Hammer mills	Size reduction/all types of wastes	Removal of large bulky items, removal of contaminants
Flail mills	Size reduction, also used as bag breaker/all types of wastes	Removal of large bulky items, removal of contaminants
Shear shredder	Size reduction, also used as bag breaker/all types of wastes	Removal of large bulky items, removal of contaminants
Glass crushers	Size reduction/all types of glass	Removal of all nonglass materials
Wood grinders	Size reduction/yard trimmings/all types of wood wastes	Removal of large bulky items, removal of contaminants
Screening	Separation of over- and under-sized material; trommel also used as bag breaker/all types of waste	Removal of large bulky items, large pieces of cardboard
Cyclone separator	Separation of light combustible materials from air stream/prepared waste	Material is removed from air stream containing light combustible materials
Density separation (air classification)	Separation of light combustible materials from air stream	Removal of large bulky items, large pieces of cardboard, shredding of waste
Magnetic separation	Separation of ferrous metal from commingled wastes	Removal of large bulky items, large pieces of cardboard, shredding of waste
Densification		
Balers	Compaction into bales/paper, cardboard, plastics, textiles, aluminum	Balers are used to bale separated components
Can crushers	Compaction and flattening/aluminum and tin cans	Removal of large bulky items
Wet separation	Separation of glass and aluminum	Removal of large bulky items
Weighing facilities		
Platform scales	Operational records	
Small scales	Operational records	
	Handling, moving, and storage facilities	
Conveyor belts	Materials transport/all types of materials	Removal of large bulky items
Picking belts	Manual separation of waste materials/source-separated and commingled MSW	Removal of large bulky items
Screw (auger) conveyors (Use not well established)	Materials transport; also used as bag breaker/all types of waste	Removal of large bulky items
Movable equipment	Materials handling and moving/all types of waste	
Storage facilities	Materials storage/all types of recovered materials	Densification, glass crushing, etc.

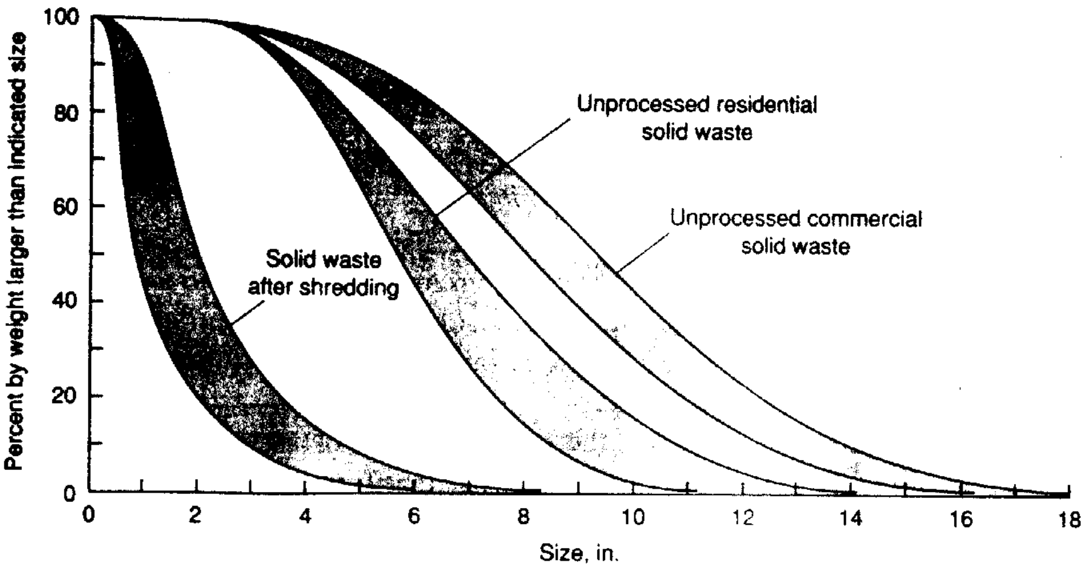


FIGURE 9-5
Typical distribution of particle sizes for the organic fraction of MSW excluding yard waste before and after shredding.

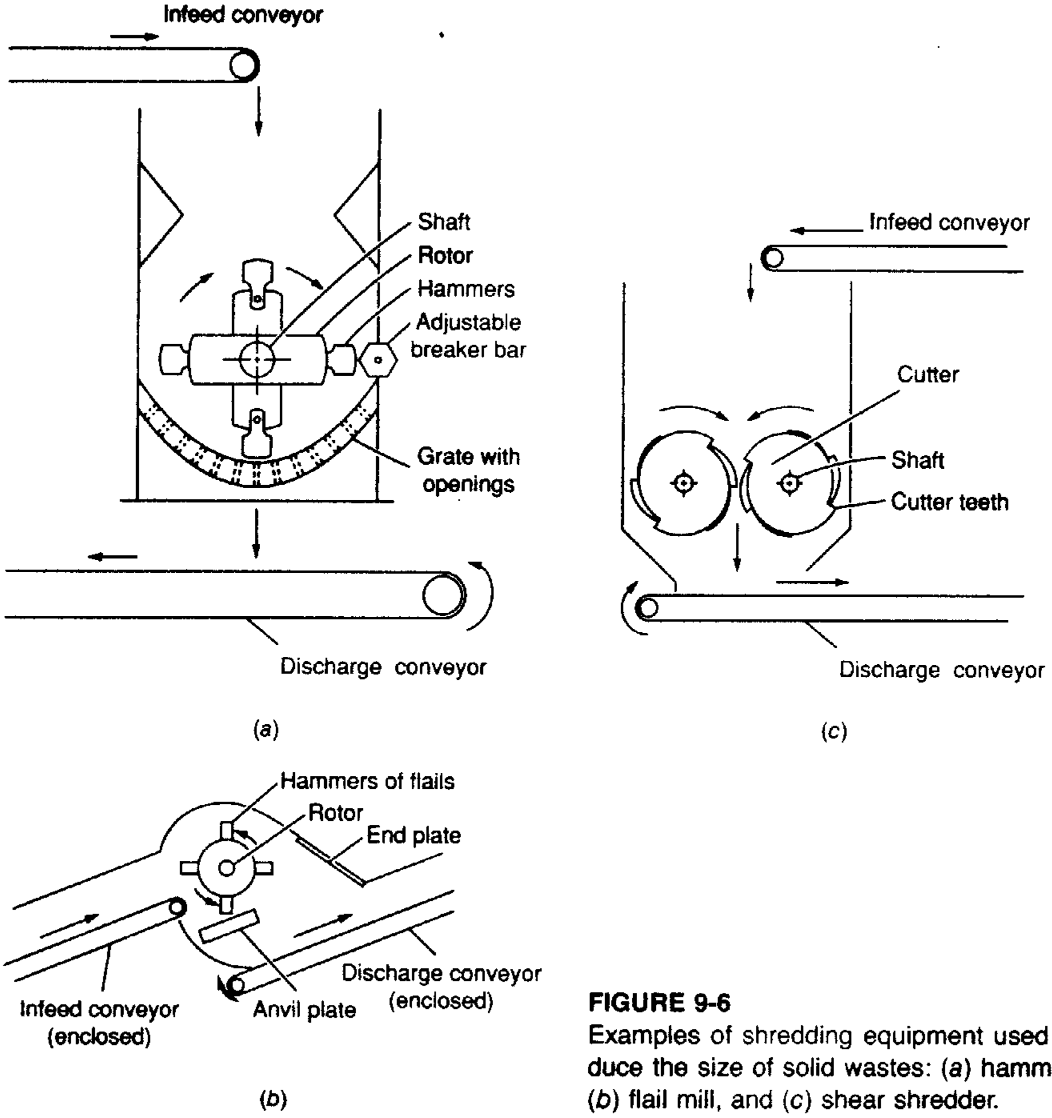


FIGURE 9-6
Examples of shredding equipment used to reduce the size of solid wastes: (*a*) hammermill, (*b*) flail mill, and (*c*) shear shredder.

of the counterrotating shafts. The size of the waste material is reduced by the shearing or tearing action of the the cutter discs. The shredded material drops or is pulled through the unit. Shear shredders have also been used as bag breakers.

Glass Crushers. Glass crushers are used to crush glass containers and other glass products found in MSW. Glass is often crushed after it has been separated to reduce storage and shipping costs. In some mechanical separation operations, glass is crushed, after one or more separation steps, to effect its removal by screening. Crushed glass can also be separated optically by color (clear and colored). However, because the equipment for the optical sorting of glass is expensive and on-line reliability of such equipment has not been good, optical sorting is not used commonly at present.

Wood Grinders. Typically, most wood grinders are wood chippers, used to shred large pieces of wood (e.g., large branches, broken pallets) into chips (see Fig. 9-7), which can be used as a fuel, and finer material, which can be composted. Tub grinders (see Fig. 9-27 in Section 9-6) are used to process yard wastes. A tub grinder consists of a large tub having a revolving upper section, and a stationary lower section containing a hammer mill. The tub grinder is fed by a front-end loader (or by a stationary grapple, if the wastes are piled close enough to the tub), and the revolving action of the tub ensures that material flows continuously to the hammer mill. The continuous stream of shredded material is carried away from the grinder by a conveyor. The wood that has been ground in a tub grinder is usually sorted by size using trommel, disc, or vibrating screens. Optical sorters have also been developed but are not used commonly because of their maintenance requirements and high initial cost. The larger-size material is used as a biomass fuel or as a bulking agent in composting operations. The fine material is usually composted.

Screening

Screening is a unit operation used to separate mixtures of materials of different sizes into two or more size fractions by means of one or more screening surfaces. Screening may be accomplished either dry or wet, with the former being more common in solid waste processing systems. The principal applications of screening devices in the processing of MSW include (1) removal of oversized materials, (2) removal of undersized materials, (3) separation of the waste into light combustibles and heavy noncombustibles, (4) recovery of paper, plastics, and other light materials from glass and metal, (5) separation of glass, grit, and sand from combustible materials, (6) separation of rocks and other oversized debris from soil excavated at construction sites, and (7) removal of oversized materials from combustion ash. The types of screens used most commonly for the separation of solid waste materials are illustrated in Fig. 9-8.

Vibrating Screens. Vibrating screens (see Fig. 9-8*a*) are used to remove undersized materials from source-separated and commingled MSW and to process

FIGURE 9-7
Large commercial wood grinder. (Courtesy of SSI Shredding Systems, Inc.)

construction and demolition wastes. Vibrating screens can be designed to vibrate from side to side, vertically, or lengthwise. Vibrating screens used for the separation of MSW are inclined and use a vertical motion. The vertical motion allows the material that is to be separated to contact the screen at different locations each time.

Rotary Screens. The most common type of rotary screen used in the processing of wastes is a trommel screen. Trommels (see Figs. 9-8*b* and 9-9*a*), also known as rotary drum screens, were first developed in England in the 1920s. Trommels are used to separate waste materials into several size fractions. Operationally, the material to be separated is introduced at the front end of the inclined rotating trommel. As the screen rotates, the material to be separated tumbles and contacts the screen numerous times as it travels down the length of the screen. Small particles will fall through the holes in the screen, while the oversized material will pass through the screen. The material falling through the screen is collectively known as *unders*, *undersize*, and *underflow*; material retained by the screen is known as *overs*, *oversize*, and *overflow*. Trommels equipped with metal blades or teeth that protrude into the drum (see Fig. 9-8*b*) are also used as bag breakers. Typically, the blades are located in the first third of the trommel. Having passed through the trommel, the oversize wastes are then sorted manually. In some systems, magnetic separation of ferrous metals will occur before manual separation. Ferrous metals will also be removed from the undersize waste materials passing through the trommel.

Disc Screens. Disc screens consist of sets of parallel horizontal shafts equipped with interlocking lobed (or star-shaped) discs (see Fig. 9-8*c* and 9-9*b*). The undersized materials to be separated fall between the spaces in the discs, and oversized materials ride over the top of the discs as in a conveyor belt. Different-sized materials can be separated using the same screen by adjusting the spacing between the rotating discs. Disc screens have several advantages over other types of screens, including self-cleaning and adjustability with respect to the spacing of the discs on the drive shafts. Disc screens are used in the same applications as trommels.

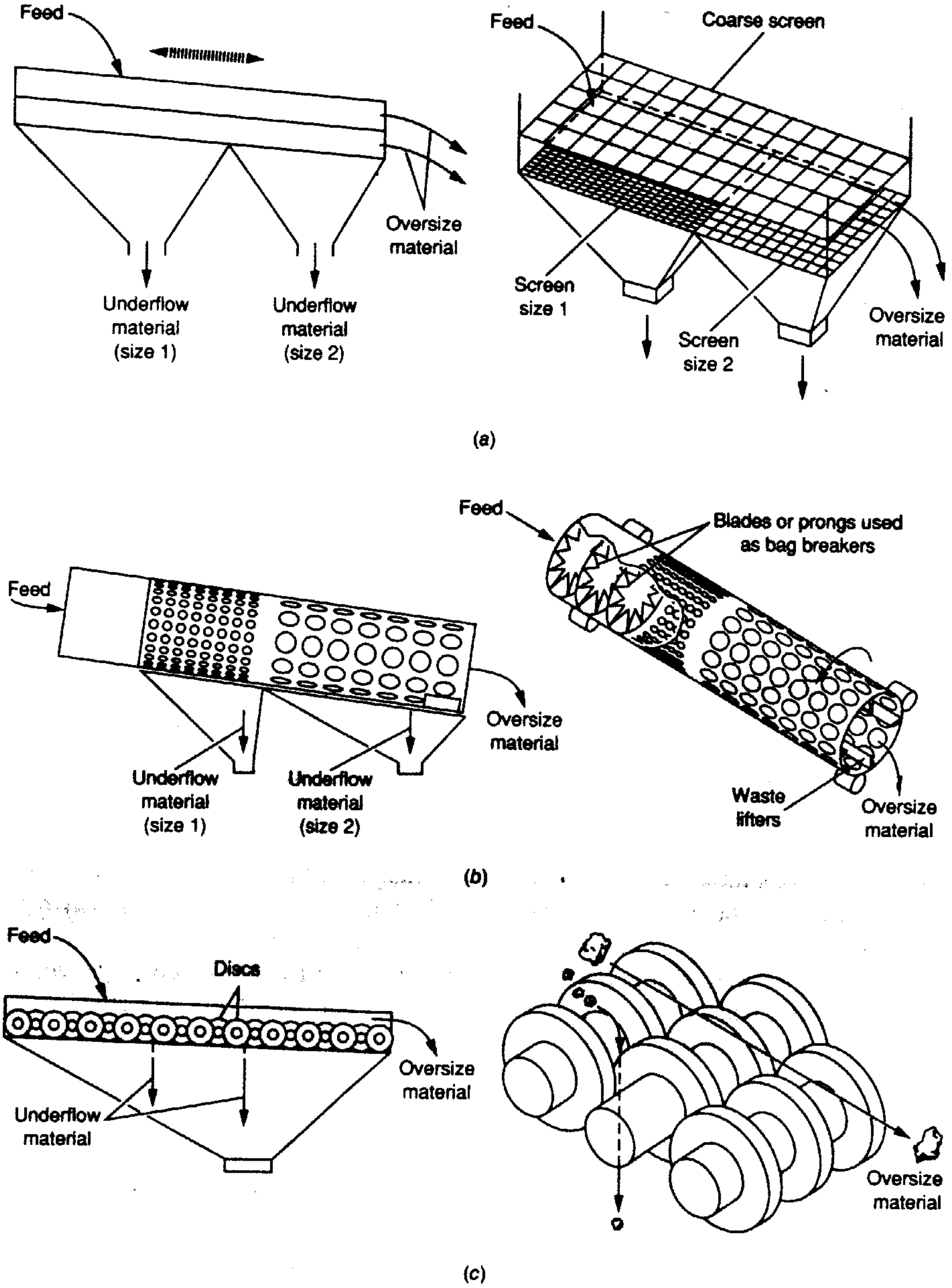


FIGURE 9-8
Typical screens used for the separation of solid wastes: (*a*) vibrating screen, (*b*) rotary drum (trommel) screen, and (*c*) disc screen.

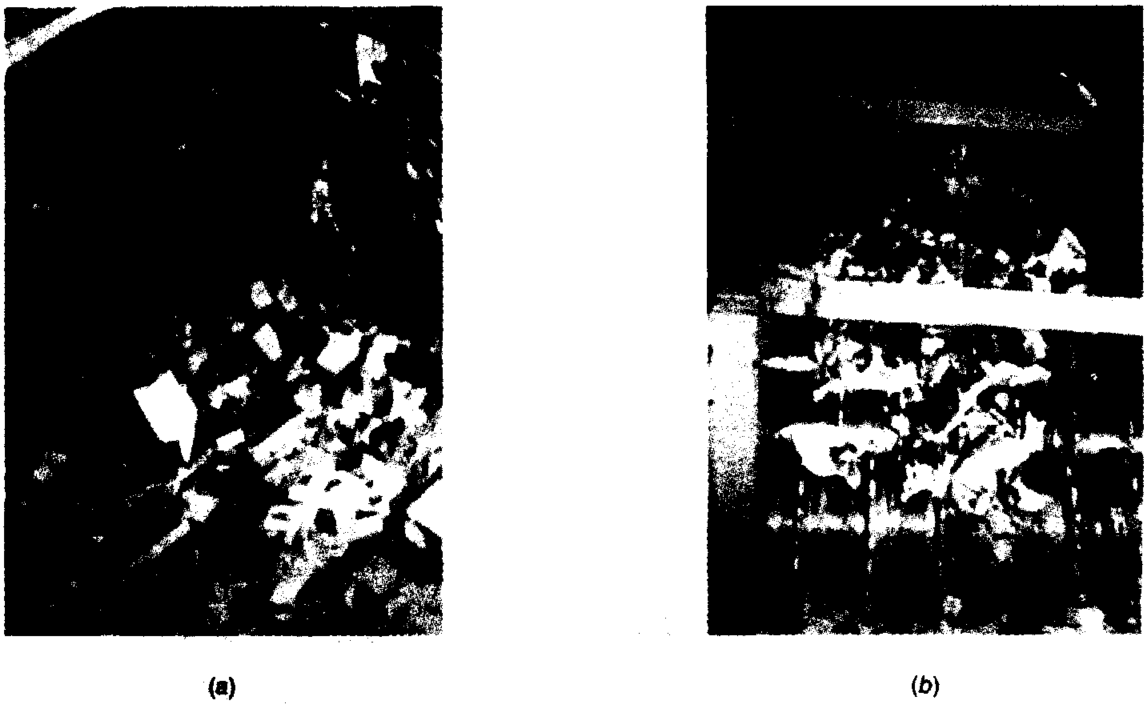

(a) (b)

FIGURE 9-9
Views of screens in operation with MSW: (*a*) large trommel screen and (*b*) disc screen. (Courtesy of Triple/S Dynamics Systems, Inc.)

Density Separation (Air Classification)

Air classification is the unit operation used to separate light materials such as paper and plastic from heavier materials such as ferrous metal, based on the weight difference of the material in an air stream. If materials of different weights are introduced into an air stream moving with sufficient velocity, the light materials will be carried away with the air while the heavier materials will fall in the counter-current direction. Air classification has been used for a number of years in industrial operations for the separation of various components from dry mixtures.

In MRFs, air classification is used to separate the organic material—or, as it is often called, the *light fraction*—from the heavier, inorganic material, which is called the *heavy fraction*. Air classification has also been used for the separation of commingled glass and plastic. A complete air classification system is comprised of the air classifier and cyclone separator, which is used to separate the solid materials from the air stream (see Fig. 9-10). Because there is movement away from the shredding of commingled MSW, air classification systems of the type shown in Fig. 9-10 are not commonly used today. In installations where one or more trommels are used, a device known as a *stoner*, which also involves the use of air to fluidize the wastes to be separated (see Chapter 12), is used to separate the heavy grit from the organic material in the trommel underflow (undersize material) waste stream.

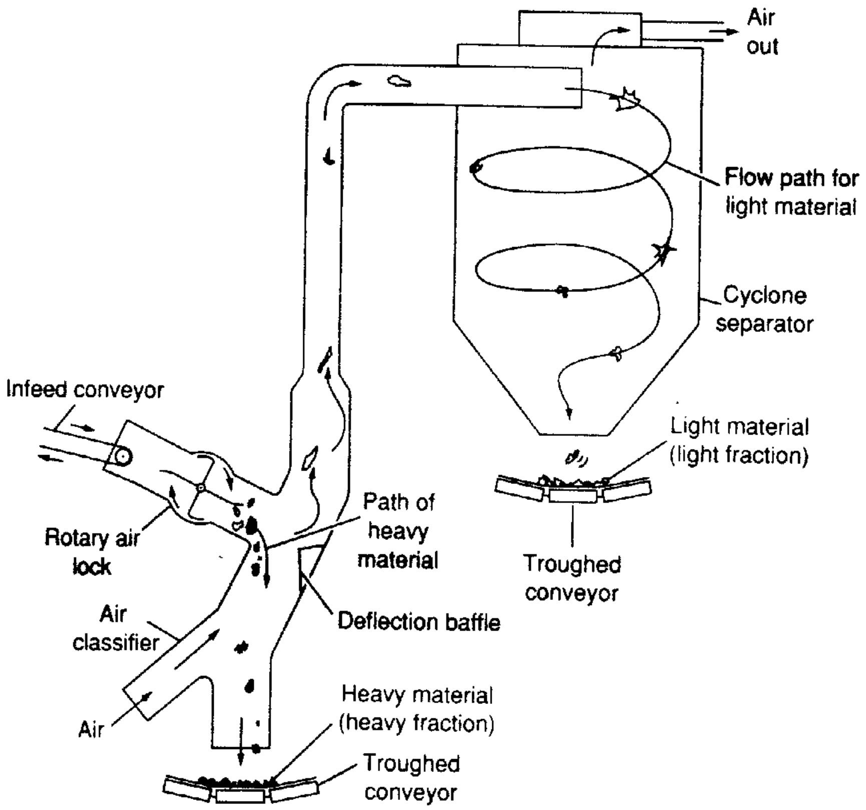


FIGURE 9-10
Typical air classification system used to separate solid waste into light and heavy fractions.

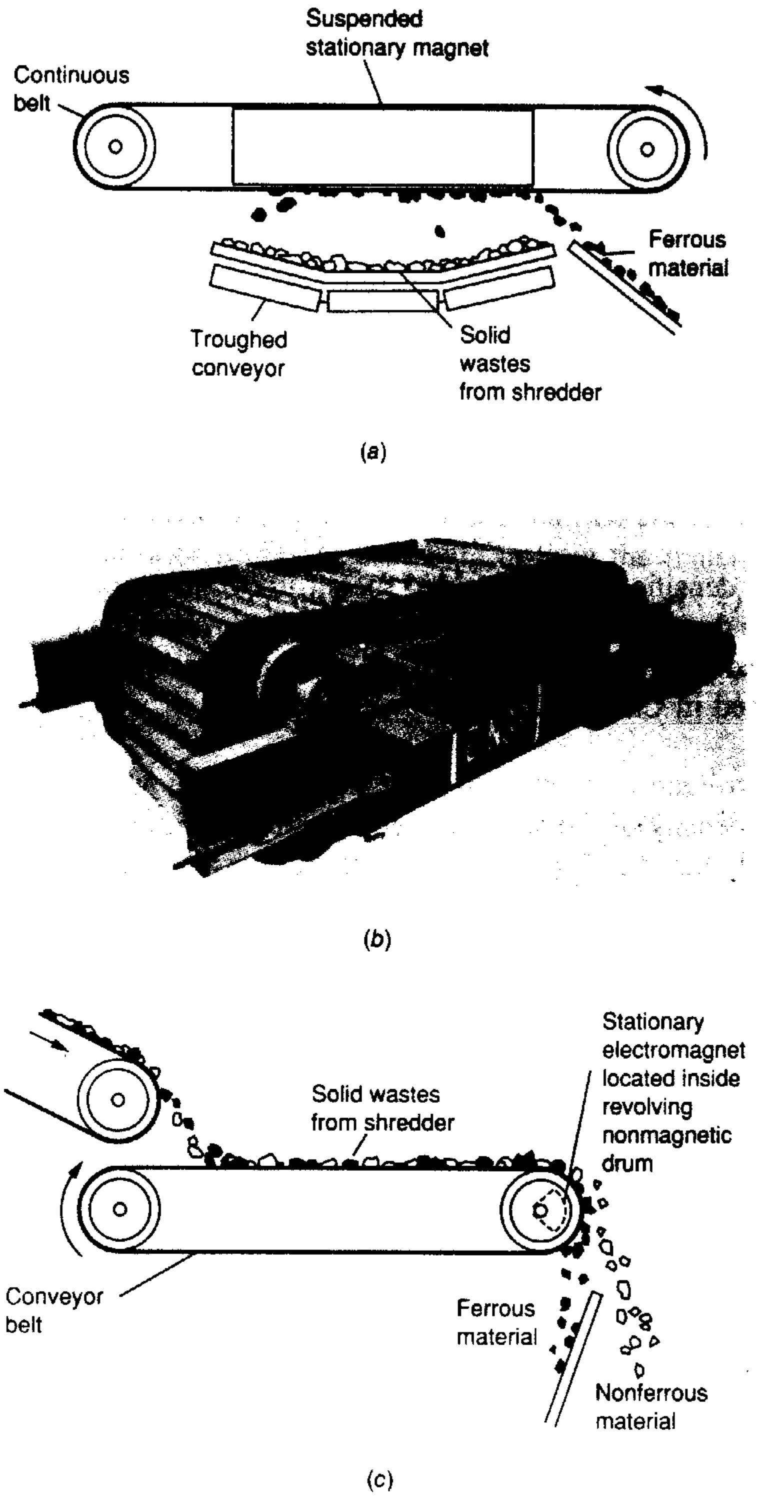
Magnetic Separation

Magnetic separation is a unit operation whereby ferrous metals are separated from other waste materials by utilizing their magnetic properties. Magnetic separation is used to recover ferrous materials from source-separated, commingled, and shredded MSW (see Fig. 9-11). Magnetic separation is used commonly to separate aluminum cans from tin cans in source-separated waste where the two types of metals are mixed. Ferrous materials are usually recovered either after shredding and before air classification or after shredding and air classification. In some large installations, overhead magnetic systems have been used to recover ferrous materials before shredding (this operation is known as *scalping*).

When commingled MSW is burned in combustors, magnetic separation is used to remove the ferrous materials from combustion residue. Magnetic recovery systems have also been used at landfill disposal sites. The specific location(s) where ferrous materials are recovered will depend on the objectives to be achieved, such as the reduction of wear and tear on processing and separation equipment, the degree of product purity to be achieved, and the required recovery efficiency.

Densification

Densification (also known as *compaction*) is a unit operation that increases the density of waste materials so that they can be stored and transported more efficiently



(a)

(b)

(c)

FIGURE 9-11
Typical magnet separators: (*a*) schematic overhead magnet and (*b*) view of commercial overhead magnet. The unit shown is equipped with an armored stainless steel self-cleaning belt for severe duty applications such as solid waste. (Courtesy of Dings Co., Magnetic Group), and (*c*) pulley magnet.

FIGURE 9-12
Baler used for paper, cardboard, plastics, aluminum cans, and tin cans.

and as a means of preparing densified refuse-derived fuels (dRDF). Several technologies are available for the densification of solid wastes and recovered materials including baling, cubing, and pelleting. Equipment for the densification of landfilled solid wastes is discussed in Chapter 11.

Balers. Balers reduce the volume of waste for storage, prepare the wastes for marketing, and increase the density of the waste thereby reducing shipping costs. The materials most commonly baled include paper, cardboard, plastics, aluminum and tin cans, and large metal components (see Fig. 9-12).

Can Crushers. These are used to crush aluminum and tin cans, thus increasing their density and reducing handling and shipping costs. Typically, aluminum cans are crushed and blown into large transport trailers for shipping (see Fig. 9-13).

FIGURE 9-13
Can crusher for aluminum cans used in conjunction with pneumatic discharge system. Crushed cans are blown into trailer.

9-5 FACILITIES FOR HANDLING, MOVING, AND STORING WASTE MATERIALS

To handle, move, and store waste materials at MRFs, the following are used: conveyors, conveyor facilities (picking belts) in conjunction with the manual separation of wastes, pneumatic conveyors, movable and fixed waste-handling equipment, scales, and storage facilities.

Conveyors

Conveyors transfer wastes from one location to another. The principal types of conveyors used for the management of solid waste may be classified as hinge, apron, bucket, belt drag, screw, vibrating, and pneumatic. Horizontal and inclined belt conveyors, where the material is carried above the belt, and drag conveyors, equipped with flights or crossbars to drag the material, are the most commonly used for handling solid wastes (see Fig. 9-14*a*, *b*, *c*).

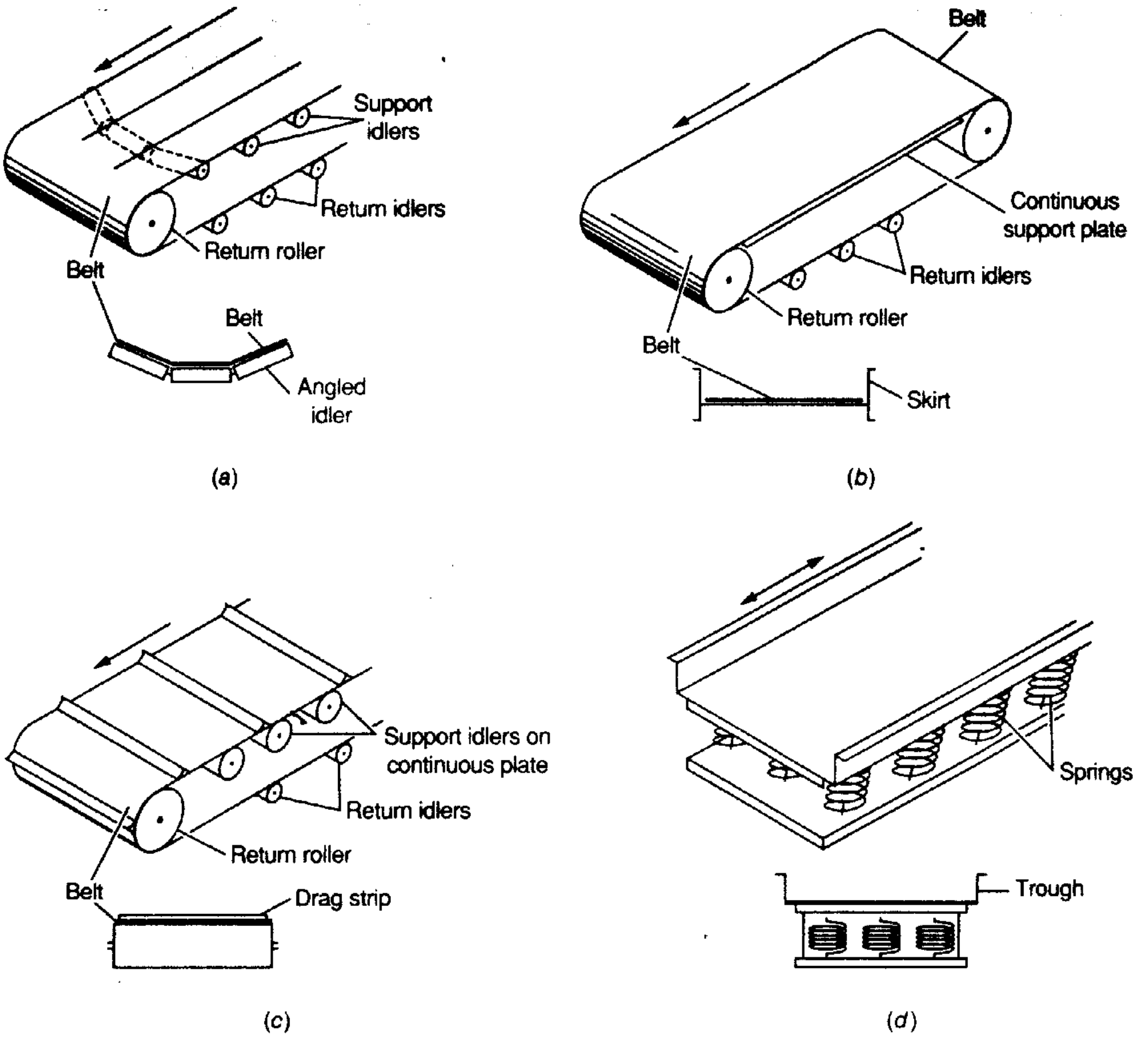
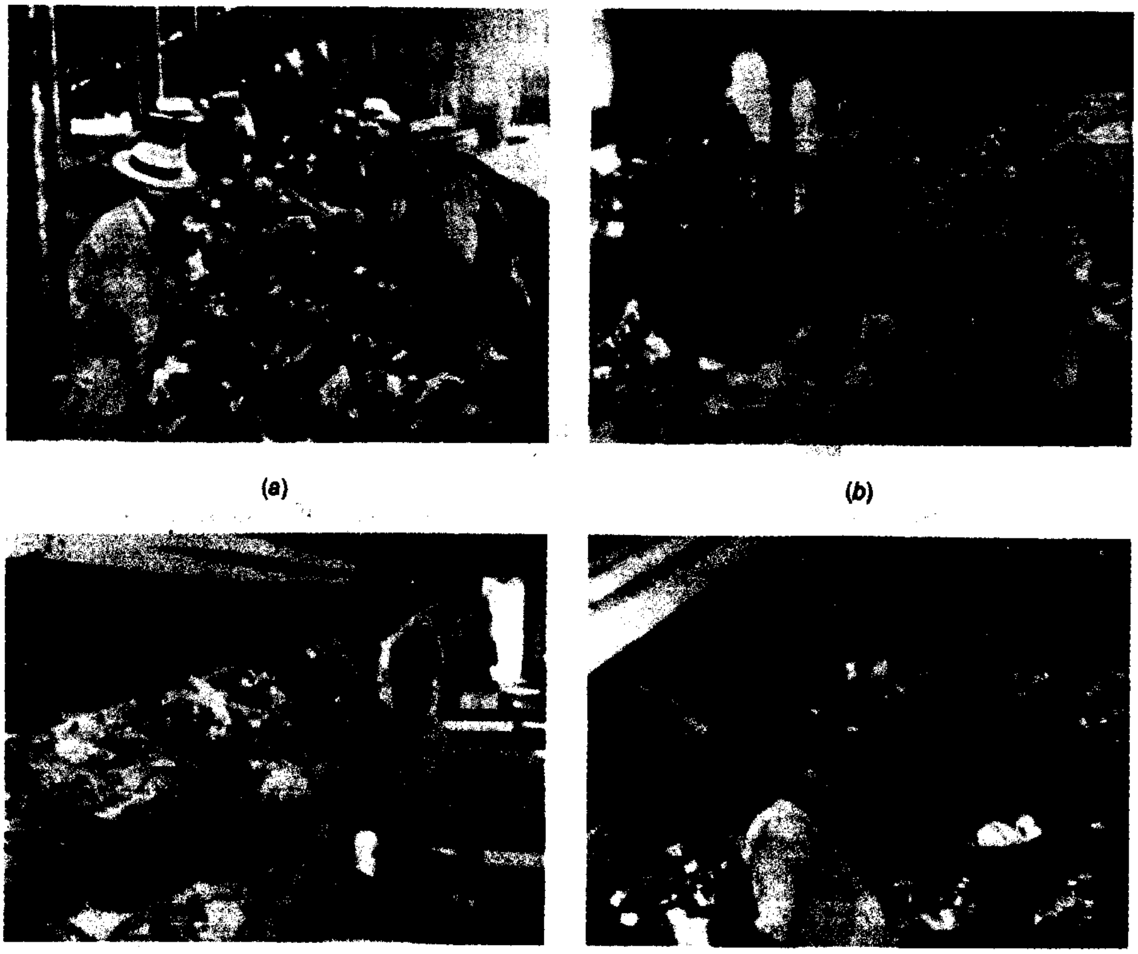


FIGURE 9-14
Conveyor belts used to transport solid waste: (*a*) troughed belt on angled idlers, (*b*) flat belt on continuous plate, (*c*) drag conveyor on idlers, and (*d*) mechanical vibrating conveyor.

The conveyance of unprocessed commingled solid wastes with conveyors has not been trouble-free. Conveyors have been damaged by solid wastes dropped onto them, especially those containing some of the heavier components often found in municipal wastes. Problems have also developed at transfer points (e.g., where the wastes are discharged from one conveyor to another or to other processing facilities). Wire and cords in the wastes become snagged on the equipment, and waste spillage and overflows are common. Binding and wedging of conveyor systems have also been a problem.

Conveyor Facilities Used in Conjunction with the Manual Sorting of Wastes

The manual separation of wastes at a MRF is usually accomplished by removing (picking) individual waste components as the waste stream, which is transported on an endless conveyor (picking) belt, moves by (see Fig. 9-15). Most facilities



(a) (b)

(c) (d)

FIGURE 9-15
Manual sorting of solid waste: (*a*, *b*) men sorting from conveyor belt, circa 1905 (note absence of plastic materials in waste that is being sorted); (*c*) modern belt-sorting facility, located in an air-conditioned room, for commingled waste; and (*d*) modern belt-sorting facility for source-seperated waste materials.

used for the separation of waste components are elevated so that the separated components can be dropped into chutes that direct the material to receiving containers located below the chute (see Fig. 9-16). To improve the separation of waste components from commingled MSW, plastic bags used for the on-site storage of wastes must be broken open and the contents spread out on the belt. In Fig. 9-15, note that the sorting facilities used at the turn of the century are essentially the same as those used today. However, one important difference is in the characteristics of the wastes to be sorted. The absence of plastic materials and the ubiquitous plastic bags found in MSW today are readily apparent. When one is considering the use of sorting facilities, one can find much useful information in the early literature [7, 8]. Another major difference is that modern sorting lines are usually located in a well-lighted and air-conditioned facility designed to meet Occupational Safety and Health Administration (OSHA) requirements.

The design of facilities for sorting waste components depends to a large extent on the characteristics of the waste, on the number of commingled recyclable items that are to be separated, and on the throughput capacity of the facility. Critical factors in the design of a picking facility are the width of the belt, the speed of the belt, and the average thickness of the waste material on the belt (often referred to as the average burden depth). The maximum belt width where separation is carried out from either side of the belt is about 4 ft. Belt speeds vary from about 15 to 90 ft/min, depending on the material to be sorted and the degree of presorting to which the material has been subjected. It is interesting to note that a belt speed of 60 ft/min was used in sorting facilities at the turn of the century [7]. The average thickness of the waste material on the belt for effective picking is about 6 in. Data on the amount of waste that can be sorted per worker are presented in Table 9-4.

Pneumatic Conveyors

Pneumatic conveying can be defined as materials transport using air as the transport medium. Two types of pneumatic transport systems (positive pressure and

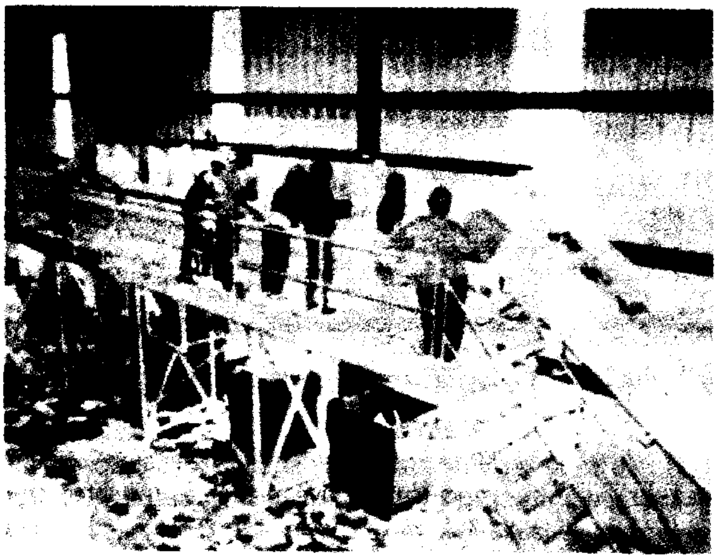


FIGURE 9-16
Storage containers for separated material, located below elevated sorting lines. (Courtesy of RYCO Manufacturing, Inc.)

TABLE 9-4
Picking rates for commingled materials from moving belts

	Waste sorted, ton/person · hr		
Type of material	**Range**	**Typical**	**Remarks**
Commingled MSW			
Residential and commercial	0.3–4	2.5	Relatively low efficiency of recovery per ton of feedstock at the higher sorting rates
Commercial	0.4–6	3.0	
Source-separated commingled materials			
Mixed paper	0.5–4	2.5	
Paper and cardboard	0.5–3	1.5	Two products
Mixed plastics	0.1–0.4	0.2	PETE and HDPE
Mixed glass and plastic	0.2–0.6	0.5	Two products: mixed glass and mixed plastic
Glass	0.2–0.8	0.4	Clear, green, amber
Plastics, glass, aluminum and tin cans	0.1–0.5	0.3	Four products

vacuum) are illustrated in Fig. 9-17. Pneumatic conveyors offer considerable design flexibility because the piping can be routed as required. As noted in the discussion of air classification, if light materials are introduced into an air stream moving with sufficient velocity, they will be carried away with the air. Shredded materials such as newsprint, plastic, or refuse-derived fuel as well as other light materials such as crushed aluminum cans have been conveyed pneumatically. Air

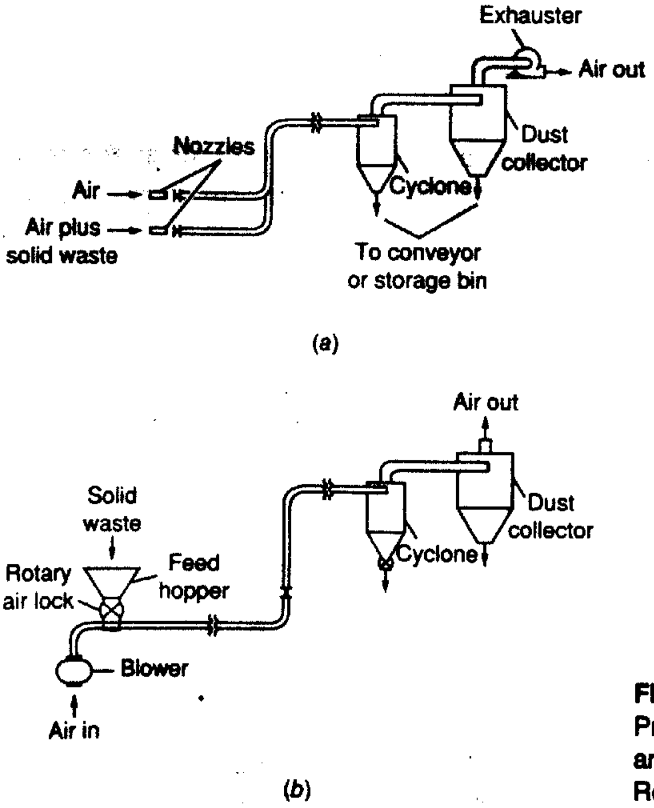


FIGURE 9-17
Pneumatic conveyor systems: (*a*) vacuum and (*b*) positive pressure. (Adapted from Ref. 15.)

velocities needed for the pneumatic transport of unprocessed solid waste are in the range of 4800 to 6000 ft/min.

Movable Waste-Handling Equipment

The use of front-end loaders and forklifts to move materials is universal in the operation of MRFs. For example, in a typical application, commingled MSW dumped on the receiving floor of the MRF by the collection vehicles is then pushed or loaded with a front-end loader onto a belt conveyor for further processing (see Fig. 9-18*a*). Front-end loaders are also used to load materials after processing, such as the loading of shredded wood waste into trucks for shipment to off-site customers. Forklifts are used almost exclusively to move baled materials from baling machines to storage areas, and then onto trucks for transport to market (see Fig. 9-18*b*).

Facilities for Weighing

Weighing facilities are an important and necessary part of any MRF. Scales of various types are used to weigh the amount of waste materials delivered, recovered, sold, and disposed of. The types of weighing facilities used at MRFs vary from the small scales used to weigh the amounts of wastes brought in by individuals (see Fig. 9-19*a*) to the platform scales used for weighing collection vehicles (see Fig. 9-19*b*).

Storage Facilities

Materials that have been separated and processed must be stored until a buyer picks them up. In some facilities, space is provided for materials to be displayed for viewing by purchasers, usually on a weekly or monthly schedule. The amount of storage space to be provided at the MRF is established by the MRF system operator

(*a*) (*b*)

FIGURE 9-18
Movable equipment used for waste handling at MRFs: (*a*) front-end loader equipped with solid rubber tires and (*b*) forklift. Although the solid rubber tires are considerably more expensive than conventional tires, they have proven cost-effective and have reduced downtime considerably.

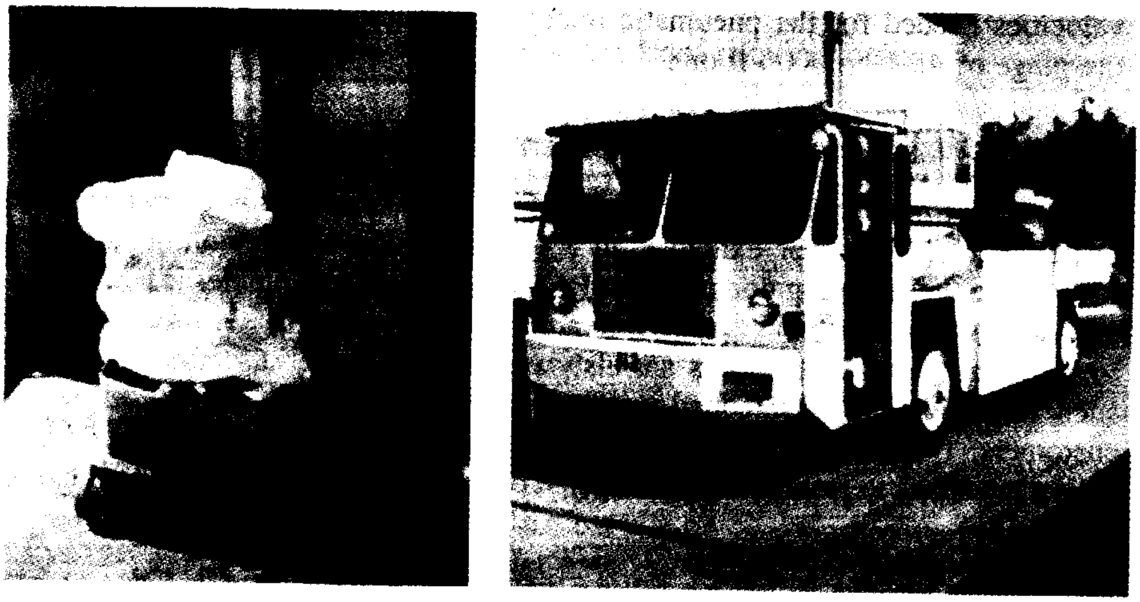

(a) (b)

FIGURE 9-19
Weighing facilities at MRFs: (a) small platform scale for weighing material brought in by homeowners and (b) platform scale for collection and other large vehicles.

in coordination with the material buyers. Key considerations are these: Will the buyer provide storage containers for recovered materials? With what frequency will the buyer pick up and remove prepared materials from the MRF? Is it possible to rent temporary storage facilities for the processed materials away from the MRF? What backup facilities exist in the community that can be used to store recovered materials when there is no available storage space at the MRF? Although each MRF must be sized for materials storage in accordance with individual site-specific criteria, it is prudent to provide sufficient storage capacity to hold processed materials for one to three months.

9-6 DEVELOPMENT AND IMPLEMENTATION OF MRFS

As we noted in the introduction to this chapter, the further separation and processing of wastes that have been source-separated, as well as the separation of commingled wastes usually occurs at materials recovery facilities (MRFs) or at large integrated materials recovery/transfer facilities (MR/TFs). The successful development and implementation of a MRF or MR/TF require that proper attention be paid to both engineering considerations and nonengineering implementation issues. An introduction to the engineering considerations involved in the implementation of MRFs, some typical examples of MRFs, planning and design considerations, and the nonengineering implementation issues are considered in this section. Further engineering details are in Chapter 12.

Engineering Considerations

Engineering considerations involved in the implementation of MRFs include (1) definition of the functions of the MRF, (2) selection of the materials to be separated (now and in the future), (3) identification of the material specifications that must be met now and in the future, (4) development of separation process flow diagrams, (5) determination of process loading rates, (6) layout and design of the physical facilities, (7) selection of the equipment and facilities that will be used, (8) environmental controls, and (9) aesthetics considerations (see also Ref. 10). The adaptability of the facility to potential changes in the characteristics or quantities of the waste must also be assessed carefully. Consideration of the functions of a MRF and the materials to be separated, the development of process flow diagrams, the development of process loading rates, the layout and design of the physical facilities, planning and design considerations, and the selection of the equipment and facilities that will be used are considered in the following discussion. These topics are also examined in greater detail in Chapter 12. Selection of the materials to be separated and the specifications for the separated materials are considered in Chapter 15.

Functions of a MRF, and Materials to Be Recovered. The functions of a MRF depend directly on (1) the role the MRF is to serve in the waste management system, (2) the types of material to be recovered, (3) the form in which the materials to be recovered will be delivered to the MRF, and (4) the containerization and storage of processed materials for the buyer. For example, the function of equipment and facilities for the separation of aluminum cans from tin cans will differ significantly from that for the separation of aluminum and tin cans from commingled MSW.

MRFs for source-separated materials. The types of materials that are commonly processed at MRFs for source-separated wastes are summarized in column 1 of Table 9-5. The functions that must be carried out at MRFs to process the source-separated materials are identified in column 2 of Table 9-5. The particular combination of materials to be separated will depend on the nature of the source separation program the community has adopted. For example, a typical source separation program might involve the use of three separate containers for recyclable materials in conjunction with one or more additional containers for other wastes; yard wastes will be collected separately. The materials separated would be as follows:

Recycle container 1	Mixed paper (cardboard is often stacked alongside)
Recycle container 2	Mixed plastics and glass
Recycle container 3	Mixed aluminum and tins cans
Yard wastes	Collected separately

With this mix of source-separated materials, four separate process lines will be required to separate and/or to process the individual components. The processing of the yard wastes could be done at a separate facility or at a large integrated MRF.

TABLE 9-5
Typical examples of the materials, functions, and equipment and facility requirements of MRFs used for the processing of source separated materials

Materials	Function/operation	Equipment and facility requirements
Mixed paper and cardboard/1	Manual separation of high-value paper and cardboard or of contaminants from commingled paper types. Baling of plastics for shipping. Storage of separated materials	Front-end loader, conveyors, baler, forklift (see Figs. 9-20a and 9-21)
Mixed paper and cardboard/2	Manual separation of cardboard and mixed paper. Baling of separated materials for shipping. Storage of baled materials	Front-end loader, conveyors, open picking station, baler, forklift
Mixed paper and cardboard/3	Manual separation of old newspaper, old corrugated cardboard, and mixed paper from commingled mixture. Baling of separated materials for shipping. Storage of baled materials	Front-end loader, conveyors, enclosed picking station, baler, forklift
PETE and HDPE plastics	Manual separation of PETE and HDPE from commingled plastics. Baling of separated materials for shipping. Storage of baled materials	Receiving hopper, picking conveyor, storage bins, baler, forklift
Mixed plastics	Manual separation of PETE, HDPE and other plastics from commingled mixed plastics. Baling of plastics for shipping. Storage of separate materials	Receiving hopper, picking conveyor, storage bins, baler, forklift
Mixed plastics and glass	Manual separation of PETE, HDPE, and glass by color from commingled mixture. Baling of plastics for shipping. Storage of separated materials	Receiving hopper, picking conveyor, glass crusher, storage bins, baler, forklift
Mixed glass	Manual separation of clear, green, and amber glass. Storage of separated materials	Receiving hopper, picking conveyor, glass crusher, storage bins, baler, forklift

(continued)

MRFs for commingled MSW. For commingled MSW, the materials to be separated and the function and equipment requirements for the MRF will depend directly on the role the MRF is to serve in the waste management system (see Table 9-6). A MRF may be used to recover materials from commingled MSW to meet mandated diversion goals. A MRF can be used to separate and process source-separated materials along with the separation of materials from commingled MSW to meet mandated diversion goals. Another common use of a MRF for commingled MSW is to remove contaminants from the waste and to prepare the waste for subsequent uses such as a fuel for combustion facilities or a feedstock for composting. The removal of contaminants from waste materials is also known as a *negative sort*. Another MRF might be used to recover only high-value items and to process the residual waste for the production of compost to be used as intermediate landfill cover. Clearly, an endless number of variations of a MRF are possible. The types of materials and/or contaminants removed and the associated

TABLE 9-5 (*continued*)

Materials	Function/operation	Equipment and facility requirements
Aluminum and tin cans	Magnetic separation of tin cans from commingled mixture of aluminum and tin cans. Baling of separated materials for shipping. Storage of baled materials	Receiving hopper, conveyor, overhead suspended magnet, magnet pulley, storage containers, baler or can crusher and pneumatic transport system, forklift
Plastic, glass, aluminum cans, and tin cans	Manual or pneumatic separation of PETE, HDPE, and other plastics. Manual separation of glass by color. Magnetic separation of tin cans from commingled mixture of aluminum and tin cans. Baling of plastic, aluminum cans, and tin cans, and crushing of glass and shipping. Storage of baled and crushed materials	Receiving hopper, conveyor, picking conveyor, overhead suspended magnet, magnet pulley, glass crusher, storage containers, baler or can crusher and pneumatic transport system, forklift
Yard wastes/1	Manual separation of plastic bags and other contaminants from commingled yard wastes, grinding of clean yard waste, size separation of waste that has been ground up, storage of oversized waste for shipment to biomass facility, and composting of the undersized material	Front-end loader, tub grinder, conveyors, trommel or disc screen, storage containers, compost-turning machine
Yard wastes/2	Manual separation of plastic bags and other contaminants from commingled yard wastes followed by grinding and size separation to produce landscape mulch. Storage of mulch and composting of undersized materials	Front-end loader, tub grinder, conveyors, trommel or disc screen, storage containers, compost-turning machine
Yard wastes/3	Grinding of yard waste to produce a biomass fuel. Storage of ground material	Front-end loader, tub grinder, conveyors, storage containers or transport trailers

activities carried out at the different types of MRFs identified above are also summarized in Table 9-6.

Development of Separation Process Flow Diagrams. Once a decision has been made on how recyclable materials are to be recovered from MSW (e.g., source separation or separation from commingled MSW), flow diagrams must be developed for the separation of the desired materials and for processing the materials, subject to predetermined specifications. A *process flow diagram* for a MRF is defined as the assemblage of unit operations, facilities, and manual operations to achieve a specified waste separation goal or goals. The following factors must be considered in the development of process flow diagrams: (1) identification of the characteristics of the waste materials to be processed, (2) consideration of the specifications for recovered materials now and in the future, and (3) the available

TABLE 9-6
Examples of the functions, materials recovered or contaminants removed, and activities associated with MRFs used for the processing of commingled MSW

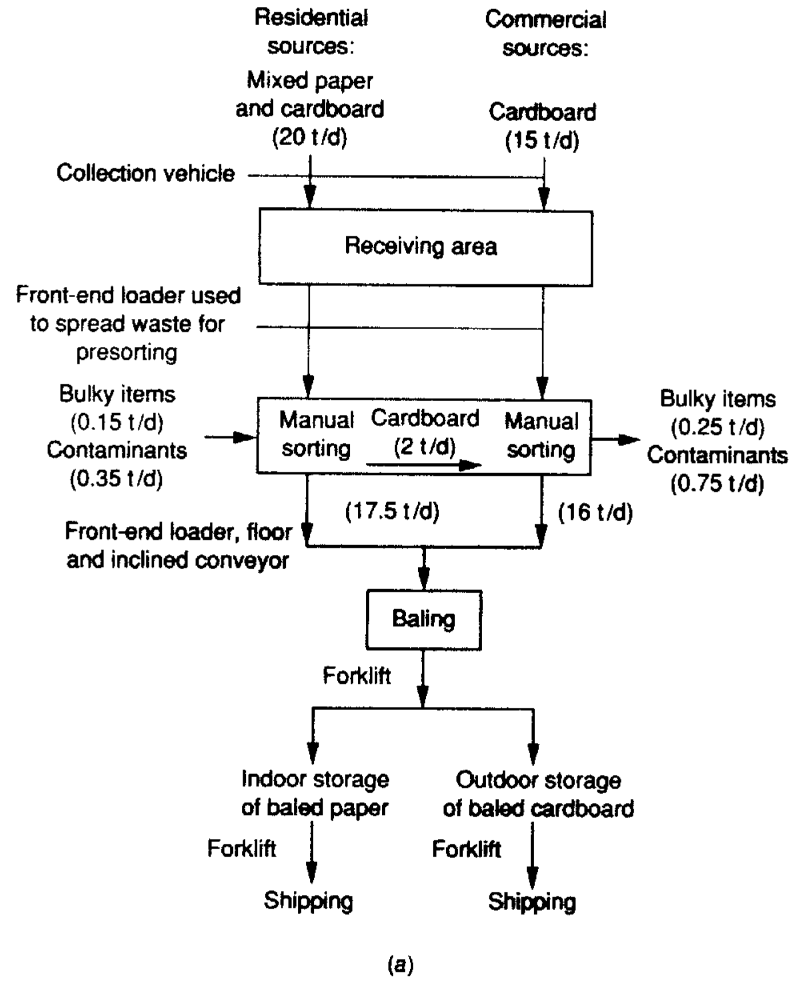
Function of MRF	Materials recovered or contaminants removed	Activities
Recovery of recyclable materials to meet mandated first-stage diversion goals (25%)	Bulky items, cardboard, paper, plastics (PETE, HDPE, and other mixed plastic), glass (clear and mixed), aluminum cans, tin cans, other ferrous materials	Manual separation of bulky items, cardboard, plastics, glass by color, aluminum cans, and large ferrous items. Magnetic separation of tin cans and other ferrous materials not removed manually. Baling of separated materials for shipping. Storage of baled materials
Recovery of recyclable materials and the further processing of source-separated materials to meet second-stage diversion goals (50%)	Bulky items, cardboard, paper, plastics (PETE, HDPE, and other mixed plastic), glass (clear and mixed), aluminum cans, tin cans, other ferrous materials. Additional separation of source-separated materials including paper, cardboard, plastic (PETE, HDPE, other), glass (clear and mixed), aluminum cans, tin cans	Manual separation of bulky items, cardboard, plastics, glass by color, aluminum cans, and large ferrous items. Magnetic separation of tin cans and other ferrous materials not removed manually. Baling of separated materials for shipping. Storage of baled materials
Preparation of MSW for use as a fuel	Bulky items, cardboard (depending on market value), glass (clear and mixed), aluminum cans, tin cans, other ferrous materials	Manual separation of bulky items, cardboard, and large ferrous items. Mechanical separation of glass, aluminum cans. Magnetic separation of tin cans and other ferrous materials not removed manually. Fuel preparation. Storage of fuel feedstock. Baling of cardboard for shipping. Storage of baled materials
Preparation of MSW for use as a feedstock for composting	Bulky items, cardboard (depending on market value), plastics (PETE, HDPE, and other mixed plastic), glass (clear and mixed), aluminum cans, tin cans, other ferrous materials	Manual separation of bulky items, cardboard, plastics, glass by color, aluminum cans, and large ferrous items. Magnetic separation of tin cans and other ferrous materials not removed manually. Baling of separated materials for shipping. Storage of baled materials. Storage of compost feedstock
Selective recovery of recyclable materials	Bulky items, office paper, old telephone books, aluminum cans, PETE and HDPE, and ferrous materials. Other materials depending on local markets	Manual separation of bulky items, cardboard. Manual separation of selected materials depending on market demands. Baling facilities, can crushers, and other equipment depending on the materials to be separated

types of equipment and facilities. For example, specific waste materials cannot be separated effectively from commingled MSW unless bulky items such as lumber and white goods and large pieces of cardboard are first removed and the plastic and paper bags in which waste materials are placed are broken open and the contents exposed. The specifications for the recovered material will affect the degree of separation to which the waste material is subjected. A typical process flow diagram for the separation of source-separated paper and cardboard is shown in Fig. 9-20*a* and discussed below. Other process flow diagrams are presented and discussed later in this section.

In Fig. 9-20*a*, mixed paper and limited amounts of cardboard from residential sources as well as cardboard from commercial sources are unloaded from the collection vehicles in separate areas of the tipping floor. Cardboard, bulky items, and nonrecyclable paper items such as spiral-bound notebooks, books, telephone books and other contaminants are removed from the mixed paper. Brown paper bags, often used to hold newspapers, are also removed and processed with the cardboard, because they command a higher market value. Bulky items and other contaminants are also removed from the cardboard. Once the mixed paper and cardboard have been sorted, a front-end loader is used to load the mixed paper onto a floor conveyor, which discharges to an inclined conveyor which, in turn, discharges into a baler. Paper bales are typically 30 × 40 × 60 in and weigh about 1400 lb. Once the paper has been baled, the cardboard is then baled. Cardboard bales are the same size as the paper bales and weigh about 1100 lb. The paper bales are stored indoors to avoid deterioration from exposure to sunlight (paper becomes brown and brittle when exposed to ultraviolet light) and water damage due to rain. The cardboard bales are stored outdoors. The same baler is also used to bale the aluminum and tin cans and the separated plastic materials processed in other parts of the facility.

Materials Balances and Loading Rates. Once the process flow diagram has been developed, the next step in the design of the MRF is to estimate the quantities of materials that can be recovered and the appropriate design loading rates. The expected process loading rates must be known in order to select and size equipment properly. Loading rates for a given process are based on a mass balance (see Chapter 6) for the preceding process. For example, if in Fig. 9-20*a* the baler is to be used for three hours per day for baling paper the loading rate would be 5.83 ton/h [(17.5 ton/d)/(3 h/d)]. The value of 17.5 ton/d is based on a materials balance analysis of the sorting operation (20 ton/d − 0.15 ton/d bulky items − 0.35 ton/d contaminants − 2 ton/d cardboard). If more operations were involved, loading rates on subsequent processes would be determined similarly, taking into account the amount of material diverted at each processing step. The development of loading rates for a variety of process flow diagrams is illustrated in detail in Chapter 12.

Loading rates for most processes are expressed in tons per hour. In determining the design loading rates, one should make a careful analysis to determine the actual number of hours per day and year the equipment will be operated. Based



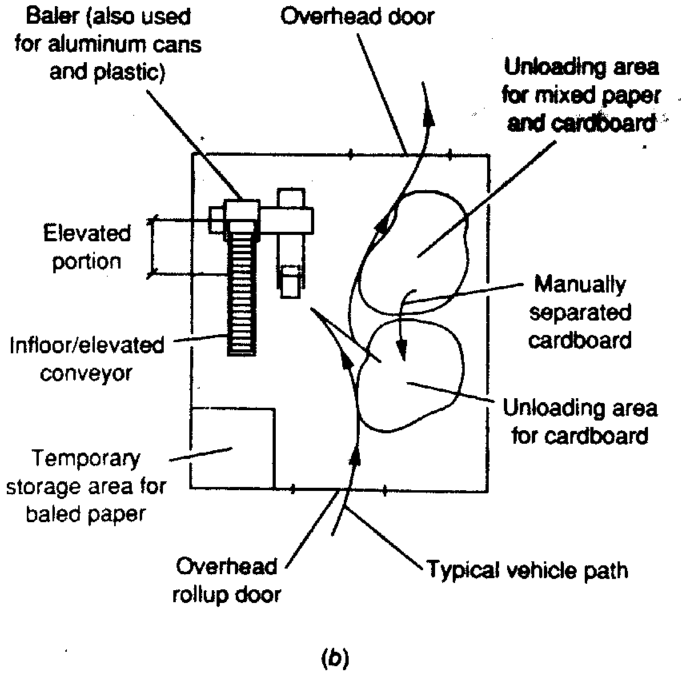


FIGURE 9-20
MRF for the processing of source-separated paper and cardboard: (*a*) process flow diagram and (*b*) layout of MRF.

on 1820 operating hours per year, the base hourly loading (or processing) rate is given by the following expression:

$$\text{Loading rate, ton/h} = \frac{\text{Number of ton/yr (or ton/d)}}{\text{1820 processing h/yr (or h/d)}} \qquad (9\text{-}1)$$

Usually, it is assumed that the separation process at the MRF will be operational for seven hours per day, where one nominal eight-hour shift will be used per day.

System Layout and Design. The layout and design of the physical facilities that make up the processing facilities will depend on the types and amounts of materials to be processed. Important factors in the layout and design of such systems include (1) the methods and means by which the wastes will be delivered to the facility, (2) estimates of materials delivery rates, (3) definition of the materials loading rates, (4) development of materials flow and handling patterns within the MRF facility, and (5) development of performance criteria for the selection of equipment and facilities. Because there are so many combinations in which the separation processes can be grouped, it is extremely important to inspect as many operating facilities as possible before settling on a final design. The layout of a facility for the processing of source-separated mixed paper and cardboard from residential sources and cardboard from commercial sources is shown in Fig. 9-20*b*. The process flow diagram for this facility appeared in Fig. 9-20*a*. The facility shown in Fig. 9-20*b* is also used for the processing of mixed plastics and glass.

Typical Materials Recovery Facilities for Source-Separated Wastes

To illustrate the many different types of MRFs that have been developed to process source-separated materials, two different types of MRFs are considered in the following discussion: (1) a MRF designed to process source-separated wastes and (2) a MRF designed to process garden trimmings and wood wastes. These two examples illustrate the general features of MRFs used in conjunction with source-separated wastes. A MRF used for the separation of mixed paper into several grades is considered in detail in Chapter 12.

MRF for Source-Separated Wastes. The process flow diagrams and the layout of the facility that is considered in the following discussion are shown in Figs. 9-21 and 9-22, respectively. The materials to be processed are mixed newspaper and cardboard, mixed plastic and glass, and aluminum and tin cans. In addition, the facility also serves as a buy-back center. The vehicle used for the collection of the separated wastes is shown in Fig. 9-23. The processing of the separated waste materials is as follows.

Paper and cardboard. Mixed paper and cardboard are unloaded onto the tipping floor. There, cardboard and nonrecyclable paper items are removed. The mixed paper is then loaded onto a floor conveyor with a front-end loader. The

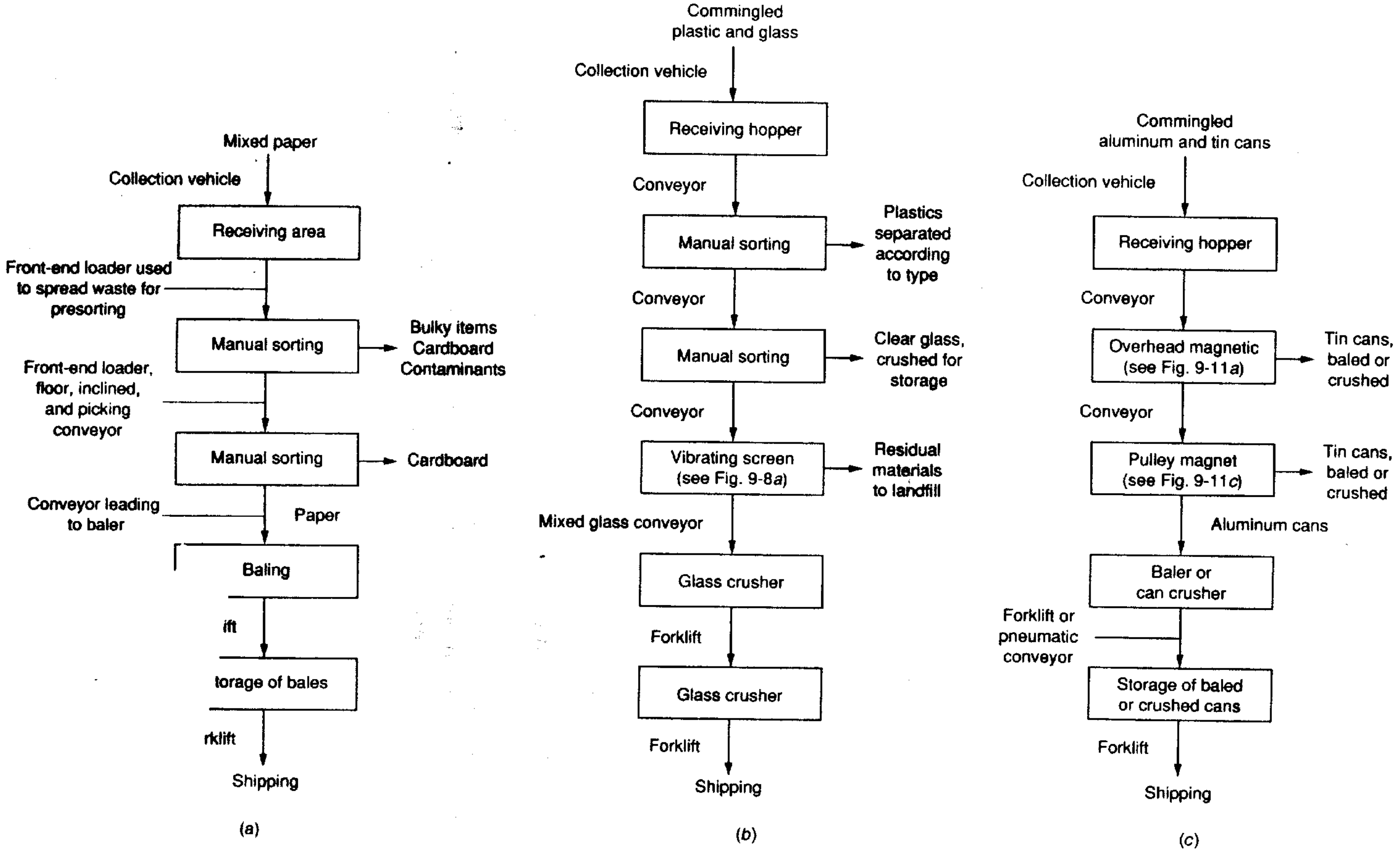
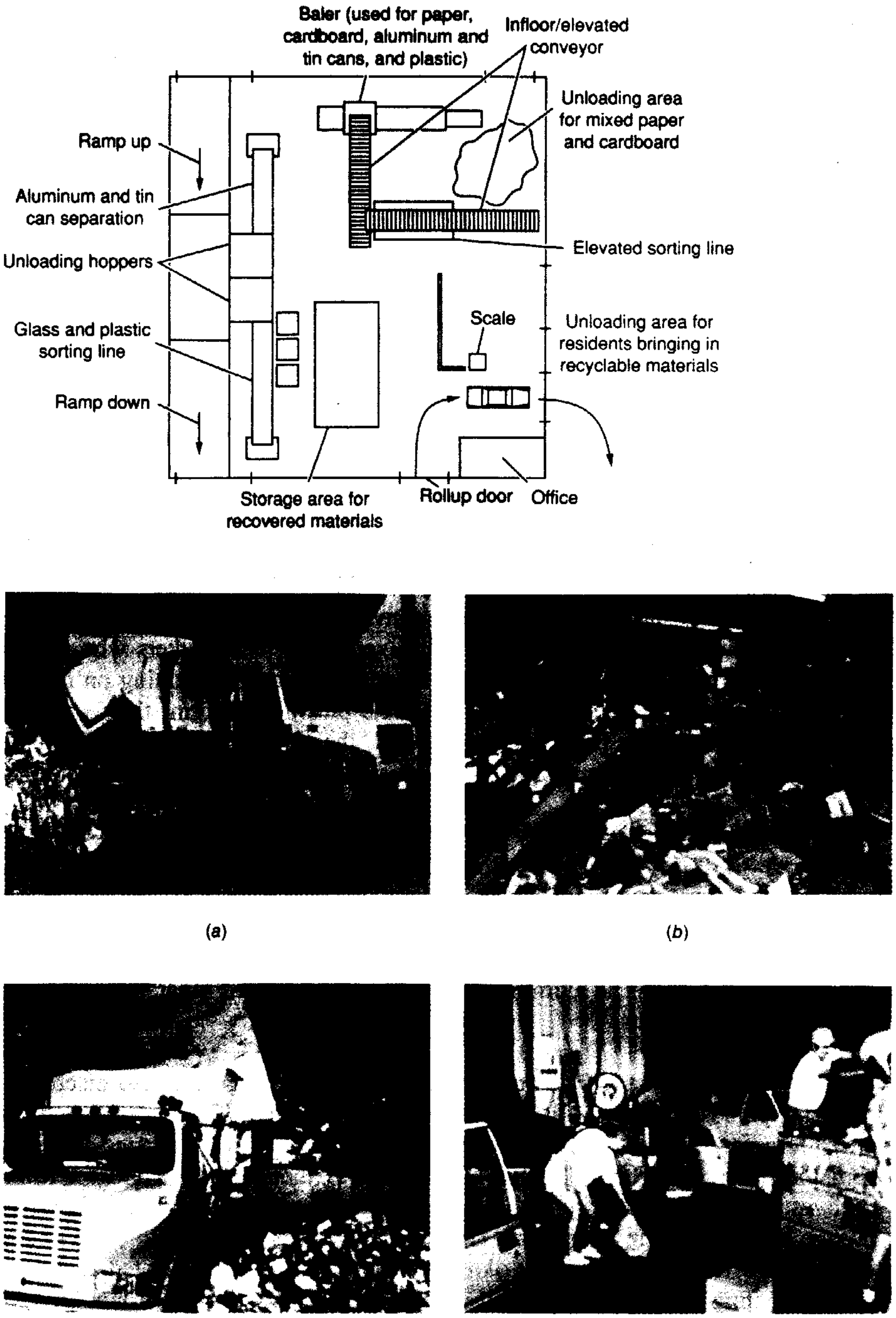


FIGURE 9-21
Flow diagrams for the separation of source-separated waste: (*a*) mixed paper, (*b*) commingled plastics and glass, and (*c*) aluminum and tin cans.

Flow diagrams for the separation of source-separated waste: (*a*) mixed paper, (*b*) commingled plastics and glass, and (*c*) aluminum and tin cans.



(*a*) (*b*)

(*c*) (*d*)

FIGURE 9-22
Layout for a MRF used to process source-separated materials: (*a*) mixed paper and cardboard deposited on tipping floor to be sorted; (*b*) elevated sorting line for paper and cardboard; (*c*) unloading aluminum and tin cans into receiving hopper; and (*d*) weighing facilities at buyback center.

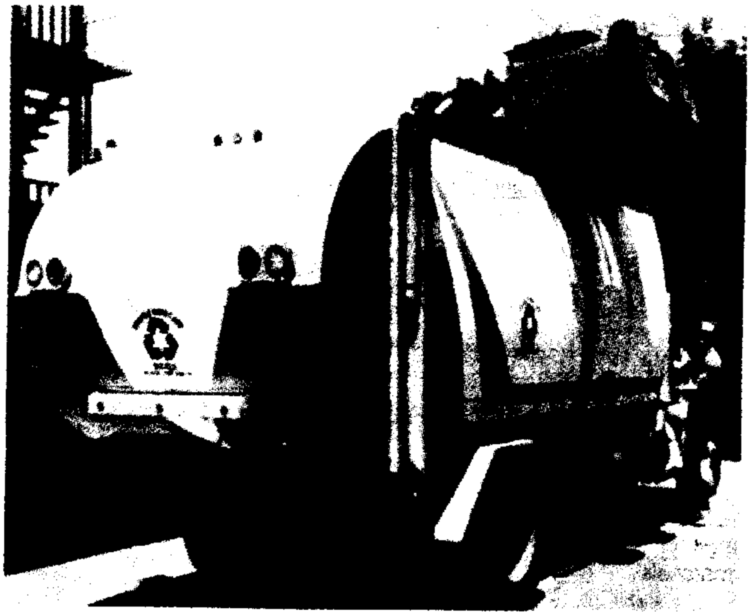


FIGURE 9-23
Specially designed collection vehicle used for the collection of source-separated wastes used in conjunction with MRF shown in Fig. 9-22.

floor conveyor discharges to an inclined conveyor, that, in turn, discharges to a horizontal conveyor, which transports the mixed paper past workers who remove any remaining cardboard from the mixed paper. The paper remaining on the belt is discharged to a conveyor, located below the picking platform, that is used to feed the baler. Once the paper has been baled, the cardboard is baled. The baler is also used to bale the aluminum and tin cans and the separated plastic materials.

Aluminum and tin cans. The commingled aluminum and tin cans are discharged into a hoppered bin, which discharges to a conveyor belt. The conveyor transports the commingled cans past an overhead magnet separator (see Fig. 9-11*a*) where tin cans are removed. The endless belt continues past a pulley magnet separator (see Fig. 9-11*c*), where any tin cans not removed with the overhead magnet are taken out. The aluminum and tin cans, collected separately, are baled for shipment to markets.

Plastic and glass. The commingled plastic and glass are also discharged into a hoppered bin, which discharges to a conveyor belt. The material is transported to a sorting area, where the plastic and clear glass are separated manually from the other materials. The remaining glass is then sent to a glass crusher. The wastes are then discharged to vibrating screens where the broken glass falls through the openings in the screen. The crushed glass is loaded onto large trailers to be transported to the purchaser. Any residual materials are collected at the end of the vibrating screen. The residual materials are disposed of in a landfill. The commingled plastic is then separated further by visual inspection or according to the type (PETE and HDPE) using the imprinted codes adopted by the plastics industry (see Chapter 3).

Buy-back center. The MRF shown in Fig. 9-22*d* also serves as a buy-back center for aluminum cans, plastic, glass, and newsprint. Operationally, homeowners drive up to the electronic scale located within the facility. Materials brought in are unloaded and weighed, and the homeowner is given a printout listing the weights of the materials he or she has brought in. The homeowner is paid immediately on the basis of the weight printout.

MRF for Source-Separated Yard Wastes. The facility to be considered in this discussion is used for processing yard wastes that are collected separately. The flow diagram for this MRF is given in Fig. 9-24. Yard wastes set out in the street by homeowners are collected using a device known as a *claw*, which clamps around these piles of wastes (see Fig. 9-25). The collected wastes are emptied into a specially equipped compactor-type collection vehicle (see Fig. 9-26). The collected wastes, along with other green wastes collected by city crews and private

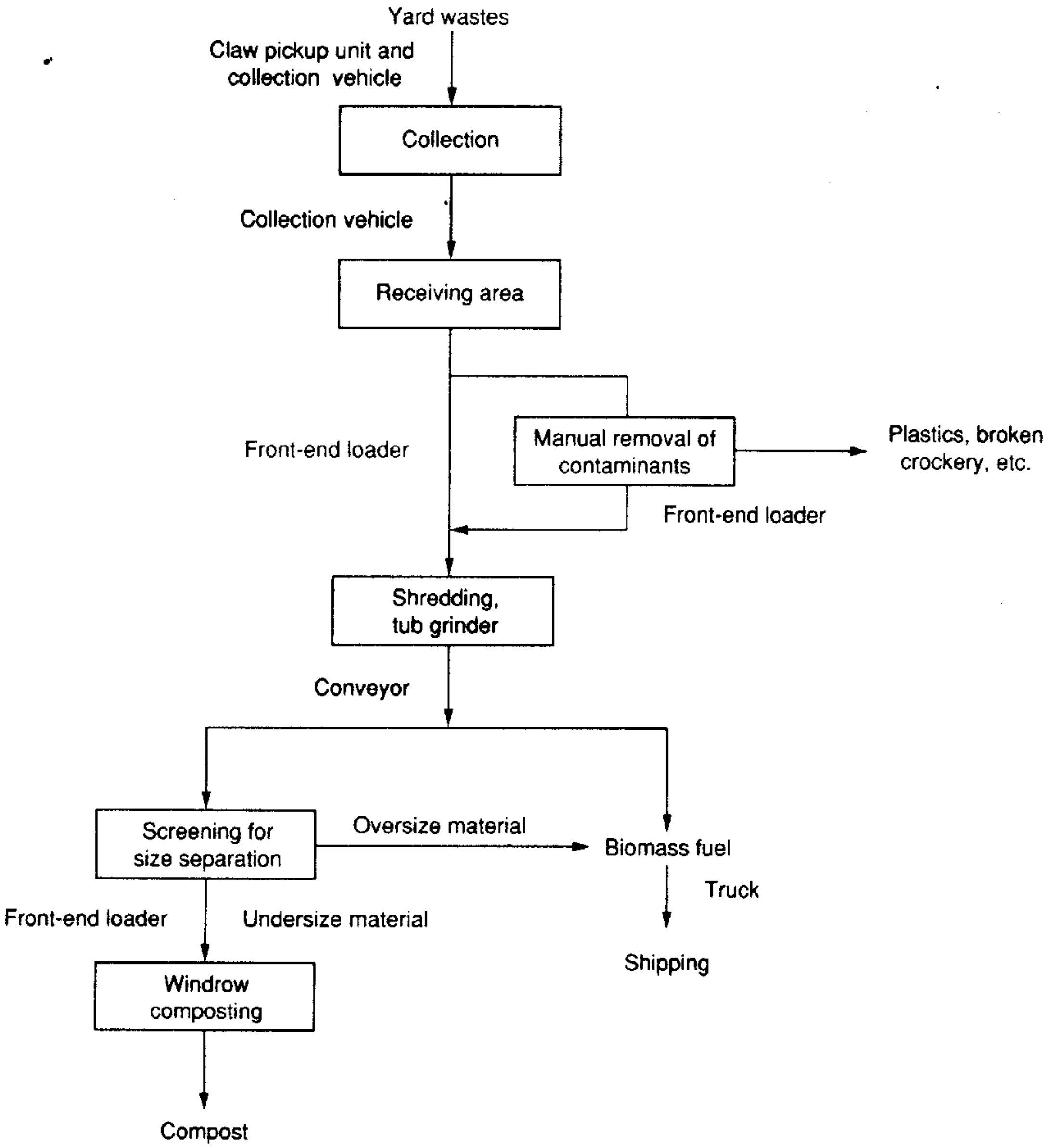


FIGURE 9-24
Flow diagram for MRF for processing yard and other green wastes.

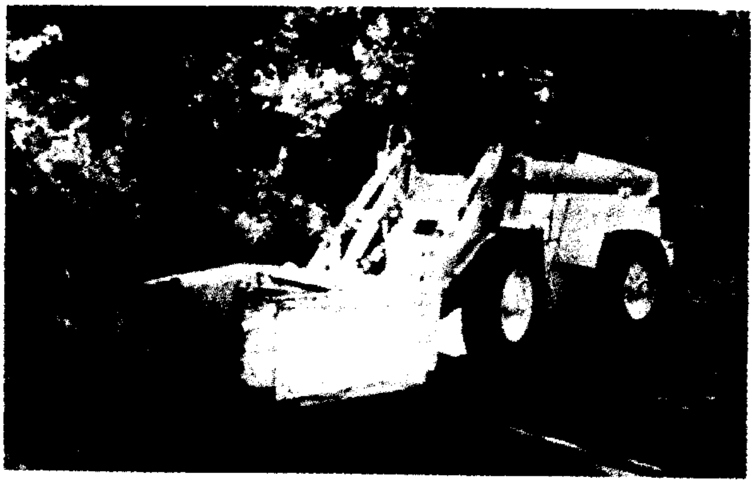


FIGURE 9-25
Claw device mounted on a wheeled tractor used to pick up yard wastes left in the street by homeowner.

haulers, are taken to a large paved area (formerly a drive-in theater). There the wastes are ground up using a tub grinder (see Fig. 9-27). The material from the tub grinder is passed through a trommel screen to separate pieces of wood larger than one-half inch. Wood chips larger than one-half inch are sold to a local biomass waste-to-energy facility. Green wastes and wood chips smaller than one-half inch are composted using the windrow method (see Section 9-8). The resulting compost is given to the local residents free for the taking. Any remaining compost is used by the city in landscaping. Depending on the market for processed biomass fuel, all of the ground-up yard wastes have, at times, been sold for use as a biomass fuel without any further processing.

To make higer-quality compost would require that the yard wastes first be spread out on the paved area and contaminants such as plastic bags, broken concrete, and metals be removed manually. The yard wastes would then be ground up for the production of compost. Unfortunately, the price offered for high quality compost in 1992 does not usually warrant the extra processing and handling costs involved in the removal of contaminants normally found in source-separated yard wastes. In the future, as material specifications become more stringent (see Chapter 15), the removal of contaminants may become necessary if the compost produced from yard wastes is to be sold commercially.

FIGURE 9-26
Collection vehicle modified to work in conjunction with the claw (see Fig. 9-25) for the collection of yard wastes.

FIGURE 9-27
Tub grinder used to process yard wastes collected separately.

Typical Materials Recovery Facilities for Commingled Wastes

The separation of waste components from commingled wastes and their processing are necessary operations in the recovery of materials for direct reuse and recycling and for the production of a feedstock that can be used for the recovery of energy and the production of compost. The purpose of this section is to illustrate how the unit operations and facilities discussed previously are grouped together to achieve the separation of materials from commingled MSW. A MRF designed to process commingled construction and demolition wastes is also described.

MRF for Recovery of Materials from Commingled MSW and for the Processing of Source-Separated Materials. Recognizing that meeting mandated waste diversion goals with source separation programs alone will be difficult, many communities have developed plans for MRFs that can be used both to separate materials from commingled MSW and to process materials from source separation programs. A typical process flow diagram for a MRF employing manual and mechanical separation of materials from commingled MSW and manual separation of source-separated wastes is illustrated in Fig. 9-28. Commingled MSW from residential and other sources are discharged in the receiving area. Recyclable, reusable, and oversized materials such as cardboard, lumber, white goods, and broken furniture are removed in the first-stage presorting operation before the commingled waste is loaded on to an inclined conveyor. Source-separated materials in see-through plastic bags also are removed from the commingled MSW. Additional cardboard and large items are handpicked from the conveyor at the second-stage presorting station as the waste material is transported to the bag-breaking station. The next step involves breaking open the plastic bags, which can be accomplished either manually or mechanically. In some facilities, a short enclosed trommel equipped with protruding blades is used as a bag breaker (see Fig. 9-9). As noted in Table 9-3, flail mills, shear shredders, and screw augers have also been used as bag breakers.

The next step in the process involves the first stage of manual separation of specific waste materials. Materials typically removed include paper, cardboard, all

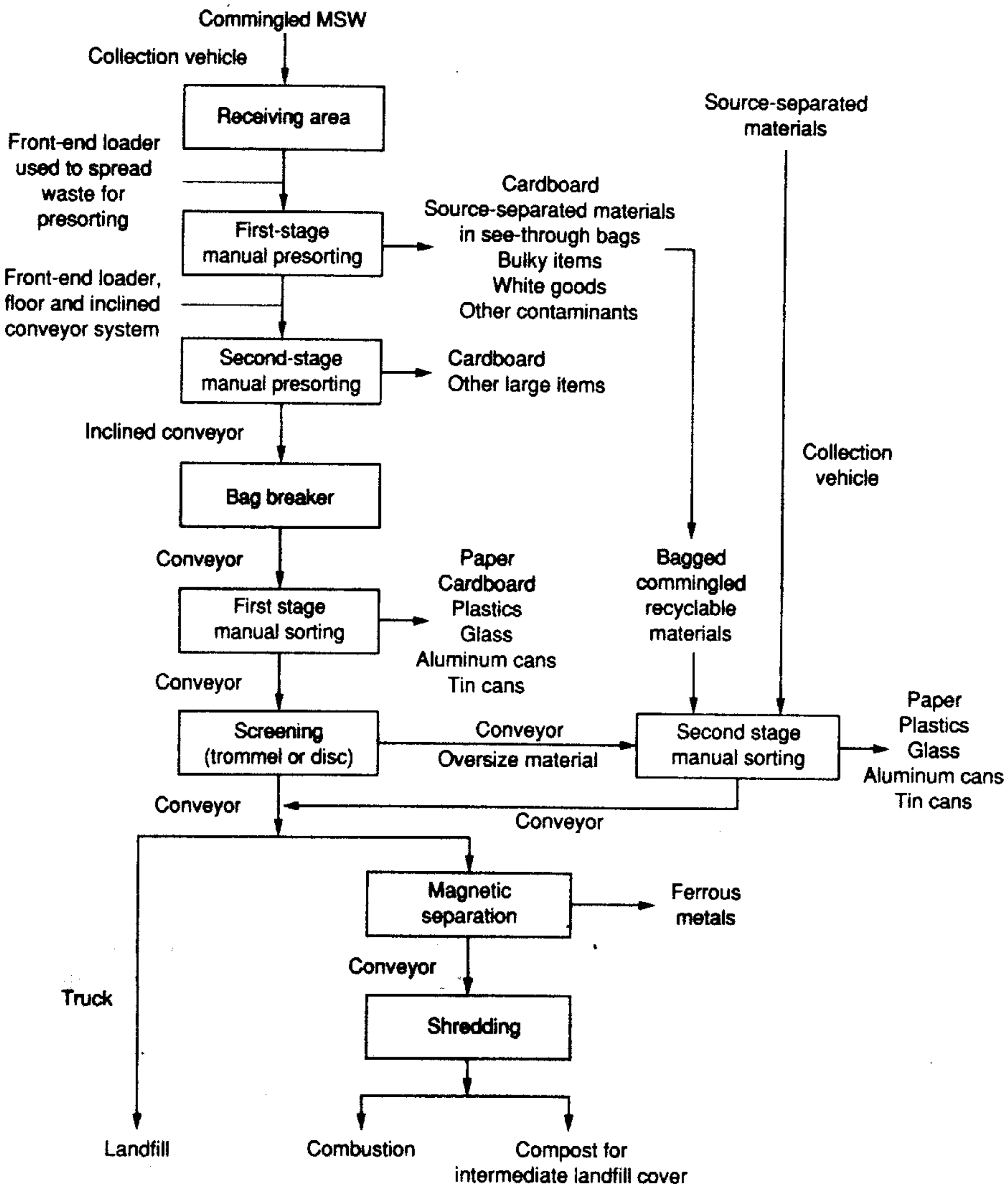


FIGURE 9-28
Flow diagram for the recovery of waste materials from commingled MSW.

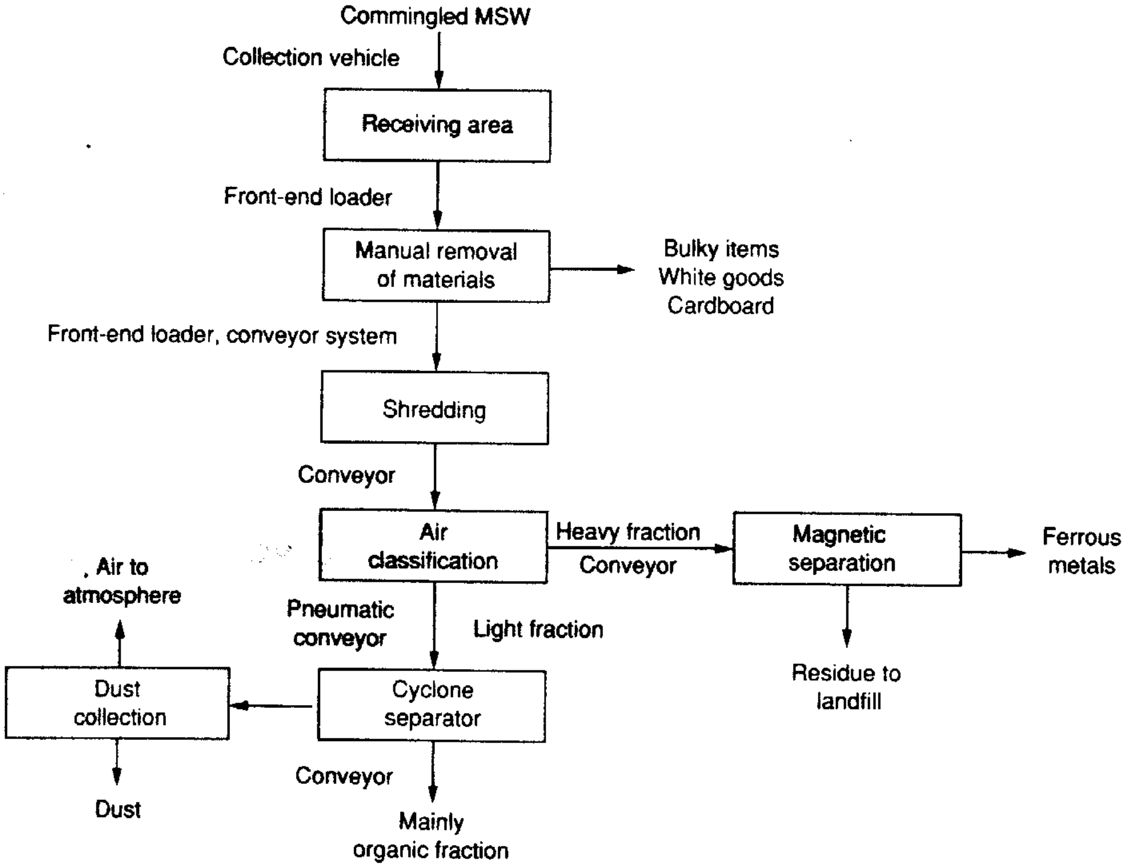
types of plastic, glass, and metals. In some operations, different types of plastic are separated simultaneously. Mixed plastics are usually separated by type in a secondary separation process. Material remaining on the conveyor is discharged into a trommel (or disc screen) for size separation. The oversized material is sorted manually a second time (second-stage sorting). Commingled source-separated materials, collected separately from residential and commercial sources, and the source-separated materials contained in see-through bags removed from the commingled MSW in the first-stage presorting operation are further sorted using the second-stage sorting line. Source-separated mixed paper and cardboard would be processed separately using a flow diagram such as the one given in Fig. 9-24. It should be noted that both the first- and second-stage sorting activities would normally be carried out in an air-conditioned facility. Depending on the extent of the first- and second-stage sorting operations, the undersized material from the trommel and the material remaining after the second-stage sorting operation are hauled away for disposal in a landfill, processed further and combusted, or used to produce compost to be used as intermediate landfill cover. As shown in Fig. 9-28, further processing of the residual materials usually involves shredding and magnetic separation. A detailed materials balance analysis of the MRF described in this section is presented in Example 12-6 in Chapter 12.

The following excerpt from a text published in 1921 provides an historical perspective on current materials separation activities at MRFs:

> The most developed case of sorting refuse in Europe is at Puchheim, a suburb of Munich, where the refuse from a population of more than 600,000 is picked over and finally disposed of. First, the finer materials and dust are sifted out on a moving and vibrating belt, and the bulky salable articles are picked out. In the adjoining room, about 40 women stand on each side of the belt, each one picking out a designated material and throwing it into a designated wire basket. The substances thus removed are chiefly: Paper, white and green glass, rags, leather, bones, tinned cans, iron, brass, copper, tin, etc. The bones are treated with benzine, and, on the premises, are converted into grease, glue, bone meal, or charcoal. Garbage is cleaned, sterilized, and fed to hogs in an adjoining building. Paper is freed from dust, pressed into bales, and utilized for the manufacture of pasteboard. Wood is burned under the boilers. Bottles are cleaned, disinfected, and sold. Tinned cans are sold as iron. No one enters the works until after donning working clothes, nor leaves them until after a good wash or bath. The working rooms are washed twice a day with dilute carbolic acid. It is reported by De Fodor that this very effective sorting contains the germ of faulty economics, in the fact that the total revenue hardly covers three-quarters of the necessary expenditure.[7]

Except for many modern sorting facilities being located in air-conditioned facilities, the similarities are striking. The economic issue remains the same today, but environmental costs were not generally considered in the 1920s.

MRFs for Preparation of Feedstock from Commingled MSW. The separation of commingled MSW in highly mechanized systems is illustrated in Fig. 9-29*a* and *b*. As shown in both these process flow diagrams, the commingled MSW is first discharged in the receiving area where lumber, white goods, and oversized items are usually removed manually before the material is loaded onto the first conveyor. In Fig. 9-29*a*, the commingled MSW is shredded as the first step in the process. Air classification is then used to recover the mainly organic fraction of the MSW. In Fig. 9-29*b*, a trommel is used to achieve a better separation of the organic fraction of the MSW and to remove small contaminants more effectively. The flow diagrams in Fig. 9-29 represent two of many different approaches that have been, and continue to be, used for the mechanical separation of waste components from commingled MSW for the production of a feedstock for the production of energy.



(*a*)

FIGURE 9-29
Flow diagrams for the recovery of waste components from solid waste: (*a*) conventional (with shredder) and (*b*) shear shredder and trommel used to replace shredder in flow diagram.

The mainly organic fraction of MSW remaining after processing is known as fluff refuse-derived fuel, commonly known as fluff-RDF. In some operations, the mainly organic fraction is used to produce a densified refuse-derived fuel known as d-RDF.

Flow diagrams similar to those shown in Fig. 9-29 have also been used to describe the preprocessing of MSW for the production of compost. Unfortunately, shredding commingled MSW before metal objects and other contaminants have been removed results in the production of compost contaminated with heavy metals and trace organic compounds. Acceptable contaminant levels for the various constituents that may be found in composted MSW are given in Table 15-8. Because of the serious problems associated with the production of contaminated compost, many communities have developed MRF process flow diagrams similar to the one given in Fig. 9-28 for the production of feedstock for composting. The picking stations are used to remove plastics, glass, aluminum and tin cans, and other contaminants before the waste is shredded to reduce the particle size for composting.

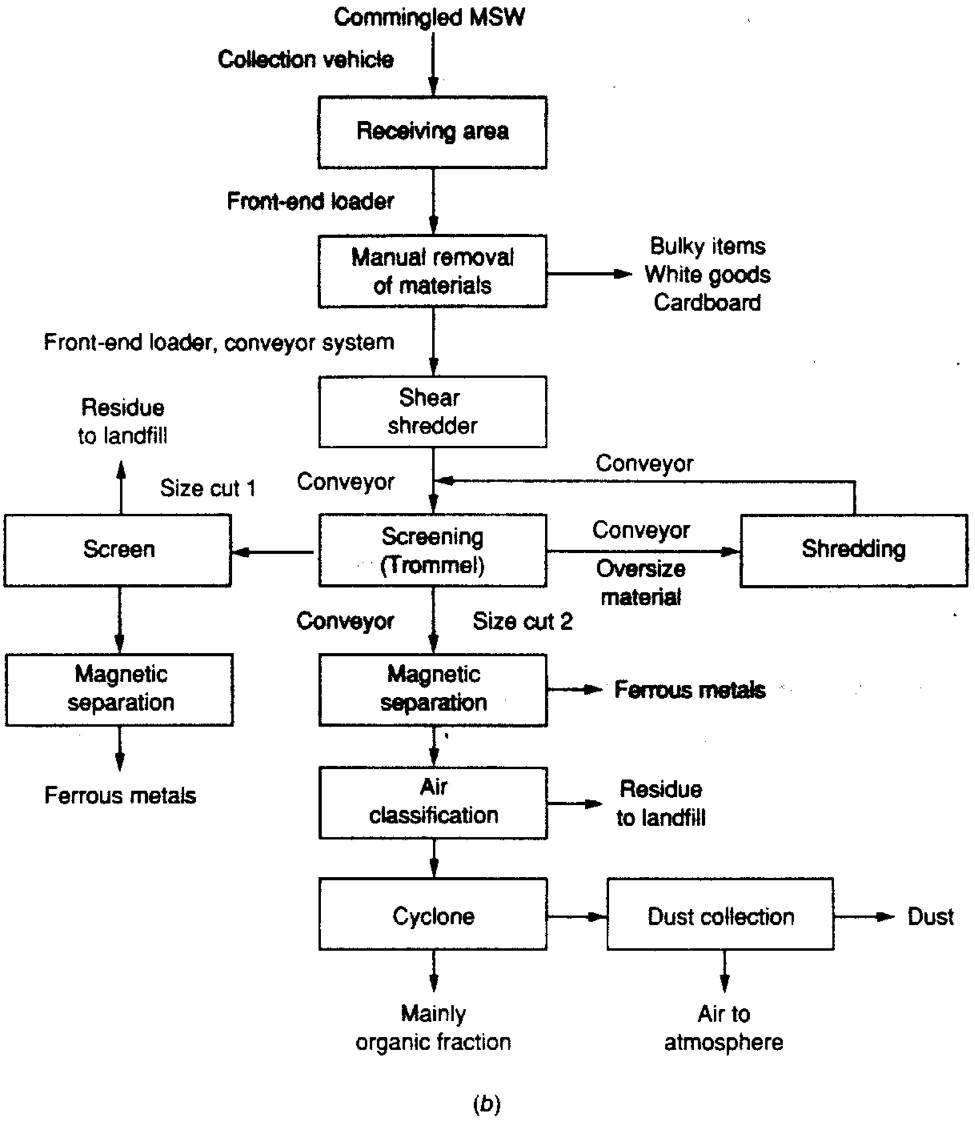


FIGURE 9-29 (*continued*)

MRF for Commingled Construction and Demolition Wastes. An overview of a MRF designed to process commingled construction and demolition wastes is shown in Fig. 9-30. Commingled construction and demolition wastes are brought to the site and dumped in an open area. The wastes are then spread out and all of the wood is removed manually (see Fig. 9-30*a*). The wood is taken to a large wood grinder, where it is converted to wood chips. After the wood has been removed, the waste is picked up with a front-end loader and discharged onto a two-stage vibrating screen (see Fig. 9-30*b*). The first screen is used to eliminate large pieces of concrete, roots and similar materials. The second screen, located immediately below the first screen, is used to remove finer pieces of broken concrete and other smaller-sized contaminants. The fine material passing the two screens is then conveyed to a second vibrating screen, where additional fine contaminants are removed. The final product, relatively clean dirt, is stockpiled for sale. The material removed by the screens is stockpiled and eventually hauled to the landfill for disposal.

(a) (b)

FIGURE 9-30
Views of an MRF for construction and demolition wastes: (*a*) wastes spread on ground where wood is removed manually and (*b*) waste being screened to produce usable product.

Planning and Design Process for MRFs

The planning and design of MRFs involve three basic steps: (1) feasibility analysis, (2) preliminary design, and (3) final design. These planning and design steps are common to all major public works projects such as landfills or wastewater treatment plants. In some cases, the feasibility analysis has already been accomplished as part of the integrated waste management planning process.

Feasibility Analysis. The purpose of the feasibility analysis is to decide whether the MRF should be built. The feasibility study should provide the decision makers with clear recommendations on the technical and economic merits of the planned MRF. A typical feasibility analysis may contain sections or chapters dealing with the following topics.

The integrated waste management plan. The coordination of the MRF with the integrated waste management plan for the community is delineated in this section. A clear explanation of the role of the MRF in achieving landfill waste diversion and recycling goals is a key element of this section.

Conceptual design. What type of MRF should be built, which materials will be processed now and in the future, and what the design capacity of the MRF should be are discussed. Plan views and renderings of what the final MRF might look like are often included in this section.

Economics. Capital and operating costs (see Appendix E) are presented and discussed. Estimates of revenues available to finance the MRF (sales of recyclables, tipping fees, subsidies) are presented. A sensitivity analysis of the effects of fluctuating prices for recyclables and the impacts of changes in the composition of the waste should be included.

Ownership and operation. An analysis of how the MRF should be owned and operated is presented. Typical options to be considered include public ownership, private ownership, or public ownership with contract operation.

Procurement. The approach to be used in the design and construction of the MRF is discussed. Several options exist including (1) the traditional architect-engineer design and contractor construct process; (2) the turnkey contracting process in which design and construction are performed by a single firm; and (3) a full-service contract in which a single contractor designs, constructs, and operates the MRF.

Preliminary Design. The preliminary design includes development of the materials flow diagram, development of materials mass balances and loading rates for the unit operations (conveyors, screens, shredders, etc.) that make up the MRF, and the layout of the physical facilities. The cost estimate developed in the feasibility study is refined in the preliminary design report using actual price quotations from vendors.

Final Design. Final design includes preparation of final plans and specifications that will be used for construction. A detailed engineers' cost estimate is made based on materials take offs and vendor quotes. The cost estimate will be used for the evaluation of contractor bids if the traditional procurement process is used.

Issues in the Implementation and Operation of MRFs

The principal nonengineering issues associated with the implementation of MRFs are related to (1) siting, (2) environmental emissions, (3) public health and safety, and (4) economics. The importance of these issues cannot be over-emphasized and special attention must be devoted to their resolution before proceeding with final plans for any proposed facility.

Siting. Although it has been possible to build and operate MRFs in close proximity to both residential and industrial developments, operators must take extreme care if MRFs are to be environmentally and aesthetically acceptable. Ideally, to minimize the impact of the operation of MRFs, they should be sited in more remote locations where adequate buffer zones surrounding the facility can be maintained. In many communities, MRFs are located at the landfill site.

Environmental Emissions. Regardless of where a MRF is located, extreme care must be taken in its operation if it is to be environmentally acceptable with respect to traffic, noise, odor, dust, airborne debris, liquid discharges, visual unsightliness, and vector control. The best approach to these design issues is to visit many operating MRFs before settling on a final design. Proper housecleaning practices and proper storage of recyclable materials will reduce public complaints.

An attractive, well-maintained and -operated MRF can be a community asset and an incentive to citizen participation in recycling programs.

Public Health and Safety. Materials recovery facilities are a relatively new type of industrial facility and do not have a long history of experience in terms of public health and safety issues. Nevertheless, one must devote special attention to these issues during the design of the process. Two principal types of public health and safety issues are involved in the design of MRFs. The first is related to the public health and safety of the employees of the MRF. The second issue is related to the health and safety of the general public, especially for MRFs that will also be used as drop-off and buy-back centers.

Worker issues. Materials recovery facilities are potentially dangerous work environments unless proper precautions are taken during design and operation. Some of the most important safety and health issues are summarized in Table 9-7. Because of the moving equipment and conveyors used in most MRFs, special attention must be devoted to materials flow and worker involvement at each stage of the process. Where the manual separation of waste materials from commingled MSW is used, careful attention must be given to the types of protective clothing, air-filtering head gear, and puncture-proof gloves supplied to the workers. In addition, worker fatigue is another important issue that must be addressed. Where

TABLE 9-7
Health and safety issues in design and operation of MRFs

Component	Safety issue
Mechanical	High-speed rotating and reciprocating parts Exposed drive shafts and belts High-intensity noise Broken glass, sharp metal objects Explosive hazards
Electrical	Exposed wiring, switches, and controls Ground faults
Architectural	Ladders, stairways, and railings Vehicle routing and visibility Ergonomics of handpick conveyor belts Lighting Ventilation and air conditioning Drainage
Operational	Housekeeping practices Safety training Safety and first aid equipment
Hazardous materials	Hazardous wastes from households and small-quantity generators Biohazards such as human blood products and pathogenic organisms
Personal safety equipment	Punctureproof, impermeable gloves; safety shoes, uniforms, eye protection, noise protection

sorting from moving belts is used, the height of the worker relative to the moving belt must be adjustable. The federal government through OSHA and state OSHA-type programs now require the development of comprehensive health and safety programs for workers at MRFs.

Public access issues. Because the activities involved with the operations of a MRF are potentially dangerous, the public should be excluded from access except under careful control, as during conducted tours. Convenience stations for the deposit of recyclables should be provided for public access away from the main traffic pattern.

Economics. Because many MRFs are often underfunded owing to local economic constraints, the facilities needed for the control of environmental emissions and the management of public health and safety issues are often not incorporated in the design of these facilities. Because a MRF can be shut down for unacceptable environmental and health and safety issues, careful attention must be devoted to the design and implementation of environmental control facilities. For example, the purchase of expensive mechanical separation equipment may be postponed or delayed in favor of manual separation and the purchase of dust control facilities. Further, because of the uncertainties concerning the future quantities and characteristics of the waste, a detailed sensitivity analysis must be performed to assess the economic viability of a MRF or MR/TF subject to a wide range of projected future changes in the characteristics or quantity of the waste.

9-7 WASTE TRANSFORMATION THROUGH COMBUSTION

The separation and processing of waste materials has been considered in Section 9-6. In this and the following sections the focus is on the transformation of waste materials. Transformation processes are used to reduce the volume and weight of waste requiring disposal and to recover conversion products and energy. The organic fraction of MSW can be transformed by a variety of chemical and biological processes. The most commonly used chemical transformation process is combustion, which can be used to reduce the original volume of the combustible fraction of MSW by 85 to 95 percent. In addition, the recovery of energy in the form of heat is another attractive feature of the combustion process. Although combustion technology has advanced in the past two decades, air pollution control remains a major concern in implementation. Even if stricter air pollution control requirements can be met through the use of existing and developing technology (see Chapter 13), the problem of siting such facilities remains monumental (see Chapter 18).

Description of Combustion Process

The basic operations involved in the combustion of commingled MSW are identified in Fig. 9-31. The operation begins with the unloading of solid wastes from

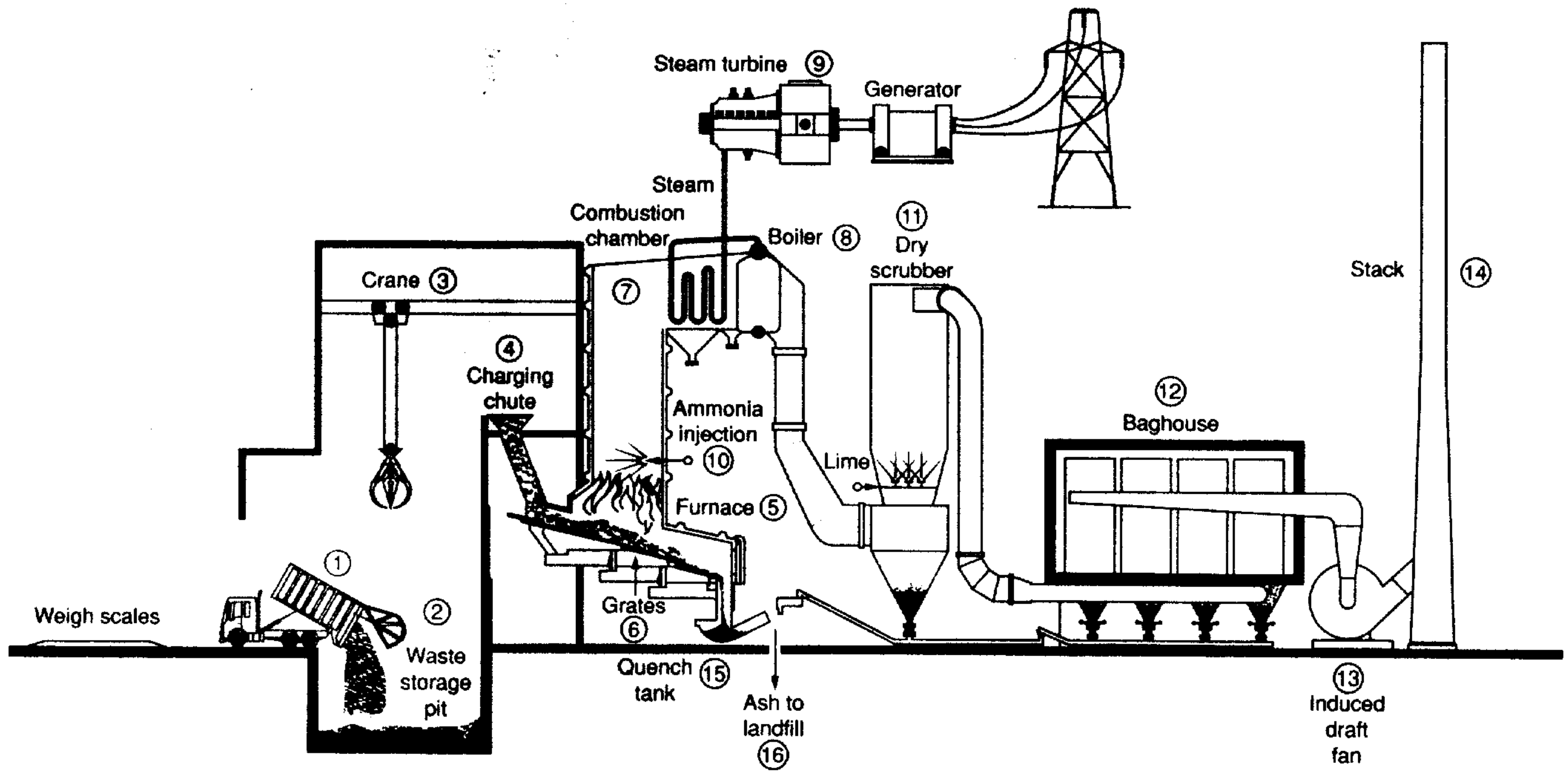


FIGURE 9-31
Section through a typical continuous-feed mass-fired municipal combustor used for the production of energy from MSW. (Courtesy of County Sanitation Districts of Los Angeles County.)

collection trucks (1) into a storage pit (2). The width of the unloading platform and storage bin is a function of the size of the facility and the number of trucks that must unload simultaneously. The depth and width of the storage bin are determined by both the rate at which waste loads are received and the rate of burning. The capacity of the storage pit is usually equal to the volume of waste for two days. The overhead crane (3) is used to batch load wastes into the feed (charging) chute (4), which directs the wastes to the furnace (5). The crane operator can select the mix of wastes to achieve a fairly even moisture content in the charge. Large or noncombustible items are also removed from the wastes with the overhead crane. Solid wastes from the feed (charging) chute fall onto the grates (6) where they are mass-fired. Several different types of mechanical stokers are commonly used.

Air may be introduced from the bottom of the grates (under-fire air) by means of a forced-draft fan or above the grates (over-fire air) to control burning rates and furnace temperature. Because most organic wastes are thermally unstable, various gases are driven off as the combustion process takes place in the furnace. These gases and small organic particles rise into the *combustion chamber* (7), and burn at temperatures in excess of 1600°F. Heat is recovered from the hot gases using water-filled tubes in the walls of the combustion chamber and with a boiler (8) that produces steam, which is converted to electricity by a turbine-generator (9).

Air pollution control equipment may include ammonia injection for NO_x (nitrogen oxides) control (10), a dry scrubber for SO_2 and acid gas control (11), and a baghouse (fabric filter) for particulate removal (12). To secure adequate air flows to provide for head losses through air pollution control equipment, as well as to supply air to the combuster itself, an induced-draft fan (13) may be needed. The end products of combustion are hot combustion gases and ash. The cleaned gases are discharged to the stack (14) for atmospheric dispersion. Ashes and unburned materials from the grates fall into a residue hopper (15) located below the grates, where they are quenched with water. Fly ash from the dry scrubber and the baghouse is mixed with the furnace ash and conveyed to ash treatment facilities (16). Details on combustion design, air pollution control equipment, and ash treatment and disposal are discussed in Chapter 13.

Combustion Products

The principal elements of solid wastes are carbon, hydrogen, oxygen, nitrogen, and sulfur (see Chapter 4). Smaller amounts of other elements will also be found in the ash. Under ideal conditions, the gaseous products derived from the combustion of municipal solid wastes with stoichiometric amounts of air, would include carbon dioxide (CO_2), water (H_2O, flue gas), nitrogen (N_2), and small amounts of sulfur dioxide (SO_2). In actuality, many different reaction sequences are possible, depending on the exact nature of the wastes and the operating characteristics of the combustion reactor. The basic reactions for the oxidation (combustion) of the carbon, hydrogen, and sulfur (and their atomic masses) contained in the organic fraction of MSW are as follows:

For carbon

$$\underset{12}{\mathrm{C}} + \underset{32}{\mathrm{O_2}} \rightarrow \mathrm{CO_2} \tag{9-2}$$

For hydrogen

$$\underset{4}{\mathrm{2H_2}} + \underset{32}{\mathrm{O_2}} \rightarrow \mathrm{2H_2O} \tag{9-3}$$

For sulfur

$$\underset{32.1}{\mathrm{S}} + \underset{32}{\mathrm{O_2}} \rightarrow \mathrm{SO_2} \tag{9-4}$$

If it is assumed that dry air contains 23.15 percent oxygen by weight, then the amount of air required for the oxidation of 1 lb of carbon would be equal to 11.52 lb [(32/12)(1/0.2315)]. The corresponding amounts for hydrogen and sulfur are 34.56 and 4.31 lb, respectively. Computation of the amount of air required for the complete combustion of an organic waste is illustrated in Example 9-2.

Example 9-2 Determination of the stoichiometric amount of air required for the combustion of an organic solid waste. Determine the amount (lbs and ft^3) of air required for the complete combustion of one ton of an organic solid waste. Assume that the composition of the organic waste to be combusted is given by C_5H_{12}. Assume the specific weight of air is 0.075 lb/ft^3.

Solution

1. Write a balanced stoichiometric equation for the oxidation of the organic compound based on oxygen:

$$\underset{72}{\mathrm{C_5H_{12}}} + \underset{256}{\mathrm{8O_2}} \rightarrow \mathrm{5CO_2} + \mathrm{6H_2O}$$

2. Write a balanced equation for the oxidation of the organic compound with air. In combustion calculations, dry air is assumed to be comprised of 21 percent oxygen and 79 percent nitrogen. Thus, the corresponding reaction to that given in Step 1 for air is

$$\mathrm{C_5H_{12}} + \mathrm{8O_2} + \mathrm{30.1N_2} \rightarrow \mathrm{5CO_2} + \mathrm{6H_2O} + \mathrm{30.1N_2}$$

3. Determine the amount of air required for combustion, assuming air contains 23.15 percent oxygen by weight.

$$\mathrm{O_2}\ \text{required} = \frac{256}{72} \times (2000\ \text{lb/ton}) = 7111\ \text{lb/ton}$$

$$\text{Air required} = \frac{7111\ \text{lb/ton}}{0.2315} = 30{,}717\ \text{lb/ton}$$

4. The amount of air required for combustion can also be computed using the factors, given previously.

$$\text{Air required for carbon, C} = \frac{60}{72} \times (2000\ \text{lb/ton}) \times 11.52 = 19{,}200\ \text{lb/ton}$$

$$\text{Air required for hydrogen, H} = \frac{12}{72} \times (2000\ \text{lb/ton}) \times 34.56 = 11{,}520\ \text{lb/ton}$$

$$\text{Total air required} = 19{,}200 + 11{,}520 = 30{,}720\ \text{lb/ton}$$

5. Determine the volume of air required for combustion.

$$\text{Volume of air} = (30{,}717\ \text{lb/ton})/(0.075\ \text{lb/ft}^3) = 409{,}560\ \text{ft}^3\text{/ton}$$

Comment. In Step 2, nitrogen is retained on both sides of the equation because it does not enter into the reaction. Although complete combustion was assumed in this example for the purposes of illustrating the computations involved in stoichiometric calculations, complete combustion is seldom achieved in practice. Typically, from 3 to 5 percent of the organic matter in the input feed will be found in the ash from a combustion facility.

Types of Combustors

Solid waste combustors can be designed to operate with two types of solid waste fuels: unseparated commingled MSW (mass-fired) and processed MSW known as refuse-derived fuel (RDF). Mass-fired (also known as mass-burn) combustors are the predominant type. In 1987, 68 percent of the operational combustor capacity in the United States was provided by mass-fired units and 23 percent by RDF-fired units. The remaining 9 percent of the capacity was provided by mass-fired modular combustion units.

Mass-Fired Combustors. In a mass-fired combustor (see Fig. 9-32), minimal processing is given to solid waste before it is placed in the hopper used to feed the combustor. The crane operator in charge of loading the charging hopper can reject obviously unsuitable items. However, one must assume that anything in the MSW stream may ultimately enter the combustor including bulky oversize noncombustible objects (e.g., broken tricycles, etc.) and even potentially hazardous wastes deliberately or inadvertently delivered to the system. For these reasons, the combustor must be designed to handle these objectionable wastes without damage to equipment or injury to operating personnel. The energy content of mass-fired waste can be extremely variable, depending on the climate, season, and source of waste. In spite of these potential disadvantages, mass-fired combustors have become the technology of choice for most existing and planned combustion facilities (see Fig. 9-33).

RDF-Fired Combustors. Compared with the uncontrolled nature of unprocessed commingled MSW, RDF can be produced from the organic fraction of MSW (see Chapter 12) with fair consistency to meet specifications for energy content, moisture, and ash content. The RDF can be produced in shredded or fluff form, or as densified pellets or cubes. Densified RDF (d-RDF) is more costly to produce but is easier to transport and store. Either form can be burned by itself, or mixed with coal.

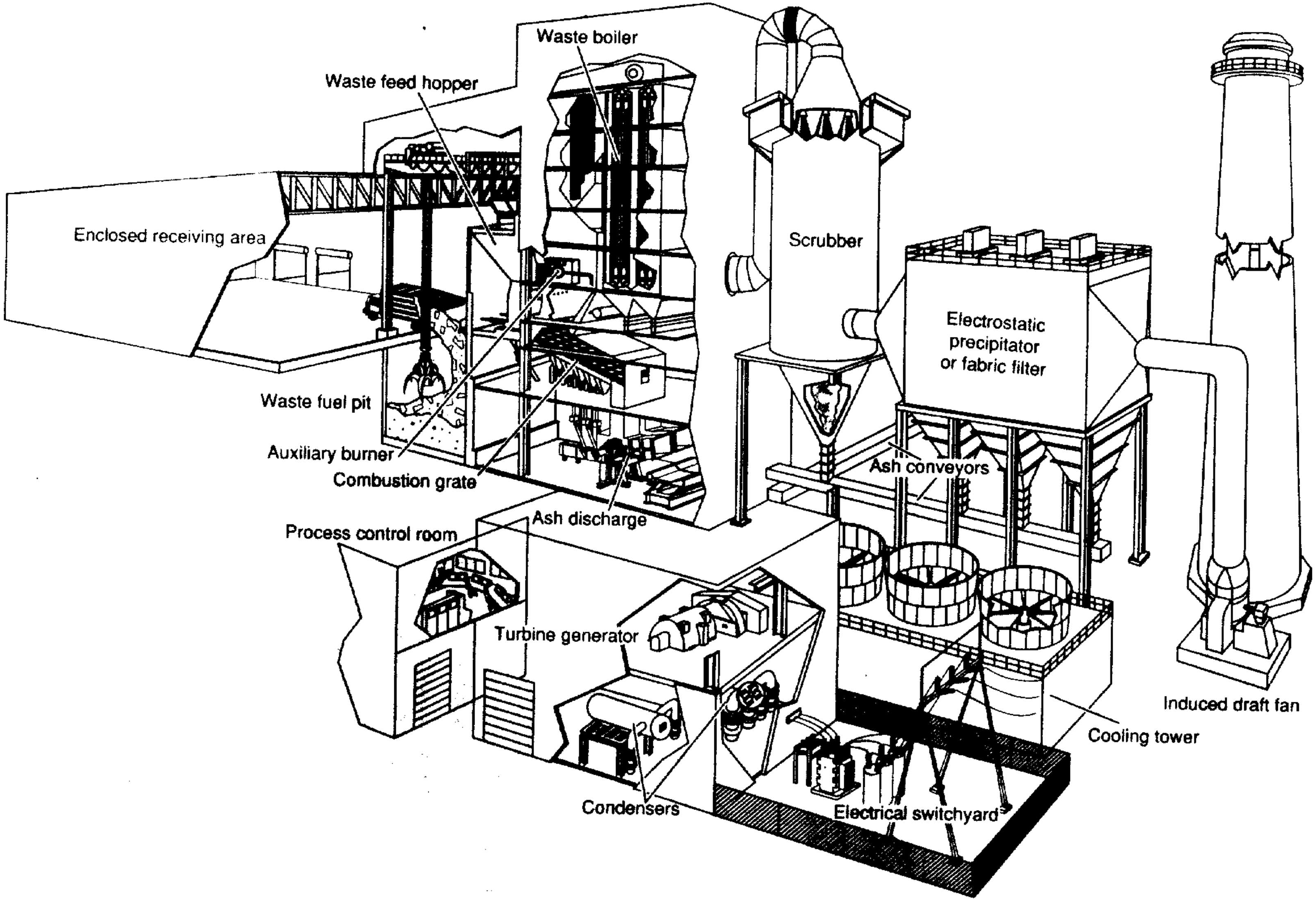


FIGURE 9-32
Section through water-wall mass-fired combustor used for the production of energy from MSW. (Courtesy of Wheelabrator Environmental Systems, Inc.)


(a) (b)

FIGURE 9-33
Views of modern continuous-feed mass-fired municipal combustor: (a) collection vehicles waiting to unload and (b) unloading the contents of collection vehicles onto the unloading platform. The unloading platform is used to provide temporary waste storage (surge) capacity for weekend operation.

Because of the higher energy content of RDF compared with unprocessed MSW, RDF combustion systems (see Fig. 9-34) can be physically smaller than comparably rated mass-fired systems. However, more space will be required if the front-end processing system needed to prepare the RDF is to be located adjacent to the combustor. A RDF-fired system can also be controlled more effectively than a mass-fired system because of the more homogeneous nature of RDF, allowing for better combustion control and better performance of air pollution control devices. Additionally, a properly designed system for the preprocessing of MSW can effect the removal of significant portions of metals, plastics, and other materials that may contribute to harmful air emissions.

Energy Recovery

Virtually all new combustors currently under construction in the United States and Europe employ some form of energy recovery to help offset operating costs and to reduce the capital costs of air pollution control equipment. Energy can be recovered from the hot flue gases generated by combusting processed MSW, from solid fuel pellets (e.g., RDF), or from unprocessed MSW by two methods: (1) the use of a water-wall combustion chamber, and (2) the use of waste heat boilers, or both. Either hot water or steam can be generated. Hot water can be used for low-temperature industrial or space heating applications. Steam is more versatile, as it can be used for both heating and generating electricity. Perhaps the most common flow diagram for the production of electric energy using steam involves the use of a steam turbine–generator combination as shown in Fig. 9-35.

Section through water-wall mass-fired combustor used for the production of energy from MSW. (Courtesy of Wheelabrator Environmental Systems, Inc.)

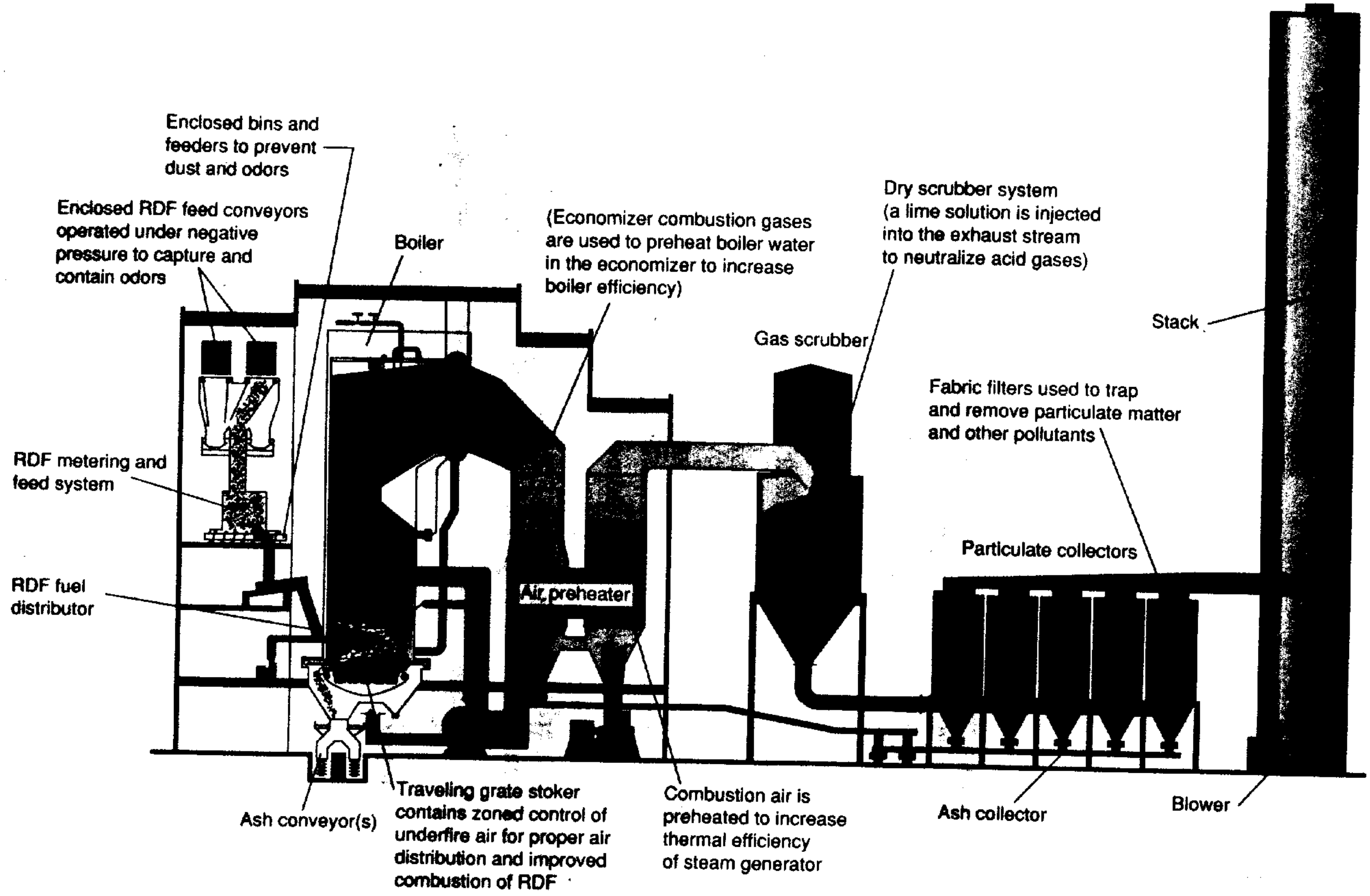


FIGURE 9-34
View of industrial water-wall boiler combustion system used for the production of energy from processed solid wastes, natural gas, oil, and coal. (Courtesy of ABB Resource Recovery Systems.)

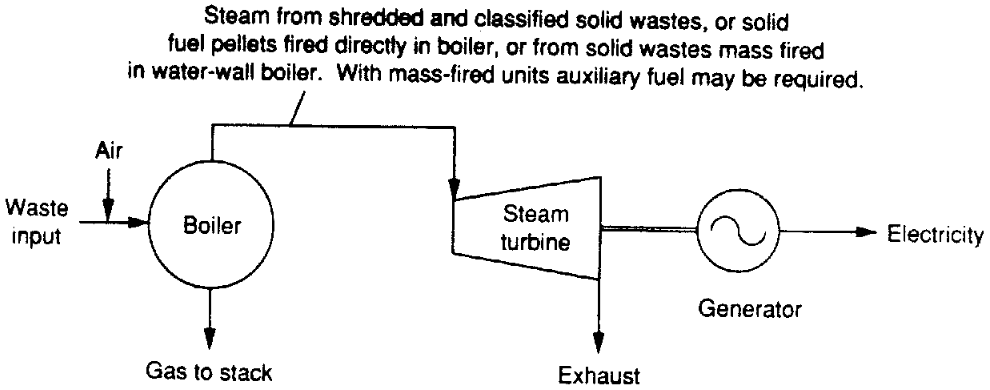


FIGURE 9-35
Schematic of energy recovery system using a steam turbine-generator combination. (See also Fig. 13-25*a*.)

Volume Reduction

Among the factors that must be considered in assessing the combustion process for MSW are the amount of residue remaining after combustion and whether auxiliary fuel will be required when heat recovery is not of primary concern. (The need for auxiliary fuel is considered in Chapter 13.) The amount of residue depends on the nature of the wastes to be combusted. Representative data on the residue from various solid waste components are reported in Table 9-8. The computations required to assess the quantity and composition of the residue after combustion are illustrated in Example 9-3.

TABLE 9-8
Composition of residue from the combustion of commingled MSW

	Percent by weight	
Component	**Range**	**Typical**
Partially burned or unburned organic matter	3–10	5
Tin cans	10–25	18
Other iron and steel	6–15	10
Other metals	1–4	2
Glass	30–50	35
Ceramics, stones, bricks	2–8	5
Ash	10–35	25
Total		100

view of industrial water-wall boiler combustion system used for the production of energy from processed solid wastes, natural gas, oil, and coal. (Courtesy of ABB Resource Recovery Systems.)

Example 9-3 Determination of volume reduction and volume of residue after combustion. Determine the quantity and composition of the residue from a combustor used for municipal solid wastes with the average composition given in Table 3-4. Estimate the reduction in waste volume if it is assumed that the specific weight of the residue is 1000 lb/yd^3.

Solution

1. Set up a computation table to determine the amount of residue and its percentage distribution by weight. The completed computation table is presented below:

Component	Solid waste,[a] lb	Inert residue,[b] %	Residue lb	Residue %
Organic				
Food wastes	90	5	4.5	1.9
Paper	340	6	20.4	8.6
Cardboard	60	5	3.0	1.3
Plastics	70	10	7.0	2.9
Textiles	20	6.5	1.3	0.5
Rubber	5	9.9	0.5	0.2
Leather	5	9.0	0.5	0.2
Yard wastes	185	4.5	8.3	3.5
Wood	20	1.5	0.3	0.1
Misc. organics	—	—	—	—
Inorganic				
Glass	80	98	78.4	33.0
Tin cans	60	98	58.8	24.7
Aluminum	5	96	4.8	2.0
Other metal	30	98	29.4	12.4
Dirt, ash, etc.	30	68	20.4	8.6
Total	1000		237.6	100.0

[a] Based on 1000 lb of solid waste (see Table 3-4).

[b] Data from Tables 4-3 and 4-4.

Note: lb × 0.4536 = kg

2. Estimate the original and final volumes before and after combustion. To estimate the approximate initial volume, assume that the average specific weight of the solid wastes in the combustor storage pit is about 375 lb/yd^3.

$$\text{Original volume} = \frac{1000 \text{ lb}}{375 \text{ lb/yd}^3} = 2.67 \text{ yd}^3$$

$$\text{Residue volume} = \frac{237.6 \text{ lb}}{1000 \text{ lb/yd}^3} = 0.24 \text{ yd}^3$$

3. Estimate the volume reduction by using Eq. (4-1).

$$\text{Volume reduction} = \left(\frac{2.67 - 0.24}{2.67}\right) 100 = 91\%$$

Issues in the Implementation of Combustion Facilities

The principal issues associated with the use of combustion facilities for the transformation of MSW are related to (1) siting, (2) air emissions, (3) disposal of residues, (4) liquid emissions, and (5) economics. Unless the questions related to these issues are resolved, the use of combustion may face an uncertain future. These subjects are introduced below and examined in detail in Chapter 13. A decision-maker's perspective is presented in Ref. 11.

Siting. As with the siting of MRFs, it has been possible to build and operate combustion facilities in close proximity to both residential and industrial developments; however, extreme care must be taken in their operation if they are to be environmentally and aesthetically acceptable. Ideally, to minimize the impact of the operation of combustion facilities, they should be sited in more remote locations where adequate buffer zones surrounding the facility can be maintained. In many communities, combustion facilities are located in remote locations within the city limits or at the landfill site.

Air Emissions. The operation of combustion facilities results in the production of a variety of gaseous and particulate emissions, many of which are thought to have serious health impacts. The demonstrated ability of combustion facilities and equipment to effectively control gaseous and particulate emissions is of fundamental importance in the siting of these facilities. The proper design of control systems for these emissions is a critical part of the design of combustion systems. In some cases, the cost and complexity of the environmental control system(s) are equal to or even greater than the cost of the combustion facilities.

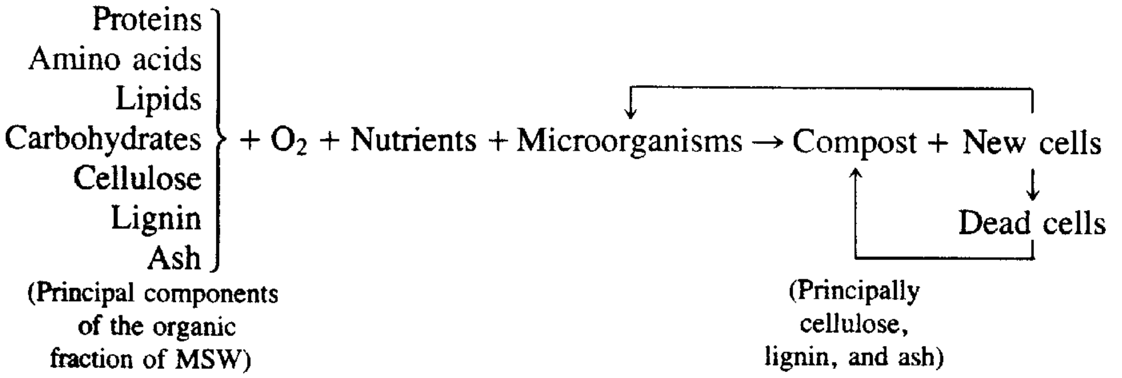
Disposal of Residues. Several solid residuals are produced by combustion facilities, including (1) bottom ash, (2) fly ash, and (3) scrubber product. Management of these solid residuals is an integral part of the design and operation of a combustion facility. Typically, bottom ash is disposed of by landfilling. The primary concern with landfilling of the ash is that it may, under certain conditions, leach contaminants into the groundwater. Consequently, ash from combustion facilities is now disposed of in lined MSW landfills or in double-lined monofills devoted solely to the disposal of ash.

Liquid Emissions. Liquid emissions from combustion facilities can arise from one or more of the following sources: (1) wastewater from the ash removal facilities, (2) effluent from wet scrubbers, (3) wastewater from pump seals, cleaning, flushing, and general housekeeping activities, (4) wastewater from treatment systems used to produce high-quality boiler water, and (5) cooling tower blowdown. The proper handling and disposal of these liquid emissions is also an important part of the design of combustion facilities.

Economics. The economics of a proposed combustion system must be evaluated carefully to permit a choice between competing systems. The best way to compare alternatives is by the use of life cycle costing, which accounts for operating and maintenance costs over the lifetime of the system. The solid waste industry has developed a standardized approach to life cycle costing through the use of the pro forma income statement.

9-8 WASTE TRANSFORMATION THROUGH AEROBIC COMPOSTING

With the exception of plastic, rubber, and leather components, the organic fraction of most MSW can be considered to be composed of proteins, amino acids, lipids, carbohydrates, cellulose, lignin, and ash [3]. If these organic materials are subjected to aerobic microbacterial decomposition, the end product remaining after microbiological activity has essentially ceased is a humus material commonly known as *compost*. In equation form the process can be described as follows:



$$\left.\begin{array}{r}\text{Proteins}\\ \text{Amino acids}\\ \text{Lipids}\\ \text{Carbohydrates}\\ \text{Cellulose}\\ \text{Lignin}\\ \text{Ash}\end{array}\right\} + O_2 + \text{Nutrients} + \text{Microorganisms} \rightarrow \text{Compost} + \text{New cells} \rightarrow \text{Dead cells}$$

(Principal components of the organic fraction of MSW)

(Principally cellulose, lignin, and ash)

$$+ CO_2 + H_2O + NO_3 + SO_4^{2-} + \text{Heat} \qquad (9\text{-}5)$$

As shown in Eq. (9-5), the new cells that are produced become part of the active biomass involved in the conversion of the organic matter and on death ultimately become part of the compost. The general objectives of composting are (1) to transform the biodegradable organic materials into a biologically stable material, and in the process reduce the original volume of waste; (2) to destroy pathogens, insect eggs, and other unwanted organisms and weed seeds that may be present in MSW; (3) to retain the maximum nutrient (nitrogen, phosphorous, and potassium) content, and (4) to produce a product that can be used to support plant growth and as a soil amendment [3, 4, 13].

In general, the chemical and physical characteristics of compost vary according to the nature of the starting material, the condition under which the composting operation was carried out, and the extent of the decomposition. Some of the properties of compost that distinguish it from other organic materials are these:

1. A brown to very dark brown color
2. A low carbon-nitrogen ratio

3. A continually changing nature due to the activities of microorganisms
4. A high capacity for cation exchange and water absorption

When added to soil, compost has been found to lighten heavy soils, to improve the texture of light sandy soils, and to increase the water retention capacity of most soils. Details on the theory and practice of composting are presented in Chapter 14.

Process Description

The composting process has always occurred in nature. One of the first organized composting operations to be reported upon in the literature was carried out in India in the early 1930s under the direction of Howard and associates [3]. The process they developed, known as the Indore process, was named for the location in India where it was developed. In its simplest form, the process involves excavating a trench in the ground 2 to 3 ft deep in which successive layers of putrescible materials such as solid waste, night soil, animal manure, earth, and straw are placed. The earliest procedure was to turn the material only twice during the composting process, which lasted six months or longer [3]. The liquid released from the decomposing waste was recirculated or added to other drier composting wastes. Because of the limited turning, one can assume that the composting mass was anaerobic for most of the composting process. The Indore process has been modified extensively, with the most important innovation being the more frequent turning of the composting material to maintain aerobic or facultative conditions and to accelerate the composting period.

Most modern composting operations consist of three basic steps: (1) preprocessing of the MSW, (2) decomposition of the organic fraction of the MSW, and (3) preparation and marketing of the final compost product. A generalized process flow diagram for the composting process is shown in Fig. 9-36. Receiving, removal of recoverable materials, size reduction, and the adjustment of the waste properties (e.g., carbon-nitrogen ratio, addition of moisture and nutrients) are essential steps in the preprocessing of MSW for composting. The degree of preprocessing depends on the specific composting process employed and the specifications for the final compost product.

To accomplish the decomposition step, several techniques have been developed including windrow, static pile, and in-vessel composting. In windrow composting, for example, prepared MSW is placed in windrows in an open field (see Fig. 9-37). The windrows are turned once or twice per week for a composting period of 4 to 5 weeks. During this time, the biodegradable portion of the organic fraction of MSW is decomposed by a variety of microorganisms, which utilize the organic matter as a carbon (food) source (see Eq. 9-5). The metabolic activity of the microorganisms alters the chemical composition of the original organic matter, reduces the volume and weight of the waste, and increases the heat of the material being composted. Turning the compost pile serves to provide oxygen for the decomposition process and to control the temperature of the

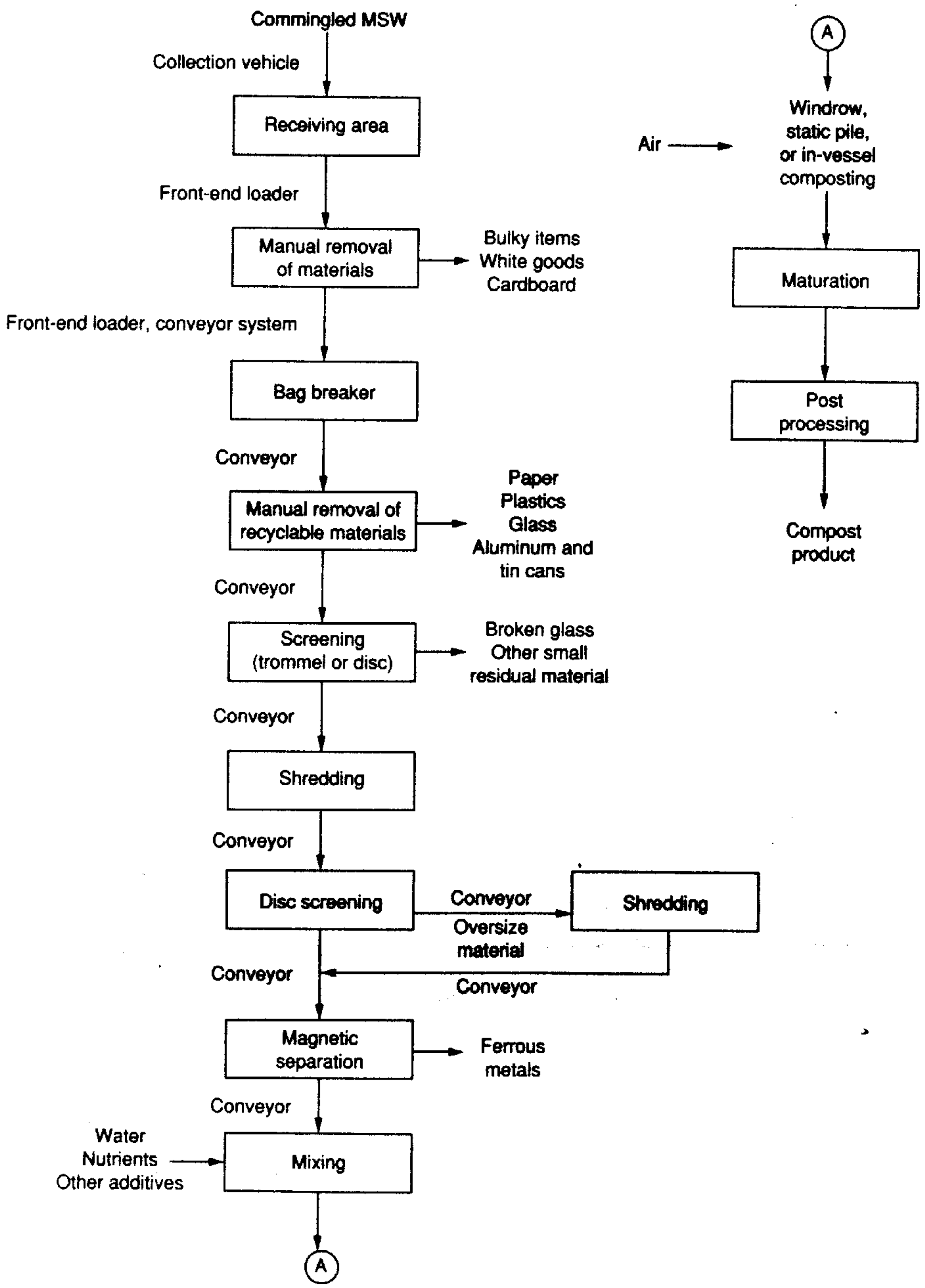


FIGURE 9-36
Generalized flow diagram for the composting process.

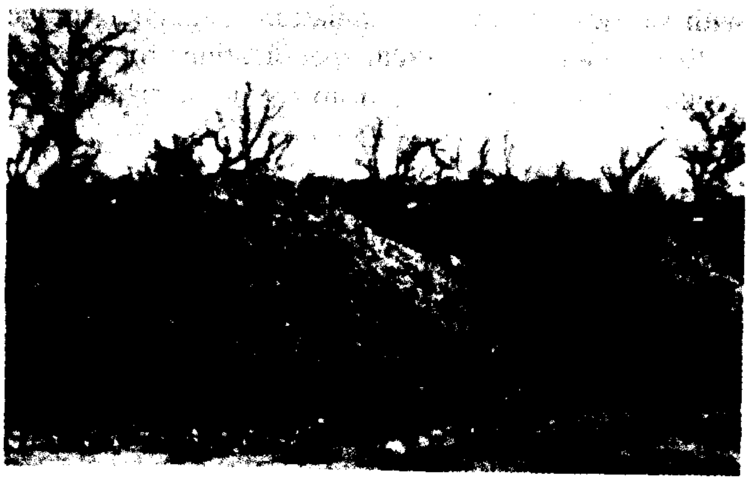


FIGURE 9-37
Compost produced from yard waste to be used in plant soil mixes, as a soil amendment, or as intermediate landfill cover material.

composting waste. When the readily biodegradable organic material is depleted, bacterial activity is reduced, the temperature of the composting material begins to drop, and the first stage of the composting process is complete (see Fig. 9-38). The composted material is usually cured for an additional 2 to 8 weeks in open windrows to ensure complete stabilization.

Preparation and marketing of the compost, the third step in the composting process, occurs once the compost has been cured and stabilized. At the present time, there is no universally accepted definition of what constitutes fully stabilized compost. Product preparation and marketing may include fine grinding, screening,

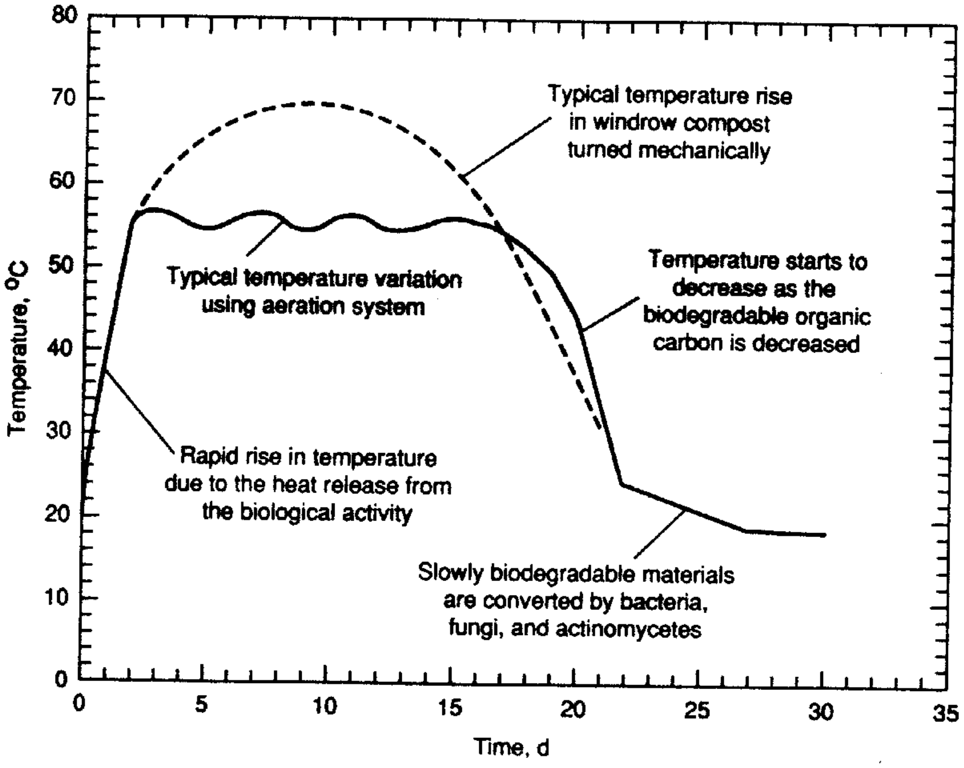


FIGURE 9-38
Variation of temperature during the composting process.

air classification, blending with various additives, granulation, bagging, storage, shipping, and in some cases, direct marketing. Typical specifications for compost produced from yard wastes, collected separately, and from the organic fraction of MSW are given in Chapter 15.

Process Design and Control

Although the composting process is easy to grasp conceptually, the actual design and control of the process are quite complex. Important process variables that must be considered in the design and operation of composting facilities include particle size and particle size distribution of the material to be composted, seeding and mixing requirements, the required mixing/turning schedule, total oxygen requirements, moisture content, temperature and temperature control, carbon-nitrogen ratio of the waste to be composted, pH, degree of decomposition, respiratory quotient (RQ), and control of pathogens.

Composting Techniques

The two principal methods of composting now in use in the United States may be classified as *agitated* and *static*. In the agitated method, the material to be composted is agitated periodically to introduce oxygen, to control the temperature, and to mix the material to obtain a more uniform product. In the static method, the material to be composted remains static and air is blown through the composting material. The most common agitated and static methods of composting are known as the windrow and static pile methods, respectively. Proprietary composting systems in which the composting operation is carried out in a reactor of some type are known as in-vessel composting systems.

Windrow Composting. Windrow composting is one of the oldest methods of composting. In its simplest form, a windrow compost system can be constructed by forming the organic material to be composted into windrows 8 to 10 ft high by 20 to 25 feet wide at the base. A minimal system could use a front-end loader to turn the windrow once per year. While such a minimal system would work, it could take up to three to five years for complete degradation. Also such a system would probably emit objectionable odors, as parts of the windrow will likely be anaerobic.

A high-rate windrow composting system employs windrows with a smaller cross section, typically 6 to 7 ft high by 14 to 16 ft wide. The actual dimensions of the windrows depend on the type of equipment that will be used to turn the composting wastes (see Fig. 9-39). Before the windrows are formed organic material is processed by shredding and screening it to approximately 1 to 3 in and the moisture content is adjusted to 50 to 60 percent. High-rate systems are turned up to twice per week while the temperature is maintained at or slightly above 131°F (55°C). Turning of the windrows is often accompanied by the release of offensive odors. Complete composting can be accomplished in three to four weeks. After

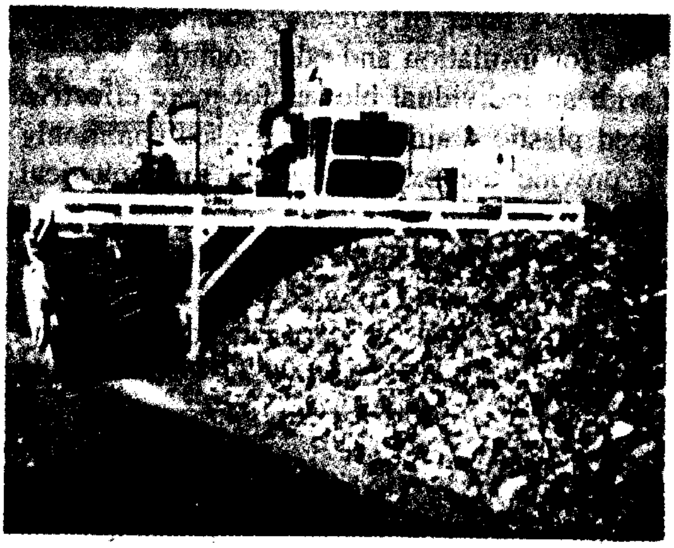


FIGURE 9-39
Specially designed machine used to turn composting material placed in windrows.

the turning period, the compost is allowed to cure for an additional three to four weeks without turning. During the curing period, residual decomposable organic materials are further reduced by fungi and actinomycetes.

Aerated Static Pile Composting. The aerated static pile composting process was developed by the U.S. Department of Agriculture Agricultural Research Service Experimental Station at Beltsville, Maryland; thus, the process is sometimes referred to as the Beltsville or ARS process. Originally developed for the aerobic composting of wastewater sludge, the process can be used to compost a wide variety of organic wastes including yard waste or separated MSW. The aerated static pile system, as shown in Fig. 9-40, consists of a grid of aeration or exhaust piping over which the processed organic fraction of MSW is placed. Typical pile

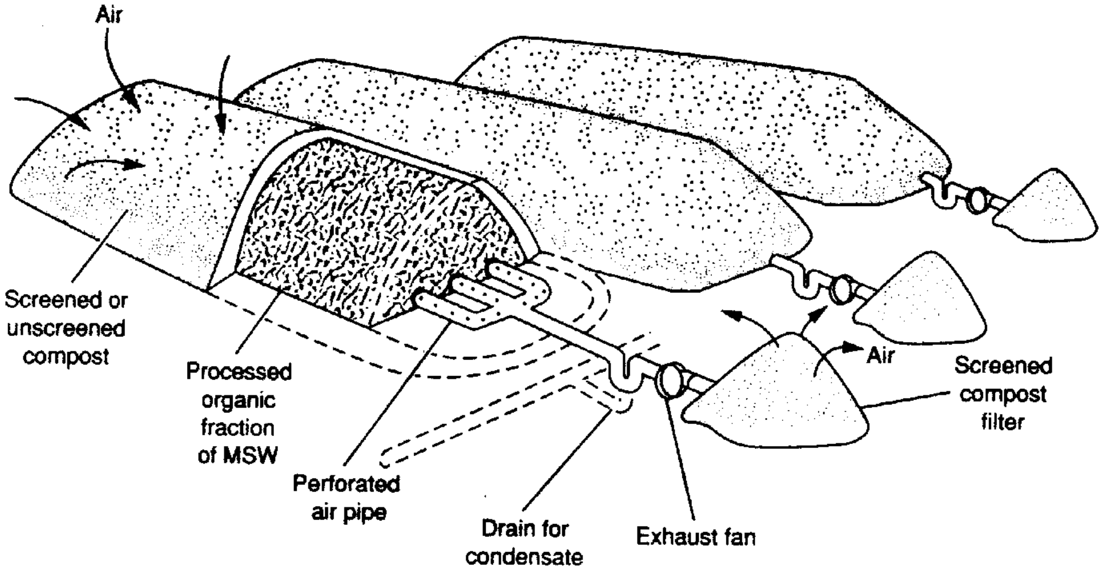


FIGURE 9-40
Schematic of aerated static pile composting system.

heights are about 7 to 8 ft (2 to 2.5 m). A layer of screened compost is often placed on top of the newly formed pile for insulation and odor control.

Each pile is usually provided with an individual blower for more effective aeration control. Disposable corrugated plastic drainage pipe is used commonly for air supply. Air is introduced to provide the oxygen needed for biological conversion and to control the temperature within the pile. Blower operation is typically controlled by a timer, or in some systems by a microcomputer to match a specific temperature profile. The material is composted for a period of three to four weeks. The material is then cured for a period of four weeks or longer. Shredding and screening of the cured compost usually is done to improve the quality of the final product. For improved process and odor control, all or significant portions of the system in newer facilities are covered or enclosed.

Where dewatered wastewater treatment plant sludge is to be composted, some type of bulking agent is required to maintain the porosity of the composting material. Wood chips are used most commonly as the bulking agent. They can also be used to absorb excess moisture. The mixture of sludge and wood chips is placed in piles over the aeration piping and covered with previously composted material. The blower can be operated either to push or to pull air through the pile. As in the high-rate windrow process, composting time is about three to four weeks. After composting, the pile is taken apart, and the bulking agent is recovered by screening. Note that a bulking agent is not usually required for composting dry materials like MSW or yard waste or mixtures of MSW and wastewater treatment plant sludge.

In-Vessel Composting Systems. In-vessel composting is accomplished inside an enclosed container or vessel. Every imaginable type of vessel has been used as a reactor in these systems, including vertical towers, horizontal rectangular and circular tanks, and circular rotating tanks (see Fig. 9-41). In-vessel composting systems can be divided into two major categories: plug flow and dynamic (agitated bed). In plug flow systems, the relationship between particles in the composting mass stays the same throughout the process, and the system operates on a first-in, first-out principle. In a dynamic system, the composting material is mixed mechanically during the processing. Examples of plug flow reactors are shown in Figs. 9-41*a*, *b* and examples of dynamic systems are illustrated in Figs. 9-41*c*, *d*.

Mechanical systems are designed to minimize odors and process time by controlling environmental conditions such as air flow, temperature, and oxygen concentration. The popularity of in-vessel composting systems has increased in recent years. Reasons for this increased use are process and odor control, faster throughput, lower labor costs, and smaller area requirements. The detention time for in-vessel systems varies from 1 to 2 weeks, but virtually all systems employ a 4- to 12-week curing period after the active composting period.

Process Applications

Composting is an increasingly popular waste management option as communities look for ways to divert portions of the local waste stream from landfills. The prin-

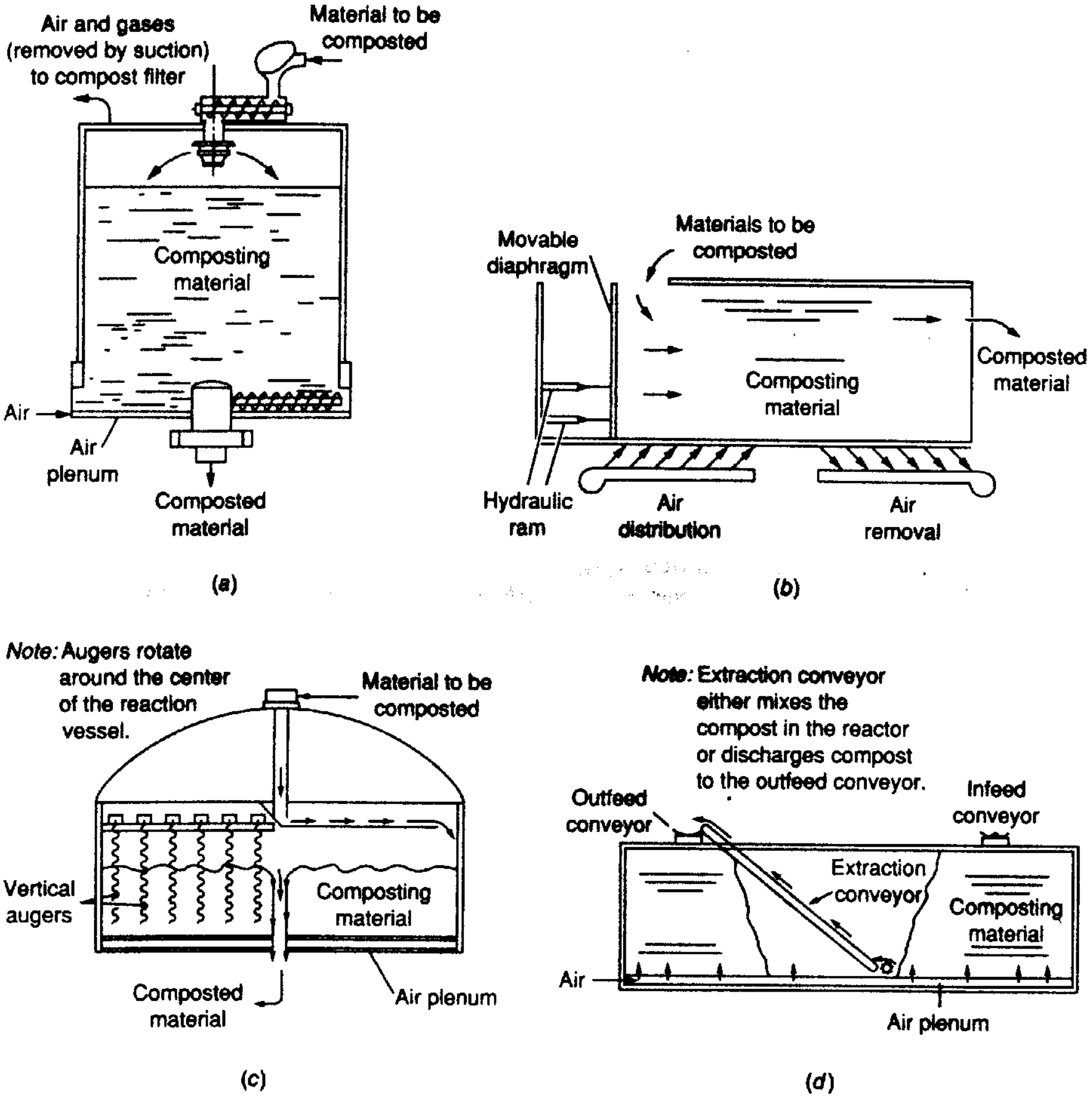


FIGURE 9-41
In-vessel composting units: (a) unmixed vertical plug flow reactor, (b) unmixed horizontal plug flow reactor, (c) mixed (dynamic) vertical reactor, and (d) mixed (dynamic) horizontal reactor.

cipal applications of composting are for (1) yard wastes, (2) the organic fraction of MSW, (3) partially processed commingled MSW, and (4) co-composting of the organic fraction of MSW with wastewater sludge. Because composting can be important in meeting mandated waste diversion goals, each of these applications is considered below. Backyard composting was considered in Chapter 7.

Composting of Yard Wastes Collected Separately. Leaves, grass clippings, bush clippings, and brush are the most commonly composted yard wastes. Stumps and wood are also compostable, but only after they have been chipped to produce a smaller, more uniform size. Five levels of technology that can be used for composting yard wastes are described in Table 9-9. Operating parameters for these five levels of composting technology are reported in Table 9-10.

TABLE 9-9
Composting technologies for yard wastes[a]

Technology level	Process description
Minimal	Involves forming large windrows that are turned once per year with a front-end loader. The minimal-level composting process usually takes 18 to 36 months.
Low-level	To limit odor problems, smaller windrows and more frequent turning are required. Piles of moderate size allow for sufficient composting activity, while limiting overheating and odors. In addition, two piles can be combined after the first "burst" of microbial activity (approximately one month). After 10 to 11 months and additional windrow turning, the piles can be formed into curing piles around the perimeter of the site, where the final stage of the composting process (stabilization) takes place. This frees area for the formation of new piles.
Intermediate-level	Similar to the low-level technology approach, except that the windrows are turned weekly with a windrow-turning machine. Use of windrow-turning machines will usually limit the size of the piles, thus increasing the total land area required.
High-level	In the high-level approach, forced aeration is used to optimze the compost process. The most common forced air approach is the static pile method. The blower in the forced aeration method is usually controlled by a temperature feedback system. When the temperature within the pile reaches a predetermined value, the blower turns on, cooling the pile and removing water vapor.
High-level in-vessel	Mechanical systems are designed to minimize odors and process time by controlling environmental conditions such as air flow, temperature, and oxygen concentration.

[a] Adapted from Ref. 11.

The collection of yard and other green wastes in specially designed containers is another recent innovation. The containers, provided with air holes, are equipped with a screened bottom (see Fig. 9-42*a*) that allows air to circulate. The yard and green wastes are collected once every two weeks. Because of the special design of the container, the material is usually dried by the time it is collected with specially equipped collection vehicles (see Fig. 9-42*b*).

Composting of Organic Fraction of MSW. Recognizing that product quality is the key to public acceptance of compost produced from municipal wastes, most operators of municipal composting systems base their efforts on separated wastes. Where mechanical means are used to separate the noncompostable materials from the compostable materials, the resulting compost often is still unacceptable because of metal contamination and the presence of trace amounts of household hazardous waste. Increasingly, professionals are recognizing that, to produce the highest-quality compost, source-separated materials should be used as the feedstock.

Composting of Partially Processed Commingled MSW. The composting of partially processed commingled municipal wastes has been suggested as a means

TABLE 9-10

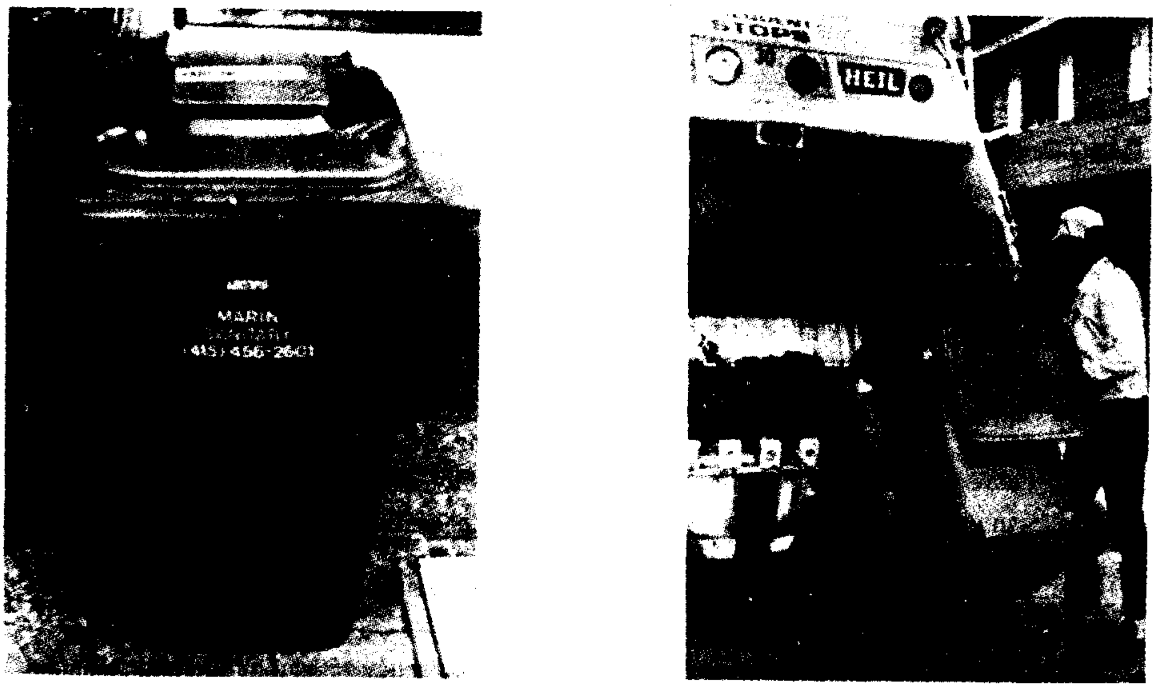
Operating parameters for various technology levels for the composting of yard wastes[a]

Technology level	Windrow dimensions, ft		Turning frequency	Time to obtain finished product, months
	Height	Width		
Minimal	10–12	20–24	1 time/yr	24–36
Low	5–7	12–14	3–5 times/yr	14–18
Intermediate	5–8	12–18	Weekly	4–6
High	8–10	16–20	Aerated static pile[b]	3–4
High-level in-vessel				2.0–2.5[c]

[a] Adapted in part from Ref. 11.

[b] Forced aeration is used for a period of 2 to 10 weeks, at which time the blowers are turned off and the piles are turned periodically.

[c] In-vessel composting times vary from 8 hours to 20 days, depending on the process. The composted material is then cured in open windrows for an additional 6 to 8 weeks.



(a) (b)

FIGURE 9-42
Specially designed system for the collection of yard and other green waste: (*a*) container equipped with air holes and a false bottom for air circulation and (*b*) specially equipped collection vehicle for emptying the containers.

of reducing the volume of wastes placed in landfills. Use of the composted material as intermediate landfill cover material has also been suggested. The composting of shredded residential and commercial MSW for these purposes is currently being done at the Escambia County landfill in Cantonment, FL. This composting operation is described in Section 11-6.

Co-composting Wastewater Treatment Plant Sludge with Organic Fraction of MSW. Composting of wastewater treatment plant sludge has been practiced since the early 1970s, and the number of composting facilities more than doubled in the 1980s [4]. Co-composting of wastewater treatment plant sludge and MSW is a relatively recent development. Mixing the sludge with the organic fraction of MSW is beneficial, as sludge dewatering may not be required and the overall metals content of the composted material will be considerably less than the composted sludge alone. Treatment plant sludges typically have a solids content ranging from 3 to 8 percent. A 2:1 mixture of compostable MSW to sludge is recommended as a minimum starting point. Both static and agitated compost systems have been

TABLE 9-11
Representative composting technologies for MSW and yard wastes[a]

Technology level	Process description
Bangalore (Indore)	Trench in ground; 2 to 3 ft deep. Material placed in alternate layers of refuse, night soil, earth, straw, etc. No grinding. Turned by hand as often as possible. Detention time of 120 to 180 days.
Casperi (briquetting)	Ground material (waste) is compressed into blocks and stacked for 30 to 40 days. Aeration by natural diffusion and air flow through stacks. Curing follows initial composting. Blocks are later ground.
DANO Biostabilizer	Rotating drum, slightly inclined from the horizontal, 9 ft to 12 ft in diameter; up to 150 ft long. One to 5 days digestion followed by windrowing. No grinding. Forced aeration into drum.
Earp-Thomas	Silo type with 8 decks stacked vertically. Ground waste is moved downward from deck to deck by ploughs. Air passes downward through the silo. Uses a patented inoculum. Digestion 2 to 3 days, followed by windrowing.
Fairfield-Hardy	Circular tank. Vertical screws, mounted on two rotating radial arms, keep ground material agitated. Forced aeration through tank bottom and holes in screws. Detention time of 5 days.
Fermascreen	Hexagonal drum, three sides of which are screens. Waste is ground. Batch loaded. Screens are sealed for initial composting. Aeration occurs during rotation with screens open. Detention time of 5 days.
Frazer-Eweson	Ground waste placed in vertical bin having 4 or 5 perforated decks and special arms to force composting material through perforations. Air is forced through bin. Detention time of 4 to 5 days.
Jersey (also known as the John Thompson system)	Structure with 6 floors, each equipped to dump ground waste onto the next lower floor. Aeration effected by dropping from floor to floor. Detention time of 6 days.

(continued)

tried. At this time, there is relatively little experience with co-composting in the United States owing to unmarketability of the final product.

Commercial Composting Systems

Over the past 50 years, more than 50 major different types of proprietary commercial composting systems have been developed and applied worldwide [3, 4, 13]. The general characteristics of the most common of these are summarized in Table 9-11. The various composting systems arranged by function or reactor type are reported in Table 9-12. A typical flow diagram for a commercial composting process is shown in Fig. 9-43. In the process shown in Fig. 9-43, MSW is first processed to remove recyclables and to reduce the size of the materials to be composted. Water and any other needed additives are added to the waste in the mixing unit. The prepared waste is then placed in plug flow compost reactors (also known as tunnel reactors). As more waste is added each day, material that has been composting is discharged from the reactor. The composted waste is aged

TABLE 9-11 (*continued*)

Technology level	Process description
Metrowaste	Open tanks, 20 ft wide by 10 ft deep by 200 ft to 400 ft long. Processed MSW shredded in pretreatment processing. Equipped to give one or two turnings during digestion period (7 days). Air is forced through perforations in bottom of tank.
Naturizer or International	Five 9 ft wide steel conveyer belts arranged to pass material from belt to belt. Each belt is an insulated cell. Air passes through digester. Detention time of 5 days.
Riker	Four-story bins with clamshell floors. Ground waste is dropped from floor to floor. Forced air aeration. Detention time of 20 to 28 days.
Ashbrook-Simon-Hartley	Tunnel reactor typically 18 ft wide by 12 ft high by 65 ft long. Plug flow with wastes pushed into and out of reactor. Pressure and vacuum blowers used to supply and exhaust air through air diffusers located in floor of reactor. Detention time of 18 to 20 days.
T. A. Crane	Two cells consisting of 3 horizontal decks. Horizontal ribbon screws extending the length of each deck recirculate ground waste from deck to deck. Air is introduced in bottom of cells. Composting followed by curing in a bin.
Tollemache	Similar to the Metrowaste digesters.
Triga	Towers or silos called "hygienisators." In sets of 4 towers. Waste is ground. Forced air aeration. Detention time of 4 days.
Windrowing (normal, aerobic process)	Open windrows, with a "haystack" cross-section. Waste is ground. Aeration by turning windrows. Detention time depends upon number of turnings and other factors.
Van Maanen process	Underground waste in open piles, 120 to 180 days.

[a] Adapted from Refs. 3, 4, 13.

TABLE 9-12
Municipal composting systems grouped by function or reactor configuration[a]

Function or configuration	Commercial process
Heaps and windrows, natural aeration, batch operation	Indore/Bangalore Artsiely Baden-Baden (hazemag) Buhler Disposals Associates Dorr-Oliver Spohn Tollemache V.A.M.
Cells with natural or forced aeration, batch operation	Beccari Biotank (Degremont) Boggiano-Pico Kirkconnel (Dumfriesshire) Metrowaste Prat (Sofranie) Spohn Verdier Westinghouse/Naturizer
Horizontal rotating and inclined drums, continuous operation	Dano Biostabilizer Dun Fix Fermascreen (batch) Head Wrightson Vickers Seerdrum
Vertical flow reactors, continuous operation, agitated bed, natural or forced aeration	Earp-Thomas Fairfield Hardy Frazer-Eweson Jersey (John Thompson) Multibacto Nusoil Snell Triga
Agitated vertical bed	Fairfield-Hardy

[a] Adapted from Refs. 3, 4, 13.

in aerated static piles. After maturation, the compost is screened and shredded to produce a uniform product.

Issues in the Implementation of Composting Facilities

The principal issues associated with the use of the compost process are (1) the production of odors, (2) the presence of pathogens, (3) the presence of heavy metals, and (4) the definition of what constitutes an acceptable compost. Blowing

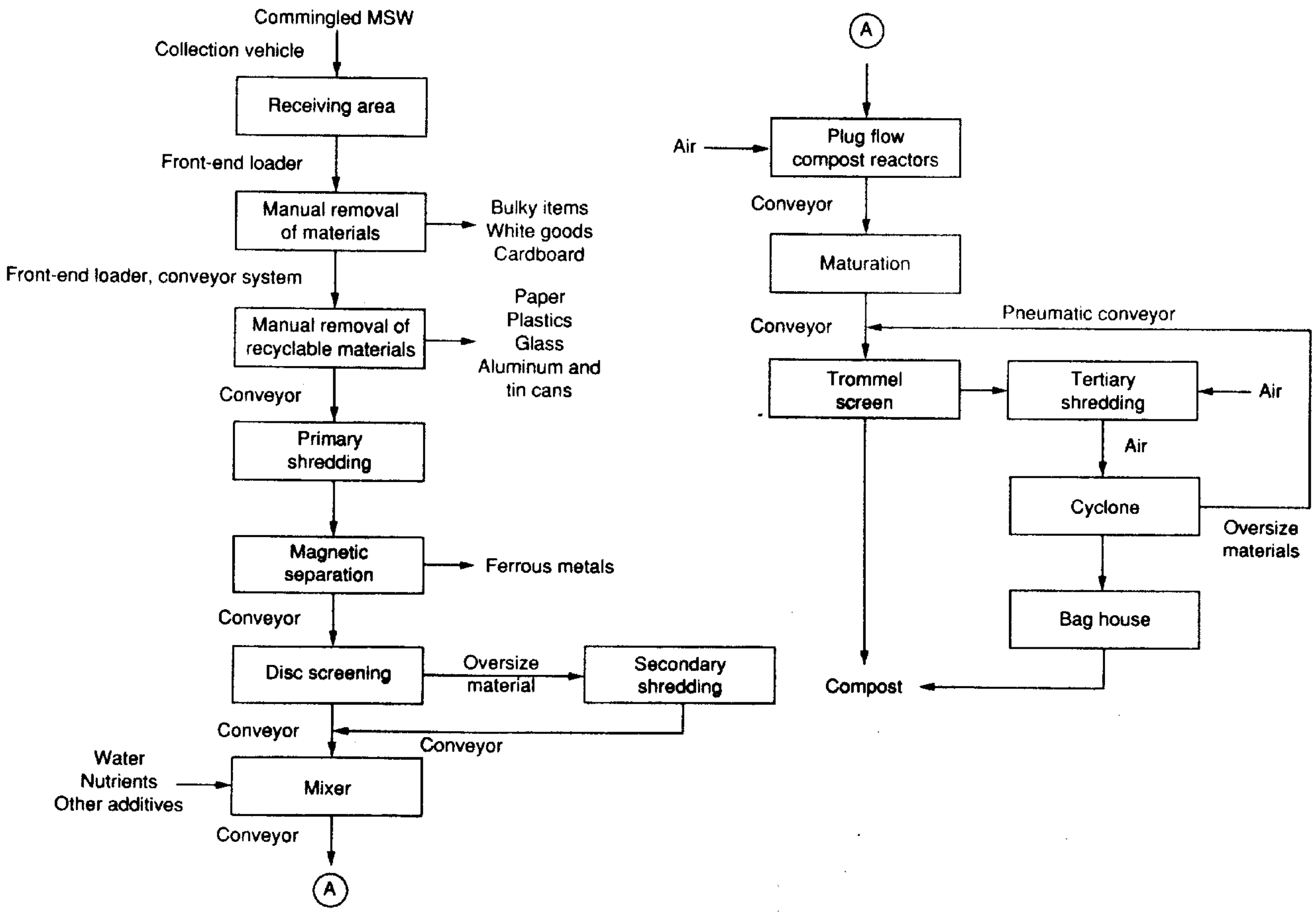


FIGURE 9-43
Flow diagrams for the Ashbrook Simon-Hartley composting process.

of papers and plastic materials is also a problem in windrow composting. Unless the questions related to these issues are resolved, composting may never be a viable technology.

Production of Odors. Without proper control of the composting process, the production of odors can become a problem, especially in windrow composting. It is fair to say that every existing composting facility has had an odor event and in some cases numerous events. As a consequence, facility siting, process design, and biological odor management are of critical importance.

Facility siting. Important issues in siting as related to the production and movement of odors include proper attention to local microclimates as they affect the dissipation of odors, distance to odor receptors, the use of adequate buffer zones, and the use of split facilities (use of different locations for composting and maturation operations).

Proper process design and operation. Proper process design and operation are critical in minimizing the potential for the production of odors. If composting operations are to be successful, special attention must be devoted to the following items: preprocessing, aeration requirements, temperature control, and turning (mixing) requirements. The facilities used to prepare the waste materials for the composting process must be capable of mixing completely and effectively any required additives, such as nutrients, inoculum (if used), and moisture with the waste material to be composted. The aeration equipment must be sized to meet peak oxygen demand requirements with an adequate margin of safety. In the static pile method of composting, the aeration equipment must also be sized properly to provide the volume of air required for cooling the composting material. The composting facilities must be instrumented adequately to provide for positive and effective temperature control. The equipment used to turn and mix the compost to provide oxygen and to control the temperature must be effective in mixing all portions of the composting mass. Unmixed compost will undergo anaerobic decomposition, leading to the production of odors. Because all of the operations cited above are critical to the operation of an odor-free composting facility, standby equipment should be available.

Biological odor management. Because occasional odor events are impossible to eliminate, special attention must be devoted to the factors that may affect biological production of odors. Causes of odors in composting operations include low carbon to nitrogen (C/N) ratios, poor temperature control, excessive moisture, and poor mixing. For example, in composting operations where the compost is not turned and the temperature is not controlled (see Fig. 9-38), the compost in the center of the composting pile can become pyrolyzed (see Chapter 13). When the composting pile is subsequently moved, the odors released from the pyrolyzed compost have been *extremely severe*. In enclosed facilities, odor control facilities such as packed towers, spray towers, activated carbon contactors, biological filters, and compost filters have been used for odor management.

In some cases, odor-masking agents and enzymes, which can split some odorous organic compound, have been used for the temporary control of odors.

Public Health Issues. If the composting operation is not conducted properly, the potential exists for pathogenic organisms to survive the composting process. The absence of pathogenic organisms is critical if the product is to be marketed for use in applications where the public may be exposed to the compost. Although pathogen control can be achieved easily with proper operation of the composting process, not all composting operations are instrumented sufficiently to allow for the reliable production of pathogen-free compost. In general, most pathogenic organisms found in MSW and other organic material to be composted will be destroyed at the temperatures and exposure times used in controlled composting operations (typically 55°C for 15 to 20 days). Temperatures required for the control of various pathogens are given in Table 14-8.

Heavy Metal Toxicity. A concern that may affect all composting operations, but especially those where mechanical shredders are used, involves the possibility of heavy metal toxicity. When metals in solid wastes are shredded, metal dust particles are generated by the action of the shredder. In turn, these metal particles may become attached to the materials in the light fraction. Ultimately, after composting, these metals would be applied to the soil. Although many of them would have no adverse effects, metals such as cadmium (because of its toxicity) are of concern. In general, the heavy metal content of compost produced from the organic fraction of MSW is significantly lower than the concentrations found in wastewater treatment plant sludges. The metal content of source-separated wastes is especially low. The co-composting of wastewater treatment plant sludges and the organic fraction of MSW is one way to reduce the metal concentrations in the sludge.

Product Quality. Product quality for compost material can be defined in terms of the nutrient content, organic content, pH, texture, particle size distribution, moisture content, moisture-holding capacity, the presence of foreign matter, the concentration of salts, residual odor, the degree of stabilization or maturity, the presence of pathogenic organisms, and the concentration of heavy metals. Unfortunately, at this time there is no universal agreement on suitable values for these parameters. This lack of agreement has been and continues to be a major impediment to the development of a uniform compost product from location to location. Some specifications that have been developed for compost are presented in Table 15-8. If compost materials are to have wide acceptance, public health issues must be resolved in a satisfactory manner.

9-9 IMPACT OF SOURCE REDUCTION AND WASTE RECYCLING ON WASTE TRANSFORMATION PROCESSES

As more states adopt legislation mandating the development of waste diversion and recycling programs, the quantities and composition of the wastes collected will change. The impact of change in composition will vary depending on the other types of waste management programs that are in place. For example, a recycling program would, as illustrated in Example 9-4, result in a reduction in the energy content of the waste. Such a reduction in the energy content could affect a waste-to-energy facility.

Example 9-4 Estimate the change in the energy content of municipal solid waste for various levels of recycling. Determine the energy content of the typical municipal solid waste given in Table 3-4 for the following levels of recycling. Also determine the overall recycle percentage, by weight, represented by each level of recycling.

	Level of recycling,* %		
Component	**One**	**Two**	**Three**
Organic			
Food wastes	0	0	0
Paper	20	35	50
Cardboard	20	30	40
Plastics	20	30	40
Textiles	10	20	30
Rubber	10	20	30
Leather	10	20	30
Yard wastes	0	15	30
Wood	10	20	30
Inorganic			
Glass	20	30	40
Tin cans	10	20	30
Aluminum	50	70	90
Other metal	10	20	30
Dirt, ash, etc.	0	0	0

*The levels of recycling are based on the total amount of material in each category.

Solution

1. Set up a computation table to determine the weight and percentage distribution of the waste remaining after various levels of recycling have been achieved. (See the computation table at the top of page 319.)
2. Set up a computation table to determine the energy content of 100 lb of the waste remaining after various levels of recycling have been achieved. The Btu values are from Table 3-13. (See the computation table at the bottom of page 319.)

Comment. As shown in the above computation, the level of recycling can have a significant impact on the energy content of the waste. For example, if a contract had been signed to deliver a firm amount of power from a waste-to-energy facility, additional amounts of waste would be needed to make up for the loss of Btu content. Without additional sources of waste the facility could easily go into default on its energy contract. Although the recycling percentages may change, the general approach developed in this example can be used to assess the impacts of alternative recycling strategies.

	Weight, lb (percent by weight)							
	Level of recycling							
Component	**None**		**One**		**Two**		**Three**	
Organic								
Food wastes	9.0	(14.0)	9.0	(10.3)	9.0	(11.9)	9.0	(13.9)
Paper	34.0	(34.0)	27.2	(31.1)	22.1	(29.1)	17.0	(26.3)
Cardboard	6.0	(6.0)	4.8	(5.5)	4.2	(5.5)	3.6	(5.6)
Plastics	7.0	(7.0)	5.6	(6.4)	4.9	(6.4)	4.2	(6.5)
Textiles	2.0	(2.0)	1.8	(2.1)	1.6	(2.1)	1.4	(2.2)
Rubber	0.5	(0.5)	0.5	(0.6)	0.4	(0.5)	0.4	(0.6)
Leather	0.5	(0.5)	0.5	(0.6)	0.4	(0.5)	0.4	(0.6)
Yard wastes	18.5	(18.5)	18.5	(21.1)	15.7	(20.7)	13.0	(20.1)
Wood	2.0	(2.0)	1.8	(2.0)	1.6	(2.1)	1.4	(2.2)
Inorganic								
Glass	8.0	(8.0)	6.4	(7.3)	5.6	(7.4)	4.8	(7.4)
Tin cans	6.0	(6.0)	5.4	(6.2)	4.8	(6.3)	4.2	(6.5)
Aluminum	0.5	(0.5)	0.3	(0.3)	0.2	(0.3)	0.1	(0.2)
Other metal	3.0	(3.0)	2.7	(3.1)	2.4	(3.2)	2.1	(3.3)
Dirt, ash, etc.	3.0	(3.0)	3.0	(3.4)	3.0	(4.0)	3.0	(4.6)
Total	100.0	(100.0)	87.5	(100.0)	75.9	(100.0)	64.6	(100.0)
Amount of waste recycled, % by weight			12.5		24.1		35.4	

	Total energy content, Btu			
	Level of recycling, %			
Component	**None**	**One**	**Two**	**Three**
Organic				
Food wastes	18,000	18,000	18,000	18,000
Paper	244,800	195,840	159,120	122,400
Cardboard	42,000	33,600	29,400	25,200
Plastics	98,000	78,400	68,600	58,800
Textiles	15,000	13,500	12,000	10,500
Rubber	5,000	5,000	4,000	4,000
Leather	3,750	3,750	3,000	3,000
Yard wastes	51,800	51,800	43,960	36,400
Wood	16,000	14,400	12,800	11,200
Inorganic				
Glass	480	380	340	290
Tin cans	1,800	1,620	1,440	1,260
Aluminum	—	—	—	—
Other metal	900	810	720	630
Dirt, ash, etc.	9,000	9,000	9,000	9,000
Total	506,530	426,100	362,380	300,680
Energy content, Btu/lb	5,065	4,261	3,624	3,007

9-10 SELECTION OF PROPER MIX OF TECHNOLOGIES

As the types and quantities of wastes that are to be diverted change in the future, it is imperative that the proper type and mix of technologies be adopted in a waste management system. Until the commodity markets for recyclable materials become stabilized, it will be prudent not to commit to capital-intensive equipment and processes with long-term contracts. Selection of the proper mix of technologies is considered in greater detail in Chapter 19.

9-11 DISCUSSION TOPICS AND PROBLEMS

9-1. Drive, walk, or pedal around your community and identify the different available types of facilities to which homeowners and others can deliver source-separated materials (e.g., igloo containers, drop-off centers, buy-back centers, redemption centers, MRFs, etc.). Are the facilities located conveniently?

9-2. Collect some aluminum cans and deliver them to a buy-back center. What is your assessment of the operation of the buy-back center? Can you suggest some improvements to enhance the operation of the facility?

9-3. What fraction of the total amount of material that is now recovered for recycling from MSW in your community is recovered at drop-off and buy-back centers versus curbside programs and materials recovery facilities?

9-4. Based on your own experience, discuss the advantages and disadvantages of using see-through plastic bags for the collection of source-separated wastes from individual residences. Do you think the use of see-through bags is feasible in your community?

9-5. Discuss the advantages and disadvantages of collecting yard wastes separately. If your community does not collect yard wastes separately, is the separate collection of yard wastes feasible given the waste management system that is now used? If your community collects yard wastes separately, develop the process flow diagram for the handling and processing of the yard wastes.

9-6. Develop a process flow diagram to separate cardboard, newsprint, high-grade office and computer paper, magazines, and contaminants such as carbon paper and FAX paper and wire-bound notebooks from mixed paper that is to be collected separately from residential and commercial sources. Prepare a listing of the equipment that will be required. Assume 50 ton/d of mixed paper will be processed 5 d/wk.

9-7. Develop a process flow diagram to process source-separated paper and mixed recyclables composed of plastics, glass, tin cans, and aluminum cans.

9-8. Develop a process flow diagram to separate cardboard, paper, plastics, glass by color, and ferrous metals from commingled waste that has the composition given in Table 3-4. Your flow diagram should incorporate the use of a trommel screen and one or more magnetic separators.

9-9. Using the process flow diagram developed in Problem 9-7, prepare a layout of a materials recovery facility.

9-10. Using the process flow diagram developed in Problem 9-8, prepare a layout of a materials recovery facility.

9-11. Prepare a layout of a materials recovery facility to be used for the processing of waste materials that have been recovered from MSW at the source of generation. Assume that mixed paper and cardboard, glass and plastics, and aluminum and tin cans are to be collected separately. Assume the separated paper, cardboard, aluminum cans, tin cans, and plastics are to be baled for shipment to markets.

9-12. A small salvage firm disposes of car batteries by transporting the batteries to a smelter. Being quite safety conscious, the owners of the salvage company remove the electrolyte from the batteries to reduce the possibility of employee injury and of accidental spills due to improper handling. The electrolyte is diluted with large amounts of water and discharged to the sewer. Are there any problems associated with the removal and discharge of the electrolyte?

9-13. The maximum amount of solid wastes collected per day for one week is presented below. All the solid wastes are to be burned at a municipal waste-to-energy combustion facility at a constant rate of 100 tons/d. What is the required capacity of the storage pit that should be designed to accommodate 1.15 times the required capacity?

Day	Solid wastes collected, tons/d
Monday	150
Tuesday	130
Wednesday	120
Thursday	120
Friday	100
Saturday	80
Sunday	0

9-14. Arrange in order of importance the following waste characteristics for a mass-burn and an RDF combustor.

(*a*) Paper content

(*b*) Fixed carbon

(*c*) As-delivered energy content

(*d*) Moisture content

(*e*) As-delivered specific weight

(*f*) As-delivered metal content

9-15. Because it will be practically impossible to prevent all hazardous materials from entering a MSW mass-fired combustion facility, what precautions should be taken to minimize the danger?

9-16. Estimate the composition of the residue if packaging material wastes with the component distribution reported in Table 3-4 are to be combusted. What would be the corresponding volume reduction?

9-17. The local waste management agency has proposed to set up a waste combustion facility next to the existing landfill to maximize the life span of the landfill. Given the following information, determine how much the life span of the landfill is increased by the combustion.

(*a*) Composition of MSW as given in column 1, Table 3-4

(*b*) Estimated landfill capacity remaining = 300,000 yd^3

(*c*) Capacity of combustion facility = 50 ton waste/h

(*d*) Effective on-line combustion time per day = 22 h

(*e*) Initial waste specific weight = 287 lb/yd^3

(*f*) Final waste specific weight in landfill = 1200 lb/yd^3

9-18. How much land area would be required per ton to compost 100 ton/d of processed (sorted and shredded) residential and commercial MSW subject to the following conditions? How does your value for the area required per ton compare with the value given in Table 9-10 and values given in the literature? Cite at least two literature references.

(*a*) Windrow composting with mechanical turning is to be used.

(*b*) Maximum width = 18 ft

(*c*) Maximum length of windrows = 500 ft

(*d*) Average distance between windrows = 8 ft

(*e*) Angle of repose of waste in windrows = 1 to 1

(*f*) Specific weight of the processed MSW as placed in windrows before water is added = 550 lb/yd^3

(*g*) Active composting period = 1 mo

(*h*) Curing period = 4 mo

(*i*) A staging/storage area equal to 15 percent of the area used for composting will be required.

9-19. Solve Problem 9-18, but assume

(*a*) Active composting period = 21 d

(*b*) Curing period = 3 mo

9-20. Using the distribution of waste given in column 1 of Table 3-4, estimate the tons of compost that can be produced from 1000 tons of MSW. Assume that all of the inorganic materials and that 50 percent of the yard wastes and wood will be removed. Assume also that the initial moisture content of the MSW is 20 percent and that the final moisture content of the compost is about 35 percent. Cite all of the assumptions used in solving this problem.

9-21. When residential and commercial MSW from a community of 250,000 persons arrives at a composting facility, the moisture content is usually below the desired range of 45 to 60 percent for optimum composting. Rather than adding city water to obtain the necessary moisture content, it has been suggested that wastewater treatment plant sludge be added to achieve the same result. Determine the required moisture content of the sludge to achieve the desired moisture content of 55 percent for the combined mixture and determine whether the sludge will have adequate moisture. Assume the following conditions apply:

Wastewater treatment plant sludge = 0.25 lb capita · d (dry sludge)

Residential and commercial MSW = 5.5 lb capita · d (at 20% moisture)

9-22. Using the data from Problem 9-21, determine the amount of sludge with a solids content of 6 percent that must be added to the MSW to achieve a final moisture content of 58 percent.

9-23. Estimate the total theoretical amount of air that would be required under aerobic conditions to oxidize completely an organic waste with a chemical formula of $C_{120}H_{180}O_{80}N_2$.

9-24. Using the data and information from Example 9-4, what would you suggest as a compromise that would allow a recycling program to be functional and at the same time allow the waste-to-energy facility to remain viable? Assume the mimimum energy content of the waste has to be 4000 Btu/lb for the waste-to-energy facility to remain viable.

9-12 REFERENCES

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