5 Solid Waste Management

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Aesthetic, land-use, health, water pollution, air pollution, and economic considerations make proper solid waste management an ongoing concern for municipal, corporate, and individual functions that must be taken seriously by all. Indiscriminate dumping of solid waste and failure of the collection system in a populated community for two or three weeks would soon cause many problems. Odors, flies, rats, roaches, crickets, wandering dogs and cats, and fires would dispel any remaining doubts of the importance of proper solid waste management.

Solid waste management is a complex process because it involves many technologies and disciplines. These include technologies associated with the generation (including source reduction), on-site handling and storage, collection, transfer and transportation, processing, and disposal of solid wastes. All of these processes have to be carried out within existing legal, social, and environmental guidelines that protect the public health and the environment and are aesthetically and economically acceptable. To be responsive to public attitudes, the disciplines that must be considered in integrated solid waste management include administrative, financial, legal, architectural, planning, environmental, and engineering functions. For a successful integrated solid waste management plan, it is necessary that all these disciplines communicate and interact with each other in a positive interdisciplinary relationship.

In the material that follows, the major issues involved with the management of solid waste are presented and discussed. These issues include the elements of integrated solid waste management; the sources, characteristics, and quantities of solid waste; on-site storage and handling, solid waste collection; transfer and transport; waste reduction, recycling, and processing; composting; sanitary landfill planning design and operation; and incineration and haz-

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ardous waste. However, before discussing these topics, it will be useful to define the terminology used in the field of solid waste management. Additional details on solid waste management may be found in the U.S. Environmental Protection Agency (EPA) (1989, 1995b), Tchobanoglous et al. (1993), Hickman (1999), and Tchobanoglous and Kreith (2002).

DEFINITION OF TERMS

To understand the elements and technologies involved in integrated solid waste management it is useful to define some of the more commonly used terms (Salvato, 1992).

Ash Residue All the solid residue and any entrained liquids resulting from the combustion of solid waste or solid waste in combination with fossil fuel at a solid waste incinerator, including bottom ash, boiler ash, fly ash, and the solid residue of any air pollution control device used at a solid waste incinerator.

Biodegradable Material Waste material capable of being broken down, usually by bacteria, into basic elements. Most organic wastes, such as food remains and paper, are biodegradable.

Commercial Waste Solid waste generated by stores, offices, institutions, restaurants, warehouses, and nonmanufacturing activities at industrial facilities.

Composting The controlled biological decomposition of organic solid waste under aerobic (in the presence of oxygen) conditions. Organic waste materials are transformed into soil amendments such as humus or mulch.

Fly Ash The ash residue from the combustion of solid waste or solid waste in combination with fossil fuel that is entrained in the gas stream of the solid waste incinerator and removed by air pollution control equipment.

Garbage Putrescible solid waste including animal and vegetable waste resulting from the handling, storage, sale, preparation, cooking, or serving of foods. Garbage originates primarily in home kitchens, stores, markets, restaurants, and other places where food is stored, prepared, or served.

Geomembrane An essentially impermeable membrane used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of a man-made structure or system designed to limit the movement of liquid or gas in the system.

Geonet A type of a geogrid that allows planar flow of liquids and serves as a drainage system.

Geotextile Any permeable textile used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of a man-made structure or system designed to act as a filter to prevent the flow of soil fines into drainage systems, provide planar flow for drainage, serve as a cushion to protect geomembranes, or provide structural support.

Groundwater Water below the land surface in the saturated zone of the soil or rock. This includes perched water separated from the main body of groundwater by an unsaturated zone.

Hazardous Waste Defined in this chapter.

Incinerator A facility designed to reduce the volume and weight of solid waste by a combustion process with or without a waste heat recovery system. Auxiliary equipment provides feed, ash handling, and environmental controls.

Industrial Waste Solid waste generated by manufacturing or industrial processes. Such waste may include, but is not limited to, the following manufacturing processes: electric power generation; fertilizer/agricultural chemicals; inorganic chemicals; iron and steel manufacturing; leather and leather products; nonferrous metals; explosives; manufacturing/foundries; organic chemicals; plastics and resins manufacturing; pulp and paper industry; rubber and miscellaneous plastic products; stone, glass, clay, and concrete products; textile manufacturing; transportation equipment; and water treatment. This term does not include oil or gas drilling, production, and treatment wastes (such as brines, oil, and frac fluids); overburden, spoil, or tailings resulting from mining; or solution mining brine and insoluble component wastes.

Infectious Waste Includes surgical waste from a patient on isolation; obstetrical waste from a patient on isolation; pathological waste; biological waste from a patient on isolation; discarded materials from treatment of a patient on isolation; waste discarded from renal dialysis, including needles and tubing; discarded serums and vaccines that have not been autoclaved; discarded laboratory waste that has come in contact with pathogenic organisms not autoclaved or sterilized; animal carcasses exposed to pathogens in research, their bedding, and other waste from such animals that is discarded; and other articles discarded that are potentially infectious, that might cause punctures or cuts, and that have not been autoclaved and rendered incapable of causing punctures or cuts. [See Centers for Disease Control and Prevention (CDS), EPA, and state definitions.]

Integrated Solid Waste Management A practice of disposing of solid waste that utilizes several complementary components, such as source reduction, recycling, composting, waste-to-energy, and landfill.

Leachate A liquid resulting from precipitation percolating through landfills containing water, decomposed waste, and bacteria. In sanitary landfills, leachate is collected and treated to prevent contamination of water supplies.

Municipal Solid Waste Includes nonhazardous waste generated in households, commercial establishments, institutions, and light industrial wastes; it excludes industrial process wastes, agricultural wastes, mining wastes, and sewage sludge.

Photodegradable A process whereby the sun's ultraviolet radiation attacks the link in the polymer chain of plastic. The breaking of this link causes the plastic chain to fragment into smaller pieces, losing its strength and ability to flex and stretch. As the photodegradable plastic is subjected to the effects of the natural environment, the material is flexed, stretched, and disintegrated into plastic dust.

Recycling A resource recovery method involving the collection and treatment of a waste product for use as raw material in the manufacture of the same or another produce (e.g., ground glass used in the manufacture of new glass).

Residuals Sludge, sewage sludge, septage, air pollution control facility waste, or any other such waste having similar characteristics or effects and solid waste remaining after the processing of solid waste by composting methods that was not made into compost suitable for use.

Resource Recovery A term describing the extraction and utilization of materials that can be used as raw material in the manufacture of new products or as values that can be converted into some form of fuel or energy source. An integrated resource recovery program may include recycling, waste-to-energy, composting, and/or other components.

Sanitary Landfill A method of disposing of solid waste on land without creating nuisances or hazards to public health or safety. Careful preparation of the fill area, including the use of clay and/or synthetic liners and control of water drainage, is required to ensure proper landfilling. To confine the solid waste to the smallest practical area and reduce it to the smallest practical volume, heavy equipment is used to spread, compact, and cover the waste daily with at least 6 in. of compacted soil. After the area has been completely filled and covered with a final 2- or 3-ft layer of soil and seeded with grass, the reclaimed land may be turned into a recreational area such as a park or golf course. Sanitary landfills have leachate collection systems, methane gas controls, and environmental monitoring systems.

Solid Waste Includes any garbage, solid waste, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations and from community activities but does not include solid or dissolved material in domestic sewage or solid or dissolved materials in irrigation return flows or industrial discharges, which are point sources subject to permit under Section 402 of the Federal Water Pollution Act (as amended), or source, special nuclear, or byproduct material as defined by the Atomic Energy Act of 1954, as amended. Also excluded are agricultural wastes, including manures and crop residues returned to the soil as fertilizers or soil conditioners and mining or milling wastes intended for return to the mine.

Solid Waste Management The systematic administration of activities that provide for the collection, source separation, storage, transportation, transfer, processing, treatment, and disposal of solid waste.

Source Reduction Refers to reducing the amount of waste generated that must eventually be discarded, including minimizing toxic substances in products, minimizing volume of products, and extending the useful life of products. Requires manufacturers and consumers to take an active role in reducing the amount of waste produced.

Source Separation The segregation of various materials from the waste stream at the point of generation for recycling. For example, householders separating paper, metal, and glass from the rest of their wastes.

Transfer Station A facility with structures, machinery, or devices that receives deliveries of solid waste by local collection vehicles and provides for the transfer of the waste to larger vehicles that are used to deliver the waste to a recycling, treatment, or disposal site.

Waste-to-Energy Incineration Disposal method in which municipal solid waste is brought to a plant where it is burned either as received or after being processed to a more uniform fuel to generate steam or electricity. Waste-to-energy plants can decrease volume by 60 to 90 percent while recovering energy from discarded products. Mass burn, modular combustion units, and solid-waste-derived fuel are the three basic waste-to-energy plants used.

INTEGRATED WASTE MANAGEMENT

Integrated waste management (IWM) can be defined as the selection and application of suitable techniques, technologies, and management programs to achieve specific waste management objectives and goals. Because numerous state and federal laws have been adopted, IWM is also evolving in response to the regulations developed to implement the various laws. The EPA has identified four basic management options (strategies) for IWM: (1) source reduction, (2) recycling and composting, (3) combustion (waste-to-energy facilities), and (4) landfills. As proposed by the EPA, these strategies are meant to be interactive, as illustrated in Figure 5-1*a*. It should be noted that some states have chosen to consider the management options in a hierarchical order, as depicted in Figure 5-1*b*. For example, recycling can only be considered after all that can be done to reduce the quantity of waste at the source has been done. Similarly, waste transformation is only considered after the maximum amount of recycling has been achieved. Further, the combustion (waste-to-energy) option has been replaced with waste transformation in California and other states. Interpretation of the IWM hierarchy will, most likely, continue to vary by state. The management options that comprise the IWM are

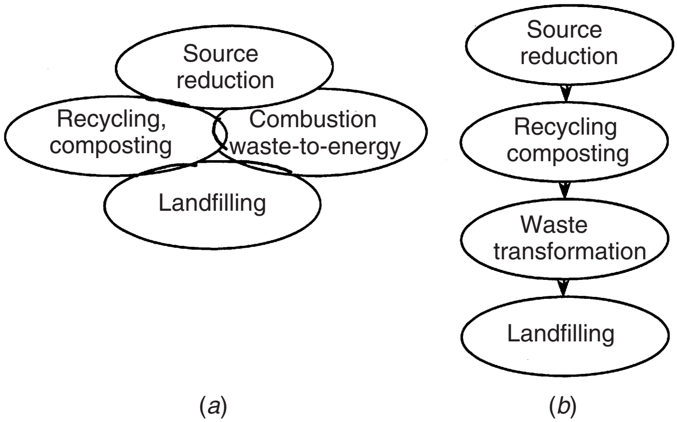

Figure 5-1 Definition sketch for integrated solid waste management: (*a*) interactive; (*b*) hierarchical.

considered in the following discussion. The implementation of IWM options is considered in the remaining sections of this chapter (Tchobanoglous et al., 2002).

Source Reduction

Source reduction focuses on reducing the volume and/or toxicity of generated waste. Source reduction includes the switch to reusable products and packaging, the most familiar example being returnable bottles. However, legislated bottle bills only result in source reduction if bottles are reused once they are returned. Other good examples of source reduction are grass clippings that are left on the lawn and never picked up and modified yard plantings that do not result in leaf and yard waste. The time to consider source reduction is at the product/process design phase.

Source reduction can be practiced by everybody. Consumers can participate by buying less or using products more efficiently. The public sector (government entities at all levels: local, state, and federal) and the private sector can also be more efficient consumers. They can reevaluate procedures that needlessly distribute paper (multiple copies of documents can be cut back), require the purchase of products with longer life spans, and cut down on the purchase of disposable products. The private sector can redesign its manufacturing processes to reduce the amount of waste generated in the manufacturing process. Reducing the amount of waste may require closed-loop manufacturing processes and the use of different raw materials and/or different production processes. Finally, the private sector can redesign products by increasing their durability, substituting less toxic materials, or increasing product effectiveness. However, while everybody can participate in source reduction, it digs deeply into how people go about their business, something that is difficult to mandate through regulation without getting mired in the tremendous complexity of commerce.

Source reduction is best encouraged by making sure that the cost of waste management is fully internalized. *Cost internalization* means pricing the service so that all of the costs are reflected. For waste management, the costs that need to be internalized include pickup and transport, site and construction, administrative and salary, and environmental controls and monitoring. It is important to note that these costs must be considered, whether the product is ultimately managed in a landfill, combustion, recycling facility, or composting facility. Regulation can aid cost internalization by requiring product manufacturers to provide public disclosure of the costs associated with these aspects of product use and development (Tchobanoglous et al., 2002).

Recycling and Composting

Recycling is perhaps the most positively perceived and doable of all the waste management practices. Recycling will return raw materials to market by separating reusable products from the rest of the municipal waste stream. The benefits of recycling are many. Recycling saves precious finite resources, lessens the need for mining of virgin materials, which lowers the environmental impact for mining and processing, and reduces the amount of energy consumed. Moreover, recycling can help stretch landfill capacity. Recycling can also improve the efficiency and ash quality of incinerators and composting facilities by removing noncombustible materials, such as metals and glass.

Recycling can also cause problems if it is not done in an environmentally responsible manner. Many Superfund sites are what is left of poorly managed recycling operations. Examples include de-inking operations for newsprint, waste oil recycling, solvent recycling, and metal recycling. In all of these processes, toxic contaminants that need to be properly managed are removed. Composting is another area of recycling that can cause problems without adequate location controls. For example, groundwater can be contaminated if grass clippings, leaves, or other yard wastes that contain pesticide or fertilizer residues are composted on sandy or other permeable soils. Air contamination by volatile substances can also result.

Recycling will flourish where economic conditions support it, not just because it is mandated. For this to happen, the cost of landfilling or resource recovery must reflect its true cost and must be at least $40 per ton or higher. Successful recycling programs also require stable markets for recycled materials. Examples of problems in this area are not hard to come by; a glut of paper occurred in Germany in the 1984 to 1986 time frame due to a mismatch between the grades of paper collected and the grades required by the German papermills. Government had not worked with enough private industries to find out whether the mills had the capacity and equipment needed to deal with low-grade household newspaper. In the United States, a similar loss of markets has occurred for paper, especially during the period from 1994 through 1997. Prices have dropped to the point where it actually costs money to dispose of collected newspapers in some parts of the country.

Stable markets also require that stable supplies are generated. This supply-side problem has been problematic in certain areas of recycling, including metals and plastics. Government and industry must work together to address the market situation. It is critical to make sure that mandated recycling programs do not get too far ahead of the markets.

Even with a good market situation, recycling and composting will flourish only if they are made convenient. Examples include curbside pickup for residences on a frequent schedule and easy drop-off centers with convenient hours for rural communities and for more specialized products. Product mail-back programs have also worked for certain appliances and electronic components.

Even with stable markets and convenient programs, public education is a critical component for increasing the amount of recycling. At this point, the United States must develop a conservation, rather than a throwaway, ethic, as was done during the energy crisis of the 1970s. Recycling presents the next opportunity for cultural change. It will require us to move beyond a mere willingness to collect our discards for recycling. That cultural change will require consumers to purchase recyclable products and products made with recycled content. It will require businesses to utilize secondary materials in product manufacturing and to design new products for easy disassembly and separation of component materials (Tchobanoglous et al., 2002).

Combustion (Waste-to-Energy)

The third of the IWM options (see Figure 5-1) is combustion (waste-to-energy). Combustion facilities are attractive because they do one thing very well; they reduce the volume of waste dramatically up to ninefold. Combustion facilities can also recover useful energy either in the form of steam or in the form of electricity. Depending on the economics of energy in the region, this can be anywhere from profitable to unjustified. Volume reduction alone can make the high capital cost of incinerators attractive when landfill space is at a premium or when the landfill is distant from the point of generation. For many major metropolitan areas, new landfills must be located increasingly far away from the center of the population. Moreover, incinerator bottom ash has a promise for reuse as a building material. Those who make products from cement or concrete may be able to utilize incinerator ash.

The major constraints of incinerators are their cost, the relatively high degree of sophistication needed to operate them safely and economically, and the fact that the public is very skeptical concerning their safety. The public is concerned about both stack emissions from incinerators and the toxicity of ash produced by incinerators. The EPA has addressed both of these concerns through the development of new regulations for solid waste combustion (waste-to-energy) plants and improved landfill requirements for ash. These regulations will ensure that well-designed, well-built, and well-operated facilities will be fully protective from the health and environmental standpoints (Tchobanoglous et al., 2002).

Landfills

Landfills are the one form of waste management that nobody wants but everybody needs. There are simply no combinations of waste management techniques that do not require landfilling to make them work. Of the four basic management options, landfills are the only management technique that is both necessary and sufficient. Some wastes are simply not recyclable, because they eventually reach a point where their intrinsic value is dissipated completely so they no longer can be recovered, and recycling itself produces residuals.

The technology and operation of a modem landfill can assure protection of human health and the environment. The challenge is to ensure that all operating landfills are designed properly and are monitored once they are closed. It is critical to recognize that today's modern landfills do not look like the old landfills that are on the current Superfund list. Today's operating landfills do not continue to take hazardous waste. In addition, they do not receive bulk liquids. They have gas control systems, liners, leachate collection systems, and extensive groundwater monitoring systems; perhaps most importantly, they are better sited and located in the first place to take advantage of natural geological conditions.

Landfills can also turn into a resource. Methane gas recovery is occurring at many landfills today and CO_2 recovery is being considered. After closure, landfills can be used for recreation areas such as parks, golf courses, or ski areas. Some agencies and entrepreneurs are looking at landfills as repositories of resources for the future; in other words, today's landfills might be able to be mined at some time in the future when economic conditions warrant. This situation could be particularly true of monofills, which focus on one kind of waste material like combustion ash or shredded tires (Tchobanoglous et al., 2002).

Implementing Integrated Solid Waste Management

The implementation of IWM for residential solid waste, as illustrated in Figure 5-2, typically involves the use of a several technologies and all of the management options discussed above. At present, most communities use two or more of the municipal solid waste (MSW) management options to dispose of their waste, but there are only a few instances where a truly integrated and optimized waste management plan has been developed. To achieve an integrated strategy for handling municipal waste, an optimization analysis com-

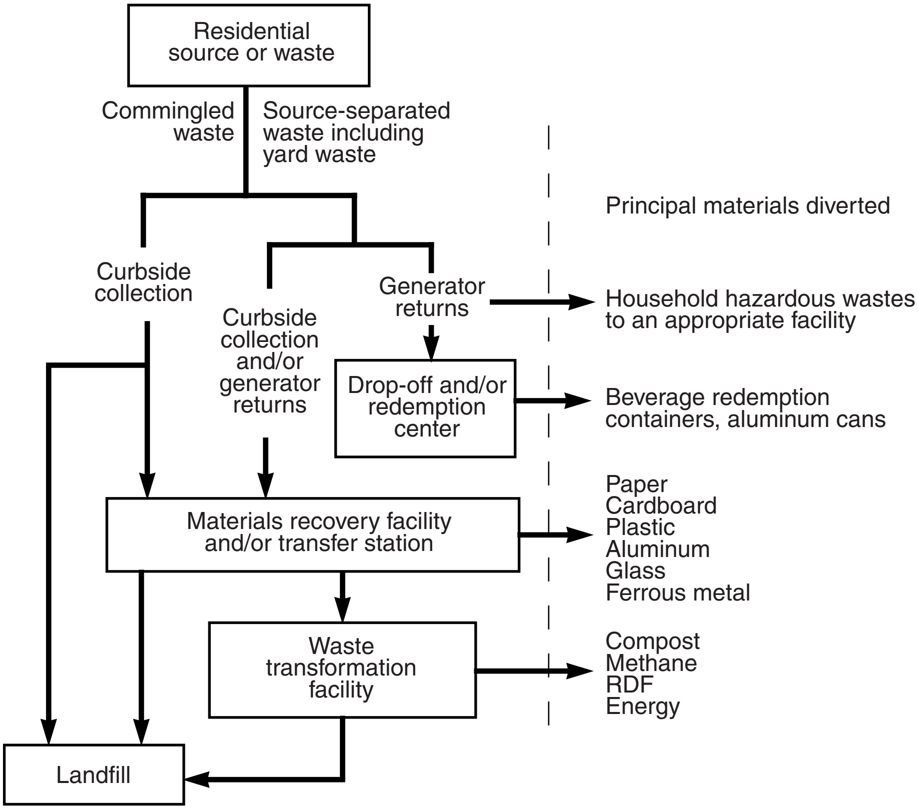

Figure 5-2 Implementation of IWM for management of residential solid wastes. Similar diagrams apply to commercial and institutional sources of solid waste (Tchobanoglous et al., 2002).

bining all of the available options should be conducted. However, at present, there is no proven methodology for performing such an optimization analysis (Tchobanoglous et al., 2002).

SOURCES, CHARACTERISTICS, AND QUANTITIES OF SOLID WASTE

In developing solid waste management programs, it is important to identify the sources, characteristics, and quantities of solid waste. Information on these subjects, as discussed in this section, is of fundamental importance in determining the types of collection service, the types of collection vehicles to be used, the type of processing facilities, and the disposal method to be used. Construction and demolition debris and special wastes that must be collected and processed separately are also considered.

Sources of Solid Waste

Sources of solid wastes in a community are, in general, related to land use and zoning. Although any number of source classifications can be developed, the following categories have been found useful: (1) residential, (2) commercial, (3) institutional, (4) construction and demolition, (5) municipal services, (6) treatment plant sites, (7) industrial, and (8) agricultural. Typical waste generation facilities, activities, or locations associated with each of these sources are reported in Table 5-1. As noted in Table 5-1, *municipal solid waste* is normally assumed to include all community wastes with the exception of wastes generated from municipal services, water and wastewater treatment plants, industrial processes, and agricultural operations. It is important to be aware that the definitions of solid waste terms and the classifications of solid waste vary greatly in the literature and in the profession. Consequently, the use of published data requires considerable care, judgment, and common sense (Tchobanoglous et al., 2002).

Characteristics of Solid Waste

Important characteristics of solid waste include the composition, quantities, and specific weight.

Composition Typical data on the general characteristics of municipal solid waste are presented in Table 5-2. Averages are subject to adjustment depending on many factors: time of the year; habits, education, and economic status of the people; number and type of commercial and industrial operations; whether urban or rural area; and location. Each community should be studied and actual weighings made to obtain representative information for design purposes.

Quantities Various estimates have been made of the quantity of solid waste generated and collected per person per day. The amount of municipal solid waste collected is estimated to be 6 lb/capita · d, of which about 3.5 lb is residential. Additional details on the quantities and characteristics of the solid waste generated in the United States may be found in Franklin Associates (1999, and yearly updates) and U.S. EPA (1999, 2001). Community wastes are not expected to exceed 1 ton/capita · yr—with the emphasis being placed on source reduction (such as less packaging) and waste recovery and recycling (such as of paper, metals, cans, and glass), the amount of solid waste requiring disposal is reduced. Recovery and recycling of hazardous wastes and toxicity reduction by substitution of less hazardous or nonhazardous materials should also be emphasized. Typical data on the quantities of waste generated from specific sources are presented in Table 5-3. Typical data on the quantities of waste generated from miscellaneous nonresidential sources are presented in Table 5-4. Typical data on the quantities of waste generated from industrial and agricultural sources are presented in Tables 5-5 and Table 5-6, respec-

TABLE 5-1 Sources Where Solid Wastes Are Generated within a Community

Source	Typical Facilities, Activities, or Locations Where Wastes Are Generated	Types of Solid Wastes
Residential	Single-family and multifamily dwellings; low-, medium-, and high-rise apartments	Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood glass, tin cans, aluminum other metal, ashes, street leaves, special wastes (including bulky items, consumer electronics, white goods, yard wastes collected separately, batteries, oil, and tires), household hazardous wastes
Commercial	Stores, restaurants, markets, office buildings, hotels, motels, print shops, service stations and auto repair shops	Paper, cardboard, plastics, wood, food wastes, glass, metal wastes, ashes, special wastes (see above), hazardous wastes
Institutional	Schools, hospitals, prisons, governmental centers	As above for commercial
Industrial (nonprocess wastes)	Construction, fabrication, light and heavy manufacturing, refineries chemical plants, power plants, demolition	Paper, cardboard, plastics, wood, food wastes, glass, metal wastes, ashes, special wastes (see above), hazardous wastes
Municipal solid waste	All of the above[a]	All of the above[a]
Construction and demolition	New construction sites, road repair renovation sites, razing of buildings, broken pavement	Wood, steel, concrete, dirt
Municipal services (excluding treatment facilities)	Street cleaning, landscaping, catch-basin cleaning, parks and beaches, other recreational areas	Special wastes, rubbish, street sweepings, landscape and tree trimmings, catch-basin debris; general wastes from parks, beaches and recreational areas
Treatment plant sites	Water, wastewater, and industrial treatment processes	Treatment plant wastes, principally composed of residual sludges and other residual materials

TABLE 5-1 (*Continued*)

Source	Typical Facilities, Activities, or Locations Where Wastes Are Generated	Types of Solid Wastes
Industrial	Construction, fabrication, light and heavy manufacturing, refineries chemical plants, power plants, demolition	Industrial process wastes, scrap materials; nonindustrial waste, including food wastes, rubbish, ashes, demolition and construction wastes, special wastes, hazardous waste
Agricultural	Field and row crops, orchards, vineyards, dairies, feedlots, farms	Spoiled food wastes, agricultural wastes, rubbish, hazardous wastes

Source: Tchobanoglous et al. (1993).

[a] The term *municipal solid waste* (*MSW*) normally is assumed to include all of the wastes generated in the community with the exception of waste generated from municipal services, treatment plants, industrial processes, and agriculture.

tively. The data presented in Tables 5-3 through 5-6 are meant to be used as a general guide to expected quantities for the purpose of preliminary planning and feasibility assessment. In all cases the quantity information in these table must be verified before final design.

TABLE 5-2 Approximate Composition of Residential Solid Wastes in 1977, 1989, and 2000

Component	Percent by Weight[a]		
	1977	1989	2000
Food waste	16–18	7–10	6–8
Paper products	30–35	36–42	34–42
Rubber, leather, textiles, wood	7–9	6–9	4–8
Plastics	3–4	6–8	8–12
Metals	9–10	7–9	6–8
Glass and ceramics	9–12	7–9	7–9
Yard wastes	16–20	16–18	16–18
Rock, dirt, miscellaneous	1–4	1–3	1–3

Source: Adapted in part from Salvato (1992).

[a] Figures do not include junked vehicles, water and wastewater treatment plant sludges, waste oil, pathological wastes, agricultural wastes, industrial wastes, mining or milling wastes.

TABLE 5-3 Approximate Solid Waste Generation Rates from Various Sources in the United States

Source of Waste	Unit	lb/unit·day
Municipal	Capita	4.0
Household	Capita	3.5
Apartment building	Capita per sleeping room	4.0
Seasonal home	Capita	2.5
Resort	Capita	3.5
Camp	Capita	1.5
School		
With cafeteria	Capita	1.0
Without cafeteria	Capita	0.5
University	Student	0.86 to 1.0
Institution, general	Bed	2.5
Hospital	Bed	12–15
	Occupied bed and 3.7 if staff added	9.5
Nurses' or interns' home	Bed	3.0
Home for aged	Bed	3.0
Rest home	Bed	3.0
Nursing home, retirement	Bed	5.0
Infectious waste		
Hospital	Bed	4.0
Residential health care facility	Bed	0.5
Diagnostic and treatment center	Patient per week	0–6.5
Hotel		
First class	Room	3.0
Medium class	Room	1.5
Motels	Room	2.0
Day use facility, resort	Capita	0.5
Trailer camp	trailer	6–10
Commercial building, office	100 ft^2	1.0
Office building	Worker	1.5
Department store	100 ft^2	40
Shopping center	Survey required	Survey required
Supermarket	100 ft^2	9.0
Supermarket	Person	2.4
Restaurant	Meal	2.0
Cafeteria	Capita	1
Fast food	Capita	0.5
Drugstore	100 ft^2	5.0
Airport	Passenger	0.5
Prison	Inmate	4.5
Retail and service facility	1000 ft^2	13.0
Wholesale and retail facility	1000 ft^2	1.2
Industrial building, factory	400–3000 employees	7
	100–400 employees	3
Warehouse	Per 100 ft^2	2.0

TABLE 5-3 (*Continued*)

Source of Waste	Unit	lb/unit · day
National Forest recreational area		
Campground	Camper	1.2–1.4
Family picnic area	Picnicker	8.0–1.2
Organized camps	Occupant	1.4–2.2
Rented cabin, with kitchen	Occupant	1.2–1.8
Lodge, without kitchen	Occupant	0.2–0.8
Restaurant	Meal served	0.5–1.2
Overnight lodge, winter sports area	Visitor	1.5–2.1
Day lodge, winter sports area	Visitor	2.4–3.4
Swimming beach	Swimmer	0.02–0.05
Concession stand	Per patron	0.10–0.16
Job Corps, Civilian Conservation		
Corps camp, kitchen waste	Per corpsman	1.8–3.0
Administrative and dormitory	Per corpsman	0.5–1.2

Source: Adapted from Salvato (1992).

TABLE 5-4 Miscellaneous Solid Waste Generation

	Solid Waste Generation Rate	
Type	Unit	Range of Values
Tires	Tires discarded per capita per year	0.6–1.0
Waste oil	5 gal per vehicle per year	2.0–3.0
Wastewater sludge, raw	Tons per day per 1000 people, dewatered to 25% solids, with no garbage grinders	0.3–0.5
	Tons per day per 1000 people, dewatered to 25% solids, with 100% garbage grinders	0.7–0.9
Wastewater sludge, digested	Tons per day per 1000 people, dewatered to 25% solids, or 3 lb per capita per day dry solids	0.20–0.30
Water supply sludge	Pounds per million gallons of raw water, on a dry-weight basis, with conventional rapid-sand filtration using alum; raw water with 10 Jackson turbidity units (JTU)	200–220
Scavenger wastes	Gallons per capita per day	0.25–0.35
Pathological wastes	Pounds per bed per day—hospital	0.6–0.8
	Pounds per bed per day—nursing home	0.4–0.6
Junked vehicles	Number per 1000 population—2002	40–80

Source: Adapted in part from Malcolm Pirnie Engineers (1969).

TABLE 5-5 Typical Solid Waste Generation Rates for Industrial Sources by SIC Code[a]

SIC Code	Industry	Waste Production Rate (tons/employee · yr)
201	Meat processing	6.2
2033	Cannery	55.6
2037	Frozen foods	18.3
Other 203	Preserved foods	12.9
Other 20	Food processing	5.8
22	Textile mill products	0.26
23	Apparel	0.31
2421	Sawmills and planing mills	162.0
Other 24	Wood products	10.3
25	Furniture	0.52
26	Paper and allied products	2.00
27	Printing and publishing	0.49
281	Basic chemicals	10.0
Other 28	Chemical and allied products	0.63
29	Petroleum	14.8
30	Rubber and plastic	2.6
31	Leather	0.17
32	Stone, clay	2.4
33	Primary metals	24
34	Fabricated metals	1.7
35	Nonelectrical machinery	2.6
36	Electrical machinery	1.7
37	Transportation equipment	1.3
38	Professional and scientific institutions	0.12
39	Miscellaneous manufacturing	0.14

Source: Weston (1970).

[a] Standard Industrial Classification (SIC) Code.

Specific Weight The volume occupied by solid waste under a given set of conditions is of importance, as are the number and size or type of solid waste containers, collection vehicles, and transfer stations. Transportation systems and land requirements for disposal are also affected. For example, the specific weight of loose solid waste will vary from about 100 to 175 lb/yd^3. Specific weights of various solid waste materials are given in Table 5-7. The variabilities in the reported data are due to variations in moisture content.

Commercial and Household Hazardous Waste

The ‘‘contamination’’ of ordinary municipal waste by commercial and household hazardous wastes has exacerbated the potential problems associated with the disposal of municipal waste by landfill, incineration, and composting.

TABLE 5-6 Typical Agricultural Solid Waste Production Rates

	Annual Waste Production Rate	
Category	Unit	Range of Values
Wet manures		
Turkeys	Tons/1000 birds	180
Chickens (fryers)	Tons/1000 birds	6–8
Hens (layers)	Tons/1000 birds	60–70
Hogs	Tons/head	3.2
Horses	Tons/head	12
Beef cattle (feedlot)	Tons/head	10.9
Dairy cattle	Tons/head	14.6
Sheep	Tons/head	0.8
Fruit and nut crops		
Class 1 (grapes, peaches, nectarines)	Tons/acre	2.4
Class 2 (apples, pears)	Tons/acre	2.25
Class 4 (plums, prunes, miscellaneous)	Tons/acre	1.5
Class 5 (walnuts, cherries)	Tons/acre	1.0
Field and row crops		
Class 1 (field and sweet corn)	Tons/acre	4.5
Class 2 (cauliflower, lettuce, broccoli)	Tons/acre	4.0
Class 3 (sorghum, tomatoes, beets, cabbage, squash, brussel sprouts)	Tons/acre	3.0
Class 4 (beans, onions, cucumbers, carrots, peas, peppers, potatoes, garlic, celery, miscellaneous)	Tons/acre	2.0
Class 5 (barley, oats, wheat, milo, asparagus)	Tons/acre	1.5

Source: Adapted from Salvato (1992).

Based on a number of past studies, the quantity of hazardous waste typically represents less than about 0.5 percent of the total waste generated by households. Typically, batteries and electrical items and certain cosmetics accounted for the largest amount.

From a practical standpoint, it would appear that more can be accomplished by identifying and prohibiting disposal of commercial hazardous waste with municipal solid waste. The minimal household hazardous wastes could, with education and municipal cooperation, be disposed of by voluntary actions. These could include periodic community collections and provision of central guarded depositories. Many communities have established ongoing programs for the collection of household hazardous waste.The amount of waste can be expected to decrease as old stockpiles are discarded. Restricting sales and promoting development and substitution of nonhazardous household products would also be indicated. It should also be remembered that a large fraction of the household hazardous waste ends up in the sewer.

TABLE 5-7 Weight of Solid Waste for Given Conditions

Condition of Solid Waste	Weight (lb/yd^3)
Loose solid waste at curb	125–240
As received from compactor truck at sanitary landfill	300–700
Normal compacted solid waste in a sanitary landfill[a]	750–850
Well-compacted solid waste in a sanitary landfill[a]	1000–1250
In compactor truck	300–600
Shredded solid waste, uncompacted	500–600
Shredded solid waste, compacted	1400–1600
Compacted and baled	1600–3200
Apartment house compactor	600–750
In incinerator pit	300–550
Brush and dry leaves, loose and dry	80–120
Leaves, loose and dry	200–260
Leaves, shredded and dry	250–450
Green grass, compacted	500–1100
Green grass, loose and moist	350–500
Yard waste, as collected	350–930
Yard waste, shredded	450–600

Source: Salvato (1992) and Tchobanoglous et al. (1993). Reproduced with permission from Cornell Waste Management Institute, Center for the Environment.

[a] Initial value.

Construction and Demolition Debris

Construction and demolition debris consists of uncontaminated solid waste resulting from the construction, remodeling, repair, and demolition of structures and roads and uncontaminated solid waste consisting of vegetation from land clearing and grubbing, utility line maintenance, and seasonal and storm-related cleanup. Such waste includes, but is not limited to, bricks, concrete and other masonry materials, soil, wood, wall coverings, plaster, drywall, plumbing fixtures, nonasbestos insulation, roofing shingles, asphaltic pavement, glass, plastics that are not sealed in a manner that conceals other wastes, electrical wiring and components containing no hazardous liquids, and metals that are incidental to any of the above (U.S. EPA, 1998c).

Solid waste that is not construction and demolition debris (even if resulting from the construction, remodeling, repair, and demolition of structures, roads, and land clearing) includes, but is not limited to, asbestos waste, garbage, corrugated container board, electrical fixtures containing hazardous liquids such as fluorescent light ballasts or transformers, carpeting, furniture, appliances, tires, drums and containers, and fuel tanks. Specifically excluded from the definition of construction and demolition debris is solid waste (including what otherwise would be construction and demolition debris) resulting from any processing technique, other than that employed at a construction and demolition processing facility, that renders individual waste components unrecognizable, such as pulverizing or shredding.

Some of this material, such as bricks, rocks, wood, and plumbing fixtures, can be recycled. However, care must be taken to ensure (by monitoring each load) that hazardous materials such as those mentioned above are excluded and that fire, odor, and groundwater pollution is prevented. Engineering plans and reports, hydrogeologic report, operation and maintenance reports, and per mits from the regulatory agency are usually required.

Special Wastes Collected Separately

In every community a number of waste materials are collected separately from residential and commercial solid waste. Special wastes include (1) medical wastes, (2) animal wastes, (3) waste oil, and (4) old tires. These wastes are considered in the following discussion.

Medical Wastes—Infectious and Pathological The Solid Waste Disposal Act, commonly referred to as the Resource Conservation and Recovery Act (RCRA), defines medical waste as "any solid waste which is generated in the diagnosis, treatment, or immunization of human beings or animals, in research pertaining thereto, or in the production or testing of biologicals. The term does not include any hazardous waste identified or listed under Subtitle C (mixtures with medical wastes are not excluded) or any household waste as defined in regulations under Code of Federal Regulations, Title 40, Subtitle C (materials found in waste generated by consumers)."

Infectious waste usually comes from a medical care or related facility. It includes all waste materials resulting from the treatment of a patient on isolation (other than patients on reverse or protective isolation), renal dialysis, discarded serums and vaccines, pathogen-contaminated laboratory waste and animal carcasses used in research (including bedding and other waste), and other articles that are potentially infectious such as hypodermic and intravenous needles.

Regulated medical waste under the Act includes the following waste categories: cultures and stock of infectious agents and associated biologicals; human blood and blood products; pathological waste; used sharps (needles, syringes, surgical blades, pointed and broken glass); and contaminated animal carcasses. The EPA is authorized to exclude, if there is no substantial threat to human health or the environment, surgery or autopsy waste, miscellaneous microbiology laboratory waste, dialysis waste, discarded medical equipment, and isolation wastes. Other waste categories may be added if they pose a substantial threat. Potential hazards associated with the handling of infectious waste necessitate certain precautions. Infectious waste needs to be segregated at the source and clearly color (red) coded and marked. The packaging is expected to maintain its integrity during handling, storage, and transportation with consideration of the types of materials packaged. The storage time should be minimal (treated within 24 hr); the packaging moisture proof, puncture resistant, and rodent and insect proof; and the storage places and containers clearly marked with the universal biological hazard symbol and secured. Packaged waste is placed in rigid or semirigid containers and transported in closed leak-proof trucks or dumpsters. It must at all times be kept separate from regular trash and other solid waste. Health care workers and solid waste handlers must be cautious.

Most infectious waste can be treated for disposal by incineration or autoclaving. The residue can be disposed of in an approved landfill. Liquids may be chemically disinfected; pathological wastes may also be buried, if permitted, or cremated; and blood wastes may, under controlled conditions, be discharged to a municipal sanitary sewer provided secondary treatment is employed. Infectious waste may also be rendered innocuous by shredding–disinfection (sodium hypochlorite), thermal inactivation, and gas–vapor treatment. Infectious waste is only one component of medical waste.

In all cases, local, state, and federal regulations should be followed closely. Public concerns and fears associated with the possible spread of the viruses causing acquired immunodeficiency syndrome (AIDS) and hepatitis B, as well as other infections, have accelerated legislative and regulatory action, tighter management practices, and provision of specialized treatment and disposal services. Complete records (medical waste tracking form) must be kept by the generator and hauler of infectious waste to the point of final disposal as part of a four-part manifest system.

Animal Wastes Animal wastes may contain disease organisms causing salmonellosis, leptospirosis, tularemia, foot-and-mouth disease, hog cholera, and other illnesses. (See Zoonoses and Their Spread, Chapter 1.) Manure contaminated with the foot-and-mouth disease virus must be buried in a controlled manner or otherwise properly treated. The excreta from sick animals should be stored 7 to 100 days or as long as is necessary to ensure destruction of the pathogen, depending on temperature and moisture. Dead animals are best disposed of at an incinerator or rendering plant or in a separate area of a sanitary landfill. Large numbers might be buried in a special trench with due consideration to protection of groundwaters and surface waters if approved by the regulatory authority.

Waste Oil Large quantities of waste motor and industrial oil find their way into the environment as a result of accidental spills, oiled roads, oil dumped in sewers and on the land, and oil deposited by motor vehicles. Used oils contain many toxic metals and additives that add to the pollution received by sources of drinking water, aquatic life, and terrestrial organisms. The lead content of oil is of particular concern. It has been estimated that industrial facilities, service stations, and motorists produce 1.2 billion gallons of used oil in the United States each year. Approximately 60 percent is used motor oil. Approximately 60 percent is reprocessed and used for fuel, but air pollution controls are needed. About 25 to 30 percent is rerefined and reused as a lubricant. The remainder is used for road oil, dirt road dust control and stabilization, and other unacceptable uses. Rerefined oil is so classified when it has had physical and chemical impurities removed and, when by itself or blended with new oil or additives, is substantially equivalent or superior to new oil intended for the same purposes, as specified by the American Petroleum Institute.

Used Tires Tire dumps can cause major fires and release many hazardous chemicals, including oil, contributing to air and groundwater pollution. Tires collect rain water in which mosquitoes breed and provide harborage for rats and other vermin. Tires are not suitable for disposal by landfill but may be acceptable if shredded or split, although recycling is preferred and may be required.

ON-SITE HANDLING AND STORAGE

Where solid waste is temporarily stored on the premises, between collections, an adequate number of suitable containers should be provided.

Low-Rise Residential Areas

To a large extent, the type of container used for the collection of residential solid waste will depend on the type of collection service provided, and whether source separtion of wastes is employed (see Table 5-8 below under Solid Waste Collection). The variation in the types of containers used for residential service are illustrated in Figure 5-3.

Low- and Medium-Rise Apartments

Large containers located in enclosed areas are used most commonly for low- and medium-rise apartments. Typical examples are shown in Figure 5-4. In most applications, separate containers are provided for recycbale and commingled nonrecycable materials.

Curbside collection service is common for most low- and medium-rise apartments. Typically, the maintenance staff is responsible for transporting the containers to the street for curbside collection by manual or mechanical means. In many communities, the collector is responsible for transporting containers from a storage location to the collection vehicle. Where large containers are used, the contents of the containers are emptied mechanically using collection vehicles equipped with unloading mechanisms.

High-Rise Apartments

In high-rise apartment buildings (higher than seven stories), the most common methods of handling commingled wastes involve one or more of the follow-

(*a*)

(*b*)

Figure 5-3 Typical containers used for collection of residential solid waste: (*a*) source-separated recyclable materials are placed in three separate containers (one for paper, one for glass, and one for cans and plastics), residual nonrecyclable wastes are placed in separate containers, and yard wastes are place in the street for collection with specialized collection equipment; (*b*) commingled mixed wastes in a single large (90-gal) container.

Figure 5-4 Typical examples of large containers used for low- and medium-rise apartments (note separate containers for recyclable materials).

ing: (1) wastes are picked up by building maintenance personnel from the various floors and taken to the basement or service area; (2) wastes are taken to the basement or service area by tenants; or (3) wastes, usually bagged, are placed by the tenants in a waste chute system used for the collection of commingled waste at a centralized service location. Typically, large storage containers are located in the basements of high-rise apartments. In some locations, enclosed ground-level storage facilities will be provided. In some of the more recent apartment building developments, especially in Europe, underground pneumatic transport systems have been used in conjunction with the individual apartments chutes.

Commercial and Institution

Bulk containers or solid waste bins are recommended where large volumes of solid waste are generated, such as at hotels, restaurants, motels, apartment houses, shopping centers, and commercial places. They can be combined to advantage with compactors in many instances (see Figure 5-5). Containers should be placed on a level, hard, cleanable surface in a lighted, open area. The container and surrounding area must be kept clean, for the reasons previously stated. A concrete platform provided with a drain to an approved sewer with a hot-water faucet at the site to facilitate cleaning is generally satisfactory.

(*a*)

(*b*)

Figure 5-5 Typical containers used for collection of large amounts of waste from commercial establishments: (*a*) open top with lids; (*b*) closed container coupled to stationary compactor.

SOLID WASTE COLLECTION

Collection cost has been estimated to represent about 50 to 70 percent of the total cost of solid waste management, depending on the disposal method. Because the cost of collection represents such a large percentage of the total cost, the design of collection systems must be considered carefully. The type of service provided, the frequency of service, and the equipment used for collection are considered in the following discussion.

Type of Service

The type of collection service provided will depend on the community solid waste management program. Typical examples of the types of collection service provided for the collection of (1) commingled and (2) source-separated and commingled wastes are reported in Table 5-8. It should be noted that numerous other variations in the service provided have been developed to meet local conditions. In addition to routine collection services, presented in Table 5-8, annual or semiannual special collections for appliances, tires, batteries, paints, oils, pesticides, yard wastes, glass and plastic bottles, and ‘‘spring cleaning’’ have proven to be an appreciated community service while at the same time providing environmental protection.

Collection Frequency

The frequency of collection will depend on the quantity of solid waste, time of year, socioeconomic status of the area served, and municipal or contractor responsibility. In residential areas, twice-a-week solid waste collection during warm months of the year and once a week at other times should be the maximum permissible interval. In business districts, solid waste, including garbage from hotels and restaurants, should be collected daily except Sundays (see Figure 5-6). Depending on the type of collection system, the containers used for the on-site storage of solid waste should be either emptied directly into the collection vehicle or hauled away emptied and returned or replaced with a clean container. Solid waste transferred from on-site storage containers will invariably cause spilling, with resultant pollution of the ground and attraction of flies. If other than curb pickup is provided, such as backyard service, the cost of collection will be high. Nevertheless, some property owners are willing to pay for this extra service. Bulky wastes should be collected every three months. Most cities have also instituted ongoing programs for the collection of household hazardous wastes, typically every three months.

Types of Collection Systems

Solid waste collection systems may be classified from several points of view, such as the mode of operation, the equipment used, and the types of wastes

TABLE 5-8 Typical Collection Services for Commingled and Source Separated Solid Waste[a]

Preparation Method for Waste Collected	Type of Service
Commingled wastes	Single collection service of large container for commingled household and yard waste
	Separate collection service for (1) commingled household waste and (2) containerized yard waste
	Separate collection service for (1) commingled household waste and (2) noncontainerized yard waste
Source-separated and commingled waste	Single collection service for a single container with source-separated waste placed in plastic bag along with commingled household and yard wastes
	Separate collection service for (1) source-separated waste placed in a plastic bag and commingled household waste in same container and (2) non-containerized yard wastes
	Single collection service for source-separated and commingled household and yard wastes using a two-compartment container
	Separate collection service for (1) source-separated and commingled household wastes using a two-compartment container and (2) containerized or noncontainerized yard waste
	Separate collection service for (1) source-separated waste and (2) containerized commingled household and yard wastes
	Separate collection service for (1) source-separated waste, (2) commingled household waste, and (3) containerized yard wastes
	Separate collection service for (1) source-separated waste, (2) commingled household waste, and (3) noncontainerized yard wastes

Source: Theisen (2002).

[a]The method of waste preparation for collection is often selected for convenience and efficiency of collection services and subsequent materials processing activities.

collected. Collection systems can be classified, according to their mode of operation, into two categories: (1) hauled container systems and (2) stationary container systems. The individual systems included in each category lend themselves to the same method of engineering and economic analysis (Theisen, 2002). The principal operational features of these two systems are delineated below.

Hauled Container Systems (HCSs) These are collection systems in which the containers used for the storage of wastes are hauled to a materials recovery facility (MRF), transfer station, or disposal site, emptied, and returned to

Figure 5-6 Commercial waste placed on sidewalk in New York City for manual collection at night or in very early morning hours.

either their original location or some other location. There are three main types of vehicles used in hauled container systems: (1) hoist truck, (2) tilt-frame container, and (3) truck tractor trash-trailer (see Figure 5-7). Typical data on the containers and container capacities used with these vehicles are reported in Table 5-9.

Hauled container systems are ideally suited for the removal of wastes from sources where the rate of generation is high because relatively large containers are used (see Table 5-9). The use of large containers eliminates handling time as well as the unsightly accumulations and unsanitary conditions associated with the use of numerous smaller containers. Another advantage of hauled container systems is their flexibility: Containers of many different sizes and shapes are available for the collection of all types of wastes.

***Stationary Container Systems* (*SCSs*)** In the stationary container system, the containers used for the storage of wastes remain at the point of generation, except when they are moved to the curb or other location to be emptied. Stationary container systems may be used for the collection of all types of wastes. The systems vary according to the type and quantity of wastes to be handled as well as the number of generation points. There are two main types: (1) systems in which manually loaded collection vehicles are used (see Figure 5-8) and (2) systems in which mechanically loaded collection vehicles are used (see Figure 5-9).

The major application of manual loading collection vehicles is in the collection of residential source-separated and commingled wastes and litter. Manual loading is used in residential areas where the quantity picked up at each location is small and the loading time is short. In addition, manual methods are used for residential collection because many individual pickup points are inaccessible to mechanized mechanically loaded collection vehicles. Special attention must be given to the design of the collection vehicle intended for use with a single collector. At present, it appears that a side-

(*a*)

(*b*)

Figure 5-7 Typical examples of collection vehicles used in hauled container system: (*a*) hoist truck; (*b*) tilt frame; (*c*) trash trailer.

(c)

Figure 5-7 (*Continued*)

loaded compactor, such as the one shown in Figure 5-8*a*, equipped with standup right-hand drive, is best suited for curb and alley collection.

Personnel Requirements

In most hauled container systems, a single collector-driver is used. The collector-driver is responsible for driving the vehicle, loading full containers on to the collection vehicle, emptying the contents of the containers at the disposal site (or transfer point), and redepositing (unloading) the empty containers. In some cases, for safety reasons, both a driver and helper are used. The helper usually is responsible for attaching and detaching any chains or cables used in loading and unloading containers on and off the collection vehicle; the driver is responsible for the operation of the vehicle. A driver and helper should always be used where hazardous wastes are to be handled. Labor requirements for curbside collection with manually and mechanically loaded vehicles with a one-person crew are reported in Table 5-10.

Labor requirements for mechanically loaded stationary container systems are essentially the same as for hauled container systems. Where a helper is used, the driver often assists the helper in bringing loaded containers mounted on rollers to the collection vehicle and returning the empty containers. Occasionally, a driver and two helpers are used where the containers to be emptied must be rolled (transferred) to the collection vehicle from inaccessible

TABLE 5-9 Typical Data on Container Types and Capacities Available for Use with Various Collection Systems

Collection System Vehicle	Container Type	Typical Range of Container Capacities
Hauled container system		
Hoist truck	Used with stationary compactor	6–12 yd^3
Tilt-frame	Open top, also called debris boxes or roll-off	12–50 yd^3
	Used with stationary compactor	15–40 yd^3
	Equipped with self-contained compaction mechanism	20–40 yd^3
Truck-tractor	Open-top trash-trailers	15–40 yd^3
	Enclosed trailer-mounted containers equipped with self-contained compaction mechanism	30–40 yd^3
Stationary container systems (compacting type)		
Compactor, mechanically loaded	Open top and closed top with side loading	1–10 yd^3
	Special containers used for collection of residential wastes from individual residences	90–120 gal
Compactor, mechanically loaded with divided hopper	Special split cart containers used for collection of recyclables and other nonrecyclable commingled waste	90–120 gal
Compactor trailer with mechanical lift assembly on semi-tractor	Special split cart containers used for collection of recyclables and other nonrecyclable commingled waste	90–120 gal
Compactor, manually loaded	Small plastic or galvanized metal containers, disposable paper and plastic bags	20–55 gal
Stationary container systems (noncompacting type)		
Collection vehicle with manually loaded side dump containers	All type of containers used for temporary storage of recyclable materials	32 gal
Collection vehicle with semiautomatic manually loaded side troughs	All type of containers used for temporary storage of recyclable materials	32 gal
Collection vehicle with semiautomatic manually loaded side troughs capable of unloading wheeled containers	All type of containers used for temporary storage of recyclable materials plus wheeled containers	60–120 gal
Collection vehicle with mechanical lift assembly	Special containers used for collection of source separated wastes from individual residences	60–120 gal

Source: Theisen (2002) and Tchobanoglous et al. (1993).

Note: $yd^3 \times 0.7646 = m^3$; $gal \times 0.003785 = m^3$.

(*a*)

(*b*)

Figure 5-8 Typical examples of manually loaded collection vehicles used in stationary container system: (*a*) side-loaded right-hand standup drive collection vehicle for commingled solid waste; (*b*) rear-loaded collection vehicle for commingled solid waste; (*c*) side-loading vehicle used for collection of source-separated materials.

(c)

Figure 5-8 (*Continued*)

locations, such as in congested downtown commercial areas. In stationary container systems, where the collection vehicle is loaded manually, the number of collectors varies from one to four, in most cases, depending on the type of service and the collection equipment. While the aforementioned crew sizes are representative of current practices, there are many exceptions. In many cities, multiperson crews are used for curb service as well as for backyard carry service.

Health Issues

The frequency and severity of injuries in the solid waste management industry are very high. The National Safety Council reported that solid waste collection workers have an injury frequency approximately 10 times the national average for all industries, higher than police work and underground mining. Workmen's compensation rates account for about 9 to 10 percent of payroll for all solid waste collectors.

TRANSFER AND TRANSPORT

The urban areas around cities have been spreading, leaving fewer nearby acceptable solid waste disposal sites. The lack of acceptable sites has led to

(a)

(b)

Figure 5-9 Typical examples of mechanically loaded collection vehicles used in stationary container system: (*a*) side-loading vehicle with dual compartment (courtesy of Heil Environmental Industries; reproduced with permission); (*b*) front-loaded collection vehicle.

TABLE 5-10 Typical Labor Requirements for Curbside Collection with Manually and Mechanically Loaded Collection Vehicle Using One-Person Crew[a]

Average Number of Containers and/or Boxes per Pickup Location	Time (min/location)	
	Manual Pickup	Mechanical Pickup
1 (60–90 gal)	—	0.5–0.6
1 or 2	0.5–0.6	
3 or 4	0.6–0.9	
Unlimited service[b]	1.0–1.2	

Source: Theisen (2002).

[a] Values given are for typical residential area with lot sizes varying from $\frac{1}{4}$ to $\frac{1}{3}$ acre.
[b] Not all residents take advantage of unlimited service each collection day.

the construction of incinerators, resource recovery facilities, or processing facilities in cities or their outskirts or the transportation of wastes longer distances to new landfill disposal sites. However, as the distance from the centers of solid waste generation increases, the cost of direct haul to a site increases. A "distance" is reached (in terms of cost and time) when it becomes less expensive to construct a transfer station or incinerator at or near the center of solid waste generation where wastes from collection vehicles can be transferred to large tractor-trailers for haul to more distant disposal sites. Ideally, the transfer station should be located at the centroid of the collection service area.

Economic Analysis of Transfer Operations

A comparison of direct haul versus the use of a transfer station and haul for various distances is useful in making an economic analysis of potential landfill sites. The transfer station site development, transportation system, and social factors involved in site selection should also be considered in making the comparison.

If the cost of disposal by sanitary landfill is added to the cost comparison, the total relative cost of solid waste transfer, transportation, and disposal by sanitary landfill can be compared to the corresponding cost for incineration, if incineration is an option. The relative cost of incineration with the cost of landfill for various haul distances and a given population is illustrated in Figure 5-10. Based on past experience, a direct-haul distance (one-way) of 25 to 30 miles is about the maximum economical distance, although longer distances are common, where other options are unacceptable or cannot be implemented for a variety of reasons, including cost. A similar comparison in which distance is shown in terms of times of travel to the disposal site is presented in Figure 5-11.

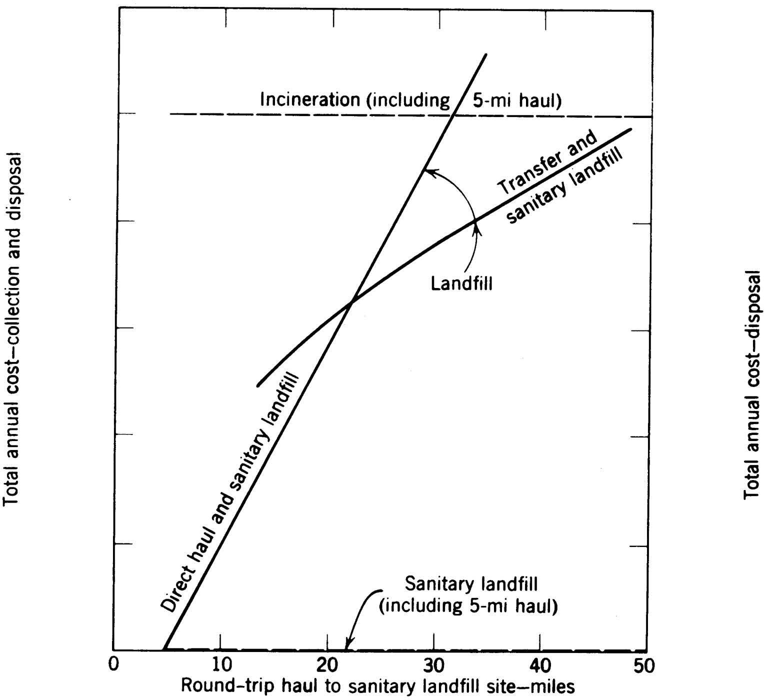

Figure 5-10 Effect of haul distances to site on cost of disposal by sanitary landfill compared to cost of disposal by incineration.

Types of Transfer Stations

Transfer stations are used to accomplish transfer of solid wastes from collection and other small vehicles to larger transport equipment. Depending on the method used to load the transport vehicles, transfer stations, as reported in Table 5-11 may be classified into two general types: (1) direct load and (2) storage load (see Figure 5-12). Combined direct-load and discharge-load transfer stations have also been developed Transfer stations may also be classified with respect to throughput capacity (the amount of material that can be transferred and hauled) as follows: small, less than 100 tons/day; medium, between 100 and 500 tons/day; and large, more than 500 tons/day.

Direct-Load Transfer Stations At direct-load transfer stations, the wastes in the collection vehicles are emptied directly into the vehicle to be used to transport them to a place of final disposition or into facilities used to compact the wastes into transport vehicles (see Figure 5-13) or into waste bales that are transported to the disposal site. In some cases, the wastes may be emptied onto an unloading platform and then pushed into the transfer vehicles, after

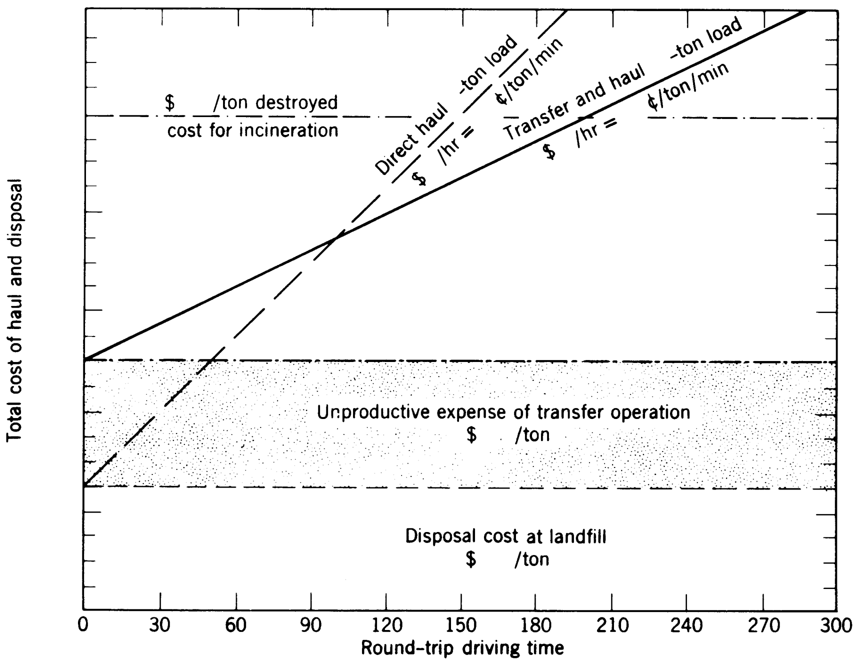

Figure 5-11 Cost comparison–incineration versus transfer and haul to landfill.

recyclable materials have been removed. The volume of waste that can be stored temporarily on the unloading platform is often defined as the *surge capacity* or the *emergency storage capacity* of the station. Small direct-load transfer stations used to serve industrial parks, rural areas, and entrances to landfills are illustrated in Figure 5-14.

Storage-Load Transfer Station In the storage-load transfer station, wastes are emptied directly into a storage pit from which they are loaded into transport vehicles by various types of auxiliary equipment (see Figure 5-1*b*). The difference between a dirtect-load and a storage-load transfer station is that the latter is designed with a capacity to store waste (typically one to three days).

Vehicles for Uncompacted Wastes

Motor vehicles, railroads, and ocean-going vessels are the principal means now used to transport solid wastes. Pneumatic and hydraulic systems have also been used. However, in recent years, because of their simplicity and dependability, open-top semitrailers have found wide acceptance for the hauling of uncompacted wastes from direct-load transfer stations (see Figure 5-15*a*). Another combination that has proven to be very effective for uncom-

TABLE 5-11 Types of Transfer Stations Used for Municipal Solid Waste

Type	Description
	Direct-Load Transfer Stations
Large- and medium-capacity direct-load transfer station without compaction	Wastes to be transported to landfill are loaded directly into large open-top transfer trailers for transport to landfill.
Large- and medium-capacity direct-load transfer stations with compactors	Wastes to be transported to landfill are loaded directly into large compactors and compacted into specially designed transport trailers or into bales, which are then transported to landfill.
Small-capacity direct-load transfer stations	Small-capacity transfer stations are used in remote and rural areas. Small-capacity transfer station are also used at landfills as a convenience for residents who wish to haul wastes directly to landfill.
	Storage-Load Transfer Station
Large-capacity storage-load transfer station without compaction	Wastes to be transported to a landfill are discharged into a storage pit where they are pulverized before being loaded into open trailers. Waste is pulverized to reduce the size of the individual waste constituents to achieve more effective utilization of the transfer trailers.
Medium-capacity storage-load transfer station with processing and compaction facilities	Wastes to be transported to a landfill are discharged into a pit where they are further pulverized before being baled for transport to a landfill.
	Other Types of Transfer Stations
Combined discharge-load and direct-load transfer station	Waste to be transported to a landfill can either be discharged on a platform or discharged directly into a transfer trailer. Wastes discharged onto a platform are typically sorted to recover recyclable materials.
Transfer and transport operations at MRFs	Depending on the type of collection service provided, materials recovery and transfer operations are often combined in one facility. Depending on the operation of the MRF, wastes to be landfilled can be discharged directly into open trailers or into a storage pit to be loaded later into open-top trailers or baled for transport to a landfill.

Source: Adapted from Tchobanoglous et al. (1993).

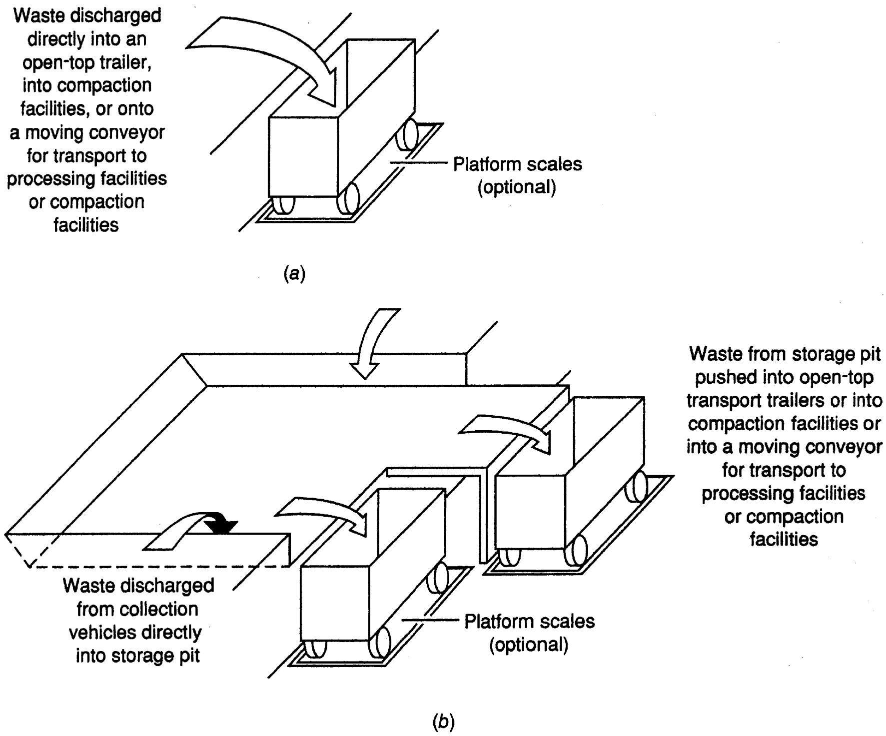

Figure 5-12 Definition sketch for two most common types of transfer stations: (*a*) direct discharge; (*b*) storage-discharge (Tchobaoglous et al., 1993).

pacted wastes is the truck-trailer combination (see Figure 5-15*b*). Transport trailers used for hauling solid waste over great distances are all of monoque construction, where the bed of the trailer also serves as the frame of the trailer. Using monoque construction allows greater waste volumes and weights to be hauled.

Transfer Station Siting Issues

A transfer station, resource recovery facility, or processing facility should be located and designed with the same care as described for an incinerator. Drainage of paved areas and adequate water hydrants for maintenance of cleanliness and fire control are equally important. Other concerns are landscaping, weigh scales, and traffic, odor, dust, litter, and noise control. Rail haul and barging to sea also involve the use of transfer stations. They may include one or a combination of grinding, baling, or compaction to increase densities, thereby improving transportation efficiency.

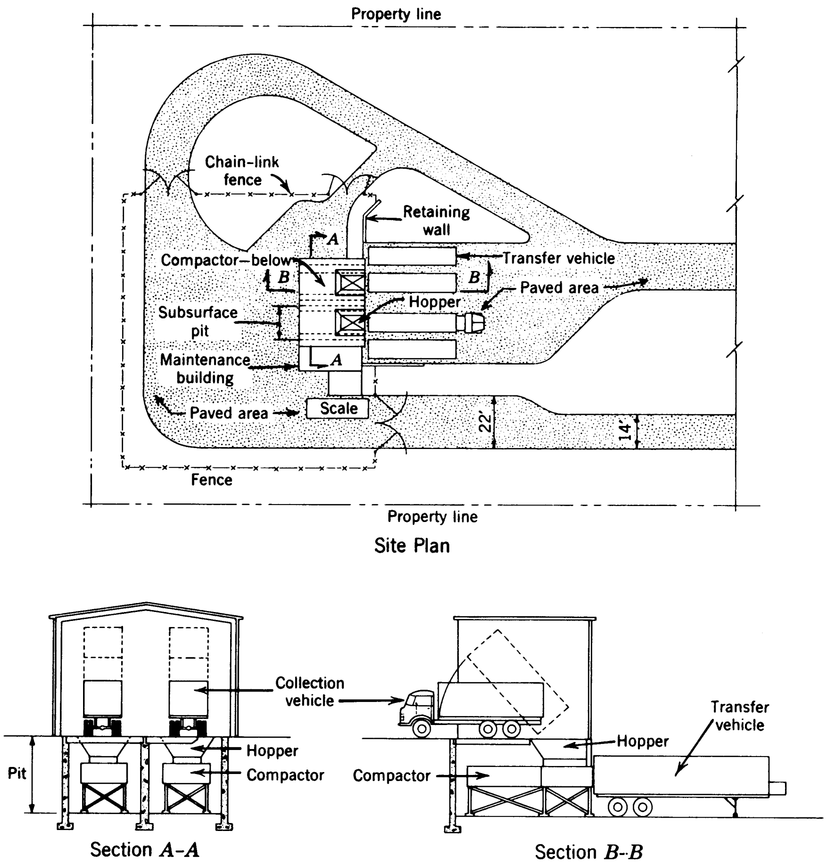

Figure 5-13 Direct-discharge transfer station equipped with stationary compactors. (Courtesy of Malcolm Pirnie, Inc. Reproduced with permission.)

WASTE REDUCTION AND MATERIALS RECOVERY

Proper solid waste management should first prevent and reduce the generation of solid wastes, reduce their hazardous characteristics, and recover and recycle waste to the extent practicable and then dispose of the remaining wastes in a manner that does not endanger public health or the environment. The focus of this section is on waste reduction and the recovery and recycling of materials.

Waste Reduction

The extent to which solid wastes can be reduced, recovered, and recycled should be an integral part of every solid waste management system study,

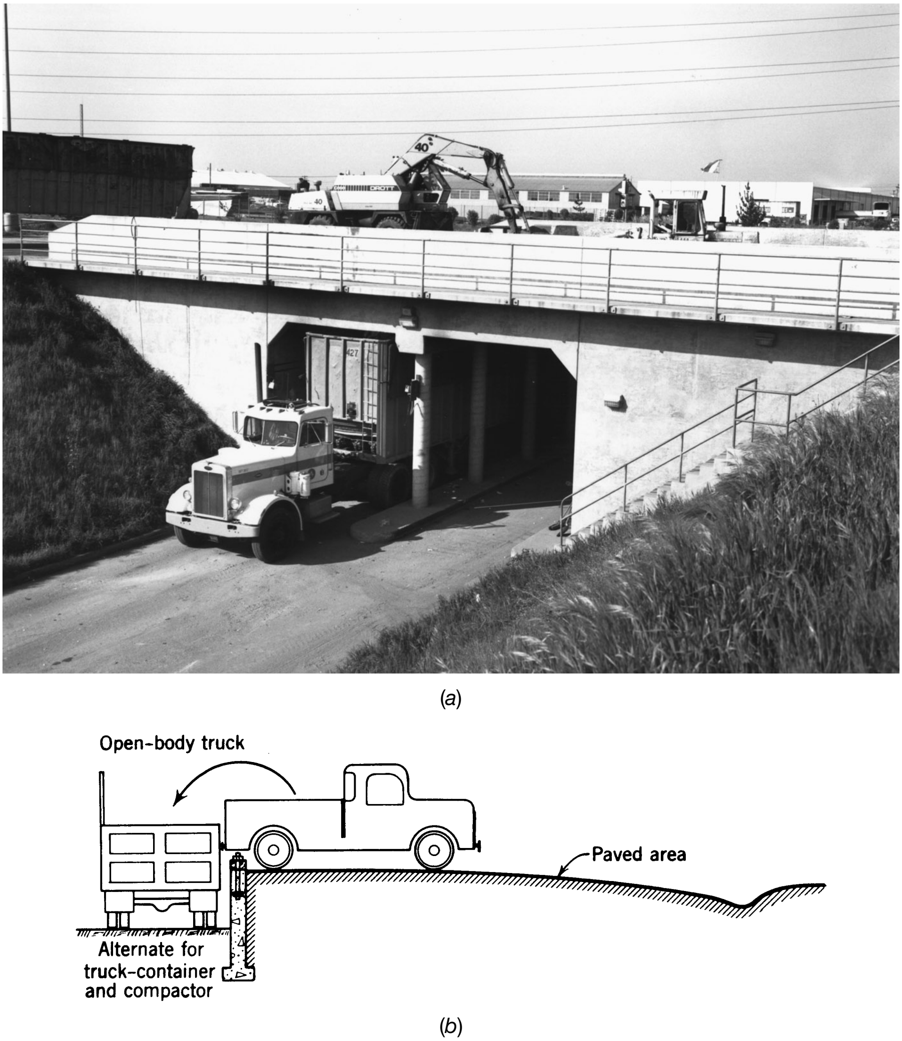

Figure 5-14 Small direct-discharge transfer stations: (*a*) transfer station located in industrial park; (*b*) convenience type located in rural areas at entrance of landfill disposal sites.

whether involving composting, a sanitary landfill, or an incinerator. Composting is also considered a form of recycling. The first step, however, should be waste reduction at the point of generation or product formulation. Industrial material, process, and packaging changes can minimize the waste or substitute a less toxic or objectionable material. The amount of waste can then be reduced and what waste is produced can be recovered, reused, or recycled to the extent feasible, thereby reducing the amount for final disposal. Additional

(*a*)

(*b*)

Figure 5-15 Typical examples of transfer trailers used to transport waste over large distances to (*a*) single large trailer with drop bottom and (*b*) tractor trailer combination in process of being unloaded at landfill.

details on source reduction may be found elsewhere (U.S. EPA, 1995c, 1996, 1998b).

There has been considerable interest in a returnable bottle deposit law in some states to reduce highway litter, conserve resources, and reduce the volume of solid wastes for disposal. The bottle law is usually applicable to all types of beverage containers, including glass, metal, and plastic, but not to other types of containers such as food jars, plastic and paper cups, wine and liquor bottles, and the like. The effectiveness of the bottle deposit law has been debated by some considering its limited application, the handling involved, and total cost, tangible and intangible. A substantial number of deposit containers are not returned by the consumer. This results in an unintended income to the supermarket or other retailer and what amounts to an additional cost to the consumer. Other alternatives should be considered. The reduction of *all* types of litter and insults to the landscape, including spillage from uncovered vehicles, elimination of junked cars, debris, and illegal dumps, and education of the public to promote a clean environment such as through Keep America Beautiful, requires greater support. Some returnable bottle laws are being amended to include liquor, wine, and wine cooler bottles and possibly other containers.

Materials Recovery and Recycling

Recovery of materials and energy from solid wastes is not new. Scavengers have salvaged newsprint and cardboard, rags, copper, lead, and iron for years. These materials, together with aluminum, glass, plastics, and wood, are being reclaimed at central collection and processing stations to a greater or lesser extent depending on the available market, tax policies, and public interest. Energy recovery, where feasible, has been an important consideration in which raw solid waste and shredded solid waste, referred to as solid-waste-derived fuel (RDF), is burned to produce steam or electricity.

Recycling can effect savings in landfill space and in energy. One ton of newspapers can save 3.0 to 3.3 yd^3 of landfill space. It is estimated that 95 percent less energy is required to produce aluminum from recycled aluminum than from bauxite. Crushed recycled glass melts at a lower temperature than virgin raw material, thereby conserving energy. Unfortunately, the recycling of glass has essentially ceased because of a glut of material available, the high cost of handling and processing recycled glass, and the cost associated with pollution control.

Resource recovery is not a municipal operation to be entered into just because it seems like the logical or proper thing to do. It is a complex economic and technical system with social and political implications, all of which require competent analysis and evaluation before a commitment is made. Included are the capital and operating costs, market value of reclaimed materials and material quality, potential minimum reliable energy sales, assured quantity of solid wastes, continued need for a sanitary landfill for the disposal of excess and remaining unwanted materials and incinerator residue, and a site location close to the centroid of the generators of solid wastes. Not all concepts are viable. Incentives and monetary support may be required to obtain an acceptable site.

Resource recovery is a partial waste disposal and reclamation process. Materials not recovered may amount to 50 to 70 percent of the original waste by weight, although a resource recovery system can theoretically be used to separate up to 90 percent of the municipal waste stream into possibly marketable components. It has been estimated that under the best conditions only about 50 to 60 percent of the solid waste will be recovered. In 1979, 7 percent was being recycled for materials or energy. In 1990, the national average was estimated to be 11 percent. In the year 2000, the average was about 26 percent. In general, it has been found that the recovery of materials from municipal solid waste is not a paying proposition. Most materials recovery operations are subsidized, in part, by the collection fees or by added montly charges. In most communities, materials recovery facilities are used to help meet mandated diversion (from landfill disposal) requirements.

Processing Technologies for the Recovery of Materials

In the not-so-distant past, solid waste processing and disposal methods have included the open dumping, hog feeding, incineration, grinding and discharge to a sewer, milling, compaction, sanitary landfill, dumping and burial at sea (prohibited in the United States), incineration, reduction, composting, pyrolization, wet oxidation, and anaerobic digestion. Currently, the most commonly accepted processing technologies involve the recovery of materials at materials recovery facilities and composting. Materials recovery facilities are considered below; composting is considered in the following section.

Implementation of Materials Recovery Facilities

Because the EPA has mandated diversion goals, most communities have developed a variety of materials recovery facilities. The purpose of this section is to define the type of materials recovery facilities now in use, to review the principal unit operations and processes used for the recovery of materials, and to highlight the planning issues associated with the implementation of a materials recovery facility. Additional details on materials recovery facilities may be found in U.S. EPA (1991).

Types of Materials Recovery Facilities (MRFs) The separation of household and commercial waste can be done at the source, at the point of collection by collection crews or at centralized *materials recovery facilities* or large integrated *materials recovery/transfer facilities* (MR/TFs). The type of MRF will depend on the type of collection service provided and the degree of source separation the waste has undergone before reaching the MRF. The two general types of MRFs are (1) for source-separated material and (2) for commingled solid waste. The functions of each of theses types of MRFs is reviewed in Table 5-12. As reported in Table 5-12, may different types of MRFs have been developed depending on the specific objective. Further, as reported

TABLE 5-12 Typical Examples of Materials and Functions/Operations of MRFs Used for Processing of Source-Separated Recycable Materials and Commingled Solid Waste

Materials	Function/Operation
	MRFs for Source-Separated Recycable Materials
Mixed paper and cardboard	Manual separation of high-value paper and cardboard or contaminants from commingled paper types; baling of separated materials for shipping; storage of baled materials
	Manual separation of cardboard and mixed paper; baling of separated materials for shipping; storage of baled materials
	Manual separation of old newspaper, old corrugated cardboard, and mixed paper from commingled mixture; baling of separated materials for shipping; storage of baled materials
PETE and HDPE plastics	Manual separation of PETE and HDPE from commingled plastics; baling of separated materials for shipping; storage of baled materials
Mixed plastics	Manual separation of PETE, HDPE, and other plastics from commingled mixed plastics; baling of separated materials for shipping; storage of baled materials
Mixed plastics and glass	Manual separation of PETE, HDPE, and glass by color from commingled mixture; baling of separated materials for shipping; storage of baled materials
Mixed glass	
With sorting	Manual separation of clear, green, and amber glass; storage of separated materials
Without sorting	Storage of separated mixed glass
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
Plastic, aluminum cans, tin cans, and glass	Manual or pneumatic separation of polyethylene terepholate (PETE), high-density polyethylene (HDPE), and other plastics; manual separation of glass by color, if separated; magnetic separation of tin cans from commingled mixture of aluminum and tin cans; magnetic separation may occur before or after the separation of plastic; baling of plastic (typically two types), aluminum cans and tin cans, and crushing of glass and shipping; storage of baled and crushed materials

TABLE 5-12 (*Continued*)

Materials	Function/Operation
Yard wastes	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 undersized material
	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
	Grinding of yard waste to produce biomass fuel; storage of ground material
	MRFs for Commingled Solid Waste
Recovery of recyclable materials to meet mandated first-stage diversion goals	Bulky items, cardboard, paper, plastics (PETE, HDPE, and other mixed plastic), glass (clear and mixed), aluminum cans, tin cans, other ferrous materials
Recovery of recyclable materials and further processing of source-separated materials to meet second-stage diversion goals	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
Preparation of MSW for use as fuel for combustion	Bulky items, cardboard (depending on market value), glass (clear and mixed), aluminum cans, tin cans, other ferrous materials
Preparation of MSW for use as 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
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

Source: Adapted from Leverenz et al. (2002).

in Table 5-13, materials recovery facilities can also be classified in terms of size and the degree of mechanization. Small MRFs associated with the further processing of source-separated materials tend to be less highly mechanized.

Methods and Equipment for the Separation and Recovery of Materials Methods and processes used singly and in various combinations to recover and prepare wastes for reuse and/or disposal are summarized in Table 5-14.

TABLE 5-13 Typical Types of Materials Recovery Facilities, Capacity Ranges, and Major Functions and System Components Based on Degree of Mechanization

System Type	Capacity (tons/day)	Major System Components
Materials recovery		
Low	5–20	Processing of source-separated materials only; enclosed building, concrete floors, elevated hand-sorting conveyor, baler (optional), storage for separated and prepared materials for one month, support facilities for workers
Intermediate	20–100	Processing of source-separated commingled materials and mixed paper; enclosed building, concrete floors, elevated hand-sorting conveyor, conveyors, baler, storage for separated and baled materials for two weeks, support facilities for workers, buy-back center
High	>100	Processing of commingled materials or MSW; same facilities as intermediate system plus mechanical bag breakers, magnets, shredders, screens, and storage for baled materials for up to two months
Composting		
Low end system	5–20	Source-separated yard waste feedstock only; grinding equipment, cleared level ground with equipment to form and turn windrows, screening equipment (optional)
High-end system	>20	Feedstock derived from source-separated yard waste or processing of commingled wastes; facilities include enclosed building with concrete floors, in vessel composting reactors; enclosed building for curing of compost product, equipment for bagging and marketing compost product

Source: Leverenz et al. (2002).

Of the methods reported in Table 5-14, manual sorting is by far the most commonly used method for processing waste materials (see Figure 5-16). It is interesting to note that no machine has been developed to date that can match the eye-hand coordination of humans. The particulate grouping of unit processes and operations will depend on the characteristics of the material to be separated.

TABLE 5-14 Typical Methods and Equipment Used for Processing and Recovery of Individual Waste Components from MSW

Processing Options	Description
Manual sorting	Unit operation in which personnel physically remove items from the waste stream. Typical examples include (1) removal of bulky items that would interfere with other processes and (2) sorting material off an elevated conveyor into large bins located below the conveyor.
Size reduction	Unit operation used for the reduction of both commingled MSW and recovered materials. Typical applications include (1) hammermills for shredding commingled MSW, (2) shear shredders for use with commingled MSW and recycled materials such as aluminum, tires, and plastics, and (3) tub grinders used to process yard wastes.
Size separation	Unit operation in which materials are separated by size and shape characteristics, most commonly by the use of screens. Several types of screens are in common use, including (1) reciprocating screens for sizing shredded yard wastes, (2) trommel screens used for preparing commingled MSW prior to shredding, and (3) disc screens used for removing glass from shredded MSW.
Magnetic field separation	Unit operations in which ferrous (magnetic) materials are separated from nonmagnetic materials. A typical application is the separation of ferrous from nonferrous materials (e.g., tin from aluminum cans).
Densification (compaction)	Densification and compaction are unit operations used to increase the density of recovered materials to reduce transportation costs and simplify storage. Typical applications include (1) the use of baling for cardboard, paper, plastics, and aluminum cans and (2) the use of cubing and pelletizing for the production of densified RDF.
Materials handling	Unit operations used for the transport and storage of MSW and recovered materials. Typical applications include (1) conveyors for the transport of MSW and recovered materials, (2) storage bins for recovered materials, and (3) rolling stock such as fork lifts, front-end loaders, and various types of trucks for the movement of MSW and recovered materials.
Automated sorting	Unit operation in which materials are separated by material characteristics. Typical examples include (1) optical sorting of glass by color, (2) X-ray detection of polyvinyl chloride (PVC), and (3) infrared sorting of mixed resins.

Source: Tchobanoglous et al. (1993).

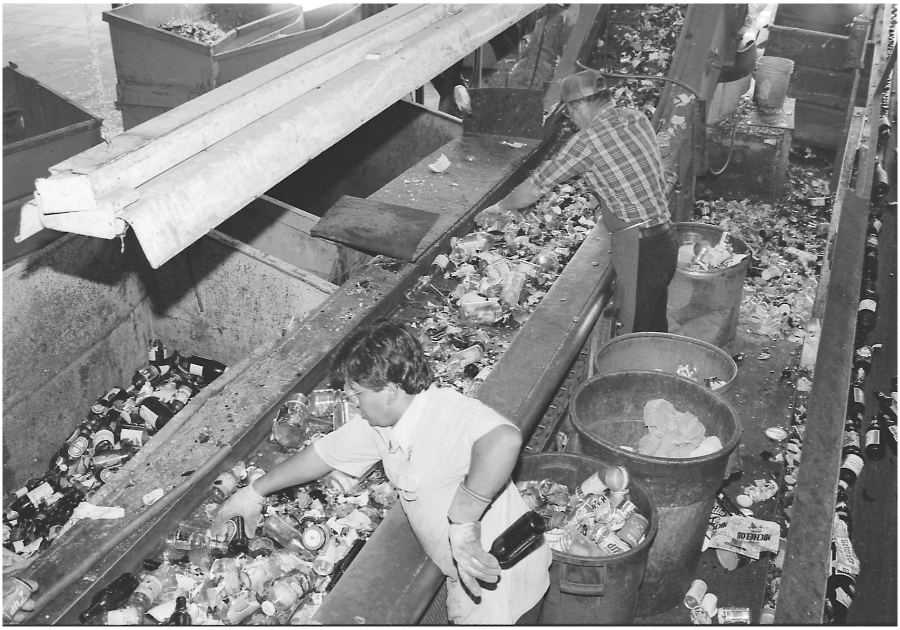

Figure 5-16 Typical sorting line for manual separation of waste components.

MRF Process Flow Diagrams Once a decision has been made on how and what recyclable materials are to be recovered, MRF process flow diagrams must be developed. In developing MRF process flow diagrams, the following factors must be considered: (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 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 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. Three typical MRF process flow diagrams are presented in Figures 5-17, 5-18, and 5-19 for source-separated recycable material, for mixed paper and cardboard, and commingled solid waste, respectively (Leverenz et al., 2002).

Technical Considerations in the Planning and Design of MRFs

Technical consideration in the planning and design of MRFs involves 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

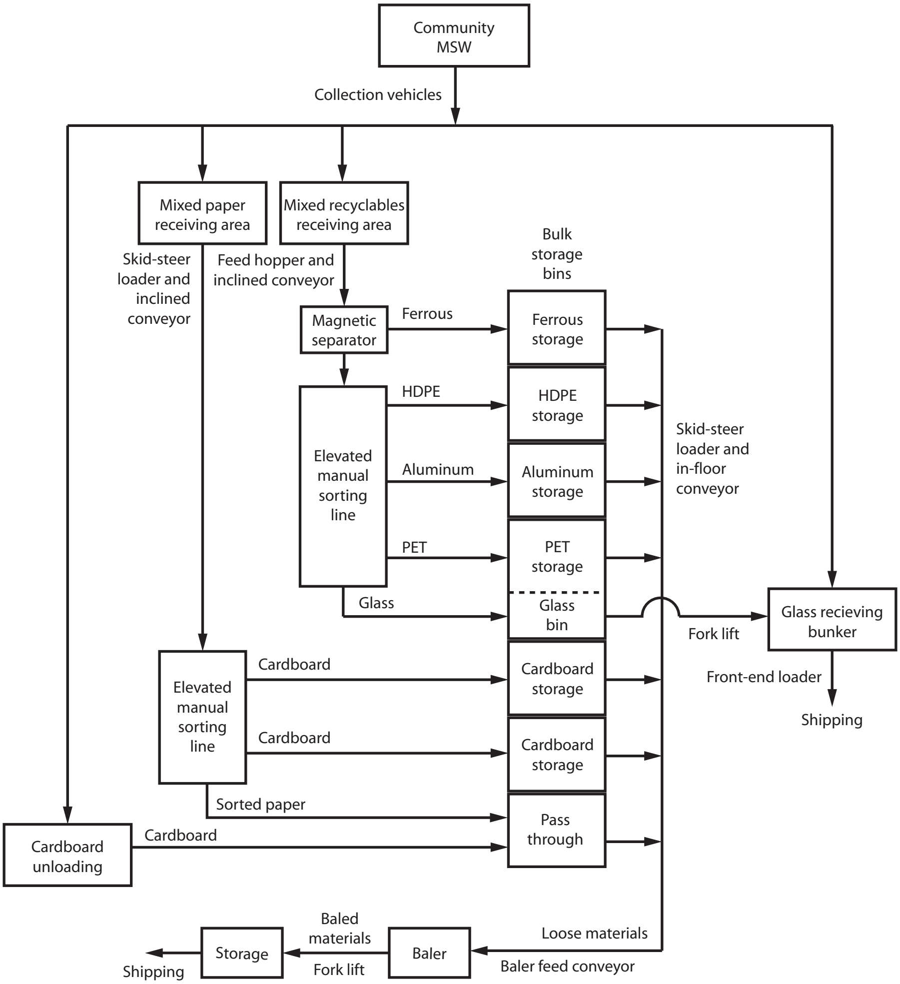

Figure 5-17 Process flow diagram for MRF used to further process source-separated waste (Leverenz et al., 2002).

feasibility analysis has already been accomplished as part of the integrated waste management planning process. These topics are considered further in Table 5-15 (Leverenz et al., 2002).

COMPOSTING

Composting is the controlled decay of organic matter in a warm, moist environment by the action of bacteria, fungi, and other organisms. The organic matter may be in municipal solid waste, sewage sludge, septage, agricultural

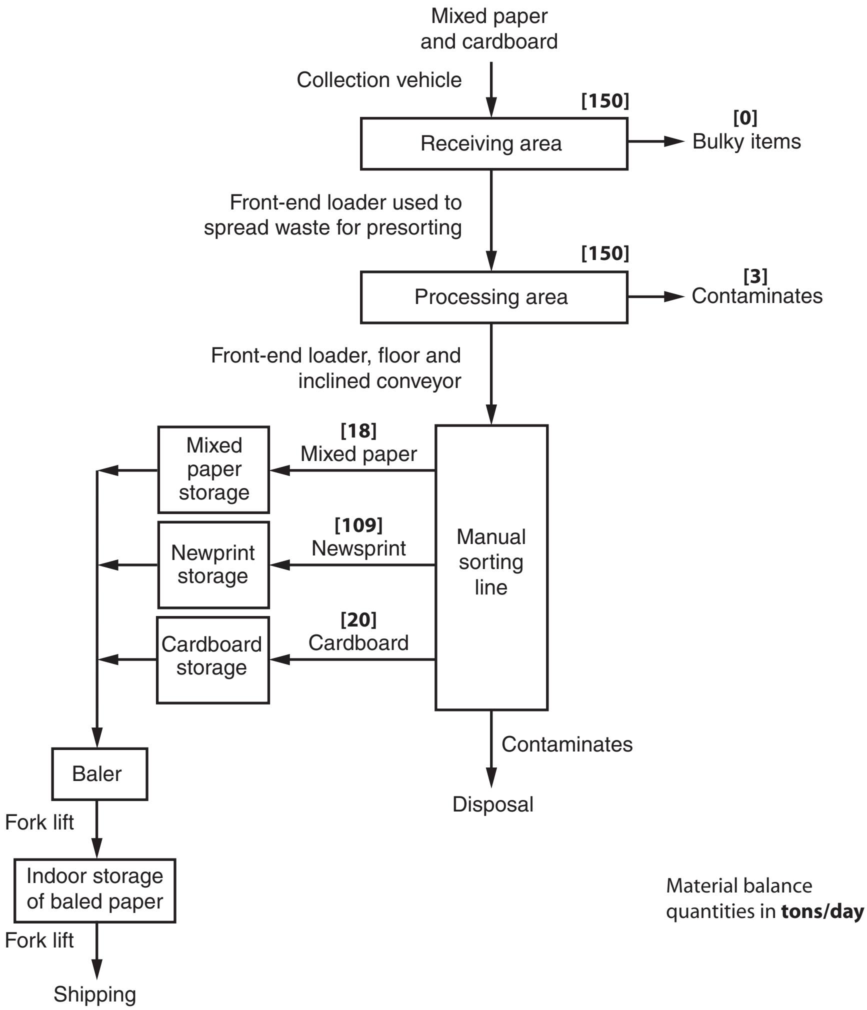

Figure 5-18 Process flow diagram for MRF used to separate mixed paper and cardboard (Leverenz et al., 2002).

waste, manure, leaves and other yard waste, or combinations of these materials and other organic wastes. Composting is becoming an increasingly popular waste management option as communities look for ways to divert portions of the local waste stream from landfills. The principal applications of composting are for (1) yard wastes, (2) the organic fraction of MSW, (3) partially processed commingled MSW, and (4) co-composting the organic fraction of MSW with wastewater sludge. Because of the importance of composting in meeting mandated waste diversion goals, the number of composting facilities has increased significantly over the past 10 years. The uses of com-

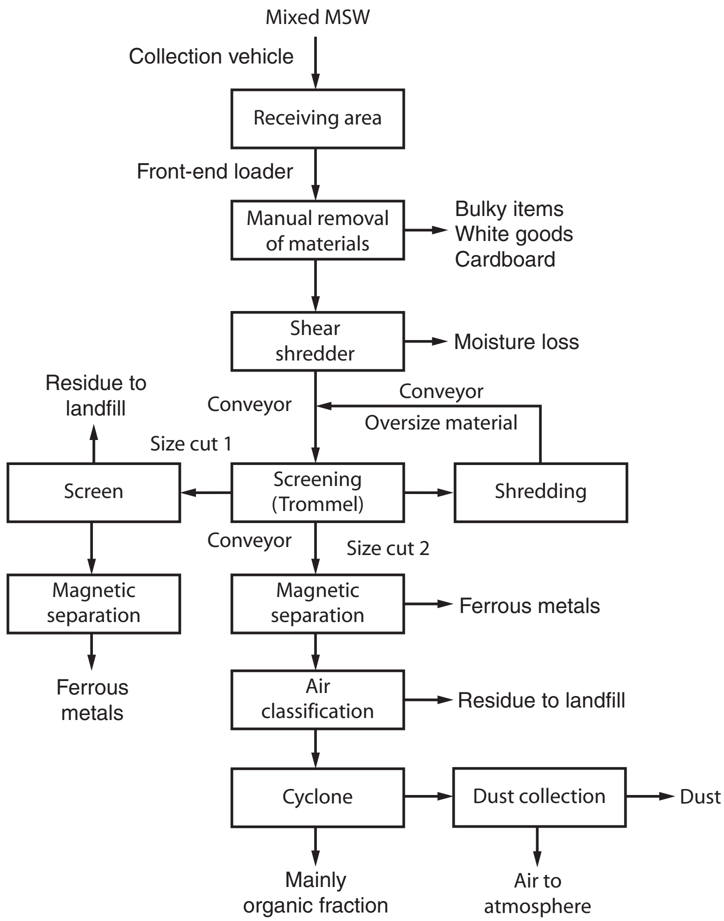

Figure 5-19 Process flow diagram for MRF used to process commingled waste for recovery of recyclable materials (Leverenz et al., 2002).

post and constraints to its use; a description of the compost process; descriptions of some of the more common composting processes, important design and operational considerations, and the implementation of the compost process are considered in the following discussion. Additional details on the compost process may be found in Benedict et al. (1988), Diaz et al. (2002), Haug (1993), and Tchobanoglous et al. (1993).

Uses of Compost and Constraints to Its Use

Compost improves soil moisture retention; it is a good soil conditioner but a poor fertilizer. Compost, depending on the waste source and its composition, may be used as a soil amendment for agricultural soil and landscaping in

TABLE 5-15 Important Technical Considerations in the Planning and Design of MRFs

	Step 1: Feasibility Analysis
Function of MRF	The coordination of the MRF with the integrated waste management plan for the community. A clear explanation of the role and function of the MRF in achieving landfill waste diversion and recycling goals is a key element.
Conceptual design, including types of wastes to be sorted	What type of MRF should be built, which materials will be processed now and in the future, and what should be the design capacity of the MRF. Plan views and renderings of what the final MRF might look like are often prepared.
Siting	While it has been possible to build and operate MRFs in close proximity to both residential and industrial developments, 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 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.
Economic analysis	Preliminary capital and operating costs are delineated. Estimates of revenues available to finance the MRF (sales of recyclables, avoided tipping fees, subsidies) are evaluated. A sensitivity analysis must be performed to assess the effects of fluctuating prices for recyclables and the impacts of changes in the composition of the waste.
Ownership and operation	Typical ownership and operation options include public ownership, private ownership, or public ownership with contract operation.
Procurement	What approach is to be used in the design and construction of the MRF? Several options exist, including (1) the traditional architect-engineer and contractor process, (2) the turn key 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, builds, and operates the MRF
	Step 2: Preliminary Design
Process flow diagrams	One or more process flow diagrams are developed to define how recyclable materials are to be recovered from MSW (e.g., source separation or separation from commingled MSW). Important factors that must be considered in the development of process flow diagrams include (1) characteristics of the waste materials to be processed, (2) specifications for recovered materials now and in the future, and (3) the available types of equipment and facilities.

TABLE 5-15 (*Continued*)

Materials recovery rates	Prediction of the materials flow to the MRF is necessary to estimate the effectiveness or performance of the recycling program. The performance of a recycling program, the overall component recovery rate, is generally reported as a materials recovery rate or recycling rate, which is the product of three factors: (1) participation factor, (2) composition factor, and (3) source recovery factor. Component capture rates for the recyclable materials most commonly collected in source separation recycling programs must be estimated. Composition factors are measured in waste composition studies. Typical component recovery rates may be found in Leverenz et al. (2002).
Materials balances and loading rates	One of the most critical elements in the design and selection of equipment for MRFs is the preparation of a materials balance analysis to determine the quantities of materials that can be recovered and the appropriate loading rates for the unit operations and processes used in the MRF.
Selection of processing equipment	Factors that should be considered in evaluating processing equipment include: capabilities, reliability, service requirements, efficiency, safety of operation, health hazard, environment impact, and economics.
Facility layout and design	The overall MRF layout includes (1) sizing of the unloading areas for commingled MSW and source-separated materials; (2) sizing of presorting areas where oversize or undesirable materials are removed; (3) placement of conveyor lines, screens, magnets, shredders, and other unit operations; (4) sizing of storage and out-loading areas for recovered materials; and (5) sizing and design of parking areas and traffic flow patterns in and out of the MRF. Many of these layout steps are also common to the layout and design of transfer stations.
Staffing	Depends on type of MRF (i.e., degree of mechanization).
Economic analysis	Refine preliminary cost estimate prepared in feasibility study.
Environmental issues	Important environmental issues include groundwater contamination, dust emissions, noise, vector impacts, odor emissions, vehicular emissions, other environmental emissions.
Health and safety issues	Important health and safety issues are related to worker and public access issues.
	Step 3: Final Design
Preparation of final plans and specifications	Plans and specifications will be used for bid estimates and construction.
Preparation of environmental documents	The necessary environmental documents (e.g., Environmental Impact Report) are prepared.

TABLE 5-15 (*Continued*)

Preparation of detailed cost estimate	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.
Preparation of procurement documents	A bidding process is used to obtain supplies, equipment, and services related to the construction, operation, and maintenance of the facility.

Source: Leverenz et al. (2002).

municipal parks, golf courses, gardens, and green belts; sod growing; home gardens; and nursery and greenhouse use. Compost may also be used as landfill cover, land reclamation, animal litter, and possibly animal feed. It may also be used as an additive to fertilizer, as a fuel, or in building materials.

The presence of toxic levels of pesticides, heavy metals, and pathogens should be determined and evaluated to ensure the levels are compatible with the intended use of the compost. A typical listing of permissible metal concentrations in compost is presented in Table 5-16. For pathogen reduction purposes, the temperature of the mixture must be maintained at or above 131°F (55°C) for at least three consecutive days.

The total composting time, including curing, is determined by the material, process used, and exposure to the elements. Two weeks to as much as 18

TABLE 5-16 Maximum Allowable Metal Concentrations for Class I and II Compost and Allowable Usage

	Concentration (ppm dry weight)	
Parameter	Class I[a]	Class II[b]
Mercury	10	10
Cadmium	10	25
Nickel	200	200
Lead	250	1000
Chromium, total	1000	1000
Copper	1000	1000
Zinc	1000	2500
Polychlorinated biphenyls (PCBs) total	1	10

Source: New York State (1988).

[a]Must not be used on crops grown for direct human consumption, i.e., crops consumed without processing to minimize pathogens. Can be used on food chain crops and other agricultural and horticultural uses. Must not exceed 10 mm (0.39 in.) particle size.

[b]Must be restricted to use on nonfood chain crops. Must not exceed 25 mm (0.98 in.) particle size.

months may be required for complete stabilization and curing of the compost. Thus, a plant location distant from habitation is recommended as odors may become a problem. Also, because the demand for compost may be seasonal, provision must be made for compost storage.

Composting Process

Composting involves the biological decomposition of organic materials (substrates) under controlled conditions that allow for the development of an end product that is biologically stable and free of viable pathogens and plant seeds and can be applied to land beneficially. The key concepts and objectives contained in the definition of compost are as follows:

- Composting is a biological process (e.g., aerobic anaerobic).
- Composting results in the production of a biologically stable end product.
- The end products free of viable pathogens.
- The end product is free of viable plant seeds.
- The end product can be applied to land beneficially.

To meet the above objectives, the composting process, as illustrated in Figure 5-20, usually involves the following three basic steps

- Preprocessing (e.g., size reduction, seeding, nutrient addition, and addition of bulking agent),

Figure 5-20 Overview of windrow composting operation.

- Decomposition and stabilization of organic material (two-stage process comprised of a first-stage high-rate phase followed by second-stage curing phase), and
- Postprocessing (e.g., grinding, screening, bagging, and marketing of compost product).

Composting of mixed solid waste should be preceded by a separation and recycling program, including glass, plastic, and metal separation; then usually shredding or grinding; and a program for the periodic collection of household hazardous waste. Industrial and other hazardous waste must be excluded.

The two-stage decomposition and stabilization of organic solid waste to a compost process can be described by the following reaction:

$$\left.\begin{array}{r}\text{Proteins}\\ \text{Amino acids}\\ \text{Lipids}\\ \text{Carbohydrates}\\ \text{Cellulose}\\ \text{Lignin}\\ \text{Ash}\end{array}\right\} \begin{array}{l} + O_2 + \text{nutrients} + \text{bacteria} \rightarrow \\ \text{compost} + \text{new cells} + CO_2 \\ + H_2O + NO_3^- + SO_4^{2-} + \text{heat}\end{array} \qquad (5\text{-}1)$$

(principal components comprising the organic fraction of MSW) (principally cellulose, lignin, and ash)

As shown by the above reaction, essentially all of the organic matter with the exception of celluose and lignin are converted during the compost process. It should be noted that in time both the cellulose and lignin will undergo further biological decompostion, primarily thorugh the action of fungi and actinomycetes.

Postprocessing will typically include screening and nutient and other amendment additions, depending on the application. Many municipalities make the compost available to the residents for a nominal price.

Composting Technologies

The three composting methods used most commonly in the United States are (1) windrow, (2) aerated static pile, and (3) in-vessel methods. It should be noted that over the past 100 years more than 50 individual compost processes have been developed. The more important of these processes based on function and/or the type of reactor used for the process are summarized in Table 5-17. Some of the processes are described below.

Although many process variations are in use, odor control is a major concern in all processes. Aeration and controlled enclosed processing facilities can be used to minimize the problem. Provision must also be made for vector control, leachate collection, and the prevention of groundwater and surface-

TABLE 5-17 Municipal Composting Systems Grouped by Function or Reactor Configuration

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
	Vuilafvoer Maatschappij (VAM)
Cells with natural or forced aeration, batch operation	Beccari
	Biotank (Degremont)
	Boggiano-Pico
	Kirkconnel (Dumfriesshire)
	Metro-Waste
	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 bed	Fairfield-Hardy

Source: Tchobanoglous et al. (2002).

water pollution. The stabilized and cured compost may be ground but is usually screened before sale. Storage space is required.

Windrow Composting In the windrow process, the sludge–amendment mixture to be composted is placed in long piles (see Figure 5-20). The windrows are 3 to 6 ft high (1–2 m) and 6 to 15 ft wide (2–5 m) at the base. The windrow process is conducted normally in uncovered pads and relies on natural ventilation with frequent mechanical mixing of the piles to maintain aerobic conditions. The windrow process can be accelerated if the compost is turned over every four or five days, until the temperature drops from about 150 or 140°F (66 or 60°C) to about 100°F (38°C) or less. Under typical operating conditions, the windrows are turned every other day. The turning is accomplished with specialized equipment (see Figure 5-21) and serves to aerate the pile and allow moisture to escape. To meet the EPA pathogen reduction requirements, the windrows have to be turned five times in 15 days, maintaining a temperature of 55°C. The complete compost process may require two to six months.

Because anaerobic conditions can develop within the windrow between turnings, putrescible compounds can be formed that can cause offensive odors, especially when the windrows are turned. In many locations, negative aeration is provided to limit the formation of odorous compounds. Where air is provided mechanically, the process is known as aerated windrow composting (Benedict et al., 1998). Odors will result if the compost is not kept aerobic. It may be necessary to enclose the operation and provide fans and collectors of the odorous air, forcing it through a scrubber or other treatment device for discharge up a stack to the atmosphere.

Aerated Static Pile Composting In the aerated static pile process, the material to be composted is placed in a pile and oxygen is provided by mechanical aeration systems. Most states require paved surfaces for the pile

Figure 5-21 View of machine used to aerate compost placed in windrows.

construction areas to permit capture and control runoff and allow operation during wet weather. The most common aeration system involves the use of a grid of subsurface piping (see Figure 5-22). Aeration piping often consists of flexible plastic drainage tubing assembled on the composting pad. Because the drainage-type aeration piping is inexpensive, it is often used only once. Before constructing the static pile, a layer of wood chips is placed over the aeration pipes or grid to provide uniform air distribution. The static pile is then built up to 8 to 12 ft (2.6–3.9 m) using a front-end loader. A cover layer of screened or unscreened compost is placed over the sludge to be composted. Typically, oxygen is provided by pulling air through the pile with an exhaust fan. Air that has passed through the compost pile is vented to the atmosphere though a compost filter for odor control.

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. 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 op-

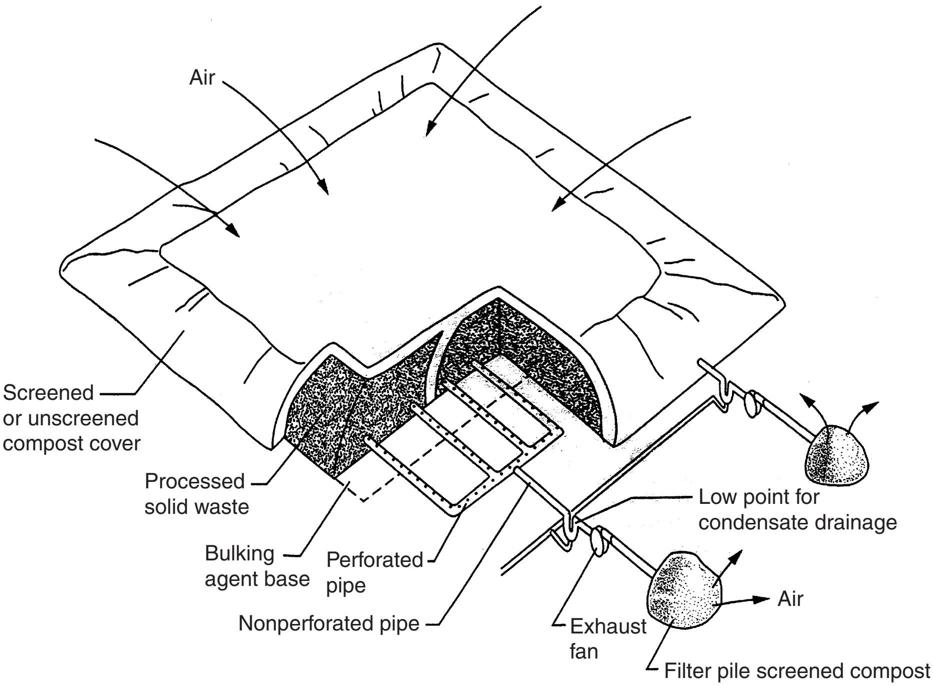

Figure 5-22 Schematic of static aerated compost pile.

erates on the basis of a first-in, first-out principle. In a dynamic system, the composting material is mixed mechanically during the processing.

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 cited 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.

Other Composting Technologies *Naturizer* composting uses sorting, grinding and mixing, primary and secondary composting including three grinding operations, aeration, and screening. Digested sewage sludge, raw-sewage sludge, water, or segregated wet garbage is added at the first grinding for dust and moisture control. The total operation takes place in one building in about six days.

The *Dano* composting (stabilizer) plant consists of sorting, crushing, biostabilization 3 to 5 days in a revolving drum to which air and moisture are added, grinding, air separation of nonorganics, and final composting in open windrows. Temperatures of 140°F (60°C) are reached in the drum. Composting can be completed in 14 days by turning the windrows after the fourth, eighth, and twelfth days. Longer periods are required if the windrows are not kept small, turned, and mixed frequently and if grinding is not thorough. In a more recent version, the drum treatment is for 8 hr followed by screening, final composting in covered aerated piles for about three weeks, and then three weeks of aging in static piles.

The *Fairfield–Hardy* process handles garbage and trash and sewage sludge. The steps in the process are (1) sorting—manual and mechanical to separate salvageable materials; (2) coarse shredding; (3) pulping; (4) sewage sludge addition, if desired; (5) dewatering to about 50 percent moisture; (6) three- to five-day digestion with mixing and forced air aeration, temperature ranges from 140 to 170°F (60–76°C); (7) air curing in covered windrows; and (8) pelletizing, drying, and bagging. Compost from the digester is reported to have heat values of 4000 Btu/lb and, when pelletized and dried, 6450 Btu/lb.

The *Bangalore* process is used primarily in India. Layers of unshredded solid waste and night soil are placed in a shallow trench; the top is covered with soil. The duration of the treatment is 120 to 150 days.

Compost Process Design and Operational Considerations

The principal design considerations associated with the aerobic biological decomposition of prepared solid wastes are presented in Table 5-18. It can be concluded from this table that the preparation of a composting process is

TABLE 5-18 Important Design Considerations for Aerobic Composting Process

Item	Comment
Particle size	For optimum results, the size of solid wastes should be between 25 and 75 mm (1 and 3 in).
Carbon to nitrogen (C/N) ratio	Initial C/N ratios (by mass) between 25 and 50 are optimum for aerobic composting. At lower ratios ammonia is given off. Biological activity is also impeded at lower ratios. At higher ratios, nitrogen may be a limiting nutrient.
Blending and seeding	Composting time can be reduced by seeding with partially decomposed solid wastes to the extent of about 1–5% by weight. Sewage sludge can also be added to prepared solid wastes. Where sludge is added, the final moisture content is the controlling variable.
Moisture content	Moisture content should be in the range between 50 and 60% during the composting process. The optimum value appears to be about 55%.
Mixing/turning	To prevent drying, caking, and air channeling, material in the process of being composted should be mixed or turned on a regular schedule or as required. Frequency of mixing or turning will depend on the type of composting operation.
Temperature	For best results, temperature should be maintained between 122 and 131°F (50 and 55°C) for the first few days and between 131 and 140°F (55 and 60°C) for the remainder of the active composting period. If temperature goes beyond 151°F (66°C), biological activity is reduced significantly.
Control of pathogen	If properly conducted, it is possible to kill all the pathogens, weeds, and seeds during the composting process. To do this, the temperature must be maintained between 140 and 158°F (60 and 70°C) for 24 hr.
Air requirements	The theoretical quantity of oxygen required can be estimated using the stiochiometrc equation for the conversion of organic matter. Air with at least 50% of the initial oxygen concentration remaining should reach all parts of the composting material for optimum results, especially in mechanical systems.
pH control	To achieve an optimum aerobic decomposition, pH should remain at 7–7.5 range. To minimize the loss of nitrogen in the form of ammonia gas, pH should not rise above about 8.5.
Degree of decomposition	The degree of decomposition can be estimated by measuring the reduction in the organic matter present using the chemical oxygen demand (COD) test. Another measurement that has been used to determine the degree of decomposition is the use of respiratory quotient (RQ)
Land requirement	The land requirements for a plant with a capacity of 50 tons/day will be 1.5–2.0 acres. The land area required for larger plant will be less.

Source: Tchobanoglous et al. (2002).

Note: $1.8 \times {}^\circ C + 32 = {}^\circ F$.

not a simple task, especially if optimum results are to be achieved. For this reason, most of the commercial composting operations that have been developed are highly mechanized and are carried out in specially designed facilities. Because of their importance, pathogen and odor control are considerd further below. Additional details on the design and operation of compost processes may be found in Haug (1980) and Diaz et al. (2002):

Pathogen Control Pathogenic organisms and weed seeds exposed to the higher temperatures for the times indicated in Table 5-19 will be destroyed. However, because of the nature of solid waste, the processes used, and the range in temperature within compost clumps or zones and between the outside and inside of a mass of compost, the required lethal temperatures cannot be ensured. The EPA requires 131°F (55°C) for three days to obtain pathogen destruction before compost land spreading, but this temperature does not kill all pathogens. The World Health Organization (WHO) recommends that the compost attain a temperature of at least 140°F (60°C). It has been found that

TABLE 5-19 Temperature and Time of Exposure Required for Destruction of Some Common Pathogens and Parasites

Organism	Observations
Salmonella typhosa	No growth beyond 46°C; death within 30 min. at 55–60°C and within 20 min. at 60°C; destroyed in a short time in compost environment.
Salmonella sp.	Death within 1 hr at 55°C and within 15–20 min. at 60°C.
Shigella sp.	Death within 1 hr at 55°C.
Escherichia coli	Most die within 1 hr at 55°C and within 15–20 min. at 60°C.
Entamoeba histolytica cysts	Death within a few min. at 45°C and within a few sec at 55°C.
Taenia saginata	Death within a few min. at 55°C.
Trichinella spiralis larvae	Quickly killed at 55°C; instantly killed at 60°C.
Brucella abortus or *Br. suis*	Death within 3 min. at 62–63°C and within 1 hr at 55°C.
Micrococcus pyogenes var. *aureus*	Death within 10 min. at 50°C.
Streptococcus pyogenes	Death within 10 min. at 54°C.
Mycobacterium tuberculosis var. *hominis*	Death within 15–20 minutes at 66°C or after momentary heating at 67°C.
Corynebacterium diphteria	Death within 45 min. at 55°C.
Necator americanus	Death within 50 min. at 45 C.
Ascaris lumbricoides eggs	Death in less than 1 hr at temperatures over 50°C.

Source: Tchobanoglous et al. (1993).

Note: 1.8 × (°C) + 32 = °F.

salmonella repopulation is possible in a soil amendment from composted sludge. Microbial activity is greatest when mean municipal compost temperature is 114 to 140°F (40–60°C), using aeration to control the temperature to achieve the highest composting rates. Temperatures above 140°F (60°C) tend to slow down the process as many organisms die off at and above this temperature.

Control of Odor The majority of the odor problems in aerobic composting processes are associated with the development of anaerobic conditions within the compost pile. In many large-scale aerobic composting systems, it is common to find pieces of magazines or books, plastics (especially plastic films), or similar materials in the organic material being composted. These materials normally cannot be decomposed in a relatively short time in a compost pile. Furthermore, because sufficient oxygen is often not available in the center of such materials, anaerobic conditions can develop. Under anaerobic conditions, organic acids will be produced, many of which are extremely odorous. To minimize the potential odor problems, it is important to reduce the particle size, remove plastics and other nonbiodegradable materials from the organic material to be composted, or use source-separated and uncontaminated feedstocks.

Issues in the Implementation of Composting Facilities

The principal issues associated with the use of the compost process are related to (1) the production of odors, (2) the presence of pathogens, (3) the presence of heavy metals, and (4) definition of what constitutes an acceptable compost. The blowing of papers and plastic materials is also a problem in windrow composting. Unless the questions related to these issues are resolved, composting may not be a viable technology in the future.

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 any required additives, such as nutrients, seed (if used), and moisture with the waste material to be composted completely and effectively. 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 of 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, the compost in the center of the composting pile can become pyrolyzed. When 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 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 produce pathogen-free compost reliably. 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 15–20 days). Temperatures required for the control of various pathogens were given previously in Table 5-19.

Health Hazard

Exposure of workers to dust at a sewage sludge and other composting site might cause nasal, ear, and skin infections, burning eyes, skin irritation, and other symptoms, pointing to the need for worker protection safeguards.

Other concerns are possible leachate contamination of groundwater and surface water, toxic chemicals remaining in the finished compost, insect and rodent breeding, noise, and survival of pathogens, including molds and other parasite spores and eggs. Pathogens may be spread by leachate, air, insects, rodents, and poor housekeeping and personal hygiene. Tests for pathogens, and the toxic level of chemicals and metals listed in Table 5-16 should be made periodically. Precautions are indicated in view of the potential hazards. Workers should be advised of the infectious and hazardous materials likely to be present in the solid waste handled and the personal hygiene precautions to be taken and be provided with proper equipment, protective gear, and housing. Their health should be monitored. All solid waste should be inspected before acceptance to ensure that it does not contain hazardous wastes. A dressing room, including lockers, toilet, lavatory, and shower facilities, is needed. Equipment cabs should have air conditioning, including dust filters.

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. While 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, presence of foreign matter, concentration of salts, residual odor, degree of stabilization or maturity, presence of pathogenic organisms, and concentration of heavy metals. Unfortunately, at this time, there is no agreement on the appropriate values for these parameters. The lack of agreement on appropriate values for these parameters has been and continues to be a major impediment to the development of a uniform compost product from location to location. For compost materials to have wide acceptance, public health issues must be resolved in a satisfactory manner.

Cost The cost of composting should reflect the total cost of the operation less the savings effected. The cost of the operation would include the cost of the site, site preparation, compost concrete or asphalt platform, worker housing and facilities, utilities, equipment (grinder, bucket loader, and composting drum and aeration facilities if part of the process), power, separation and recycling preparation, and disposal of noncompostable materials as well as leachate collection, treatment and disposal, odor control, final screening, bagging, and maintenance. Savings would include reduced landfill disposal cost, income from sale of salvaged material, and sale of stabilized compost. Under favorable conditions, the total net cost of composting might be less compared to other methods. The size of the operation, labor costs, process used, sustained market for recovered materials, need for an enclosure, and other factors will determine the net cost.

A comprehensive market analysis should be made in the planning stage. The cost of an indoor system is much higher than an outdoor system. The operation of an outdoor system is significantly affected by the ambient temperature and precipitation. The indoor system makes possible better temperature, leachate, odor, and operation control as well as better public relations. Composting is not a profit-making operation.

SANITARY LANDFILL PLANNING, DESIGN, AND OPERATION

A sanitary landfill is a controlled method of solid waste disposal. The site must be geologically, hydrologically, and environmentally suitable. *It is not an open dump*. The nuisance conditions associated with an open dump, such as smoke, odor, unsightliness, and insect and rodent and seagull and other bird problems, are not present in a properly designed, operated, and maintained sanitary landfill. Professional planning and engineering supervision is required. A well-designed and operated landfill must prevent groundwater pollution, provide for gas (methane) venting or recovery, have a leachate collection and treatment system, provide gas and leachate monitoring wells, and be located above the 100-year flood level. A typical cross section through a modern landfill is shown in Figure 5-23. The EPA and states have detailed regulations governing landfill siting, design, construction, operation, gas and water monitoring, landscape plan, closure monitoring, and maintenance for 30 years. The purpose of this section is to identify and discuss important issues in the implementation of landfills, including planning, design and operation, and landfill closure.

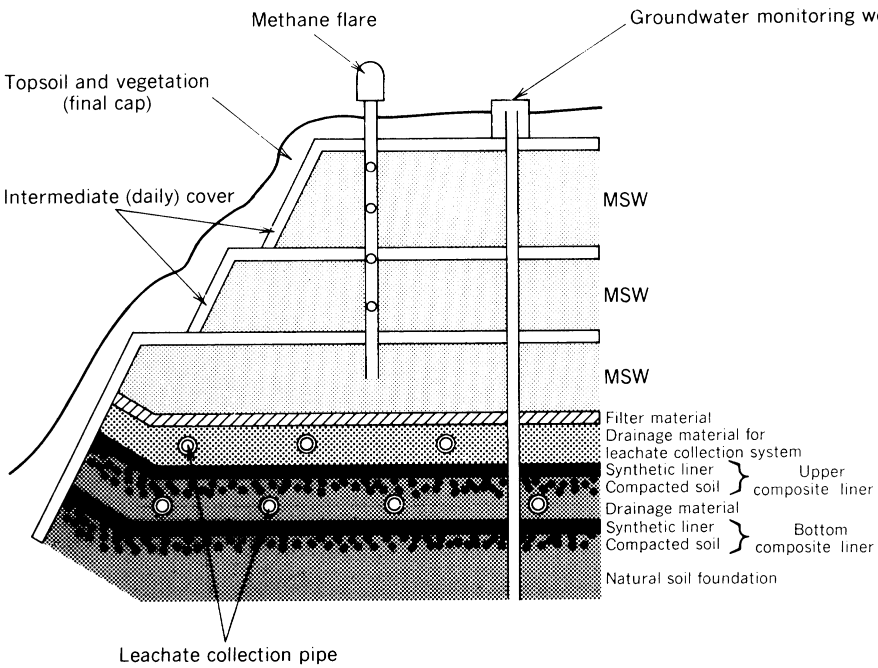

Figure 5-23 Schematic diagram of configuration of selected engineering features at MSW landfills.

Sanitary Landfill Planning

Key elements in the planning and implementation of a landfill include (1) legal requirements, (2) intermunicipal cooperation, (3) social and political factors, and (4) long-term planning issues. Landfill design considerations are considered in the section following the description of the types of landfills.

Legal Requirements State environmental protection agency regulations and local sanitary codes or laws usually build on federal regulatory requirements. A new solid waste disposal location may not be established until the site, design, and method of proposed operation, including waste reduction, resource recovery, and recycling, have been approved by the agency having jurisdiction. The agency should be authorized to approve a new solid waste disposal area and require such plans, reports, specifications, and other necessary data to determine whether the site is suitable and the proposed method of operation feasible. Intermunicipal planning and operation on a multimunicipal, multicounty, or multiregional basis should be given very serious consideration before a new solid waste disposal site is acquired. Larger landfills usually are more efficient and result in lower unit costs.

The principal federal requirements for municipal solid waste landfills are contained in Subtitle D of the Resource Conservation and Recovery Act (RCRA) and in EPA Regulations on Criteria for Classification of Solid Waste Disposal Facilities and Practices (*Code of Federal Regulations,* Title 40, Parts 257 and 258). The final version of Part 258—Criteria for Municipal Solid Waste Landfills (MSWLFs)—was signed on September 11, 1991. The subparts of Part 258 deal with the following areas:

Subpart A	General
Subpart B	Location restrictions
Subpart C	Operating criteria
Subpart D	Design criteria
Subpart E	Groundwater monitoring and corrective action
Subpart F	Closure and postclosure care
Subpart G	Financial assurance

In addition, many state environmental protection agencies have parallel regulatory programs that deal specifically with their unique geologic and soil conditions and environmental and public policy issues.

Intermunicipal Cooperation—Advantages County or regional areawide planning and administration for solid waste collection, treatment, and disposal can help overcome some of the seemingly insurmountable obstacles to satisfactory solution of the problem. Some of the advantages of county or regional areawide solid waste management are the following:

1. It makes possible comprehensive study of the total area generating the solid wastes and consideration of an areawide solution of common problems on short-term and long-term bases. A comprehensive study can also help overcome the mutual distrust that often hampers joint operations among adjoining municipalities.
2. There is usually no more objection to one large site operation than to a single town, village, or city operation. Coordinated effort can therefore be directed at overcoming the objections to one site and operation, rather than to each of several town, village, and city sites.
3. The unit cost for the disposal of a large volume of solid waste is less. Duplication of engineering, overhead, equipment, labor, and supervision is eliminated.
4. Better operation is possible in an areawide service, as adequate funds for proper supervision, equipment, and maintenance can be more easily provided.
5. More sites can be considered. Some municipalities would have to resort to a more costly method because suitable landfill sites may not be available within the municipality.

6. County or regional financing for solid waste disposal often costs less, as a lower interest rate can usually be obtained on bonds because of the broader tax base.
7. A county agency or a joint municipal survey committee, followed by a county or regional planning agency, and then an operating department, district, or private contractor, is a good overall approach because it makes possible careful study of the problem and helps overcome interjurisdictional resistance.

Social and Political Factors An important aspect of solid waste disposal site selection, in addition to the factors mentioned below, is the evaluation of public reaction and education of the public so that understanding and acceptance are developed. A long-term program of public information is needed. Equally important are the climate for political cooperation, cost comparison of alternative solutions, available revenue, aesthetic expectations of the people, organized community support, and similar factors. Films and slides that explain proper sanitary landfill operations are available from state and federal agencies and equipment manufacturers. Sites having good operations can be visited to obtain first-hand information and show the beneficial uses to which a completed site can be put.

Long-Term Planning and Design Issues Local officials can make their task easier by planning ahead together on a county or regional basis for 20 to 40 years in the future and by acquiring adequate sites at least 5 years prior to anticipated needs and use. The availability of federal and state funds for planning, collection, recycling, treatment, and disposal of solid waste on an areawide basis such as a county or region should be explored. The planning will require compliance with public health, environmental, planning, and zoning requirements, both state and local; and an engineering analysis of alternative sites. Also required are population projections, volume and characteristics of all types of solid wastes to be handled, cost of land and site preparation, expected life of the site, haul distances from the sources of solid waste to the site, cost of equipment, cost of operation, cost of closure and maintenance, and possible use and value of the finished site.

Consideration must also be given to the climate of the region, including precipitation and prevailing winds; geology, soils, hydrology, flood levels, and topography; and the need for liners, leachate collection and treatment [National Pollutant Discharge Elimination System (NPDES) permit], and methane gas control. Location and drainage to prevent surface-water and groundwater pollution, groundwater monitoring (at least one well up gradient and three wells down gradient), access roads to major highways, location of airports and wetlands, and availability of suitable cover material are other considerations. *Public information and involvement should be an integral and continuing part of the planning process leading to a decision.* The reader is referred to Chapter 2 for a discussion of the broad aspects of community and facility planning and environmental impact analysis.

Once a decision is made, it should be made common knowledge and plans developed to show how it is proposed to reclaim, improve, and reuse the site upon completion. Public education should include a series of talks, slides, news releases, question-and-answer presentations, and inspection of good operations. To aid in the planning process, some general guidelines for landfill design, construction, and operation are presented in Table 5-20. Artist's renderings and architectural models are very helpful in explaining construction methods and final land use. Landscape architects can make a contribution in converting the sanitary landfill to a community asset, such as parks, playgrounds with picnic areas, nature trails, bicycle and jogging paths, and hills with scenic observation sites. Unfilled land sites or islands could be set aside for permanent buildings.

Sanitary Landfill Methods

There are many methods of operating a sanitary landfill. The most common are the trench, area, ramp, and valley fill methods, as illustrated in Figure 5-24. These landfill methods are described below. With the regulatory requirements for constructed liner and leachate collection and removal systems now imposed by the EPA as set forth in RCRA, a defined operational area and well-designed operational plan are essential and must be closely followed to ensure an efficient and environmentally sound operation.

Trench Method The trench method (see Figure 5-24*a*) is used primarily on level ground, although it is also suitable for moderately sloping ground. In this method, trenches are constructed by making a shallow excavation and using the excavated material to form a ramp above the original ground. Solid waste is then methodically placed within the excavated area, compacted, and covered at the end of each day with previously excavated material. Because of the need to install landfill control measures (e.g., liners), a number of trenches are typically excavated at one time. Trenches are made 20 to 25 ft wide and at least twice as wide as any compacting equipment used. The depth of fill is determined by the established finished grade and depth to groundwater or rock. If trenches can be made deeper, more efficient use is made of the available land area.

Area or Ramp Method On fairly flat and rolling terrain, area method (see Figure 5-24*b*) can be utilized by using the existing natural slope of the land. The width and length of the fill slope are dependent on the nature of the terrain, the volume of solid waste delivered daily to the site, and the approximate number of trucks that will be unloading at the site at one time. Side slopes are 20 to 30 percent; width of fill strips and surface grades are controlled during operation by means of line poles and grade stakes. The working

TABLE 5-20 Some General Sanitary Landfill Design, Construction, and Operation Guidelines

Benchmark—Survey benchmark measured from U.S. Geological Survey benchmark established on-site and landfill cells referenced to it; a benchmark for each 25 acres of landfill.

Bottom liners—As specified by the regulatory agency and as indicated by the hydrogeological survey. See Figure 5-27.

Distance from any surface water—Based on soil attenuation, drainage, natural and man-made barriers, but not less than 100 ft, preferably 200 ft or more.

Equipment—Adequate numbers, type, and sizes; properly maintained and available.

Equipment shelter—Available for routine maintenance and repair.

Flood plains—No solid waste management facility permitted unless provisions made to prevent hazard.

Gas control—Prevent hazard to health, safety, and property; provide vents, barriers, collection, monitoring. Gas monitoring is required, also for volatile organic chemical and toxic emissions. See Figures 5-32 to 5-35.

Leachate—Not to drain or discharge into surface waters, except pursuant to State Pollutant Discharge Elimination System, and shall not contravene groundwater quality standards. Leachate collection system maintained.

Limits of fill—No closer than 100 ft from boundary lines of property. Restrictions primarily on proximity to water supply aquifers, wellhead areas, wetlands, floodplains, and surface waters.

Monitoring wells—Four or more at new or modified facility; at least three located down gradient for a small site. Regulatory agency may require wells at existing facility. Off-site wells may be used. Wells must reflect groundwater flow and quality under the landfill site.

- Water monitoring may be required. Safe Drinking Water Act MCLs are used to determine pollution and evaluate pollution travel.
- Baseline water quality and annual seasonal data are required at a new site and some existing sites.

Plans and construction—Engineering plans and specifications as required and approved by regulatory agency. Construction under supervision of project engineer who certifies construction is in accordance with approved plans and specifications.

Site—A hydrogeological survey of the site and surrounding land, soil borings, permeability, and groundwater levels. Check with Federal Aviation Administration.

Termination—Prevent contravention of surface water, groundwater, and air quality standards and gas migration, odors, vectors, and adverse environmental or health effects. At least 2 ft final cover, including an impervious barrier and gas-venting layer, along with an upper grass cover crop; 4% slope to minimize infiltration, prevent ponding and a surface water drainage system.

Vertical separation—five-foot separation between bottom liner and high groundwater. If natural soil is equivalent to 10 ft of soil with coefficients of permeability less than 5×10^{-6} cm/sec, separation may be reduced if a double-liner system is provided; 10-ft vertical separation required to bedrock.

Access—Permitted when attendant on duty; controlled by fencing, signs, or other means.

TABLE 5-20 (*Continued*)

Compaction and cover—Solid waste spread in 2-ft or less layers and promptly compacted. Working face minimal.
- Ten feet of maximum lift height.
- At least 6 in. daily cover at end of each day, or more often.
- At least 12 in. intermediate cover if solid waste not deposited within 30 days.
- Surface water drainage control during operation.
- Final cover when additional lift is not applied within 1 year; when final elevation is reached and within 90 days; when a landfill is terminated. Capped as required by regulatory agency. See Figure 5-37.

Hazardous wastes—No industrial or commercial solid waste or septage, or other materials producing hazardous waste, without specific permit authorization. No bulk liquids or 55-gal drums filled with liquids.

Litter and papers—Confined by fencing or suitable means. Vehicles confining papers and litter to be admitted.

Maintenance—Cover material and drainage control designed and maintained to prevent ponding and erosion, and to minimize infiltration, based on a 25-year storm and from a 24-hour, 25-year storm. Prepare a landscape plan.
- Grass or ground cover established within 4 months and maintained.
- Soil cover integrity, slopes, cover vegetation, drainage, groundwater and gas monitoring, and structures maintained for a period of 30 years or longer.
- Leachate collection and removal system, inspection manholes, and lift stations maintained operational as long as necessary.
- Liner leakage monitored and reported to regulatory agency.
- Establish a trust fund, surety bond, insurance, etc., to ensure long-term maintenance.

Noise—Shall not cause excessive sound levels beyond property lines in residential areas. Level 7 a.m.–10 p.m.: rural 60 dBA, suburban 65 dBA, urban 70 dBA. Level 10 p.m.–7 a.m., rural 50 dBA, suburban 55 dBA, urban 60 dBA.

On-site roads—Maintained passable and safe.

Open burning—Prohibited except under permit.

Personnel shelter—Adequately heated and lighted; includes safe drinking water, sanitary toilet and shower facilities, telephone or radio communications.

Reports—As required in permit.

Safety—Safety hazards minimized.

Salvaging—Controlled, if permitted.

Small loads—Separate facility (convenience station) at the site for use of local residents and small trucks.

Solid waste disposal—Confined to an area effectively maintained, operated, and controlled. No industrial, commercial solid waste, no sludge or septage unless specifically approved. Inspection for hazardous waste required.

Supervision—Operation supervised by a certified operator, including dumping sequence, compaction, cover, surface drainage.

Vectors, dust, and odors—Controlled to prevent nuisance or hazard to health, safety, or property.

Weigh station—For weight measurement, fees, and waste inspection.

Source: Salvato (1992).

Note: See also applicable federal and state regulations.

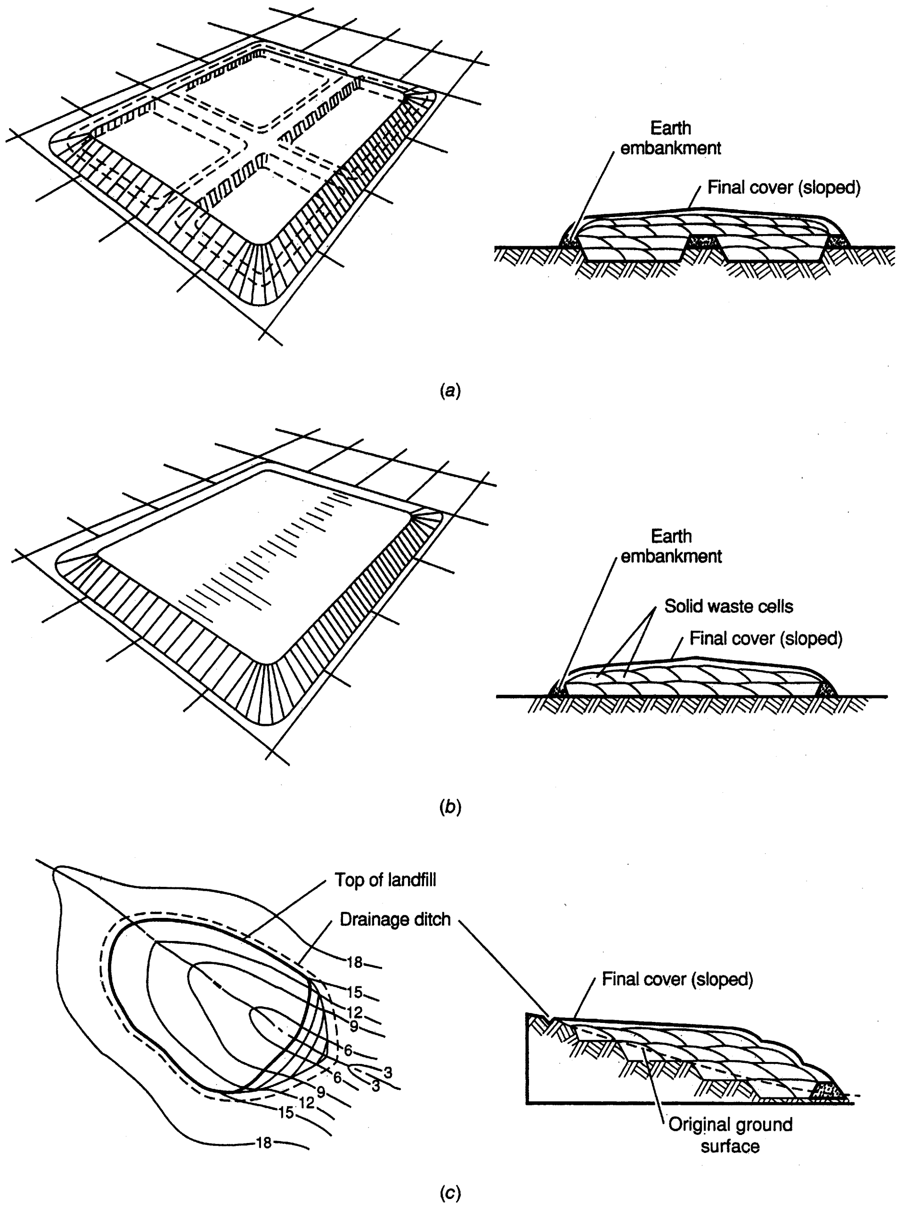

Figure 5-24 Schematic view of different types of landfills: (*a*) trench, (*b*) area; (*c*) canyon or ravine (Tchobanoglous et al., 1993).

face should be kept as small as practical to take advantage of truck compaction, restrict dumping to a limited area, and avoid scattering of debris. In the area method, cover material is hauled in from a nearby stockpile or other source. The base of the landfill is established by the previously determined elevation of bedrock, groundwater, and bottom liners and leachate collection and removal systems.

Valley or Ravine Area Method In valleys and ravines, the ravine method (see Figure 5-24*c*) is usually the best method of operation. The development of a large ravine landfill site is illustrated in Figure 5-25. In those areas where the ravine is deep, the solid waste should be placed in ''lifts'' from the bottom up with a depth of 8 to 10 ft. Cover material is obtained from the sides of the ravine. It is not always desirable to extend the first lift the entire length of the ravine. It may be desirable to construct the first layer for a relatively short distance from the head of the ravine across its width. The length of this initial lift should be determined so that a one-year settlement can take place before the next lift is placed, although this is not essential if operation can be controlled carefully. Succeeding lifts are constructed by trucking solid waste over the first lift to the head of the ravine. When the final grade has

Figure 5-25 Development of large ravine landfill site. Equipment is compacting subbase of landfill in preparation for placement of geomembrane liner.

been reached (with allowance for settlement), the lower lift can be extended and the process repeated. The bottom landfill liner and leachate collection and removal system must be designed carefully to ensure that slope stability of the liner system and the waste placed is adequately maintained.

General Landfill Design Issues

The general planning process described above is followed by specific site selection and preparation. Site preparation requires that an engineering survey be made and a map drawn at a scale of not less than 200 ft to the inch with contours at 2-ft intervals, showing the boundaries of the property; location of lakes, streams, springs, marine waters, and structures within 1000 ft; adjoining ownership; and topography. Also required are soil borings, including *in situ* hydraulic conductivity determinations, designs for liners and leachate collection systems, groundwater levels, up-gradient and down-gradient monitoring wells, water quality samples, prevailing winds, and drainage plans.

Location The site location directly affects the total solid waste collection and disposal cost. If the site is remotely situated, the cost of hauling to the site may become high and the total cost excessive. It has been established that the normal, economical hauling distance to a solid waste disposal site is 10 to 15 miles, although this will vary depending on the volume of solid waste, site availability, and other factors. Actually, a suitable site and the hauling time and route are more important than the hauling distance. The disposal site may be as far as 40 to 80 miles away if a transfer station is used. Rail haul and barging introduce other possibilities. The cost of transferring the solid waste per ton is used to compare solid waste collection and disposal costs and make an economic analysis. Open excavations left by surface mining operations may be considered for solid waste disposal as a means of reclaiming land and restoring it to productive use.

Accessibility Another important consideration in site selection is accessibility. A disposal area should be located near major highways to facilitate use of existing arterial roads and lessen the hauling time to the site. Highway wheel load and bridge capacity and underpass and bridge clearances must also be investigated. It is not good practice to locate a landfill in an area where collection vehicles must constantly travel through residential streets to reach the site. The disposal area itself should normally be located at least 500 ft from habitation, although lesser distances have been successfully used to fill in low areas and improve land adjacent to residential areas for parks, playgrounds, or other desirable uses. Where possible, a temporary attractive screen should be erected to conceal the operation. To allow vehicular traffic to utilize the site throughout the year, it is necessary to provide good access roads to the site so that trucks can move freely in and out of the site during all weather conditions and seasons of the year. Poorly constructed and maintained roads to a site can create conditions that cause traffic tie-ups and time loss for the collection vehicles.

Land Area (Volume) Required The volume needed for solid waste disposal is a function of population served, per-capita solid waste contribution, resource recovery and recycling, density and depth of the solid waste in place, number of lifts, total amount of earth cover used, and time in use, adjusted for nonhazardous commercial and industrial wastes. Because of the high start-up costs associated with a modern landfill, the capacity of a proposed landfill should be sufficient for a 20- to 40-year period (see Figure 5-25). Further, because the population in an area will not usually remain constant, it is essential that population projections and development be taken into account. These factors plus the probable nonhazardous solid waste contributions by commercial establishments, industry, and agriculture must be considered in planning for needed land. A density of compacted fill of 800 to 1000 lb/yd^3 is readily achieved with proper operation; 600 lb/yd^3 or less is poor; 1200 lb/yd^3 or more is very good.

Leachate Generation, Control, and Treatment

The best solution to the potential leachate problem is to prevent its development. Landfill leachate generation cannot in practice be entirely avoided, particularly during operation, except possibly in some arid climates. However, a tight soil cap and/or liner on completion can greatly minimize the possibility; however, a leachate-free landfill may not be *entirely* desirable, as discussed below. Leachate control measures for groundwater and surface-water quality protection must be incorporated in the site design and monitoring started before operation (see Figure 5-26). A water balance for the landfill disposal facility should be established to serve as a basis for the design of leachate control and surface runoff systems, taking into consideration heavy rainfall, landfill, cap construction, in addition to runoff, infiltration, and evapotranspiration.

Leachate from existing community sanitary landfills and from industrial waste storage and disposal sites can be expected to contain organic and inorganic chemicals characteristic of the contributing community and industrial wastes. Household hazardous wastes may include small amounts of cleaning solvents, paints and paint thinners, oils, pesticides, and drugs if not restricted or their sale prohibited. The EPA and others have reported that hazardous wastes probably represent less than 0.5 percent of the total waste generated by households. A knowledge of the industry and its production will provide a starting point in the selection of parameters to be analyzed in characterizing the leachate from an existing site.

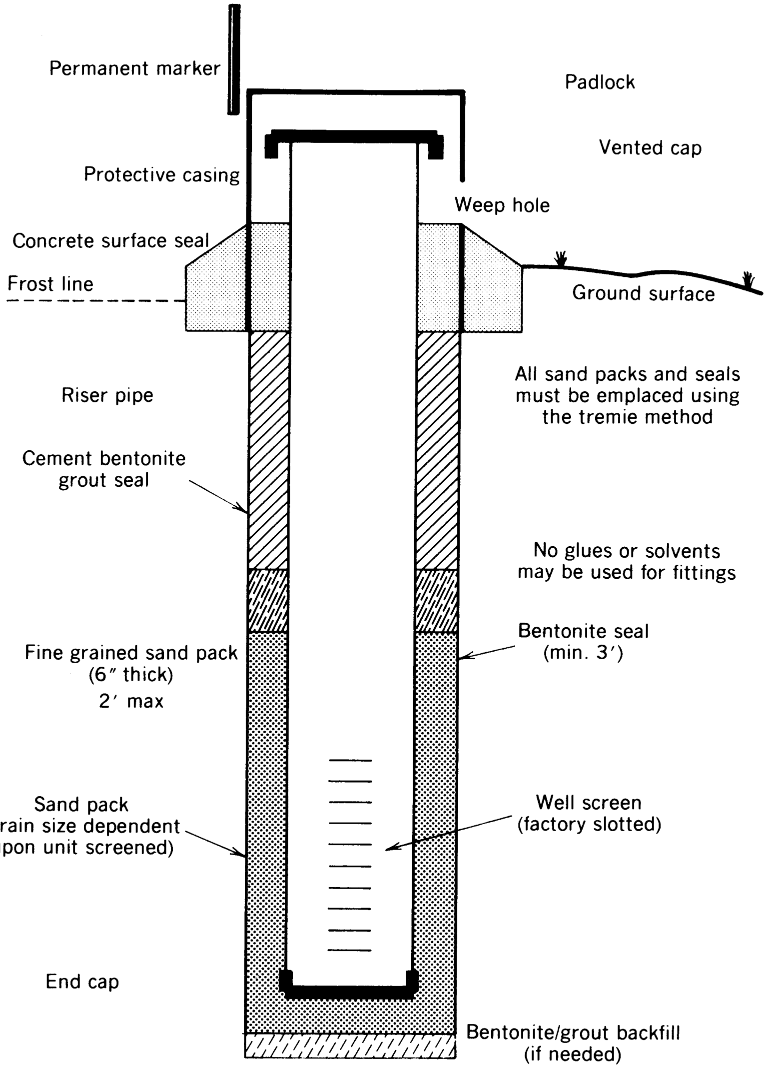

Figure 5-26 Typical monitoring well diagram (New York State, 1990a).

Leachate Generation The precipitation less runoff, transpiration, and evaporation will determine the amount of infiltration. Infiltration and percolation will, in the long term, after field capacity has been reached, determine the amount of leachate, if any, produced, assuming groundwater and lateral flow are excluded. A major factor is a cover material that is carefully graded, which ideally permits only limited infiltration and percolation to support vegetative cover and solid waste decomposition, with optimal runoff but without erosion to prevent significant leachate production. The soil cover should have a low permeability with low swell and shrink tendency upon wetting and drying. Runoff depends on rainfall intensity and duration, permeability of the cover soil, surface slope (4 percent, not greater than 30 percent for side slopes), condition of the soil and its moisture content, and the amount and type of vegetative cover. Evapotranspiration during the growing season for grasses and grains may be 20 to 50 in.

Leachate Control It should be noted that if all infiltration is excluded and the solid waste kept dry, biodegradation by bacteria, fungi, and other organisms will cease and the solid waste will be preserved in its original state. Bacterial activity will generally cease when the moisture content drops below 14 to 16 percent. The maintenance of an optimal amount of moisture in the fill, as in controlled composting (an aerobic process), is necessary for biodegradation (an anaerobic process in a landfill), methane production, final stabilization, and possible future recycling of the solid waste or reuse of the site.

The objective in the design of landfill liners is to minimize or eliminate the infiltration of leachate into the subsurface soils below the landfill so as to eliminate the potential for the groundwater contamination. A number of liner designs have been developed to minimize the movement of leachate into the subsurface below the landfill. One of the many types of liner designs that have been proposed is illustrated in Figure 5-27. In the multilayer landfill liner design illustrated in Figure 5-27, each of the various layers has a specific function. For example, in Figure 5-27, two composite liners are used as a barrier to the movement of leachate and landfill gas. The drainage layer is to collect any leachate that may be generated within the landfill. The final soil layer is used to protect the drainage and barrier layers. The placement of a geomembrane liner in an area-type landfill is illustrated in Figure 5-28. A modification of the liner design shown in Figure 5-27 is shown in Figure 5-29. The liner system shown in Figure 5-29 is for a monofill (e.g., a landfill for a single waste component such as glass). Composite liner designs employing a geomembrane and clay layer provide more protection and are hydraulically more effective than either type of liner alone.

If leachate migration is or may become a problem at an old or existing landfill, and depending on the local situation and an engineering evaluation, several options may be considered. These include a cap on the surface consisting of clay or a liner regraded with topsoil seeded to grass to effectively shed precipitation, cutoff walls or dams keyed into an impermeable stratum to isolate the fill, pressure treatment and sealing of the bottom and sides of the fill, surface-water drains up-gradient and around the landfill area, curtain drains or wells to intercept and drain away the contributing groundwater flow, collection and recirculation of leachate with treatment of any excess, or, in special cases and if warranted, the material in the landfill can be excavated, treated, recycled, and/or disposed of at a controlled site. The excavation of

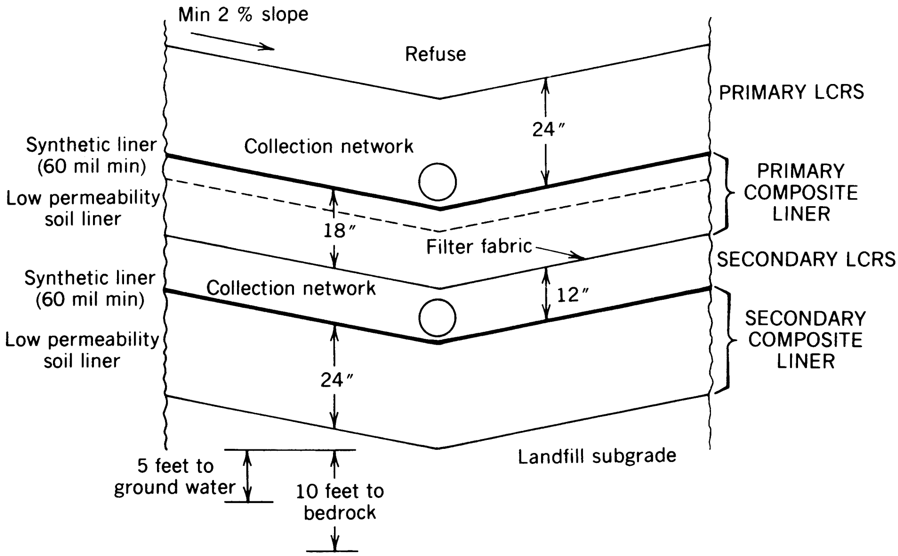

Figure 5-27 Double-bottom composite liner system (New York State, 1990a).

an existing landfill may, however, introduce other problems if hazardous wastes are involved and hence must be carefully evaluated in advance.

Leachate Recirculation Waste biodegradation and stabilization of the biodegradable organic matter in a landfill can be accelerated by leachate recirculation. Controlled leachate recirculation, including nutrient addition to maintain optimum moisture and pH, can enhance anaerobic microbial activity, break down organics as shown by reduced total organic carbon (TOC) and chemical oxygen demand (COD, convert solid waste organics to methane and carbon dioxide, and precipitate heavy metals. Complete biological stabilization can be achieved in four to five years. Heating of recirculated leachate to 86°F (30°C) has been found to accelerate the stabilization process.

A landfill designed for leachate recirculation should, as a minimum, incorporate a conservatively designed liner system and an effectively maintained leachate collection, removal, and recirculation distribution system, in addition to a gas collection and venting system (see Figure 5-30). A double-liner system with leak detection monitoring wells would enable the landfill owner and regulatory agency to monitor the liner system performance. The leachate collection and removal system should be designed to be accessible for routine maintenance and cleaning in view of the potential for biological film clogging. Recirculation would increase the strength of the recirculated leachate and

Figure 5-28 Placement of geomembrane liner in area-type landfill.

accelerate fill stabilization. Establishment of early gradual recirculation and an active anaerobic biomass is important as each cell is closed. A final site closure utilizing a relatively impermeable crowned cap and surface-water drainage system should be implemented for final site closure.

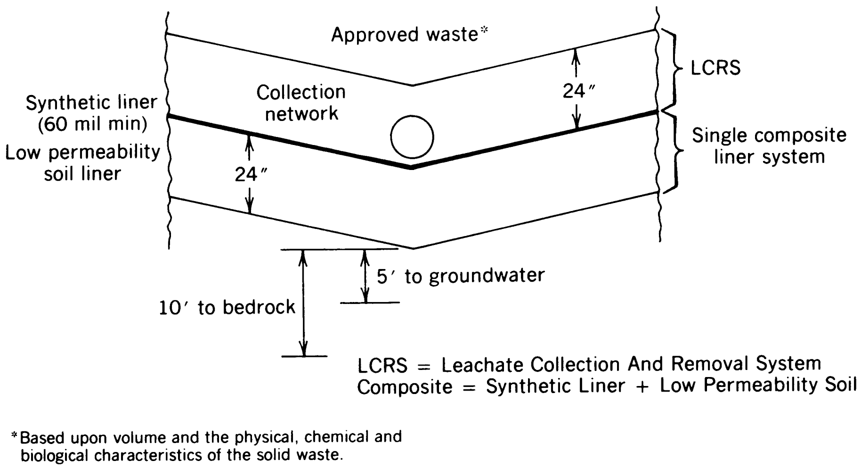

Figure 5-29 Industrial/commercial and ash monofill waste landfill liner configuration (New York State, 1990a).

Leachate Treatment Leachates containing a significant fraction of biologically refractory high-molecular-weight organic compounds (i.e., those in excess of 50,000) are best treated by physicochemical methods, such as lime addition followed by settling. Leachates containing primarily low-molecular-weight organic compounds are best treated by biological methods, such as activated sludge. Combinations of these methods may be required to achieve permit requirements and stream discharge standards. In the final analysis, the treatment required will depend on the composition of the fill material, leachate

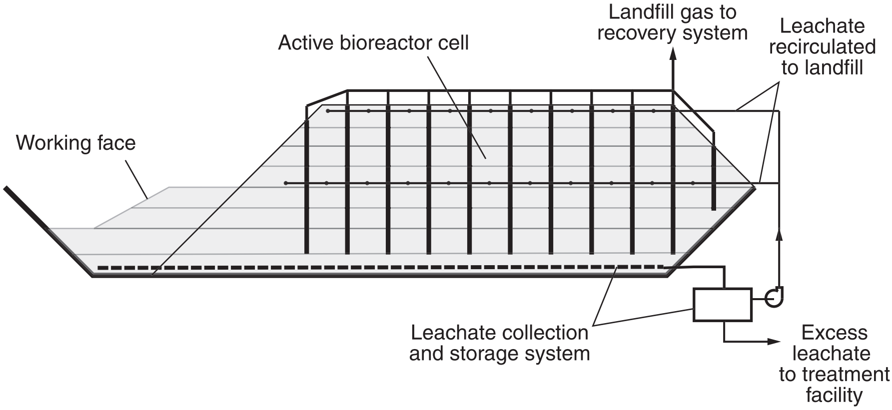

Figure 5-30 Schematic diagram for landfill with leachate recirculation (O'Leary and Tchobanoglous, 2002).

volume and characteristics, and the water pollution control standards to be met.

Landfill Gas Generation, Control, and Recovery and Utilization

Gases found in landfills include ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4), nitrogen (N_2), and oxygen (O_2). The typical percentage distribution of the gases found in the landfill is reported in Table 5-21. As shown in Table 5-21, methane and carbon dioxide are the principal gases produced from the anaerobic decomposition of the biodegradable organic waste components in MSW. In addition, a number of trace gases will also be found in landfill gas. The type and concentration of the trace gases will depend to a large extent on the past history of the landfill. Issues related to the generation, control of migration, and utilization of landfill gas are considered in the following discussion.

Generation of the Principal Landfill Gases The generation of principal landfill gases is thought to occur in five more or less sequential phases, as illustrated in Figure 5-31. Each of these phases is described briefly below; additional details may be found in Tchobanoglous et al. (1993).

Phase I. Initial Adjustment Phase I is the *initial adjustment phase,* in which the organic biodegradable components in municipal solid waste

TABLE 5-21 Typical Constituents in Landfill Gas

Component	Percent (dry volume basis)
Methane	45–60
Carbon dioxide	40–60
Nitrogen	2–5
Oxygen	0.1–1.0
Sulfides, disulfides, mercaptans, etc.	0–1.0
Ammonia	0.1–1.0
Hydrogen	0–0.2
Carbon monoxide	0–0.2
Trace constituents	0.01–0.6
Characteristic	**Value**
Temperature, °F	100–120
Specific gravity	1.02–1.06
Moisture content	Saturated
High heating value, Btu/sft^3 [a]	475–550

Source: Tchobanoglous et al. (1983).

[a] sft^3 = standard cubic foot.

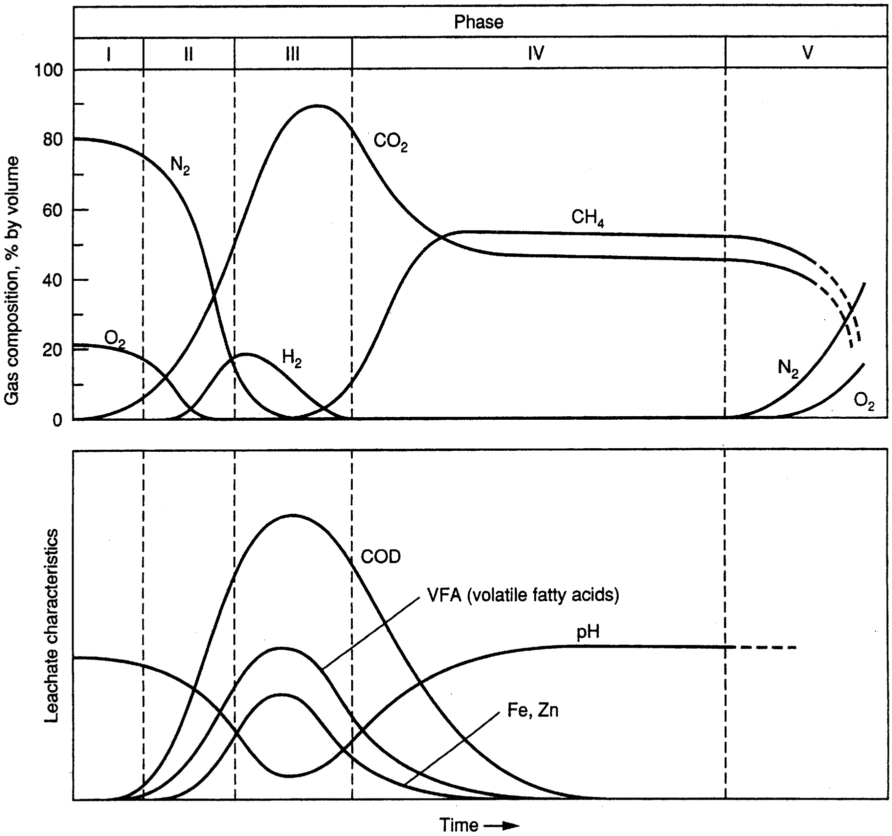

Figure 5-31 Generalized phases in generation of landfill gases (I—initial adjustment, II—transition phase; III—acid phase; IV—methane fermentation; V—maturation phase) (Tchobanoglous et al., 1993).

begin to undergo bacterial decomposition soon after they are placed in a landfill. In phase I, biological decomposition occurs under aerobic conditions because a certain amount of air is trapped within the landfill.

Phase II. Transition Phase In phase II, identified as the *transition phase*, oxygen is depleted and anaerobic conditions begin to develop.

Phase III. Acid Phase In phase III, the bacterial activity initiated in phase II is accelerated with the production of significant amounts of organic acids and lesser amounts of hydrogen gas. The first step in the three-step process involves the enzyme-mediated transformation (hydrolysis) of higher molecular mass compounds (e.g., lipids, organic polymers, and proteins) into compounds suitable for use by microorganisms as a source of energy and cell carbon. The second step in the process (acidogenesis) involves the bacterial conversion of the compounds resulting from the first step into lower molecular weight intermediate compounds, as typified by acetic acid (CH_3COOH) and small concentrations of fulvic and other more complex organic acids. Carbon dioxide (CO_2) is the principal gas generated during phase III.

Phase IV. Methane Fermentation Phase In phase IV, a second group of microorganisms that convert the acetic acid and hydrogen gas formed by the acid formers in the acid phase to methane (CH_4) and CO_2 becomes more predominant. Because the acids and the hydrogen gas produced by the acid formers have been converted to CH_4 and CO_2 in phase IV, the pH within the landfill will rise to more neutral values in the range of 6.8 to 8.

Phase V. Maturation Phase Phase V occurs after the readily available biodegradable organic material has been converted to CH_4 and CO_2 in phase IV. As moisture continues to migrate through the waste, portions of the biodegradable material that were previously unavailable will be converted.

Control of Landfill Gas Migration When methane is present in the air in concentrations between 5 and 15 percent, it is explosive. Because only limited amounts of oxygen are present in a landfill when methane concentrations reach this critical level, there is little danger that the landfill will explode. However, methane mixtures in the explosive range can be formed if landfill gas migrates off site and is mixed with air. The lateral migration of methane and other gases can be controlled by impermeable cutoff walls or barriers (see Figure 5-32) or by the provision of a ventilation system such as gravel-filled trenches around the perimeter of the landfill (see Figure 5-33). Gravel-packed perforated pipe wells or collectors may also be used to collect and diffuse the gas to the atmosphere, if not recovered. To be effective, the system must be carefully designed, constructed, and maintained.

Cutoff walls or barriers should extend from the ground surface down to a gas-impermeable layer such as clay, rock, or groundwater. Clay soils must be water saturated to be effective. Perforated pipes have been shown to be of limited effectiveness and are not recommended for the reduction of gas pressure when used alone. Gravel-filled trenches may permit migration of gases across the trench, especially when covered by snow or ice; vertical perforated pipes reduce somewhat the effect of snow or ice. Gravel-filled trenches require removal of leachate or water from the trench bottom and are susceptible to plugging by biomass buildup. Gravel-filled trenches in combination with an impermeable barrier provide good protection against gas migration when keyed to a gas-impermeable strata below the landfill. Induced exhaust wells or trenches with perforated pipes and pump or blower are reported to be very effective. Where enclosed structures are constructed over or in close proximity to a landfill, it is necessary to have these places continuously monitored. A combustible gas detection system to provide early warning (light and alarm) can alert personnel. The monitors comprising the detection system can also

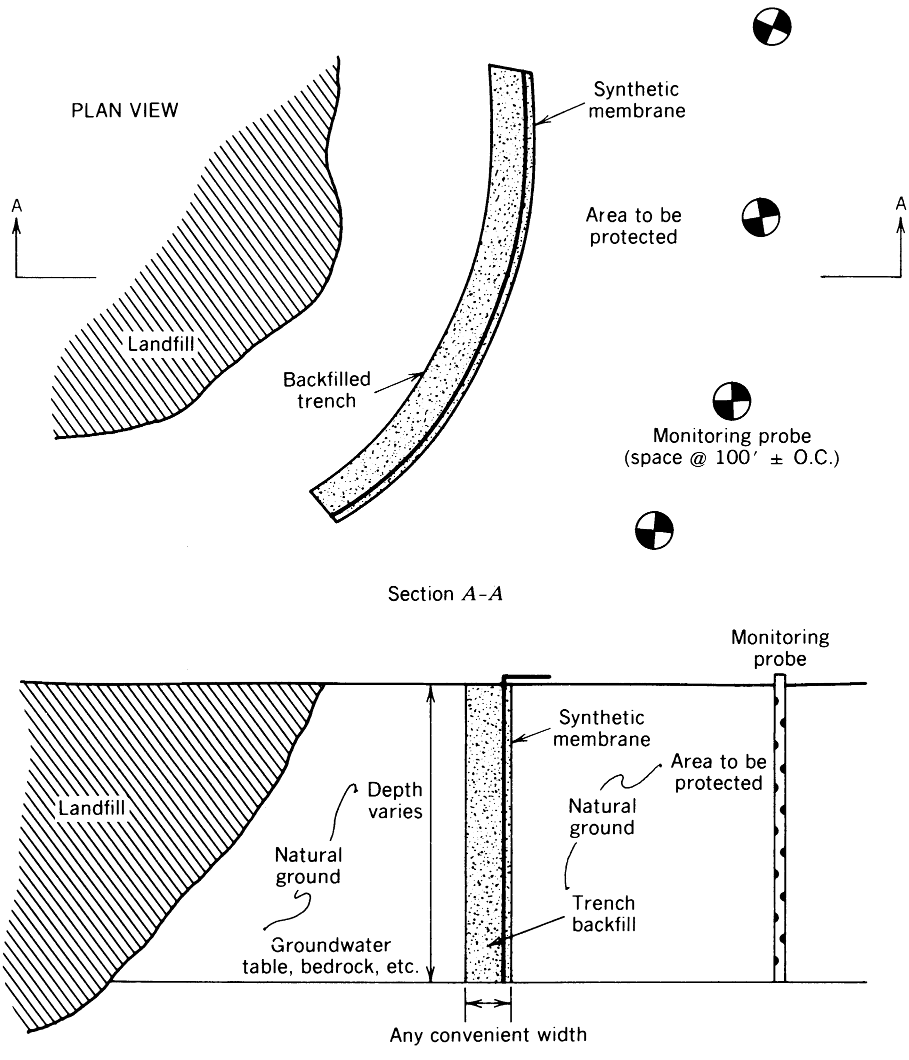

Figure 5-32 Typical passive gas control synthetic membrane.

activate ventilation fans at preset low methane levels. Soil and cement bentonite trenches or cutoff walls have also been used to prevent lateral gas migration.

Methane Recovery and Utilization Methane is produced in a landfill when anaerobic methane-producing bacteria are active. The condition shown in Figure 5-31 may be reached in six months to five years depending on the landfill. Acidic conditions inhibit growth of methane-producing bacteria; alkaline conditions have the opposite effect. Methane production is quite variable de-

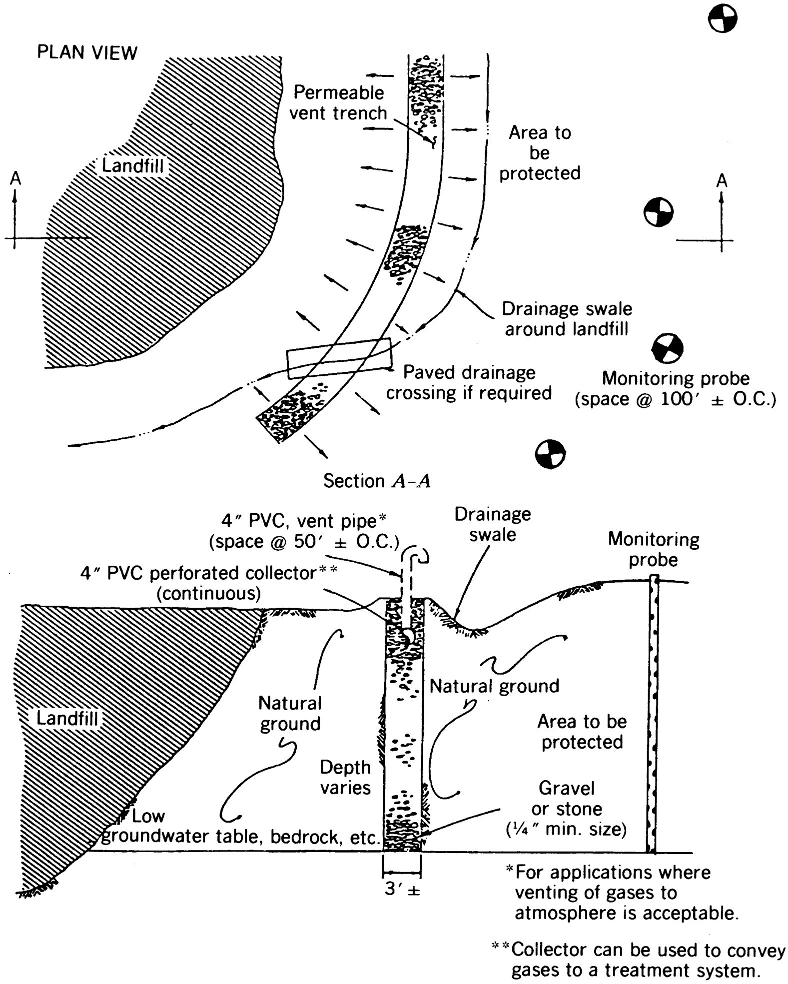

Figure 5-33 Passive gas control using permeable trench (SCS, 1980).

pending on the amount and type of decomposable material in the landfill, moisture content, temperature, and resulting rate of microbial decomposition under anaerobic conditions.

Methane is odorless, has a heat value of about 500 Btu/ft^3 compared to 1000 Btu for commercial gas, has a specific gravity less than air, and is nearly insoluble in water. The gases from landfills, after anaerobic conditions have been established, are quite variable, ranging from 50 to 60 percent methane and 40 to 50 percent carbon dioxide. Included are small amounts of nitrogen, oxygen, water, mercaptans (very odorous), and hydrocarbons. Hydrogen sulfide may also be released if large amounts of sulfates are in the landfill. Vinyl chloride, benzene, and other toxics in trace amounts may also be produced by the action of bacteria on chlorinated solvents deposited in the fill. The presence of oxygen and nitrogen with methane gas would indicate the entrance of air into the landfill due to methane being withdrawn too rapidly. If methane extraction is not controlled to reduce or eliminate the entrance of oxygen and nitrogen, the production of methane will slow down or stop.

In the early stages the landfill gases are primarily carbon dioxide with some methane. The carbon dioxide is heavier than air and can dissolve in water to form carbonic acid, which is corrosive to minerals with which it comes into contact. Mercaptans, carbon dioxide, and water are usually extracted to upgrade the methane to pipeline quality. Removal of carbon dioxide may improve Btu content to 900 or 1000 Btu/ft^3. Methane as it comes from a landfill is often very corrosive. Deep landfills, 30 ft or deeper, and 30 acres or more in area with a good cover are better methane producers. Actually, gas will be generated as long as biodegradable material remains and is primarily dependent on precipitation, infiltration, and moisture content. Gas can be extracted using plastic tube wells in each cell with perforations or well screens toward the bottom connected to a controlled vacuum pump (see Figure 5-34) or a series of covered horizontal gravel trenches connected to a pipe collection system (see Figure 5-35). The extracted gas may be used for heating and generating electricity.

Management of Surface Waters

The runoff from the drainage area tributary to the solid waste disposal site must be determined by hydraulic analysis to ensure that the surface-water drainage system, such as ditches, dikes, berms, or culverts, is properly designed and that flows are diverted to prevent flooding, erosion, infiltration, and surface-water and groundwater pollution, both during operation and on completion. The design basis should be the maximum 25-year 24-hr precipitation. The topography and soil cover should be examined carefully to ensure that there will be no obstruction of natural drainage channels. Obstructions could create flooding conditions and excessive infiltration during heavy rains and snow melt. Uncontrolled flooding conditions can also erode the cover material.

A *completed* landfill for residential solid waste that is properly capped should, ideally, not present any serious hazard of groundwater pollution, *provided surface water* (*and groundwater*) *and most of the precipitation are drained, transpired, and evaporated off the landfill and the landfill site*. Two different types of landfill covers are presented in Figures 5-36 and 5-37. The major source of water for leachate production would then be precipitation–infiltration during operation, before the final cap is put in place. Precipitation–infiltration can be minimized by the temporary use of impervious geomembrane sheets over the completed landfill. A small amount of infiltration is desirable to support biological decomposition of the solid waste, as noted above. It becomes essential, therefore, that the solid waste working face be

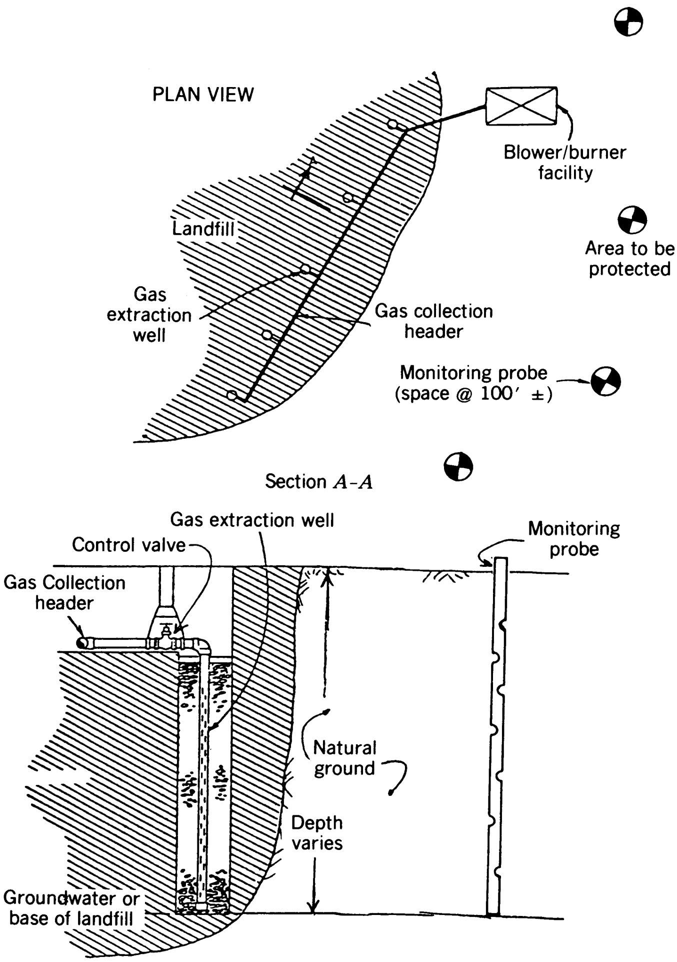

Figure 5-34 Typical gas extraction system (U.S. EPA, 1985).

kept at a minimum, that the final cover be placed and graded promptly, and that a surface-water drainage system be installed as soon as possible.

Cover Material The site should preferably provide adequate and suitable cover material. The most suitable soil for cover material is one that is easily worked and yet minimizes infiltration; however, this is not always available. It is good practice to stockpile topsoil for final cover and other soil for cold-weather operation and access road maintenance. Shredded (milled) solid waste in a landfill does not cause odors, rodent or insect breeding, or unsightliness, and it may not require daily earth cover. However, precipitation will

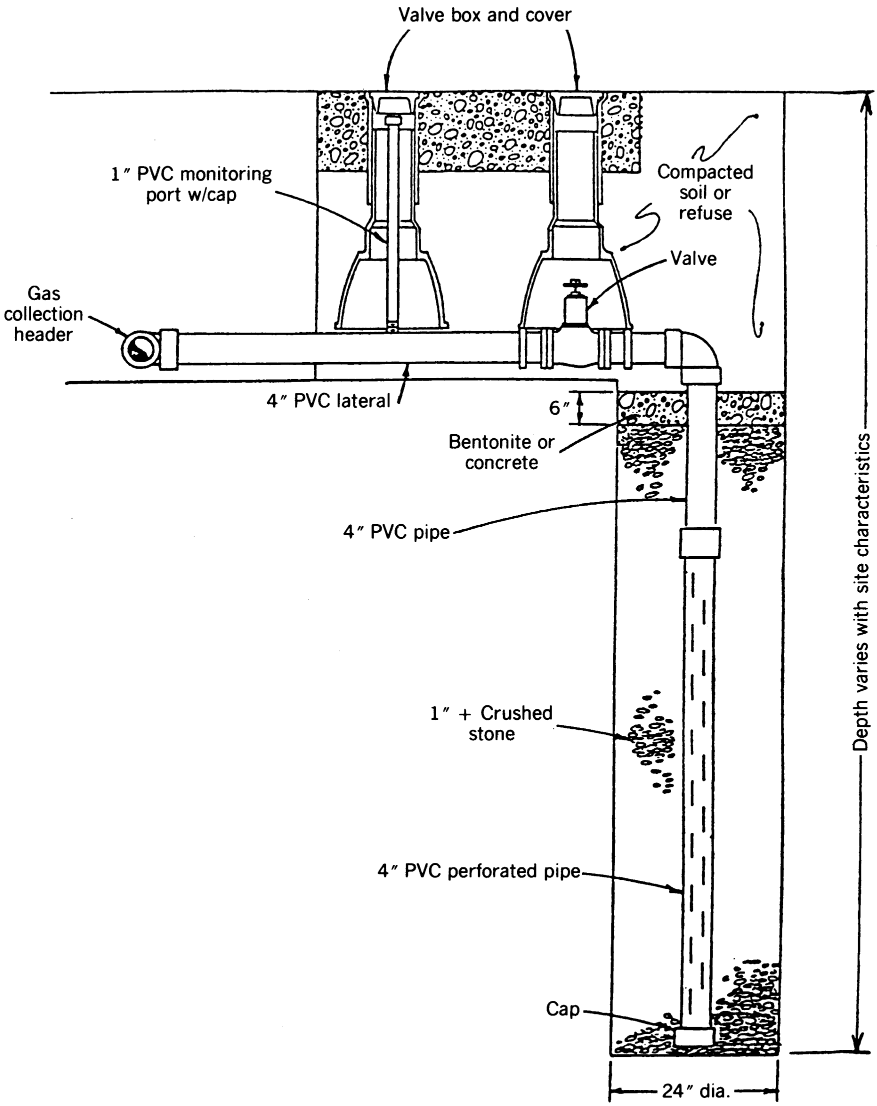

Figure 5-35 Typical gas extraction well (U.S. EPA, 1985).

be readily absorbed and leachate produced unless the waste is covered with a low-permeability soil that is well graded to shed water.

The control of leachate and methane and the role played by the final earth cover, including the importance of proper grading of the landfill final cover (4 percent slope) to minimize infiltration, promote runoff, and prevent erosion, have been previously discussed. A final cover to minimize infiltration of pre-

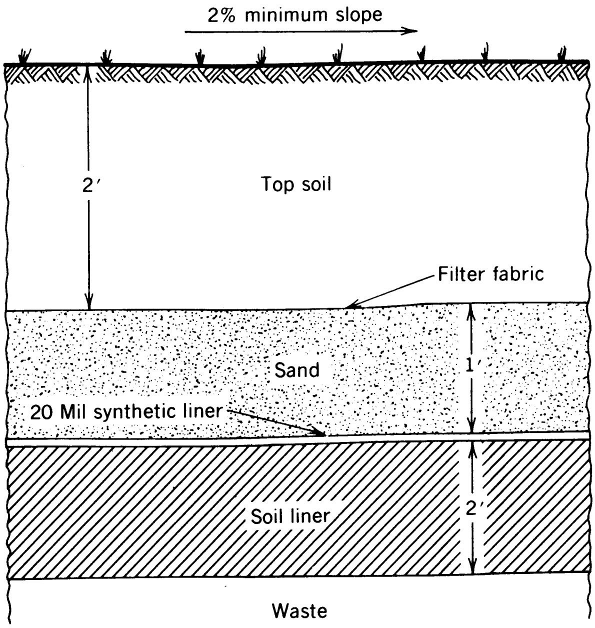

Figure 5-36 Typical multiplayer landfill cap. Minimum of 4 percent surface slope is usually preferred (U.S. EPA, 1985).

cipitation, support vegetation, and encourage evapotranspiration is recommended. The vegetation, such as seeded grass (hydroseeded for rapid cover), will prevent wind and water erosion and contribute to transpiration and evaporation. The final slope should be maintained at 1 : 30. A tight cover or membrane cap requires provision for effective gas collection and release.

Landfill Vegetation Four feet or more earth cover is recommended if the area is to be landscaped, but the amount of cover depends on the plants to be grown. Native grasses may require 2 ft of topsoil, and large trees with deep tap roots may require 8 to 12 ft. The carbon dioxide and methane gases generated in a landfill may interfere with vegetation root growth, if not prevented or adequately diffused. The gases can be collected and disposed of through specially designed sand or gravel trenches or a porous pipe gas-venting system. Oxygen penetration to the roots is necessary. Carbon dioxide as low or lower than 10 percent in the root zone can be toxic to roots; methane-utilizing bacteria deplete the oxygen. Precautions to help maintain a healthy vegetation cover include selecting a tolerant species and seeking professional advice, avoiding areas of high gas concentrations, excluding gas from root zone (use built-up mounds for planting or line with membrane or clay soil barrier and vent trench and plant in suitable backfill soil), avoiding heavily compacted soil (loosen first if necessary and supplement soil fertility

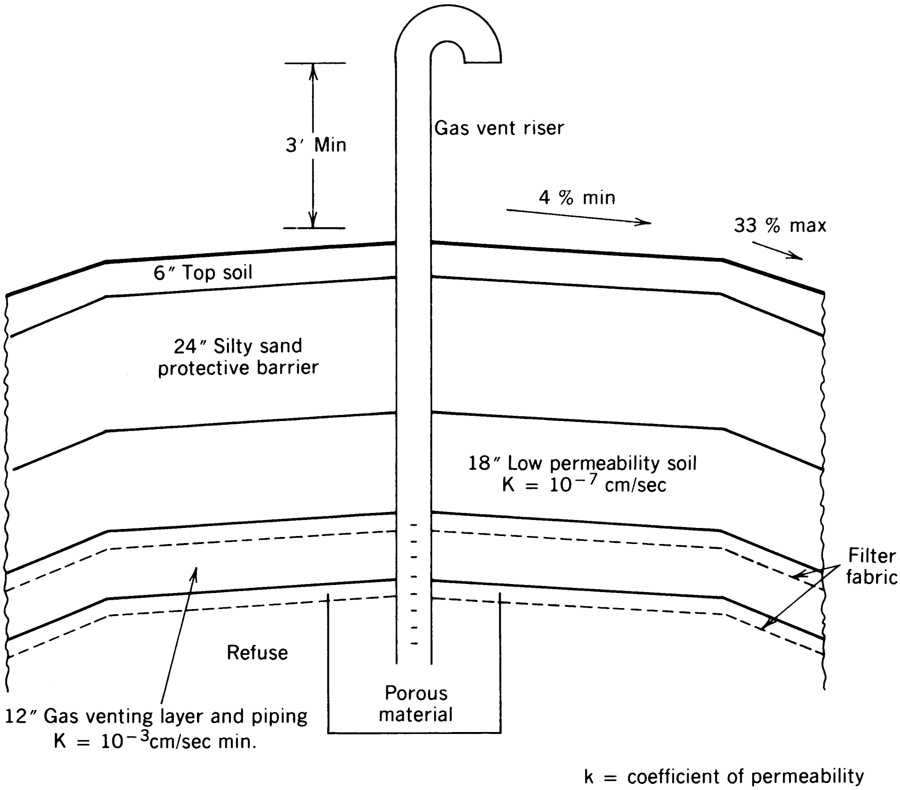

Figure 5-37 Final cover with passive gas vent. (Courtesy of New York State.)

and improve its physical condition following good nursery practice), using smaller plant stock, and providing adequate irrigation (see Figure 5-38).

Landfill Mining

The excavation and recycling of a landfill waste appears to be feasible where there has been adequate moisture to permit decomposition and stabilization of the waste. In locations where rainfall averages 60 in./year or more, a portion of the decomposed waste is generally suitable for recycling or for use as cover material for a new landfill at the same location excavated. On the other hand, in arid regions where the rainfall averages 10 to 20 in./year or less, the waste placed in landfills is often well preserved after more than 20 years. Other factors such as landfill design, type of cover material, waste composition, and age of the landfill must be evaluated and regulatory approval obtained.

A thorough hydrogeological investigation of an old landfill site is necessary before considering its excavation (mining), recycling, and possible reuse. The

Figure 5-38 Completed landfill with irrigation system.

up-gradient and down-gradient groundwater levels and quality, the depth and type of soil beneath the fill, the thickness of the fill and its composition, including the possible presence of hazardous wastes, are among the conditions to be investigated. Numerous tests are necessary as landfill waste is not homogeneous. If reuse of the excavated site as a municipal landfill site is proposed, preliminary discussions with the regulatory agency are essential.

Landfill Facilities and Equipment for Disposal by Sanitary Landfill

In addition to the control of leachate and landfill gases, a number of other facilities and operating equipment are required for the effective implementation of a sanitary landfill. Personnel requirements are discussed in the following section.

Fire Protection The availability of fire protection facilities at a site should also be considered as fire may break out at the site without warning. Protective measures may be a fire hydrant near the site with portable pipe or fire hose, a watercourse from which water can be readily pumped, a tank truck, or an earth stockpile. The best way to control deep fires is to separate the burning solid waste and dig a fire break around the burning solid waste using a bulldozer. The solid waste is then spread out so it can be thoroughly wetted down or smothered with earth. Limiting the solid waste cells to about 200 tons, with a depth of 8 ft and 2 ft of compacted earth between cells (cells 20 $\times$ 85 ft assuming 1 yd^3 of compacted solid waste weighs 800 lb), will minimize the spread of underground fires. The daily 6-in. cover will also minimize the start and spread of underground fires. Fires are a rare occurrence at a properly compacted and operated sanitary landfill.

Weigh Station It is desirable to construct a weigh station at the entrance to the site. Vehicles can be weighed upon entering and, if necessary, billed for use of the site. Scales are required to determine tonnage received, unit operation costs, relation of weight of solid waste to volume of in-place solid waste, area work loads, personnel, collection rates, organization of collection crews, and need for redirection of collection practices. However, the cost involved in construction of a weigh station cannot be always justified for a small sanitary landfill handling less than 20 to 50 tons/day. Nevertheless, estimates of volume and/or weights received should be made and records kept on a daily or weekly basis to help evaluate collection schedules, site capacity, usage, and so on. At the very least, an annual evaluation is essential.

Equipment Requirements To attain proper site development and ensure proper utilization of the land area, it is necessary to have sufficient proper equipment available at all times at the site (see Figure 5-39). One piece of solid waste compaction and earth-moving equipment is needed for approximately each 80 loads per day received at the solid waste site. The type of equipment should be suitable for the method of operation and the prevailing soil conditions. Additional standby equipment should be available for emergencies, breakdowns, and equipment maintenance. Typical equipment requirements are summarized in Table 5-22.

Tractors Tractor types include the crawler, rubber-tired, and steel-wheeled types equipped with bulldozer blade, bullclam, or front-end loader. The crawler tractor with a front-end bucket attachment is an all-purpose piece of equipment (see Figure 5-40). It may be used to excavate trenches, place and compact solid waste, transport cover material, and level and compact the completed portion of the landfill. Some types can also be used to load cover material into trucks for transportation and deposition near the open face. The steel-wheeled compactor is a common piece of equipment at landfills.

A bulldozer blade on a crawler tractor is good for landfills where hauling of cover material is not necessary. It is well suited for the area method landfill in which cover material is taken from nearby hillsides. It can also be used for trench method operation where the trench has been dug with some other type of equipment. A bulldozer is normally used in conjunction with some other type of earth-moving equipment, such as a scraper, where earth is hauled in from a nearby source.

The life of a tractor is figured at about 10,000 hr. Contractors usually depreciate their equipment over a 5-year period. On a landfill, if it is assumed that the equipment would be used 1000 hr a year, the life of the equipment could be 10 years. After 10 years, operation and maintenance costs can be

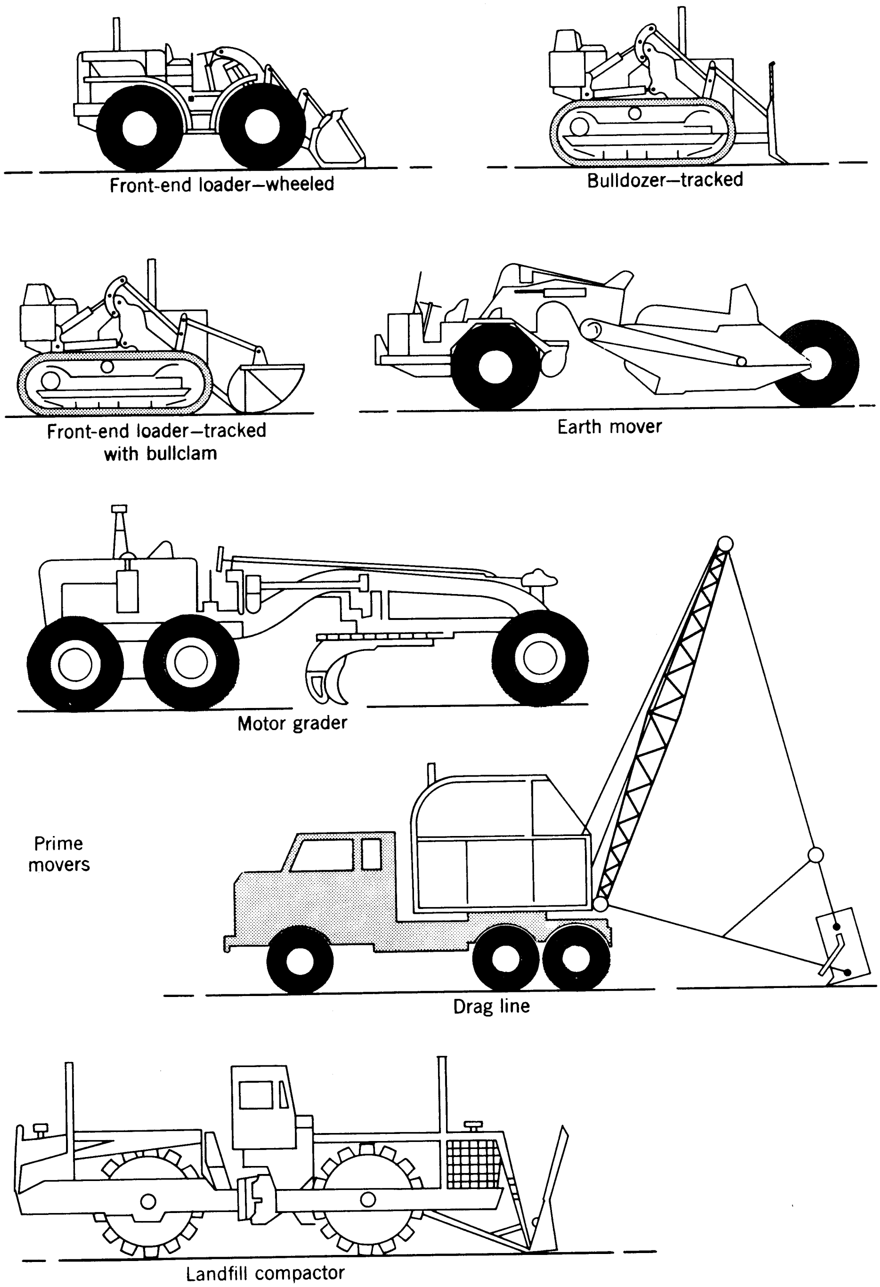

Figure 5-39 Typical equipment used for operation of sanitary landfill.

TABLE 5-22 Typical Minimum Landfill Equipment Requirements

Service Population	Daily Tonnage	Equipment Number	Equipment Type	Equipment Size (lb)	Accessory
0–15,000	0–50	1	Tractor, crawler, or rubber-tired	10,000–30,000	Dozer blade, landfill blade, front-end loader (1–2 yd^3)
15,000–50,000	50–150	1	Tractor, crawler, or rubber-tired	30,000–60,000	Dozer blade, landfill blade, front-end loader (2–4 yd) multipurpose bucket
		1 each	Scraper or dragline, water truck		
50,000–100,000	150–300	1–2	Tractor, crawler, or rubber-tired	30,000 or more	Dozer blade, landfill blade, front-end loader (2–5 yd), multipurpose bucket
		1 each	Scraper or dragline, water truck		
100,000 or more	300 or more	2 or more	Tractor, crawler, or rubber-tired	45,000 or more	Dozer blade, landfill blade, front-end loader, multipurpose bucket
		1 each	Scraper, dragline, steel-wheeled compactor, road grader, water truck		

Source: Adapted from Brunner and Keller (1972).

(*a*)

(*b*)

Figure 5-40 Common types of crawler tractors used at sanitary landfills: (*a*) tractor with dozer blade (wheeled compactor with trash blade also shown); (*b*) tractor with trash blade.

expected to approach or exceed the annual cost of new equipment. Lesser life is also reported. Equipment maintenance and operator competence will largely determine equipment life.

The size and type of machine needed at the sanitary landfill are dependent on the amount of solid waste to be handled, availability of cover material, compaction to be achieved, and other factors (Brunner and Keller, 1972). A rule that has been used is that a community with a population of less than 10,000 requires a $1\frac{1}{8}$-yd^3 bucket on a suitable tractor. Communities with a population between 10,000 and 30,000 should have a $2\frac{1}{4}$-yd^3 bucket, and populations of 30,000 to 50,000 should have at least a 3-yd^3 bucket. Larger populations will require a combination of earth-moving and compaction equipment depending on the site and method of operation. A heavy tractor (D-8) can handle up to 200 tons of solid waste per day, although 100 to 200 tons per day per piece of equipment is a better average operating capacity. Tire fill foam and special tire chains minimize tire puncture and other damage on rubber-tired equipment.

Many small rural towns have earth-moving equipment that they use for highway maintenance and construction. For example, a rubber-tired loader with special tires can be used on a landfill that is open two days a week. On the other three days the landfill can be closed (with fencing and locked gate), and the earth-moving equipment can be used on regular road construction work and maintenance. The people and contract users of the site should be informed of the part-time nature of the operation to receive their full cooperation. The public officials responsible for the operation should establish a definite schedule for the assignment of the equipment to the landfill site to ensure the operation is always under control and maintained as a sanitary landfill.

Other Equipment The dragline is suitable for digging trenches, stockpiling cover material, and placing cover material over compacted solid waste. An additional piece of equipment is necessary to spread and compact the solid waste and cover material. Although not commonly used, the backhoe is suitable for digging trenches on fairly level ground, and the power shovel is suitable for loading trucks with cover material.

In large operations, earth movers can be used for the short haul of cover material to the site when adequate cover is not readily available nearby. Dump trucks may also be needed where cover material must be hauled in from some distance. Other useful equipment is a grader, a sheepsfoot roller, and a water tank truck equipped with a sprinkler to keep down dust or a power sprayer to wet down the solid waste to obtain better compaction.

Equipment Shelter An equipment shelter at the site will protect equipment from the weather and possible vandalism. The shelter can also be used to store fire protection equipment and other needed materials and for routine equipment maintenance and repair. Operators of sanitary landfills have found a shelter to be of great value during the winter months since there is much less difficulty in starting motorized equipment. However, the shelter location must be on solid ground, not subject to gas migration from the landfill.

Landfill Operation and Supervision

Operational issues for modern landfills include operational control, personnel and operation, salvaging policy, area policing, insect and rodent control, maintenance, and operational policies (see also Table 5-20).

Operation Control The direction of operation of a sanitary landfill should be with the prevailing wind to prevent the wind from blowing solid waste back toward the collection vehicle and over the completed portion of the landfill. To prevent excessive wind scattering of solid waste throughout the area, snow fencing or some other means of containing papers should be provided. The fencing can be utilized in the active area and then moved as the operation progresses. In some instances, the entire area is fenced. Other sites have natural barriers around the landfill, such as is the case in heavily wooded areas. It is desirable to design the operation so that the work area is screened from the public line of sight. Noise levels between 7 a.m. and 10 p.m. are generally required to be kept below 60 dBA in rural areas, 65 in suburban areas, and 70 in urban areas beyond property lines.

Large items such as refrigerators, ranges, and other "white goods" and tires should be recycled. Brush and yard wastes are preferably composted. Other bulky items not recyclable should be placed in a separate area of the landfill for periodic burial. Prior compression or shredding of bulky objects will improve compaction of the fill, reduce land volume requirements, and allow more uniform settlement. Consideration should always be given to resource recovery and recycling where possible. Tires are usually not acceptable in landfills but may be if chipped or properly cut.

Drivers of small trucks and private vehicles carrying rubbish and other solid wastes interfere with the operation of a landfill. To accommodate these individuals on weekends and avoid traffic and unloading problems during the week, it is good practice to provide a special unloading area (convenience station) adjacent to the landfill entrance. A satellite transfer station is also an alternative, in conjunction with a regional landfill.

Personnel and Operation Proper full-time supervision is necessary to control dumping, compaction, and covering. Adequate personnel are needed for proper operation. Depending on the size of the community, there should be a minimum of one man at a site and six men per 1000 yd^3 dumped per day that the site is open. The supervisor should erect signs for direction of traffic to the proper area for disposal. It is essential that the supervisor be present at all hours of operation to ensure that the landfill is progressing according to plan. Days and hours of operation should be posted at the entrance to the landfill. A locked gate should be provided at the entrance to keep people out when closed. It is also advisable to inform the public of the days and hours of operation.

Solid waste treatment and disposal facilities represent very large investments. They have the potential for grave air, water, and land pollution and contain complex equipment and controls. Proper operation meets regulatory agency permit conditions and requires continuous, competent operational control. The training and certification of operators of resource recovery facilities, landfills, incinerators, and hazardous waste sites are provided by various state and private organizations.

In supervising an operation, the length of the open face should be controlled since too large an open face will require considerably more cover material at the end of a day's operation. Too small an open face will not permit sufficient area for the unloading of the expected number of collection vehicles that will be present at one time. After vehicles have deposited the solid waste at the top or, preferably, at the base of the ramp as directed, the solid waste should be spread and compacted from the bottom up into a 12- to 18-in. layer (24 in. maximum) with a tractor. Three to five passes should give a compaction of 1000 to 1250 lb/yd^3. *Passing over the waste should be done continually throughout the day* to ensure good compaction and vermin and fire control. If solid waste is allowed to pile up without spreading and compaction for most of the day, proper compaction will not be achieved, resulting in uneven settlement and extra maintenance of the site after the fill is completed. At the end of each day, the solid waste should be covered with at least 6 in. of earth or a suitable foam. For final cover of solid waste, at least 2 ft of earth is required.

No Burning or Salvaging Air pollution standards and sanitary codes generally prohibit any open burning. Limited controlled burning might be permitted in some emergency cases (for uncontaminated wood and stumps), but special permission would be required from the air pollution control agency, health department, and local fire chief. Arrangements for fire control, complete burning in one day, control over material to be burned (no rubber tires or the like), and restrictions for air pollution control would also be required. Salvaging at sanitary landfills is not recommended since, as usually practiced, it interferes with the operation. It will slow down the entire operation and thus result in time loss. Salvaging can also result in fires and unsightly stockpiles of the salvage material in the area.

Area Policing Since wind will blow papers and other solid waste around the area as the trucks are unloading, it will be necessary to clean up the area and access road at the end of each day. One of the advantages of portable snow fencing is that it will usually confine the papers near the open face, thereby make the policing job easier and less time consuming. At many sanitary landfills, dust will be a problem during dry periods of the year. A truck-mounted water sprinkler can keep down the dust and can also be used to wet down dry solid waste to improve compaction. The bulldozer operator should be protected by a dust mask, special cab, or similar device.

Insect and Rodent Control An insect and rodent control program is not usually required at a properly designed and operated landfill. However, from time to time, certain unforeseen conditions may develop that will make control necessary. For this reason, prior arrangement should be made to take care of such emergencies until the proper operating corrections can be made. Prompt covering of solid waste is necessary. See Chapter 10.

Maintenance Once a sanitary landfill, or a lift of a landfill, is completed or partially completed, it will be necessary to maintain the surface to take care of differential settlement. Settlement will vary, ranging up to approximately 20 to 30 percent, depending on the compaction, depth, and character of solid waste. Ninety percent of the settlement can be expected in the first 5 years. Settlement maintenance is required for perhaps 20 or 30 years. Maintenance of the cover is necessary to prevent excessive precipitation and surface-water infiltration, erosion, ponding, and excessive cracking, allowing insects and rodents to enter the fill and multiply.

It is necessary to maintain proper surface-water drainage to reduce precipitation–infiltration and minimize percolation of contaminated leachate through the fill to the groundwater table or the surface. A final 4 percent grade, with culverts and lined ditches as needed, is essential. The formation of water pockets is objectionable since this will promote surface-water infiltration. Vehicular traffic over these puddles will wash away the final earth cover over the solid waste and cause trucks to bog down. The maintenance of access roads to the site is also necessary to prevent dust and the formation of potholes, which will slow down vehicles using the site. Finally, provision must be made for groundwater, surface-water and gas monitoring, and control. The landfill surface should be properly capped, graded, and planted with suitable tolerant vegetation as previously noted.

Summary of Recommended Operating Practices

1. The sanitary landfill should be planned as an engineering project, to be constructed, operated, and maintained by qualified personnel under technical direction, without causing air, land, or water pollution, safety or health hazards, or nuisance conditions. Surveying benchmarks should be established and maintained to guide fill progression and site closure. Careful supervision must be given to landfill bottom separation and soil compaction, construction of primary and secondary composite liners, synthetic liner placement and seals, and leachate drainage and collection system. Construction of the landfill cap requires similar supervision.

2. The face of the working fill should be kept as narrow as is consistent with the proper operation of trucks and equipment in order to keep the area of exposed waste material to a minimum.
3. All solid waste should be spread as dumped and compacted into 12- to 18-in.-thick layers as it is hauled in. Operate tractor up- and down-slope (3:1) of fill to get good compaction—three to five passes.
4. All exposed solid waste should be covered with 6 in. of earth at the end of each day's operation.
5. The final earth covering for the surface and side slopes should minimize infiltration, be compacted, and be maintained at a depth of at least 24 in. See state regulations.
6. The final level of the fill should provide a 4 percent slope to allow for adequate drainage. Side slopes should be as gentle as possible to prevent erosion. The top of the fill and slopes should be promptly seeded. Drainage ditches and culverts are usually necessary to carry away surface water without causing erosion.
7. The depth of solid waste should usually not exceed an average depth of 8 to 10 ft after compaction. In a landfill where successive lifts are placed on top of the preceding one, special attention should be given to obtain good compaction and proper surface water drainage. A settlement period of preferably one year should be allowed before the next lift is placed.
8. Control of dust, wind-blown paper, and access roads should be maintained. Portable fencing and prompt policing of the area each day after solid waste is dumped are necessary. If possible, design the operation so that it is not visible from nearby highways or residential areas.
9. Salvaging, if permitted by the operator of the solid waste disposal area, should be conducted in such a manner as not to create a nuisance or interfere with operation. Salvaging is not recommended at the site.
10. A separate area or trench may be desirable for the disposal of such objects as tree stumps, large limbs, if not shredded and recycled, and nonrecyclable miscellaneous materials.
11. Where necessary, provision should be made for the disposal, under controlled conditions, of small dead animals and septic tank wastes. These should be covered immediately. The disposal of sewage sludge, industrial or agricultural wastes, and toxic, explosive, or flammable materials should not be permitted unless study and investigation show that the inclusion of these wastes will not cause a hazard, nuisance, or groundwater or air pollution. See appropriate regulatory agency for details.
12. An annual or more frequent inspection maintenance program should be established for completed portions of the landfill to ensure prompt repair of cracks, erosion, and depressions.
13. Sufficient equipment and personnel should be provided for the spreading, compacting, and covering of solid waste. Daily records should be

kept, including type and amount of solid wastes received. *At least annually,* an evaluation should be made of the weight of solid waste received and volume of solid waste in place as a check on compaction and rate at which the site is being used.

14. Sufficient standby equipment should be readily available in case there is a breakdown of the equipment in use.
15. The breeding of rats, flies, and other vermin; release of smoke and odors; pollution of surface waters and groundwaters; and causes of fire hazards are prevented by proper operation, thorough compaction of solid waste in 12- to 18-in. layers, daily covering with earth, proper surface-water and groundwater drainage, and good supervision.
16. Leachate and gas-monitoring wells should be sampled periodically to detect significant changes. This should include methane concentrations in on-site or other nearby buildings.

Site Closure or Conversion

If a disposal site is to be closed, the users, including contractors, should be notified and an alternate site designated. A rat-poisoning (baiting) program should be started at least two weeks before the proposed closing of a site that has not been operated as a sanitary landfill and continued until the site has been completely closed. The site should be closed off and made inaccessible; it should be covered with at least 2 ft of compacted earth on the top and all exposed sides or as required by the regulatory agency, graded to shed water, seeded to grass, and then posted to prohibit further dumping. Side slopes should be no greater than 3 : 1 to reduce erosion and maintenance. Steps must be taken to prevent contravention of surface-water and groundwater standards, gas migration, or adverse health or environmental hazards. If the site is adjacent to a stream, the solid waste must be moved an appropriate distance back from the high-water level to allow for the construction of an adequate and substantially protected earth dike. Legal closure requirements may be quite onerous if groundwater pollution is suspected or if enclosed structures are in a vicinity that might be affected by methane migration. This is discussed further below.

Where adequate land is available and the site is suitable as determined by an engineering and hydrogeological analysis, it may be possible to convert the landfill into a properly designed, constructed, operated, and maintained sanitary landfill. Conversion of a *suitable* existing site can overcome the problems associated with the selection of a new site.

Landfill Closure Requirements The state regulatory agency closure requirements must be followed.

Use of Completed Landfill A sanitary landfill plan should provide for landscaping and a specific use for the area after completion. Final grades for a sanitary landfill should be established in advance to meet the needs of the proposed future use. For example, the use of the site as a golf course can tolerate rolling terrain while a park, playground, or storage lot would be best with a flat graded surface. Other uses of completed landfills include toboggan and ski runs for children, nature areas, bicycle and hiking paths, open areas, and airport runway extensions. In planning for the use of such an area, permanent buildings or habitable dwellings should not be constructed close to or over the fill since gas production beneath the ground may migrate into sewers, utility conduits, and basements or through floor slabs and sump drains of such dwellings or buildings, reaching explosive levels. Some open structures that would not require excavation, such as grandstands and open equipment shelters, can be built on a sanitary landfill with little resulting hazard. Buildings constructed on sanitary landfills can be expected to settle unevenly unless special foundation structures such as pilings are provided; however, special provisions must be made to monitor and dissipate gas production. When the final land use is known beforehand, selected undisturbed ground islands or earth-fill building sites are usually provided to avoid these problems, but gas monitoring is still necessary.

INCINERATION

The incineration of solid waste involves the conversion of solid wastes into gaseous, liquid, and solid conversion products with the concurrent or subsequent release of heat energy. Incineration is typically implemented to reduce the volume of solid waste and, to the extent possible, recover energy. A properly designed and controlled incinerator is satisfactory for burning combustible municipal solid waste and chemical, infectious, and pathological wastes. In general, incineration is not generally recommended for small towns, villages, apartment buildings, schools, institutions, camps, and hotels unless good design and supervision can be ensured and cost is not a factor. Further, a landfill is a necessary adjunct for the disposal of incinerator residue and unrecycled solid waste. The purpose of this section is to review (1) the basic operations involved in the incineration of solid waste, (2) briefly the principal combustion products and residues formed during combustion, (3) the types of incinerators that are used for solid waste, (4) factors that must be controlled in the incineration process, (5) residuals management, (6) site selection, plant layout, and building design, and (7) issues in the implementation of incineration facilities.

Description of Operation of MSW Incinerator

The basic operations involved in the combustion of commingled MSW are identified in Figure 5-41. The operation begins with the unloading of solid

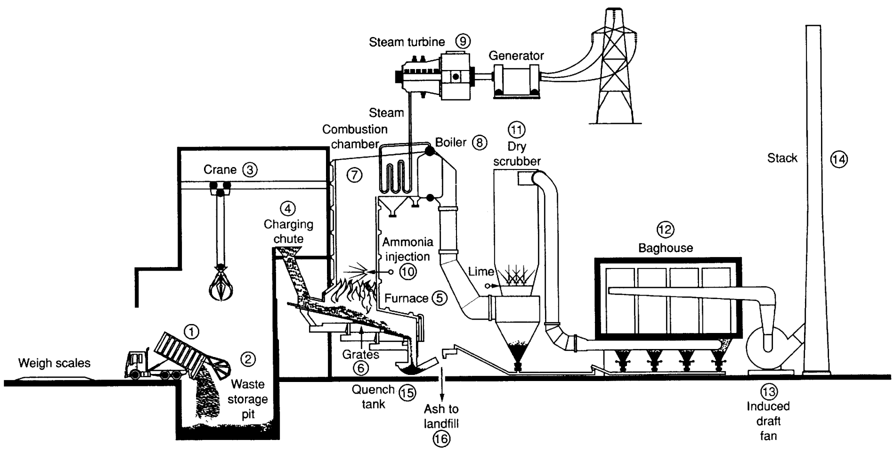

Figure 5-41 Definition sketch for operation of modern mass-burn incinerator.

wastes from collection trucks (1) into a storage pit (2). The length 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 to four 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. Solid wastes from the feed (charging) chute fall onto the grates (6), where they are mass fired. Several different types of mechanical grates are commonly used. Typical physical and chemical characteristics of incinerator solid waste are reported in Table 5-23.

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 in the combustion process taking 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 that is converted to electricity by a turbine generator (9). When 30 percent or less of the solid waste is rubbish or when the solid waste contains more than 50 percent moisture, additional supplemental fuel will be needed.

Air pollution control equipment is required on all new incinerators. Air pollution control equipment may include ammonia injection for NO_x (nitrogen oxides) control (10), a dry scrubber for SO and acid gas control (11), and a bag house (fabric filter) for particulate removal (12). To secure adequate air

TABLE 5-23 Physical and Chemical Characteristics of Incinerator Solid Waste[a]

Constituents	Percent by Weight (as received)
Proximate analysis	
Moisture	15–35
Volatile matter	50–65
Fixed carbon	3–9
Noncombustibles	15–25
Ultimate analysis	
Moisture	15–35
Carbon	15–30
Oxygen	12–24
Hydrogen	2–5
Nitrogen	0.2–1.0
Sulfur	0.02–0.1
Noncombustibles	15–25
Higher heating value (Btu/lb as received)	
Without recycling	3000–6000
With recycling	3000–5000

Source: DeMarco et al. (1969) and Tchobanoglous et al. (1993).

[a]Principally residential–commercial waste.

flows to provide for head losses through air pollution control equipment, as well as to supply air to the combustor 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 bag house is mixed with the furnace ash and conveyed to ash treatment facilities (16). Details on incinerator design, air pollution control equipment, and ash treatment and disposal may be found in Tchobanoglous and Kreith (2002) and Tchobanoglous et al. (1993).

In addition to the above operational aspects, complex instrumentation, including transmission to a central control panel, is necessary to properly operate a modern incinerator. Included are temperature indicators, air and water flows, pressure indicators, alarms, waste feed cutoffs when combustion and emission regulations are violated, and other indicators and controls that may be required by the regulatory authority.

Combustion Products and Residues

Municipal solid waste burned in incinerators will result in the production of combustion gases, particulates, and bottom and fly ash. The characteristics of these products will depend on the types of wastes burned and the incinerator design, operating temperature, residence time, and controls.

Combustion Essentials The three essentials for combustion, as outlined above, are (1) time, (2) temperature, and (3) turbulence, including sufficient oxygen. There must be sufficient time to drive out the moisture, the temperature must be raised to the ignition point, and there must be sufficient turbulence to ensure mixing of the gases formed with enough air to burn completely the volatile combustible matter and suspended particulates. The combustion process involves first, drying, volatilization, and ignition of the solid waste and, second, combustion of unburned furnace gases, elimination of odors, and combustion of carbon suspended in the gases. The second step requires a high temperature, at least 1500 to 1800°F (816–982°C) sufficient air, and mixing of the gas stream to maintain turbulence until burning is completed. The temperature in the furnace may range from 2100 to 2500°F (1149–1371°C) if not controlled. A combustion temperature of 2500°F (1371°C) is normal for steam generation and energy recovery.

When the gases leave the combustion chamber, the temperature should be between 1500°F and 1800°F (816 and 982°C), and the gas entering the stack should be 1000°F (538°C) or less. The minimum temperature for burning carbonaceous wastes to avoid release of smoke is 1500°F (816°C). A temperature of less than 1500°F will also permit the release of dioxins and furans. The exit temperature will have to be lowered to 200°F (93°C) for wool or cotton filters, 450 to 500°F (232–260°C) for glass fiber filters before the gas is filtered, or 600°F (316°C) or less if electrical precipitators are used. At a temperature of 1200 to 2000°F (649–1093°C) or higher, depending on temperature and residence time, oxides of nitrogen are formed that contribute to air pollution. Hospital wastes require incineration at a temperature of 1800 to 2000°F (982–1093°C) to ensure degradation of organic compounds. Inorganic agents are not destroyed.

Gaseous Combustion Products The principal elements of solid wastes are carbon, hydrogen, oxygen, nitrogen, and sulfur. Under ideal conditions, the gaseous products derived from the combustion of municipal solid wastes would include carbon dioxide (CO_2), water (H_2O, flue gas), oxygen (O_2), nitrogen (N_2) , and small amounts of sulfur dioxide (SO_2). Because many different reaction sequences are possible, depending on the exact nature of the wastes and the operating characteristics of the combustion reactor, the gaseous emissions from combustion may include sulfur and nitrogen oxides and smaller amounts of hydrogen chloride, mercury, lead, arsenic, cadmium, dioxins and furans, and organic compounds. The amounts and concentrations going up the stack are determined also by the combustion effectiveness and the efficiency of air pollution control equipment.

The basic reactions for the oxidation (combustion) of the carbon, hydrogen, and sulfur contained in the organic fraction of MSW are as follows:

$$\underset{(12)}{C} + \underset{(32)}{O_2} \rightarrow CO_2 \quad \text{(for carbonA)} \tag{5-2}$$

$$\underset{(4)}{2H_2} + \underset{(32)}{O_2} \rightarrow 2H_2O \quad \text{(for hydrogen)} \tag{5-3}$$

$$\underset{(32.1)}{S} + \underset{(32)}{O_2} \rightarrow SO_2 \quad \text{(for sulfur)} \tag{5-4}$$

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. Thermal processing systems are often categorized on the basis of their air requirements. Combustion with exactly the amount of oxygen (or air) needed for complete combustion is known as *stoichiometric combustion*. Combustion with oxygen in excess of the stoichiometric requirements is termed *excess air combustion*.

Combustion Residues The principal solid residues are (1) bottom ash, (2) fly ash, and (3) noncombusted organic and inorganic materials. The residue after burning (bottom and fly ash) is about 25 percent of the original weight (10–15 percent by volume), 5 percent where intensive recycling is practiced. Other residuals associated with the incineration of solid waste may include scrubber sludge and wastewater treatment plant sludge, both of which will tend to concentrate contaminants. It is essential, therefore, that the fly ash, bottom ash, and scrubber and wastewater sludge be analyzed for contaminants likely to be present and evaluated for their significance. The disposal method and facility should be tailored to ensure protection of the public health and the environment.

Types of Incinerators

A variety of incinerator types have been used for the combustion of solid waste, including (1) mass-fired combustors, (2) refuse-derived fuel- (RDF) fired combustors, (3) modular combustion units, and (4) on-site commercial and industrial incinerators.

Mass-Fired Combustors In a mass-fired combustor, 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 manually reject obviously unsuitable items. However, it must be assumed that anything in the MSW stream may ultimately enter the combustor, including bulky oversize noncombustible objects (e.g., broken tricycles) 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 operational personnel. The energy content of mass-fired waste can be extremely variable, dependent 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 incineration facilities (Tchobanoglous et al., 1993).

A typical mass-burn incinerator schematic showing steam and electricity production is illustrated in Figure 5-42. Types of furnaces used are the rectangular refractory lined (Figure 5-43), the rotary kiln (Figure 5-44), and the rectangular furnace with waterwalls (Figure 5-45). In the rectangular furnace, two or more grates are arranged in tiers. The rotary kiln furnace incorporates a drying grate ahead of a rotary drum or kiln where burning is completed. Waterwall furnaces substitute water-cooled tubes for the exposed furnace walls and arches. Other types of furnaces are also available. All furnaces should be designed for continuous feed. Reciprocating or moving and traveling grates are the most common. Mass-burn incinerators usually burn raw solid wastes in a refractory-lined rotary kiln after drying and combustion, with underfire and overfire air and a tube boiler to generate steam, hot water, or electricity. A diagram of a modern mass-burn facility is shown in Figure 5-46. In a cogeneration incinerator, steam and electricity are produced.

Modern furnace walls are usually lined with tile or have waterwalls. With tile refractories, repairs can be readily made without the need for expensive and time-consuming rebuilding of entire solid brick walls found in old plants. Special plastic or precast refractories can be used for major or minor repairs. Waterwalls in a furnace actually consist of water-cooled tubes that also serve

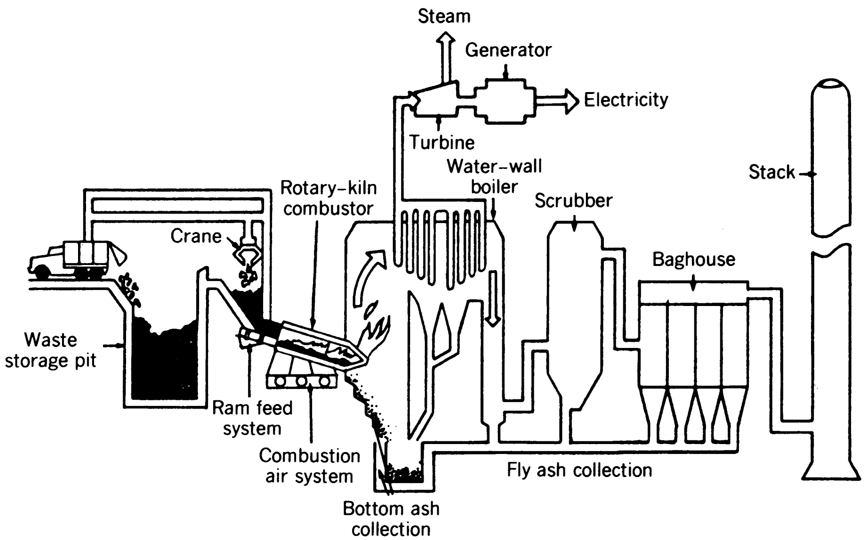

Figure 5-42 Schematic of typical mass-burn municipal waste combustion facility with energy production facilities (U.S. EPA, 1989).

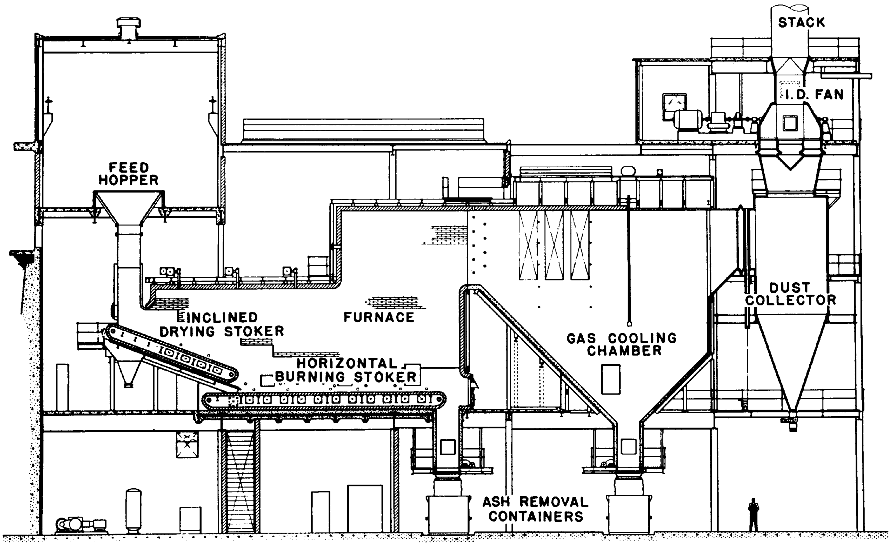

Figure 5-43 Modern continuous-feed, refractory-lined incinerator with traveling-grate stokers (rectangular type) (Corey, 1969).

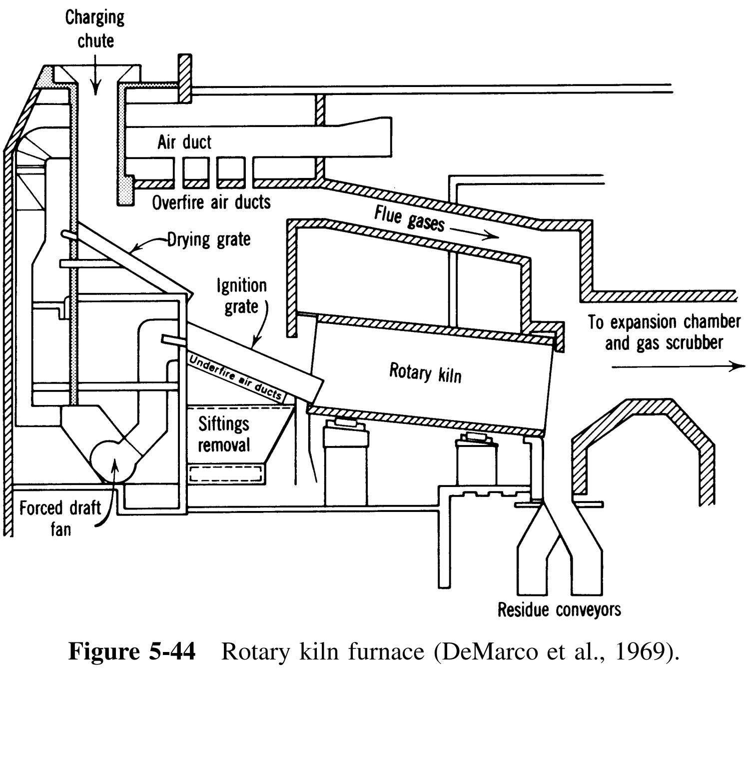

Figure 5-44 Rotary kiln furnace (DeMarco et al., 1969).

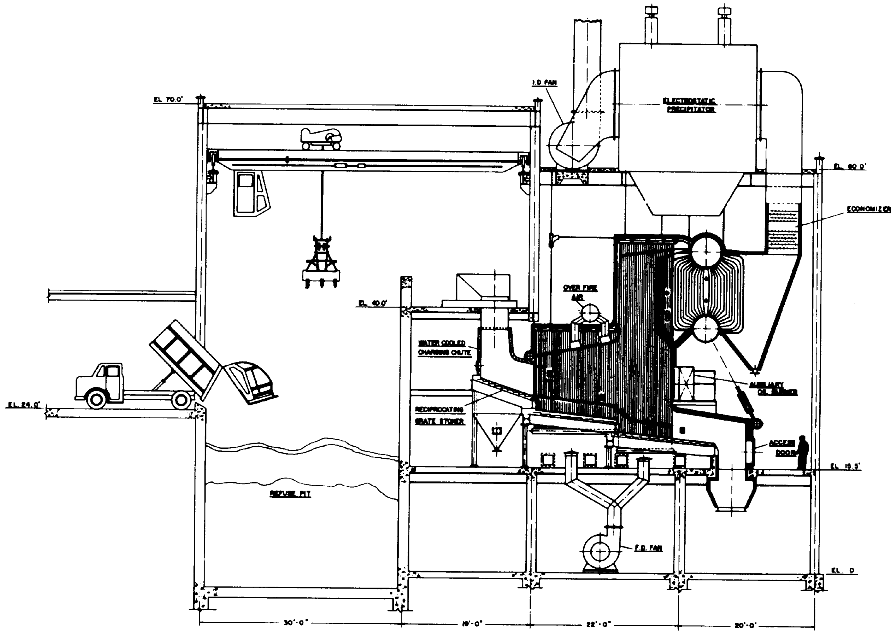

Figure 5-45 Continuous-feed incinerator with rocking-grate stoker and waterwalls (Corey, 1969).

as heat exchangers, thereby reducing the outlet gas temperature and simplifying dust collection. The tubes also cover and protect exposed furnace walls and arches. Less air is required: 100 to 200 percent excess air for refractory walls compared to less than 80 percent for waterwalls. External pitting of the water-cooled tubes may occur if the water temperature drops below 300°F (149°C) due to condensation of the corrosive gases. Internal tube corrosion must also be prevented by recirculation of conditioned water.

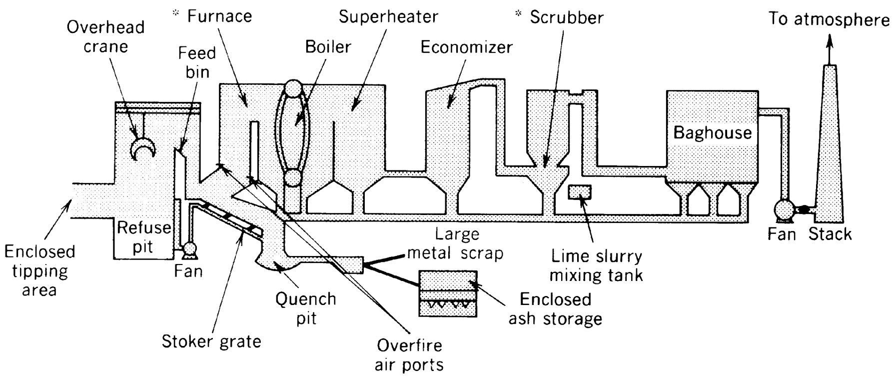

Figure 5-46 Diagram of modern mass burn facility (U.S. EPA, 1987a).

RDF-Fired Combustors Compared to 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 easier to transport and store. Either form can be burned by itself or mixed with coal and combusted in a waterwall furnace (see Figure 5-13) equipped with a traveling gate for ash management.

Because of the higher energy content of RDF compared to unprocessed MSW, RDF combustion systems can be physically smaller than comparatively 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 (Tchobanoglous et al., 1993).

Modular Combustion Units Modular combustion units are available for capacities of less than 700 lb/hr to 250 tons/day and include a secondary combustion chamber. These units may be used for the batch incineration of municipal, hospital, commercial, and industrial wastes. Volume reduction of 80 to 90 percent and energy recovery of about 55 percent are claimed. Emission control (scrubber and/ or baghouse) is needed and skilled operation is required.

On-Site Commercial and Industrial Incinerators When possible, a large municipal incinerator should be used in preference to a small on-site incinerator. Better operation at lower cost with less air pollution can usually be expected. Based on past experience, conventional mass-fired incinerators generally are not economically feasible for communities with a population of less than 50,000 to 100,000, but modular controlled air units incorporating heat recovery are suitable for smaller volumes of waste. However, on-site incinerators are used in hospitals, schools, and commercial and industrial establishments. Their continued use is being severely limited by air pollution control requirements. Many of the units now in use need to be replaced or redesigned to meet modern air pollution control standards. The controlled-air incinerator with a waste-heat boiler for energy recovery can overcome many, if not all, of the deficiencies.

Incinerator Capacity and Stack Heights Incinerators are rated in terms of tons of burnable or incinerable waste per day. For example, an incinerator having a furnace capacity of 600 tons/day can theoretically handle 600 tons in 24 hr with three-shift operation, 400 tons in 16 hr with two-shift operation, and 200 tons in 8 hr with one-shift operation. Hence, if 400 tons of incinerable wastes collected per day are to be incinerated in 8 hr, an incinerator with a rated capacity of 1200 tons per day will be required plus a 15 percent downtime allowance for repairs. In determining design capacity, consideration must also be given to daily and seasonal variations, which will range from 85 to 115 percent of the median.

High stacks (chimneys) 150 to 200 ft above ground level are usually constructed to provide natural draft and air supply for combustion. Stack heights of 300 to 600 ft are not uncommon. Discharge of gases at these heights also facilitates dilution and dispersal of the gases. In some designs, short stacks are used for aesthetic reasons, and the equivalent effective stack height is obtained by induced draft. Meteorological conditions, topography, adjacent land use, air pollution standards, and effective stack height should govern.

Control of the Incineration Process

The poor image that incineration has in the eyes of many people is due largely to the failure to control the operation, with resultant destruction of the equipment and air pollution. A properly designed and operated incinerator requires control instrumentation for (1) temperature, (2) draft pressures, (3) smoke emission, (4) weights of solid wastes coming in and leaving the plant, and (5) air pollution control equipment. Competent well-trained operators are also essential.

Temperature Temperature monitoring is necessary for control purposes to monitor the incoming air and gases leaving the combustion chamber at the settling chamber outlet, the cooling chamber outlet, the dust collector inlet and outlet, and the stack temperature. Furnace temperature can be controlled by adjusting the amount of overfire or underfire air. The temperature of the gases leaving the furnace is reduced by spraying with water (causes a white stack plume unless the flue gas is reheated before discharge), dilution with cool air (high equipment cost to handle large volumes of diluted gases), or passing through heat exchangers (ready market for heat, steam, electricity, or high-temperature water needed). Gas scrubbers using water sprays can be used to cool effluent gas so that an induced-draft fan can be used to reduce the chimney height; large particulates can also be removed.

Draft Pressure Draft pressure measurements are needed to control the induced-draft fan and the stack draft. Measurements should be made at the underfire air duct, overfire air duct, stoker compartment, sidewall air duct, sidewall low-furnace outlet, dust collector inlet and outlet, and induced fan inlet. Control of underfire air can provide more complete combustion with less fly-ash carryover up the stack.

Smoke Density The smoke emission can be controlled by continuous measurement of the particulate density in the exhaust gas. A photoelectric pickup of light across the gas duct is used, preferably located between the particulate collector and the induced fan duct.

Weigh Station Platform scales to weigh and record the incoming solid waste and outgoing incinerator residue, fly ash, siftings, and other materials are generally required.

Instrumentation Devices should include those to keep record of overfire and underfire air flow rates; temperature and pressure in the furnace, along gas passages, in the particulate collectors, and in the stack; electrical power and water use; and grate speed.

Odor Odor control requires complete combustion of hydrocarbons, that is, excess air and a retention time of 1 sec at 1500°F (816°C) [above 1400°F (760°C) at the exit of the furnace]. Adequate dilution of gases leaving the stack by an effective stack height (actual stack height plus plume rise) is another possible method for odor control, but its effectiveness is related to meteorological conditions and persistence of the odors. Wet scrubbers can also be used to absorb odors while removing particulates.

Gaseous Emissions The principal gaseous emissions from the combustion of mixed wastes are: carbon dioxide, water vapor, sulfur oxides, nitrogen oxides, carbon monoxide, and hydrogen chloride. Hydrogen chloride and other acids can cause corrosion of air pollution control equipment. A lime spray dry scrubber followed by a baghouse (fabric) filter is effective in greatly reducing sulfur dioxide and hydrogen chloride gases, metals, dioxins, furans, and organic emissions, as well as fly ash. There is some evidence that the lower the temperature of flue gases [below about 300°F (149°C)] entering the pollution control devices, the greater the amount of phenols, benzenes, dioxins, and other organics condensed and collected on the particulates. Typical gaseous emission guidelines are presented in Table 5-24.

Particulate Emissions These can be controlled by settling chambers, wetted baffle spray system, cyclones, wet scrubbers, electrostatic precipitators, and fabric filters. Their efficiencies and other details are discussed in Chapter 6. Apparently, only wet scrubbers, electrostatic precipitators, and bag filters can meet air pollution code requirements. Cyclones in combination with other devices might approach the standard. Typical particulate emission guidelines are presented in Table 5-24.

TABLE 5-24 Some Municipal Solid Waste Incineration Emission Design and Operation Guidelines

Control	Guidelines
Particulate emissions	Not greater than 0.010 grains[a] per dry standard cubic foot of exhaust (stack) gas, corrected to 7% oxygen; not greater than 0.015 grains at startup; existing, small to midsize units, up to 0.030 grains
Carbon monoxide	Outlet concentration not greater than 50 ppm on an 8-hr average; 4-hr average and 100 ppm maximum proposed
Hydrogen chloride emissions	A running 8-hr average emission of not greater than 10% by weight of uncontrolled emissions reduced by not less than 90%, or less than 50 ppm stack concentration (25 ppm proposed); flue gas at control device outlet not greater than 300°F (149°C); RCRA requires, for hazardous waste, 99% HCl removal, unless less than 4 lb/hr
Sulfur dioxide	Not greater than 30 ppm or not less than 70% reduction, 24-hr daily average
Nitrogen oxides	Best available technology to limit emissions, additional requirements in nonattainment areas
Furnace design—operating temperature and residence time	Residence time for flue gas of at least 1 sec at no less than 1800°F (982°C) in combustion zone or a furnace design to provide a residence time for flue gas and a temperature which, in combination, are shown to be equivalent; auxiliary burner required; combustion index[b] of 99.9% for 8-hr average or 99.5% based on 7-day average; minimum furnace temperature of 1500°F (816°C) after last overfire air injection and 10% plume opacity, 15 min average; auxiliary burners to maintain furnace temperature.
Stack testing (at startup and at 18-month interval)	Within specified periods for carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen dioxide, oxygen, hydrogen chloride, and trace contaminants including arsenic, beryllium, cadmium, chromium, copper, zinc, lead, mercury[c], nickel; polychlorinated dibenzo-*p*-dioxins, polychlorinated dibenzofurans, benzo-*a*-pyrene, total aromatic hydrocarbons, formaldehyde, and polychlorinated biphenyls; also particulates
Continuous emission monitoring	Instrumentation for continuously monitoring emissions and operation parameters, including oxygen, plume opacity, sulfur dioxide, hydrogen chloride, nitrogen oxides, carbon monoxide, carbon dioxide, temperatures, and combustion index[b]; file is kept of measurements and operation parameters, including steam pressure and flow, auxiliary fuel used, operation controls of electrostatic precipitators, fabric filters, gaseous contaminant emission control devices.

TABLE 5-24 (*Continued*)

Control	Guidelines
Dioxin or furan emissions[d]	Minimize to approach 0.2 ng/dry m^3 corrected to 7% oxygen, but not in excess of 2.0 ng/dry m^3 [e]
Startup shutdown	Plan of practices and procedures to avoid unacceptable or excess emissions
Operator certification	Operator training program; operation directed at all times by certified operator
Noise	Not greater than 60 dBA between 7 a.m. and 10 p.m. in rural area, 65 dBA suburban, and 70 dBA urban; between 10 p.m. and 7 a.m., 50 dBA rural, 55 dBA suburban, and 70 dBA urban
Opacity	No emissions having average opacity of 10% or greater for any consecutive 6-min period, but may exceed 20% in 60-min period
Operating records	As specified, retained at least 3 years; plan prepared for proper operation and maintenance prior to operation

Source: Salvato (1992).

Note: Plants and animals around incinerators can cumulate pollutants (contaminants) and serve as biological monitors for airborne metal and organic pollutants. Additional guidelines (and regulations) are being developed. See the Clean Air Act of 1990 and state regulations.

[a] 1 grain = 0.064 g ≤ 180 mg/dry m^3 (RCRA).

[b] $Cl = CO_2 \times 100/CO_2 + CO$; CO_2 and CO in the exhaust gas, ppm by volume (dry) = combustion Index at 7% oxygen (≤99.80% 8-hr average). Continuous monitoring is required.

[c] Mercury and mercury compounds in flue gas exist as a gas. They are not captured by fabric filters or electrostatic precipitators and hence may escape out of the stack. Mercury release should not exceed 0.002 lb Hg/ton of solid waste. Wet scrubbers remove mercury by condensing, but sludge requires treatment.

[d] RCRA requires 99.9999% destruction and removal efficiency.

[e] Approximately equivalent to 70 nanograms per normal cubic meter (ng/Nm^3) (EPA). One nanogram = one billionth of a gram. A limit of 30 ng/m^3 has been proposed.

Residue Management

Incinerator ash and fly ash leaving the furnace (collected by scrubber, baghouse, electrostatic precipitator) may contain various concentrations of hazardous pollutants. These may require treatment and disposal so as not to endanger the public health or the environment. Concentrations of pollutants in incinerator bottom ash and fly ash will be determined by the characteristics of the waste burned, plant design, operation, efficiency of air cleaning devices, and other factors. It should also be noted that the EPA does not consider ash from an incinerator burning residential solid waste a hazardous waste, even though it may contain some metals.

To minimize the potential for the release of leachate from incinerator ash, there is a trend toward stabilization of the ash by cementing, vitrification, or asphalting. Recycling of ash into a useful material is the preferred solution.

Prevention of hazardous leachate is the goal. Up to 30 percent ash, by weight, can be used as an additive to cement for building materials and solidification in ceramics or glass. Incinerator bottom ash can be mixed with fly ash and lime from a dry scrubber. When properly moistened, the resultant ash–lime mixture will form a pozzolanic-like cement in which the metals are immobilized and cannot leach out under normal conditions. It can be used as a road base or for similar purposes.

It is recommended that bottom and fly ash, if not reused, be disposed of in a properly designed and constructed sanitary landfill with a double liner or a dedicated monofill. Bottom ash alone or bottom ash combined with fly ash may be disposed of in a sanitary landfill with a single liner. Control of dioxin, cadmium, and lead in ash is the major concern. The preferred landfill design would have two liners with groundwater monitoring and leachate collection above and between the liners, or the equivalent, to prevent the migration of hazardous leachate into groundwater.

Site Selection, Plant Layout, and Building Design

It is extremely important that a careful investigation be made of the social, physical, and economic factors involved when incineration is proposed. Some of the major factors are the following:

1. Public acceptance in relation to the surrounding land use and precautions to be taken in location and design to offset public objections should be considerations. A location near the wastewater treatment plant, for example, may meet with less objection. Heat utilization for sludge drying or burning and use of treated wastewater for cooling are possibilities.
2. Site suitability in reference to foundation requirements, prevailing winds, topography, surface water and groundwater, floods, adjacent land uses, and availability of utilities should be considered. A location central to the source of wastes for minimum haul distance and smooth movement of traffic in and out of the site and readily accessible to major highways without interrupting traffic are important considerations.
3. Plant layout should be arranged to facilitate tasks to be performed and provide for adequate space, one-way traffic, parking, paving, drainage, and equipment maintenance and storage.
4. Building design should be attractive and provide adequate toilets, showers, locker room, and lunchroom. A control room, administrative offices, weighmaster office, maintenance and repair shops, and laboratory should be included. Adequate lighting contributes to attractiveness, cleanliness, and operating efficiency. Good landscaping will promote public acceptance.

5. Also to be evaluated are the availability and cost of providing electric power, water supply, sanitary sewers, and pretreatment required before plant wastewater can be discharged to the sewer and availability of storm sewers, telephone, and fuels.
6. The proposed method and cost of handling bulky and nonincinerable wastes should be taken into consideration when incineration is proposed. Also to be determined are the location and size of the sanitary landfill and its ability to receive incinerator residue as well as the bulky and nonincinerable solid wastes that are not recycled.
7. The incinerator design should provide for resource and energy recovery to the extent feasible.

The reader is referred to Chapter 2 for the broad aspects of community and facility planning and environmental impact analysis.

Issues in the Implementation of Incineration Facilities

The principal issues associated with the use of the incineration facilities for the transformation of MSW are related to (1) siting, (2) management of emissions, (3) public health, and (4) economics. Unless the questions related to these issues are resolved, implementation of solid waste incineration facilities will continue to be an uphill battle. These subjects are introduced briefly below.

Siting As with the siting of MRFs, discussed previously, 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 or at the landfill site.

Management of Emissions The operation of incineration facilities, as noted previously, results in the production of a variety of emissions, including (1) gaseous and particulate emissions, many of which are thought to have serious health impacts; (2) solid residuals, including bottom ash, fly ash, and scrubber product; and (3) liquid emissions, which can result from one or more of the following sources: wastewater from the ash removal facilities; effluent from wet scrubbers; wastewater from pump seals, cleaning, flushing, and general housekeeping activities; wastewater from treatment systems used to produce high-quality boiler water; and cooling tower blowdown. The demonstrated ability to control these emissions from an incineration facility effectively is of fundamental importance in the siting of incineration facilities. The proper design of control systems for these emissions is a critical part of the design of incineration facilities. In some cases, the cost and complexity of the environmental control system(s) are equivalent to or even greater than those of the combustion facilities.

Public Health Issues Emissions from a modern, properly designed and operated incineration facility are considered to be of little, if any, health significance but are perceived by some to be a serious hazard. The evidence is not conclusive as emissions are widely dispersed and their effects are difficult to evaluate. Nevertheless, pollution controls to prevent accidental emissions must be ensured. Sensitive individuals who have been exposed to high concentrations of dioxin have developed chloracne, a persistent skin dermatitis, and suffered liver and other disorders. Birth defects and cancer have not been demonstrated. Additional studies are needed to better identify and measure the effects of air pollutants inhaled and the effects of fallout. The significance of the types and amounts of pollutants and their persistence in the environment remain to be clarified.

Economics The economics of incineration must be evaluated carefully to choose between competing systems. The least expensive operation for a particular community would be determined by comparing the total annual cost, including operating costs and fixed charges on the capital outlay, for each method. It will generally be found that, for large cities, three-shift operation will be the least expensive. The two- or one-shift operation will be somewhat cheaper for the smaller community. The relative cost of maintenance, however, will be higher and the efficiency poor because of startup and shutdown of the furnace, with accompanying refractory brick spalling due to differential expansion and air pollution from fly ash. 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.

HAZARDOUS WASTES

The identification and management of hazardous waste have become a major environmental undertaking and are the subject of a number of textbooks and numerous reference books. The purpose here is to introduce the subject of hazardous waste management. Topics to be considered include (1) definition of hazardous waste, (2) a review of pertinent legislation, (3) the generation of hazardous wastes, and (4) an introduction to hazardous waste management. Additional details may be found in LaGrega et al. (2001).

Definition of Hazardous Waste

Under the RCRA of 1976, the term *hazardous waste* means a solid waste, or combination of solid wastes, that, because of its quantity, concentration, or physical, chemical, or infectious characteristics, may

1. cause or significantly contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illness or
2. pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of or otherwise managed.

Hazardous wastes include chemical, biological, flammable, explosive, and radioactive substances. They may be in a solid, liquid, sludge, or gaseous (contained) state and are further defined in various federal acts designed to protect the public health and welfare, including land, air, and water resources.

A waste is regarded as hazardous if it is lethal, nondegradable, and persistent in the environment, can be magnified biologically (as in food chains), or otherwise causes or tends to cause detrimental cumulative effects. The EPA lists four characteristics of hazardous wastes:

1. *Ignitability*—wastes that pose a fire hazard during routine management. Fires not only present immediate dangers of heat and smoke but also can spread harmful particles (and gases) over wide areas.
2. *Corrosivity*—wastes requiring special containers because of their ability to corrode standard materials or requiring segregation from other wastes because of their ability to dissolve toxic contaminants.
3. *Reactivity* (or explosiveness)—wastes that, during routine management, tend to react spontaneously, react vigorously with air or water, are unstable to shock or heat, generate toxic gases, or explode.
4. *Toxicity*—wastes that, when improperly managed, may release toxicants in sufficient quantities to pose a substantial hazard to human health or the environment. Toxic wastes are harmful or fatal when ingested or absorbed. When toxic wastes are disposed of on land, contaminated liquid may drain (leach) from the waste and pollute groundwater. Toxicity is identified through a laboratory procedure called the toxicity characteristics leaching procedure, which replaces the extraction procedure leach test. Organic chemicals, metals, and pesticides regulated under the toxicity rule are reported in Table 5-25.

Not included in RCRA hazardous waste regulations are domestic sewage, irrigation waters or industrial discharges permitted under the federal Water Pollution Control Act, certain nuclear materials as defined by the Atomic Energy Act, household wastes (including toxic and hazardous waste), certain

TABLE 5-25 Organic Chemicals, Metals, and Pesticides Regulated Under RCRA Toxicity Characteristic Rule[a]

New Constituents	Regulatory Levels[b] (mg/l)	Old EP Constituents	Regulatory Levels[c] (mg/l)
Benzene	0.50	Arsenic	5.0
Carbon tetrachloride	0.50	Barium	100.0
Chlordane	0.03	Cadmium	1.0
Chlorobenzene	100.0	Chromium	5.0
Chloroform	6.0	Lead	5.0
m-Cresol	200.0[d]	Mercury	0.2
o-Cresol	200.0	Selenium	1.0
p-Cresol	200.0	Silver	5.0
1,4-Dichlorobenzene	7.5	Endrin	0.02
1,2-Dichloroethane	0.50	Lindane	0.4
1,1-Dichloroethylene	0.70	Methoxychlor	10.0
2,4-Dinitrotoluene	0.13[e]	Toxaphene	0.5
Heptachlor (and its hydroxide)	0.008	2,4-Dichlorophenoxycetic acid	10.0
Hexachloro-1,3-butadiene	0.5	2,4,5-Trichlorophenoxy propionic acid	1.0
Hexachlorobenzene	0.13[e]		
Hexachloroethane	3.0		
Methyl ethyl ketone	200.0		
Nitrobenzene	2.0		
Pentachlorophenol	100.0[f]		
Pyridine	5.0[e]		
Tetrachloroethylene	0.7		
Trichloroethylene	0.5		
2,4,5-Trichlorophenol	400.0		
2,4,6-Trichlorophenol	2.0		
Vinyl chloride	0.20		

Source: U.S. EPA (1990).

[a] Based on the Toxicity Characteristics Leaching Procedure (TCLP)

[b] Added in 1990.

[c] Based on old Extraction Procedure (EP) leach test

[d] If o-, m-, and p-Cresol concentrations cannot be differentiated, the total cresol concentration is used. The regulatory level for total cresol is 200.0 mg/L.

[e] Quantification limit is greater than the calculated regulatory level. The quantification limit, therefore, becomes the regulatory level.

[f] The agency will propose a new regulatory level for this constituent, based on the latest toxicity information.

mining wastes, agricultural wastes (excluding some pesticides), and small-quantity wastes from businesses generating fewer than 220 lb of hazardous waste per month.

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), as amended in 1986, defines hazardous substances as used in the Clean Air Act and the Clean Water Act (federal Water Pollution Control Act). The Department of Transportation, the Food and Drug Administration, the Occupational Safety and Health Administration, and the Consumer Product Safety Commission also define toxic or hazardous substance exposure.

Legislation

The RCRA of 1976, as amended, expands the purposes of the Solid Waste Disposal Act of 1965. It promotes resource recovery and conservation and mandates government (federal and state) control of hazardous waste from its point of generation to its point of ultimate disposal, including a manifest identification and permitting system. Legislation was prompted by the serious dangers associated with the improper handling and disposal of hazardous waste. The most common problems associated with the disposal of hazardous waste, in addition to public opposition, are groundwater pollution from lagoons, landfills, dumps, sludge disposal, other land disposal systems, spills, and unauthorized dumping.

1984 RCRA Ammendments In 1984, the RCRA was amended to require double liners or the equivalent and leachate collection systems at hazardous waste surface impoundments and landfills. Variances from groundwater monitoring to characterize the water quality before, during, and after operation are not allowed. The Act as amended in 1984 applies to generators producing as little as 220 lb (100 kg) of hazardous waste in a calendar month, which must be sent to a state or federal approved facility.

The RCRA as amended also prohibits land disposal of certain classes of untreated hazardous wastes beyond specified dates unless it can be demonstrated to the EPA that there will be no migration of hazardous constituents from the land disposal unit for as long as the wastes remain hazardous. Land disposal includes landfill, surface impoundment (treatment and surface storage), waste pile, injection well, land treatment facility, salt dome or salt bed formation, and underground mine or cave.

It should be noted that domestic wastewater, any mixture of domestic wastewater and any other waste that passes through a sewer system to a publicly operated treatment works (POTW) for treatment, and industrial wastewater discharges that are point-source discharges subject to NPDES permits are not considered to be solid or hazardous wastes. The POTW is then responsible to ensure that discharges to its sewers or plant do not contravene its NPDES permit or interfere with plant operation or sludge management.

Comprehensive Environmental Response, Compensation, and Liability Act of 1980 CERCLA (Superfund) regulates leachate and other releases of hazardous substances from inactive and abandoned hazardous waste sites or from sites operating prior to November 1980. Businesses that produce between 220 and 2000 lb of hazardous wastes in a calendar month are also regulated.

Most of the existing hazardous waste sites were created by the petroleum and chemical industries. Some municipal landfills received mixed solid waste, including toxic and hazardous commercial and industrial waste, in addition to small quantities of household cleaners, solvents, and pesticides. The result was pollution of the soil, groundwater, and surface water due to the infiltration and percolation of rain and snow melt, dissolution, and migration in the waste. In addition, toxic gases could be released from evaporating liquids, sublimating solids, and chemical reactions. CERCLA comes into play when hazardous waste sites are identified and classified.

The federal government can require the "person" who generated or transported the waste or owned or operated the disposal site to clean up the site. If a responsible person cannot be found, the federal government can perform the cleanup using a special fund (Superfund) established mainly by a tax on chemical production. Under such circumstances, states are required to contribute 10 percent of the cost of the cleanup. The federal and state governments may recover the cost, if the responsible person can be found.

Toxic Substances Control Act of 1976 The Toxic Substances Control Act (TSCA) of 1976 regulates the production, use, and disposal of chemical substances that may present an unreasonable risk of injury to health or environment. Manufacturers must give notice of plans to produce a new chemical or market a significant new use for an old chemical; they may be required to provide and keep records and reports.

Other Laws Other laws controlling hazardous substances are:

Clean Air Act (EPA)—regulates the emission of hazardous air pollutants.

Clean Water Act (EPA)—regulates the discharge of hazardous pollutants into the nation's waters.

Marine Protection, Research, and Sanctuaries Act (EPA)—regulates waste disposal at sea.

Occupational Safety and Health Act (OSHA)—regulates hazards in the workplace, including worker exposure to hazardous substances.

Hazardous Materials Transportation Act (Department of Transportation)—regulates the transportation of hazardous materials.

Atomic Energy Act (Nuclear Regulatory Commission)—regulates nuclear energy production and nuclear waste disposal.

Surface Mining Control and Reclamation Act (Department of the Interior)—regulates the environmental aspects of mining (particularly coal) and reclamation.

Priority Toxic Pollutants and Hazardous Wastes

Twenty-four toxic substances have been identified by the EPA, the Consumer Products Safety Commission (CPSC), the Food and Drug Administration (FDA), and the Occupational Safety and Health Administration (OSHA) for *joint* attack. The National Institute for Occupational Safety and Health (NIOSH) is also concerned with the control of toxic substances. The substances include acrylonitrile, arsenic, asbestos, benzene, beryllium, cadmium, chlorinated solvents (trichloroethylene, perchloroethylene, methylchloroform, and chloroform), chlorofluorocarbons, chromates, coke oven emissions, diethylstilbestrol (DES), dibromochloropropane (DBCP), ethylene dibromide, ethylene oxide, lead, mercury and mercury compounds, nitrosamines, ozone, polybrominated biphenyls (PBBs), polychlorinated biphenyls (PCBs), radiation, sulfur dioxide, vinyl chloride and polyvinyl chloride, and toxic waste disposals that may enter the food chain. Initially, the EPA listed 129 specific toxic pollutants, as reported in Table 5-26, for priority action.

Although legislation is very important, control also requires consideration of the social, political, and economic impacts of hazardous materials, in addition to health and environmental factors. Continual surveillance of spills and existing and abandoned waste sites for the present and for as long as the waste remains hazardous will be necessary.

Generation of Hazardous Waste

The major generators of hazardous waste among 15 industries studied by the EPA are as follows, more or less in order of the quantities produced:

- primary metals,
- organic chemicals,
- electroplating,
- inorganic chemicals,
- textiles,
- petroleum refining, and
- rubber and plastics.

Examples of hazardous waste types generated by businesses and industries are given in Table 5-27. Hazardous wastes that are characterized as ignitable,

TABLE 5-26 Original 129 Priority Toxic Pollutants Identified by Council on Environmental Quality

Pollutant	Characteristics	Sources	Remarks
Pesticides: Generally chlorinated hydrocarbons	Readily assimilated by aquatic animals, fat soluble, concentrated through food chain (biomagnified), persistent in soil and sediments	Direct application to farmland and forestland, runoff from lawns and gardens, urban runoff, discharge in industrial wastewater	Several chlorinated hydrocarbon pesticides already restricted by EPA; aldrin, dieldrin, DDT, DDD, endrin, heptachlor, lindane, chlordane
Polychlorinated biphenyls (PCBs): used in electrical capacitors and transformers, paints, plastics, insecticides, other industrial products	Readily assimilated by aquatic animals, fat soluble, subject to biomagnification, persistent, chemically similar to chlorinated hydrocarbons	Municipal and industrial waste discharges disposed of in dumps and landfills	TSCA ban on production after June 1, 1979 but will persist in sediments; restrictions on many freshwater fisheries as result of PCB pollution (e.g., lower Hudson, upper Housatonic, parts of Lake Michigan)
Metals: antimony, arsenic, beryllium, cadmium, copper, lead, mercury, nickel, selenium, silver, thallium, zinc	Nonbiodegradable, persistent in sediments, toxic in solution, subject to biomagnification	Industrial discharges, mining activity, urban runoff, erosion of metal-rich soil, certain agricultural uses (e.g., mercury as fungicide)	
Asbestos	May cause cancer when inhaled, aquatic toxicity not well understood	Manufacture and use as retardant, roofing material, brake lining, etc.; runoff from mining	
Cyanide	Variably persistent, inhibits oxygen metabolism	Wide variety of industrial uses	
Halogenated aliphatics: used in fire extinguishers, refrigerants, propellants, pesticides, solvents for oils and greases and dry cleaning	Largest single class of "priority toxics," can cause damage to central nervous system and liver, not very persistent	Produced by chlorination of water, vaporization during use	Large-volume industrial chemicals, widely dispersed, but less threat to environment than persistent chemicals

Ethers: Used mainly as solvents for polymer plastics	Potent carcinogen, aquatic toxicity and fate not well understood	Escape during production and use	Though some are volatile, ethers have been identified in some natural waters
Phthalate esters: Used chiefly in production of polyvinyl chloride and thermoplastics as plasticizers	Common aquatic pollutant, moderately toxic but teratogenic and mutagenic properties in low concentrations; aquatic invertebrates are particularly sensitive to toxic effects; persistent and can be biomagnified	Waste disposal vaporization during use (in nonplastics)	
Monocyclic aromatics (excluding phenols, cresols, and phthalates): used in manufacture of other chemicals, explosives, dyes, and pigments and in solvents, fungicides, and herbicides	Central nervous system depressant; can damage liver and kidneys	Enters environment during production and byproduct production states by direct volatilization; wastewater	
Phenols: large-volume industrial compounds used chiefly as chemical intermediates in production of synthetic polymers, dyestuffs, pigments, pesticides, and herbicides	Toxicity increases with degree of chlorination of phenolic molecule; very low concentrations can taint fish flesh and impart objectionable odor and taste to drinking water; difficult to remove from water by conventional treatment; carcinogenic in mice	Occur naturally in fossil fuels, wastewater from coking ovens, oil refineries, tar distillation plants, herbicide manufacturing, and plastic manufacturing; can all contain phenolic compounds	

TABLE 5-26 (*Continued*)

Pollutant	Characteristics	Sources	Remarks
Polycyclic aromatic hydrocarbons: used as dyestuffs, chemical intermediates, pesticides, herbicides, motor fuels, and oils	Carcinogenic in animals and indirectly linked to cancer in humans; most work done on air pollution; more is needed on aquatic toxicity of these compounds; not persistent and are biodegradable though bioaccumulation can occur	Fossil fuels (use, spills, and production), incomplete combustion of hydrocarbons	
Nitrosamines: used in production of organic chemicals and rubber; patents exist on processes using these compounds	Tests on laboratory animals have shown nitrosamines to be some of most potent carcinogens	Production and use can occur spontaneously in food cooking operations	

Source: Council on Environmental Quality (1978).

TABLE 5-27 Examples of Hazardous Waste Generated by Business and Industries

Waste Generators	Waste Type
Chemical manufacturers	Strong acids and bases, spent solvents, reactive wastes
Vehicle maintenance shops	Heavy-metal paint wastes, ignitable wastes, used lead acid batteries, spent solvents
Printing industry	Heavy-metal solutions, waste inks, spent solvents, spent electroplating wastes, ink sludges containing heavy metals
Leather products manufacturing	Waste toluene and benzene
Paper industry	Paint wastes containing heavy metals, ignitable solvents, strong acids and bases
Construction industry	Ignitable paint wastes, spent solvents, strong acids and bases
Cleaning agents and cosmetics manufacturing	Heavy-metal dusts, ignitable wastes, flammable solvents, strong acids and bases
Furniture and wood manufacturing and refinishing	Ignitable wastes, spent solvents
Metal manufacturing	Paint wastes containing heavy metals, strong acids and bases, cyanide wastes, sludges containing heavy metals

Source: U.S. EPA (1986).

corrosive, explosive, or toxic should be removed from industrial wastes prior to discharge to a municipal sewer. Many toxic wastes upset biological wastewater treatment processes and are transferred to the effluent and sludge, adding to the disposal problem.

Hazardous Waste Management

Hazardous waste management is a major health and environmental challenge. The ultimate *goal* should be "zero discharge." However, until that goal is approached, the elements of hazardous waste management that must be dealt with include (1) source reduction at the point of generation; (2) recycling both on- and off-site; (3) transportation to processing and/or disposal facilities; (4) treatment and processing to reduce or eliminate toxicity, to reduce the volume, and to immobilize contaminants; and (5) secure long-term storage and disposal. Each of these subjects is considered briefly in the following discussion. Details on hazardous waste management may be found on the EPA website and in LaGrega et al. (2001).

Hazardous Waste Reduction In plant waste, reduction measures can be most effective in reducing the air, liquid, and solid waste contaminants generated, and hence the treatment needed to meet disposal standards, with resultant cost savings. In addition, treatment can result in the recovery of valuable materials that can offset, in whole or in part, the cost of treatment. However, treatment to recover valuable materials may result in the production of other hazardous wastes, which in turn would require treatment and disposal.

Hazardous Waste Recycling Often it may not be possible to reduce the volume or toxicity of some hazardous wastes. However, it may be possible to reuse the waste material in other processes within the same facility or other related facilities. Hazardous wastes that may be recycled either directly or after processing include water, solvents, spent oils, and selected solids. To enhance the recycling of waste materials at other facilities, waste exchange clearinghouses have been developed to facilitate such exchanges. Information that is required for waste exchange programs includes company ID code, category (acid, solvent, cutting fluid, etc.), primary usable constituents, contaminants, physical state, quantity, packaging, and geographic location (LaGrega et al., 2001).

Hazardous Waste Transportation The transportation of hazardous wastes always introduces the possibility of accidental spills. Should this happen, the transporter is required to immediately notify the appropriate authorities (state police, environmental protection agency) and take whatever action is necessary to protect the public health and the environment. Information and advice on what to do and on the characteristics of the chemicals involved (see manifest) in an emergency is available 24 hr a day, 365 days a year, from the Chemical Emergency Center (CHEMTREC) operated by the Chemical Manufacturers Association. Their telephone number is 800-424-9300.

In case of fire or other emergency at a facility having hazardous materials, information concerning the site, materials, and precautions to be taken can be immediately obtained by response personnel from the National Oceanic and Atmospheric Administration (NOAA). A Computer-Aided Management Emergency Operations (CAMEO) system has been developed to facilitate immediate communication. More information is available from NOAA at 206-526-6317. Information availability is required by the Superfund Amendments and Reauthorization Act (SARA).

Hazardous Waste Processing Technologies The principal objectives of hazardous waste treatment are (1) toxicity reduction, (2) conversion to forms that can subsequently be processed by other technologies, (3) total elimination (e.g., complete destruction), (4) volume reduction, and (5) immobilization. Treatment technologies used to process hazardous wastes may be classified as (1) biological methods, (2) physicochemical processes, (3) stabilization and solidification, and (4) thermal destruction. The principal processes comprised by these technologies are reported in Table 5-28. Additional details on treatment methods for hazardous waste may be found in Dawson and Mercer (1986), U.S. EPA (1985, 1986, 1987b), and LaGrega et al. (2001),

Long-Term Storage of Hazardous Wastes So-called secure land burial and deep-well disposal under carefully controlled conditions, *where permitted*, are a last resort. In general, these types of disposal are strongly discouraged as they simply transfer the problem to another environmental media and must be monitored for the life of the hazardous waste. Some hazardous wastes, both solid and liquid, may be temporarily stored in clay, asphalt, concrete, soil cement, or (sodium) bentonite–soil lined basins, or in polymeric membrane lined basins, pending a decision on the best methods for treatment and disposal. Membrane linings are made of special rubber, polyethylene, polyolefin, polychloroprene, and polyvinyl chloride. All are usually suitable for wastewater and biodegradable industrial wastes. However, solvents, strong acids and caustics, and brines could damage clay or soil-based linings. Benzene and toluene, for example, are not contained by a clay liner, but when mixed with a small proportion of water and placed in a landfill, clay remains a good barrier. These chemicals, including pesticides, are best destroyed by controlled incineration. Petroleum-based organic wastes could damage some polymeric membranes and asphaltic materials. Carbon tetrachloride and xylene cause soil dehydration and possible cracking of clay soil. Clay liners must be carefully constructed with concern for lift thickness, soil moisture, type and weight of roller and number of passes, soil texture, and dry density to achieve the required permeability.

In view of the many limitations, *wastes and lining materials should be tested for effectiveness and compatibility before use*. In any case, all liners should be carefully placed on well-compacted subbases and, in addition, all basins storing hazardous wastes should incorporate a groundwater monitoring and surveillance system, including a leachate collection system and peripheral well monitoring. Two layers of linings with intermediate collection systems to collect possible leachate percolation and a groundwater monitoring system are required by the EPA. It can be assumed that all liners, cutoff walls, or other containments will eventually leak to some degree. Storage should be considered a temporary expedient. In all cases, strict compliance with approved design and construction specifications, and continuous professional inspection during construction must be ensured.

Monitoring of the air, surface water, and groundwater for as long as the waste remains a threat to the public health and the environment is an essential component of any site. Surface-water runoff and groundwater would be monitored for organic and inorganic chemicals. The air would be monitored for odors, volatile organics, and indicated toxic chemicals.

TABLE 5-28 Typical Treatment Methods for Hazardous Wastes

Method	Typical Processes	Description
Biological methods	(1) Suspended growth processes (aerobic, anoxic, and anaerobic); (2) attached growth processes (aerobic, anoxic, and anaerobic); (3) combined suspended and attached growth processes (aerobic, anoxic, and anaerobic)	Biological processes are used to treat (1) liquids (contaminated groundwater, industrial process wastewaters, and landfill leachate); (2) slurries (sludges and contaminated soils with clean or contaminated water); (3) solids (contaminated soils); and (4) vapors (from other treatment processes).
Physicochemical processes	(1) Carbon adsorption; (2) chemical oxidation; (3) gas stripping; (4) steam stripping; (5) membrane separation; (6) supercritical fluids extraction and supercritical water oxidation	Granular activated carbon adsorption is used for the sorption of organic compounds from liquids. Powdered activated carbon is typically used in conjunction with the activated sludge treatment process. Chemical oxidation is used to detoxify a wide array of organic compounds. Stripping processes are used to remove volatile and semivolatile organics from industrial process waters. Membrane separation is used to remove contaminants from a variety of process waters and liquids. Supercritical fluids extraction and supercritical water oxidation are used to remove organics from water, sediments, and soil.
Stabilization and solidification	(1) Cement-based solidification; (2) pozzolan-based aggregate; (3) thermoplastic; (4) organic polymers	Stabilization and solidification processes are used for the (1) treatment of industrial wastes; (2) treatment of a variety of wastes, including incinerator bottom and fly ash, before placement in a secure landfill; and (3) treatment of large quantities of contaminated soil. These processes are all used to immobilize hazardous waste contaminants.
Thermal methods	(1) Vapor, liquid, and solid combustion; (2) catalytic volatile organic chemical (VOC) combustion; (3) fluidized-bed incinerators; (4) pyrolysis reactors	Thermal processes are used to destroy organic fraction of hazardous waste contaminants found in all types of waste streams, including gases and vapors, liquids, slurries, and solids.
Land disposal	(1) Municipal landfills; (2) monofill landfills; (3) land farming; (4) impoundment and storage facilities; (5) deep-well injection	The objective of land disposal is to ensure that wastes placed in such facilities do not migrate off-site. In land framing the objective is to bring about natural and biological decay of hazardous waste materials. The problem with deep-well injection is that the final location of the injected wastes is unknown.

Source: Adapted in part from LaGrega et al. (2001).

Basic Control Principles for Hazardous Waste Management As with most air, water, solid waste, and other pollution control activities, certain general and basic control principles can also be applied, as appropriate, to hazardous wastes. These include the following:

1. Elimination and reduction of waste at the source by prevention of leakage, segregation of hazardous waste, product reformulation, process or materials change, good housekeeping practices, and inventory control.
2. Recovery, reuse, and recycling of wastes, including return to the manufacturer, energy recovery, and waste exchange among compatible industries.
3. Concentration of waste by treatment—centrifugation, coagulation, sedimentation, filtration, flotation, surface impoundment, distillation, reverse osmosis, precipitation, solidification, encapsulation, evaporation, electrodialysis, absorption, or blending.
4. Thermal decomposition—controlled high-temperature incineration and proper disposal of residue, also ocean incineration. Incinerators used include refractory lined, fixed hearth (controlled air), rotary kiln, cement kiln furnace, and fluidized bed.
5. Chemical treatment—chemical oxidation, precipitation, reduction, neutralization, chlorination, pyrolysis, detoxification, ion exchange, absorption, or chemical dechlorination processes.
6. Burial in a secure landfill; storage or containment with proper monitoring and surveillance (may be banned by the EPA or state).
7. Biological degradation; activated sludge, lagoon, or other biological treatment.
8. Stabilization, solidification, or encapsulation; also in-place vitrification on-site.
9. Deep-well, mine, and ocean disposal under controlled conditions and if permitted; possibly composting and microwave decomposition. Ocean disposal of sludge has been banned effective December 31, 1991, but this prohibition is being reevaluated.

The methods available are not always completely effective and must be tailored to specific contaminants.

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