WASTE MANAGEMENT, SOLID

1. Introduction

Solid waste management has evolved significantly in the past century. Although the practice initially targeted collection and disposal of household garbage from big cities, since the 1970s, recycling and ideas regarding reuse started to gain attention. It is essential to mention that this article will include discussion on nonhazardous solid waste only, which include both municipal and industrial waste. Information regarding identification of hazardous waste will be included to help identify the line of demarcation between hazardous and nonhazardous waste. Infectious waste, also known as biohazardous waste, is in many instances, considered as "nonhazardous", and hence will be discussed in this article. Advancements in environmental science, pollution related health problems, and better understanding regarding finiteness of mineral and energy resources helped increase public awareness regarding environmental issues. In the early days of solid waste management, land disposal and incineration were the only options. As mentioned earlier, since the 1970s, recycling was gaining wider acceptance as good management practice. Initially, to minimize waste generation, emphasis was put on the practice of three R's: reduction, reuse, and recycle. Accordingly, a waste reduction hierarchy was developed, the goal of which was to reduce waste through three R's and incineration. At present all these concepts and goals have been consolidated under a new management practice known as integrated solid waste management (ISWM). Although ISWM lack a widely accepted definition, its primary goal is to choose a combination of elements from the hierarchy that will minimize energy use, environmental impact and landfill space use at a cost, affordable to a community or a region that adopts the concept. It is possible that for a particular community at a particular time the best possible combination, in terms of affordability, may be recycling part of the waste stream (eg, paper and plastics from garbage), reusing another part (eg, beneficial reuse of foundry sand), and segregating a third part (eg, source separating infectious waste and noninfectious waste in hospitals). Nevertheless, the goal should be to develop an affordable system, which minimizes energy use and reduces discarded waste going to landfills.

Many communities and companies are adopting a new concept of "zero waste"; concerns for global warming and sustainable development are the driving forces. It is a philosophy that includes recycling, but goes beyond recycling by taking a whole system approach. The concept looks at overall picture of consumption and disposal. Even 100% reuse and recycling creates quite a significant volume of waste during mining and manufacturing of goods delivered to the consumers. Industries, governmental bodies, and citizenry need to work together to implement the following key elements for achieving the goal of zero waste (1): (a) investment in community for waste reduction and resource recovery; (b) citizen's participation in recycling; (c) product redesign to make it nontoxic and reusable after useful life; (d) extension of producer's responsibility beyond initial sale that will enhance buy back programs; and (e) end of subsidies to enterprises that uses virgin resources only.

At a local level, the designer for a ISWM practice must choose proper elements so that ultimately the goal of zero waste is achieved. A successful ISWM program should include both short- and long-term goals.

This article discusses ISWM programs at a local level; discussion on policies and programs at state, national or international level is beyond the scope of this article. Ideally, an ISWM program consists of the following items: (*1*) identification and characterization of waste sources; (*2*) development of efficient waste collection system; (*3*) reduction of volume and toxicity of waste; (*4*) disposal arrangement; and (*5*) program optimization.

Issues associated with each of the above items are different. Optimization of the program must include, in addition to the above four items, applicable environmental regulation, community needs and funding. Although important, currently (to the best of author's knowledge) ISWM program optimization is not undertaken at local levels. At a local level, reduction of waste volume and its toxicity are of primary interest. Since ISWM program optimization is not in practice, this article includes subsections to address only first four of the five items mentioned above. The discussion of program optimization is beyond the scope of this article.

2. Identification and Characterization of Waste Sources

For proper management, each waste source must be identified and characterized. Separation of various waste types generated from a waste source will reduce management costs significantly.

Table 1. **Typical Range of Major Components of Municipal Garbage in the United States**[a]

Sl number	Major components	Range (% of weight)
1	food waste	4.4–15.3
2	garden waste	12.5–24.2
3	glass	6.5–10.9
4	metals (iron and aluminum)	4.0–9.0
5	moisture	27.1–35
6	other combustible	1.6–12.1
7	other noncombustible	1.8–11.1
8	paper	41.6–53.5
9	plastics	0.76–5.7

[a]Reprinted with permission from Ref. 2.

2.1. Identification of Waste Sources. In a community, there are two main categories of solid waste: municipal and industrial. Municipal solid waste (MSW) is generated primarily from three different sources: households, commercial establishments, and health care and bioresearch institutions (commonly termed as medical or biohazardous waste). Although composition and characteristics of each of these sources are different, all sources include both biodegradable and nonbiodegradable fractions. A small volume of hazardous waste is found in all three sources. In addtion to hazardous waste, medical waste contains a small percent of low level radioactive waste.

Household Waste. Household wastes are generated from multifamily apartment buildings and single-family houses. A typical composition of household garbage is indicated in Table 1 (2). The composition of household waste has locational as well as seasonal variation. Recycling efforts also influence waste composition. In general, household hazardous waste and electronic waste (e-waste) from single and multifamily dwellings are allowed to be disposed in landfills.

Commercial Waste. Composition of waste from commercial establishments is similar to household waste, with the exception that it may contain a significant volume of food waste and e-waste. It is estimated that food waste is 30% of waste generated in restaurants. Although commercial waste is similar to household waste, there may be additional disposal restrictions on commercial waste. For example, commercial establishments are usually not allowed to dispose hazardous waste and e-waste along with other wastes.

Medical or Biohazardous Waste. Medical waste refers to all wastes generated in hospitals and clinics (for both humans and animals), nursing homes, laboratories for clinical testing of blood, body fluid and tissues, and laboratories that use various microorganisms for research purposes. Wastes generated in these institutions have several components, each with distinct characteristics; Figure 1 shows management options for these wastes (2). The fraction of the waste, which is similar to household waste, may be managed as household municipal waste. However, this waste fraction must be separated at source to manage as municipal waste.

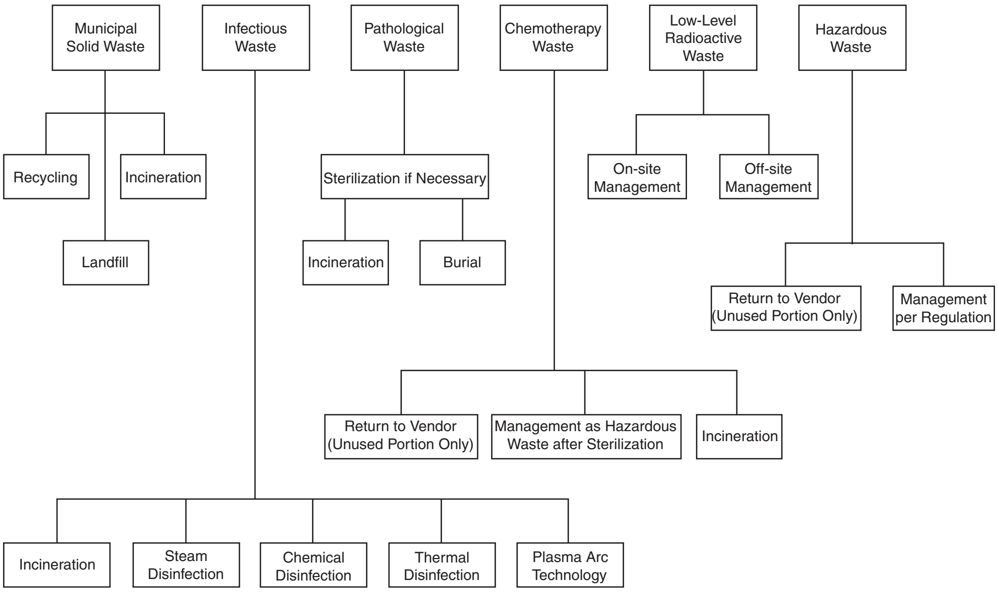

Fig. 1. Management options for biohazardous waste. (Reprinted with permission from Ref. 2.)

Infectious Waste. Infectious waste is solid waste that contains pathogens with sufficient virulence and in sufficient quantity, exposure of which by a susceptible human or animal will cause disease. The waste generated in medical institutions is 10–15% infectious waste. Infectious waste may be subdivided into: sharps (eg, needles, scalpel blades), waste containing microorganisms and pathogens (eg, bodily fluid, blood soaked towels), and pathological waste (eg, discarded body parts from operating rooms). Pathological wastes are incinerated. Several treatment options are available (eg, microwave, autoclave) for the other two waste categories.

Chemotherapy Waste. Most drugs used for chemotherapy are mutagenic, teratogenic, and/or carcinogenic to both humans and animals. Several chemotherapy drugs (also known as antineoplastic drugs) are listed as toxic by the U.S. Environmental Protection Agency (EPA). Chemotherapy waste (eg, bottles and tubing used for drug administration, gloves) is generated during patient treatment. Chemotherapy waste also includes unused portions of drugs and drug mixtures, and expired drugs. Depending on the amount of remaining chemicals, regulators may allow management of this waste as nonhazardous waste. In many instances, chemotherapy waste is incinerated.

Hazardous Waste. Many of the chemicals used as drugs and in research laboratories are hazardous. Hazardous waste management regulations apply to this waste type.

Low Level Radioactive Waste. Few of the drugs and chemicals used in healthcare and research institutions contain radionuclides, mostly with a half-life of 90 days or less. If stored in a secured place until the radioactivity reduces to background level, this type of waste may be permitted to be disposed with

MSW. However, the disposal of low level radioactive waste should be discussed with appropriate regulatory agencies.

2.2. Waste Characterization. Since regulations for hazardous and nonhazardous waste are different, it is important to identify these two waste types from a source. Further identification of waste categories, within a waste type, is necessary for proper management and/or treatment. For example, nonhazardous solid waste may contain recyclable items (eg, paper, plastics) that need to be separated at the source for easy management. Municipal waste composition study, commonly known as waste sort, is undertaken to estimate the various materials fractions present in a waste stream. Table 2 includes a typical leachate characteristic of MSW (2).

In general, characterization of industrial waste is done to find out whether the waste is hazardous. Identification of hazardous waste is done through listing and characteristic tests, namely, corrosivity, toxicity characteristics leaching procedure (TCLP) test, ignitability, and reactivity. It may be noted that a nonhazardous waste, if mixed with hazardous waste, is to be managed as hazardous waste. So, comingling of hazardous waste with nonhazardous waste must be avoided to minimize the cost of managing the waste.

The waste characterization information provided in this section are primarily for industrial waste. The material safety data sheet identifying the chemicals used in the process is studied to obtain information regarding probable constituents of the waste, which helps to narrow the list of parameters for chemical analysis. The next step is to study the process flow diagram to identify waste streams. Many industries practice in-house recycling of waste. Only those waste streams that leave the facility are characterized. A typical flow diagram is shown in Figure 2 (2). The waste stream(s) leaving the facility are sampled. The sampling is done in such a way that the test data reflects the correct characteristics of the waste. Both frequency and sample volume are important for proper characterization. Sampling protocols for various waste types are found in American Society for Testing and Materials (ASTM) standards (eg, D346-75 for crushed or powdered waste). Two types of chemical tests are done on each waste stream: bulk chemical analysis and leach test.

Bulk Chemical Analysis. The aim of bulk chemical analysis is to determine the chemical makeup of the waste. In a bulk chemical analysis, waste constituents are solubilized and identified in such a way that the sum total of all constituents is 99.99% of the bulk weight of the sample. Bulk chemical analysis is necessary for the following reasons:

1. To determine the total contaminant content of the waste.
2. To assess the contamination potential of the waste.
3. To develop a baseline for comparing the waste with other waste or natural materials.
4. To develop a list of parameters for leach test.

Leach Test. Leach test provide information regarding pollutants that may leach out of the waste and their probable concentration. Leaching media is decided based on disposal scenario. For example, for monofills water leaching

Table 2. **Range of Concentration of Different Parameters in Leachate of Municipal Waste**[a]

Sl number	Parameter	Range of concentration (mg/L except as indicated)
1	TDS[b]	584–55,000
2	specific conductance	480–72,000 μmho/cm
3	total suspended solids	2–140,900
4	BOD[c]	ND-195,000
5	COD[d]	6.6–99,000
6	TOC[e]	ND-40,000
7	pH	3.7–8.9 units
8	total alkalinity	ND-15,050
9	hardness	0.1–225,000
10	chloride	2–11,375
11	calcium	3.0–2,500
12	sodium	12–6010
13	total Kheldahl nitrogen	2–3,320
14	iron	ND-44,000
15	potassium	ND-3,200
16	magnesium	4.0–780
17	ammonia–nitrogen	ND-1,200
18	sulfate	ND-1,850
19	aluminum	ND-85
20	zinc	ND-731
21	manganese	ND-400
22	total phosphorus	ND-234
23	boron	0.87–13
24	barium	ND-12.5
25	nickel	ND-12.5
26	nitrate–nitrogen	ND-250
27	lead	ND-14.2
28	chromium	ND-5.6
29	antimony	ND-3.19
30	copper	ND-9.0
31	thallium	ND-0.78
32	cyanide	ND-6
33	arsenic	ND-70.2
34	molybdenum	0.01–1.43
35	tin	ND-0.16
36	nitrite–nitrogen	ND-1.46
37	selenium	ND-1.85
38	cadmium	ND-0.4
39	silver	ND-1.96
40	beryllium	ND-0.36
41	mercury	ND-3.0
42	turbidity	40–500 Jackson units

[a]Reprinted with permission from Ref. 2.
[b]Total dissolved solids (TDS).
[c]Biological oxygen demand (BOD).
[d]Chemical oxygen demend (COD).
[e]Total organic carbon (TOC).

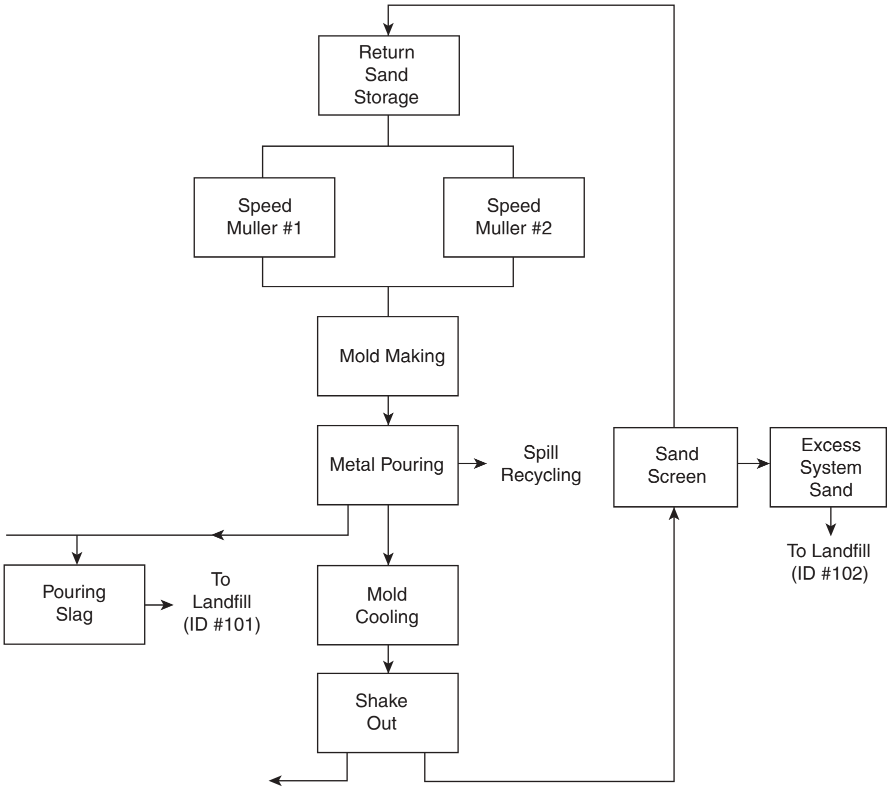

Fig. 2. Typical flow diagram used for identifying waste sampling points. (Reprinted with permission from Ref. 2.)

may be appropriate; however, if the waste is codisposed with MSW then acidic leaching media is recommended. There is no internationally accepted standard leach test protocol. In the United States, several leach tests are used; each uses a different leaching media and protocol.

In ASTM water leach test (D.3987-85) 1400-mL water (meeting the specification of D1193) is used to leach 70-g waste. The mixer is agitated for 18 h at 18–27°C in a vented watertight container. The extract is analyzed for required pollutants. The method is not suitable for organic, monolithic, and solidified waste.

In a toxicity characteristic leaching procedure (TCLP), promulgated by the EPA, for highly alkaline waste a 0.5 N acetic acid is used as leaching media and pH 5 acetate buffer is used for all other waste types. The elutriate is tested for a list of chemicals. Details of the test may be found elsewhere (3).

In a synthetic precipitation leachate procedure, choice of leaching media depends on landfill site location and whether leachability of cyanide and volatiles needs to be determined. Based on the above criteria, three different types of leaching media is used for this test: (*1*) Fluid 1: a 60:40 wt% mixture of sulfuric and nitric acid is mixed with necessary amount of reagent water (ASTM type II or equivalent) to achieve a pH of 4.2 + (−0.5). This leaching media is to be used for landfill sites located east of the Mississippi river in the United States. (*2*) Fluid 2: The composition is same as fluid 1 except that the pH is adjusted to $5.00 + (-0.05)$. This leaching media is to be used for landfills located west of Mississippi river, in the United States. (*3*) Fluid 3: ASTM type II reagent water. This leaching media is used to determine leachability of cyanide and volatiles from the waste. Details regarding the test may be found elsewhere (3).

In a multiple extraction procedure (MEP) the goal is to simulate 1000 years of freeze thaw cycles and prolonged exposure to leaching. The MEP may be used for liquid, solid as well as multiphase samples. A 24-h extraction is done using a liquid/liquid ratio of 16:1. The extraction is repeated until the concentration of target chemicals decreases. A better understanding of behavior for metals is obtained due to the removal of excess alkalinity caused by repeated extraction. Details of the test may be found elsewhere (3).

Physical Tests. Physical tests of waste are performed only when necessary landfill design related physical characteristics is completely unknown. Landfill designers need to use judgment when choosing a physical test. Physical tests for MSW are not routinely undertaken because of the extreme heterogeneity of the waste. In few cases, especially while studying a landfill slope failure, properties, such as compacted bulk density, permeability, consolidation, and strength characteristics, becomes necessary. Although standard soil testing methods may be used for testing waste (eg, foundry sand), difficulty arises when testing putrescible or industrial waste sludges.

3. Development of Efficient Waste Collection System

Collection systems are different for putrescible, recyclable, as well as industrial wastes. Although solid waste is mostly transported on road, transportation via waterways and railroads are also undertaken. In addition to municipal solid waste, construction and demolition (C&D) waste, ash, sludge are also transported via rail (4). Choice of proper vehicle and routing are two important issues for efficient collection.

Collection strategy for putrescible waste depends on type of dwelling (eg, individual homes vs. apartment buildings), size of community and population density, and suitable road for movement of collection vehicles. To reduce transportation costs to the final destination, waste collected by relatively smaller vehicles is delivered to a transfer station where it is consolidated into bigger vehicles and transported to either landfills or incinerators. For successful collection systems macro-routing, route balancing, and micro-routing are needed. Macro-routing helps choose a location of transfer station(s), which is most suitable for the destination (eg, landfills). Route balancing help develop boundaries of collection districts. Micro-routing helps in minimizing collection vehicle travel time and to identify a specific route a vehicle would undertake for collection of waste from individual homes, apartments and commercial establishments. The MSW is collected using one of the following three alternatives: (a) Source separated recyclable items (eg, plastics and paper are put in separate containers or bags) and nonrecyclable items (garbage) are collected separately, either in the same vehicle or using different vehicles. (b) Commingled recyclable items (eg, plastics, paper, and glass in one container) and garbage are collected separately, either in the same vehicle or using different vehicles. (c) Commingled recyclable items and garbage are put in one container or bag and collected in the same vehicle. In general, source separated individual or commingled recyclable items are “cleaner”, and hence may earn higher revenue.

Load limits on roads (due to bridges and culverts), allowable design load of roads and available funding are primary issues in choosing a vehicle size. In addition, the recyclable item collection strategies mentioned above influence vehicle design. Mainly three types of vehicles are used for residential collection: top loading, rear loading, and side loading. Waste and recyclables may be dumped manually in vehicles or robotic arms (automatic) are used for picking up and dumping wastes and recyclables in vehicles. Mostly rear loading automatic vehicles are used for commercial establishments. Vehicles for industrial waste collection, top or rear loading, are usually dedicated to one generation source within a manufacturing facility. For sludge type waste, the collection vehicles must be leakproof to avoid dripping of liquid while transporting. For dusty waste, either a turf to cover the waste, or closed container type vehicles are used.

4. Reduction of Volume and Toxicity of Waste

Volume and toxicity reduction are important for both land disposal and incineration of waste. Volume reduction help minimize landfill space use whereby the life of a landfill increases. Volume reduction also helps in minimizing design capacity of incinerators. However, reduction of most recyclable items (eg, paper) impacts the incinerability of waste, which may increase the operational cost of incineration. Toxicity reduction helps in reducing pollutant load in landfill leachate as well as in incinerator air emission.

4.1. Volume Reduction. The various options for reducing waste volume are recycling, incineration, composting, land spreading, and reuse of industrial by-products. Items, which are reused or recycled, depend on available technology, participation of community members, and cost of running the program. In addition, reuse is also practiced to reduce waste.

Recycling. With the improvement in technology, more items from MSW are being recycled. Proper planning and marketing strategies are needed for a sustained waste volume reduction program. Governmental agencies, community members, businesses, industries and consumers are all important role players for a successful recycling program. Governmental agencies (both national and state) have significant roles in developing recycling programs. Promulgation of recycling related laws and rules, funding for program initiation at the local level and research in universities and research institutes need to be undertaken by governmental agencies. Since use of recycled materials lead to reduction in energy use, pollution and natural resource use, many manufacturers are becoming more inclined in recycling. Currently, many manufactureres have initiated in-house and/or postconsumer recycling program. Environmental awareness of consumers plays a big role in increased use of recycled materials by businesses and manufacturers.

The following items are usually recovered from municipal solid waste: plastics, paper, glass, aluminum cans, metal and steel cans, electronic items, white goods (eg, refrigerators, air conditioners), and tires. In addition, construction and demolition wastes are also recycled.

Plastics. Mainly the following six types of resins are used in disposable packaging: polyethylene terephathalate (PET), high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinylchloride (PVC), polypropylene (PP), and polystyrene (PS). While PET is usually used to manufacture milk containers, laundry detergent containers are made of HDPE. After plastics are separated into various types based on resin content, each is chopped up and cleaned in detergent bath and reused in plastic making process. Resale value of all recycled plastics is not same.

Paper. Newspapers, corrugated paper and office paper are the three types of paper salvaged for recycling. Recycled papers are deinked before pulping. Holograms and glues are difficult to remove from papers. Market value of presorted paper is higher compared to mixed waste paper. Due to improved technology, currently market value of recycled paper pulp is close to that of virgin pulp.

Glass. Glass containers are usually manufactured using recycled glass. Nine gallons (34 L) of fuel oil is saved per ton of recycled glass (2). Market value of color separated glass is high. In addition to use in manufacturing, crushed glass may be used in bituminous road paving as well as in bedding for gas extraction pipes in landfills.

Aluminum. Aluminum cans recycling may save up to 95% energy. Melted aluminum cans are mixed with other materials to form a metal suitable for industrial use (5). Aluminum cans may be easily separated from commingled recycling materials. Market value of aluminum cans is high and usually remains steady throughout the year.

Steel Cans. Steel cans are used as containers for food, paint, various chemicals, etc. Separated metal and steel cans are flattened, bundled together, and transported to various industries for processing. Although the percentage of metals and steel cans is low in MSW, a big source of these is the scarp metal industry. Each ton of recycled scarp metal saves 2500 lb (1.13 ton) of iron ore. Seventy-five percent of energy may be saved in the steel making process by using scarp metal.

Electronic Items. If not recycled e-waste may cause significant pollution. There are many parts in electronic items which may generate hazardous waste. For example, cathode ray tubes (CRTs), contain lead, flat liquid-crystal display (LCD) monitors may contain mercury, etc. Currently, many industries have started buy-back programs to reduce pollution. However, a significant amount of e-waste is still discarded in landfills rather than being recycled.

White Goods. White goods, may contain polychlorniated diphenyls (PCBs) and chlorfluorocarbons (CFCs). Capacitors used in refrigerators, washing machines, etc. may contain PCBs that are known carcinogens. Refrigerants may contain CFCs that are linked to the depletion of the ozone layer. Use of CFCs in refrigerants has been reduced significantly. While recycling white goods, parts suspected of containing PCBs or CFCs are removed before baling or shredding. Steel and nonferrous metal (eg, copper), and lead are also separated before shredding. The CFCs and PCBs are rendered nonhazardous by chemical processes.

Tires. Whole tires tend to float toward the landfill surface due to buoyancy created by air and landfill gas trapped within the hollow spaces of tires. "Floated" tires crack landfill final covers, causing uncontrolled escape of landfill gas containing air pollutants and increase in generation of leachate due to infiltration of additional precipitation. Scarp whole tire stock piles cause rodent, snake, and mosquito problems. Tire stock piles that are >10 ft (3.05 m) in hight may catch fire releasing smoke and toxic chemicals. Waste tire recycling can eliminate these problems. Shredded waste tire may be used in coal fired utility furnaces. Shredded waste tires are also used to manufacture rubber goods (eg, floor mats). Pyrolysis of waste tires generate gas and oil. Whole waste tires are used to create fish habitat and crash barriers in highway bridges.

Incineration. Currently, in most cases, MSW is incinerated to recover energy. Although not common in the United States, waste-to-energy (WTF) facilities are widely used in Europe and Japan (6). In addition to MSW, sludge type waste (eg, waste water treatment plant sludge) are also incinerated. In a modern WTE facility, incineration of a ton of MSW will generate about one-sixth green house gas compared to landfills with methane recovery (7). Incinerability of MSW depends primarily on moisture content and heating value. However, the percentage of contaminants (eg, household hazardous waste) may influence decision regarding incineraion due to air emission standards and waste characteristics of the ash. For efficient operation of a WTE facility, waste loads must be within the design range. Figure 3 shows various types of MSW incinerators (8).

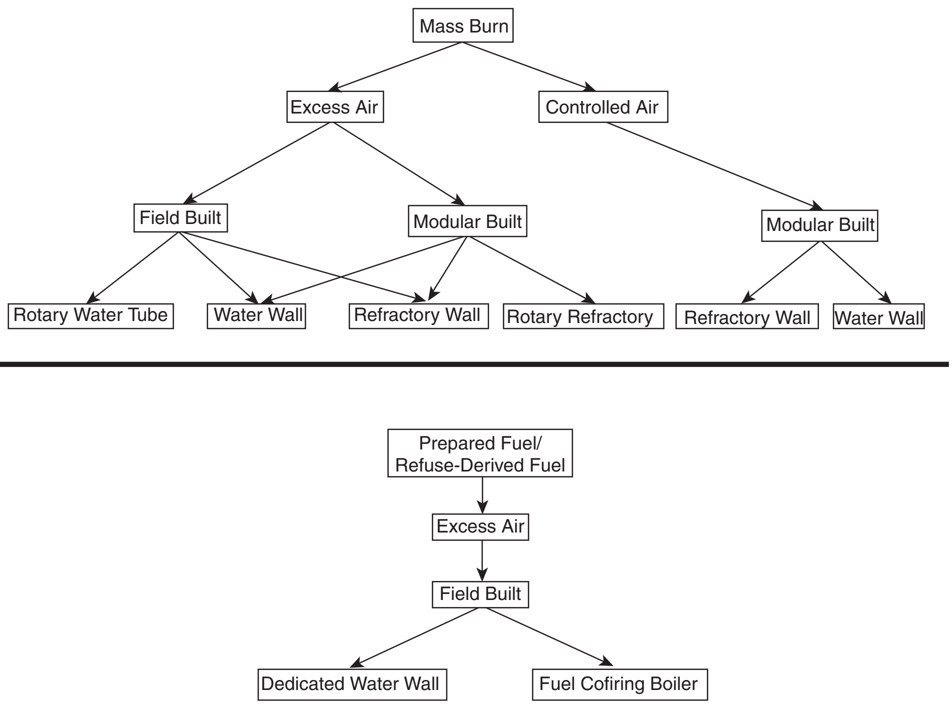

Fig. 3. Names of various types of MSW Incinerators. (From Ref. 8.)

Rotary kiln, controlled air incineration (both hydrolysis units and starved air units), fluidized beds and moving grate furnaces are used for MSW incineration. Multiple-hearth incinerators, conveyor furnaces, and cyclonic furnaces are used for sludge incineration. Air emission control and management of incinerator ash are important environmental issues for design and operation of WTE facilities.

The heating value of MSW destined for incineration must be high enough so that it may be used for WTE facilities. Since paper and plastics are two items with high heating value, removal or significant reduction of these items through successful recycling programs reduces quality of incinerable waste. In general, the environmental benefit of reuse, recycling and composting when combined, is much higher than reducing the waste volume through incineration.

Composting. Composting transforms organic matters into water carbon dioxide, energy, and a nutrient rich composted matter (suitable for plant growth) through biodegradation. Composting is achieved through a series of microbial activities (9). Most important bacteria and fungi involved in composting may be classified into two broad groups: mesophilic (those that grow best within the temperature range of 77−113°F, ie, 25−45°C) and thermophilic (those that grow best within the temperature range of 113−158°F, ie, 45−70°C). Mesophites are dominant in composting initially where as thermophiles are dominant at a later stage.

Thermophiles multiply rapidly and raise the temperature, killing most pathogens and weed seeds. With the depletion of suitable nutrients, thermophiles die, causing lowering of temperature of the compost pile. Additional stabilization, known as curing, is done for several weeks allowing slow decomposition of cellulose and lignin. After composting a biodegradable material is reduced to a soil-like material. High tech composting may take 6 months, whereas low tech composting may take up to 4 years to complete. Usually, a long curing process results in better quality product.

Microbial activities are influenced by the following parameters: particle size, moisture content, temperature, pH, nutrient levels, and time (10–12). Figure 4 shows influence of temperature and pH on microbial activities (10).

Composting facilities vary in size and complexity; while only a bin or wooden box may be sufficient for single-family home, larger area and several equipment is necessary for running a composting operation for a community.

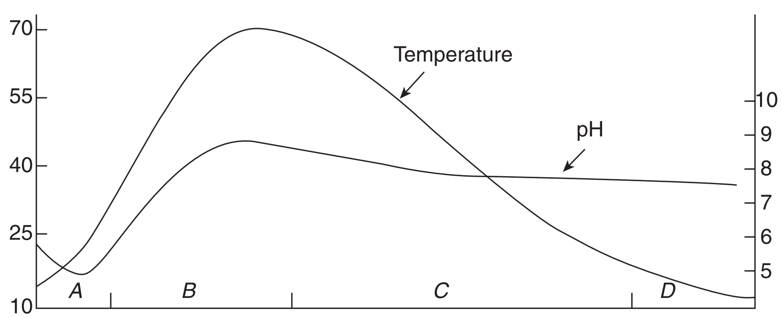

Fig. 4. Influence of temperature and pH on microbial activities: A, mesophilic; B, thermophilic; C, cooling; and D, maturing. (From Ref. 10.)

Preprocessing, consisting of sorting, size reduction, and pretreatment is necessary for obtaining a good quality compost. Passive, active, and in-vessel composting methods are available. In a passive method, material to be composted is kept in elongated rows (known as windrows) with a height and width of 8 ft (2.5 m) and several feet long, which is turned occasionally. In an active method, the windrow is turned more frequently, every 2–3 days. Static windrows may also be aerated with a forced air system. In vessel, systems consist of horizontal or vertical cylindrical vessels that may use either flow through or batch system. Compost should be tested routinely for quality control purposes. The following parameters may be used for product specification: pH, soluble salt content, nutrient content, water holding capacity, bulk density, moisture content, organic water content, and particle size (13).

Composting may impact groundwater, surface water, soil, and air. Biological oxygen demand (BOD), nitrate, phenols, PCBs, and herbicide concentration may be high in leachate from a composting operation. Impact on groundwater, surface water, and soil may be minimized through control of leachate generation and surface water run on and runoff due to precipitation. Leachate generation may be minimized by regulating moisture content of the piles and ensuring adequate oxygen throughout the pile. Dust, bioaerosol and odor from a compost pile operation may degrade air quality surrounding compost site. Adequate measures should be taken to abate air quality degradation. Proper care and operational methods should be taken to minimize or eliminate vectors, liter, and noise due to a compost pile site. Fire hazards from a composting operation should be given due consideration. Spontaneous ignition of organic matter is possible if the moisture content is between 25 and 45% and the temperature is $>199^{\circ}$F (93°C). This type of condition may develop within 12 ft (4 m) or higher compost piles (10).

Land Spreading. Land spreading, which is primarily reuse of waste, reduces disposal need of sludge whereby it is effective for waste volume reduction. Nonhazardous sludge with significant organic material (eg, wastewater treatment facility sludge, paper mill sludge) is land spread to enhance soil nutrient. Land spreading is done in both agricultural and forestlands. Waste characterization of the sludge is done to assess its value as soil conditioner or fertilizer and whether it will have any detrimental effect on public health or the environment. Sludge parameters, eg, biodegradable organic matter, nutrients, carbon/nitrogen ratio, pathogens are determined and judged against soil nutrient requirements. The type of crop to be grown on the land influences application rates. A land spreading project site needs proper operation and monitoring to be successful.

Reuse of Industrial By-Products. Although industrial by-products are being used for construction for quite some time, the practice has significantly increased since late 1980s primarily due to shortage of landfill space. Industrial by-products are primarily used to replace soil, aggregates and cement. A comprehensive knowledge about the construction requirements, economics, and environmental regulations relative to the site of reuse is essential to choose a by-product (14). Although existing models for soil may represent the engineering behavior of the by-product, it may not be the case always. Table 3 provides a list of widely used industrial by-products and their reuse in civil engineering

Table 3. **By-Products and Their Reuse in Civil Engineering Projects**[a]

By-product	Reuse
fly ash	partial replacement for Portland cement
	mineral filler in asphalt
	embankments or backfills
bottom ash	road base and subbase
	backfills
	asphaltic concrete
	fine aggregate (crushed bottom ash) in concrete masonry
blast furnace slag	aggregate in asphalt mix
	aggregate in concrete mix
	partial replacement (crushed slag) for cement
foundry sand	embankments and backfills
	final and daily covers in landfills
	road subbase
tire chips	embankments fills
	road construction
	liner, drainage layer, and final cover in landfills

[a]Reprinted with permission from Ref. 2.

projects (2). In addition, many innovative reuse projects utilizing industrial by-products, eg, discarded lime from wastewater treatment processes, flue gas desulfurization sludge, wood waste are reported in the literature. Waste characterization of the by-product is essential to assess possible environmental impact of the proposed use. In general, if a by-product is reused for manufacture of a product, eg, use of fly ash as cement replacement, its potential for environmental impact reduces significantly. However, there are situations where environmental monitoring of a by-product use site (eg, use of $>$30,000 yd^3 (23,000 m^3) of foundry sand as embankment fill) may be required by regulatory agencies.

Toxicity Reduction. Many toxic chemicals, some of which are listed in Table 4, may be found in MSW (2). A study by the EPA found $>$100 hazardous substances in household products (15). Toxicity reduction helps in improving leachate quality and easier management of waste. Currently, programs for collecting household hazardous waste (also known as clean sweep program) are used to remove hazardous waste from MSW. Attempts are also being made in many industries to change chemical constituents of household products to reduce the product toxicity.

In a clean sweep program, one or more collection sites are chosen where household products containing hazardous material may be dropped. The clean sweep program organizers publish a list of acceptable materials at the site. Each item is collected and labeled. The collected items are transported to a hazardous waste treatment facility. The clean sweep site may require a hazardous waste storage license. The cost of running a clean sweep program depends on publicity, personnel salary and training, and proximity of treatment facility.

Table 4. **Chemicals Usually Found in Municipal Landfill Leachate and Their Potential Contributor**[a]

Parameter	Products
lead	batteries, electrical solder, paints
cadmium	paint, pigment, plastics
chromium	cleaners, paint pigments, linoleum, batteries
nickel	batteries, spark plugs, electrodes
zinc	batteries, solder, TV screens
acetone	carburetor and fuel injection cleaners, paint, thinners, paint strippers and removers, adhesives, fingernail polish removers
methylene chloride	oven cleaners, tar removers, wax, degreasers, spay deodorants, paint brush cleaners
toluene	contact cement, degreasers, paint brush cleaners, perfume, dandruff shampoo, carburetor and fuel injection cleaners, paint thinners, paint strippers and removers adhesives, paints
benzene	adhesives, antiperspirants, deodorants, oven cleaners, tar removers, solvents

[a]Reprinted with permission from Ref. 2.

Since clean sweep programs, usually run by local governments, help reduce waste toxicity, private owners of landfills may also provide funds for the program.

Involvement of national, state or local government is needed for an effective program for reducing chemical constituents of household products. Because of growing environmental awareness of consumers, industries and retailers are increasingly opting for toxicity reduction programs. For example, trichloroethylene is no longer being used in typewriter correction fluid. Several countries have certifying organizations, which identify "eco-friendly" products based on recyclability, and toxicity (16).

Pollution prevention programs are also being used in many industries. The aim of pollution prevention is to design products, which have no toxic materials, last longer, are easily repairable and may be recycled. If managed properly, pollution prevention programs may reduce both product cost as well as waste toxicity.

5. Waste Disposal

There always remains a need for disposing waste, even after reuse and recycling. However, every effort should be made for volume and toxicity reduction prior to land disposal of waste. There are two types of landfills: natural attenuation type and engineered or containment type. Natural attenuation landfills do not have a liner where as containment landfills have a liner. Currently only containment type landfills are used for waste disposal. Usually natural attenuation landfills are allowed for small ($<$50,000 yd^3, ie, 38,000 m^3) construction and demolition (C&D) waste landfills. The C&D waste typically consists of concrete, bricks,

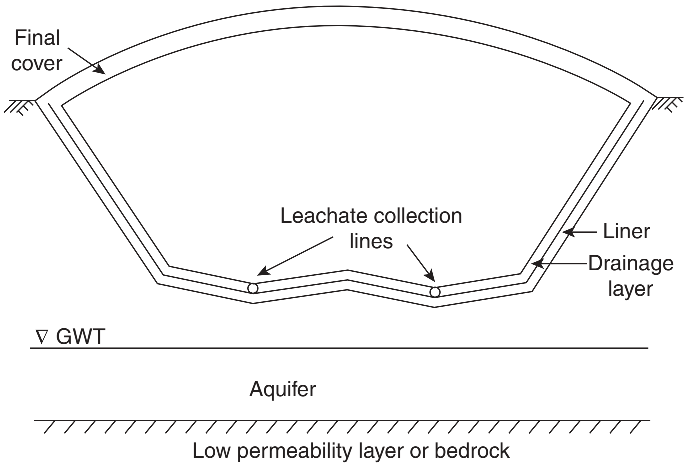

Fig. 5. Typical cross-section of containment landfills.

bituminous concrete, wood, glass, masonry, roofing, siding and plaster, alone or in combinations. Regulatory agencies may impose landfill siting restrictions within specified distances of the following: navigable lake, pond or flowage; river and stream; flood plain; state or federal highways; and airports. Only issues related with containment landfills are discussed briefly in this article. Detailed discussion regarding design, construction, operation and monitoring of landfills may be found elsewhere (2,17,18).

5.1. Landfill Design and Construction. Containment landfill are constructed with a base liner and a leachate collection system. The primary purpose of the liner is to prevent groundwater pollution. Figure 5 shows typical cross section of containment landfills. The liner is constructed with at least a 2% slope toward the leacahte collection lines to direct leachate to a collection system. Containment landfills may be single lined or double lined. In single-lined landfills, usually clay is used as the liner. In double-lined landfills, a synthetic membrane is placed directly over the clay liner. This liner system is known as composite liner. Although other schemes of double-lined landfills are possible, the above scheme is widely used. Multiple lined landfills with two collection systems are also used. Selection of single or double lined landfill depends primarily on the waste type. In general, 3–5 ft (0.9–1.5 m) thick single clay lined landfills are used for most types of industrial wastes and composite liner is used for municipal waste. In the United States, use of composite liner for municipal waste landfills is mandatory in most states.

The purpose of landfill liners is to minimize or eliminate leakage. Solute transport across a liner occur due to both advection and diffusion. In advection, solute transport is due to hydraulic conductivity and in diffusion, solute transport is due to concentration difference of the solute on either side of the liner. (*Note*: The solute concentration is assumed to be zero at the liner sub base.) In high hydraulic conductivity media, advection is the dominant mode of solute transport, whereas diffusion is the dominant mode in low hydraulic conductivity medium. Figure 6 shows the effect of hydraulic conductivity on solute transit

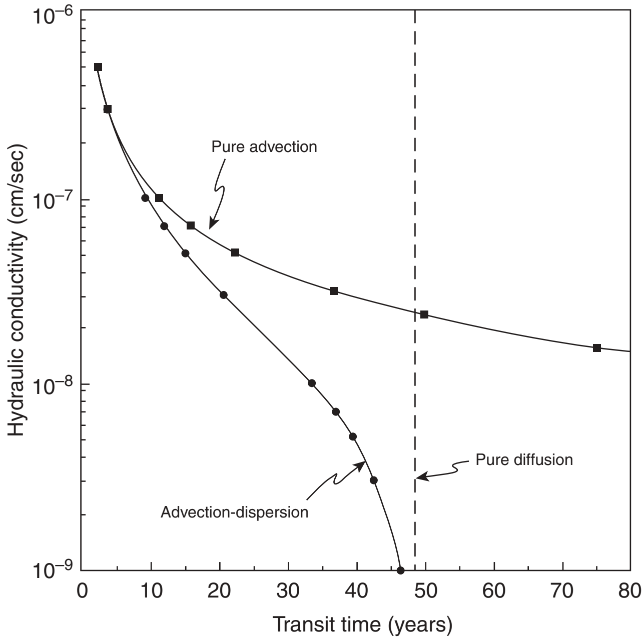

Fig. 6. Effect of hydraulic conductivity on solute transit time. (Reprinted with permission from Ref. 19.)

time for various flow types (19). To provide a perspective, with a hydraulic conductivity of 1×10^{-9} cm/s, the transit time for a solute to reach 50% of input concentration at the base of a 3 ft (0.9 m) liner with a leachate head of 1 ft (0.3 m) is 50 years. Chemical composition of leachate may influence clay conductivity.

The clay hydraulic conductivity is influenced by leachate chemistry, compaction (note: sheep's foot roller must be used to achieve low hydraulic conductivity of clay), water content during compaction, clod size of clay before compaction, frost depth, number of freeze–thaw cycles during winter, and ground temperature during summer months. Unprotected liner surfaces may develop cracks in winter months when the ground temperature is below freezing and in dry hot summer months.

Hydraulic conductivity of liners depends on properties of liner materials (eg, clay, HDPE sheets), construction techniques, and maintenance prior to waste disposal. Rigorous quality assurance/quality control tests are important while constructing liners and final covers.

The function of the drainage layer is to facilitate transport of leachate to the collection pipes. Typically the permeability of the drainage layer is 1×10^{2} cm/s or higher. Course sand or pea gravel is usually used for the drainage layer. If the amount of fines (<0.06 mm) in the waste is high, then a layer of geotextile should be used to minimize clogging of drainage layer pores whereby the permeability of the drainage layer will not decrease. The thickness of the drainage layer, although depends on the leachate head, is typically 1 ft (30 cm).

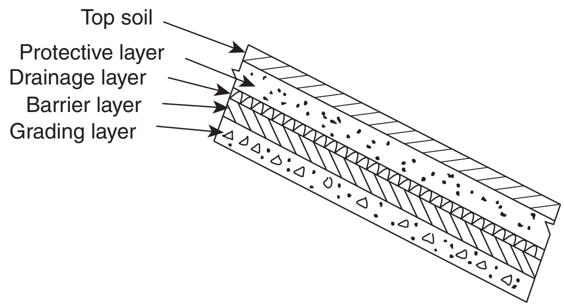

Fig. 7. Final cover.

The leachate collection system consists of the leachate collection lines, a system for removing leachate, and a leachate holding tank (or a direct connection to a sewer line). Typically, the leachate collection lines are schedule 80 perforated pipes. The leachate collection lines in each phase are sloped towards the perimeter because it is easier to collect and withdraw leachate from the perimeter. Leachate removal from within the landfill is done by either gravity flow or by using a side slope riser. In a side slope riser, a submersible pump is placed at the lower end of each leachate collection pipe. The pump is installed within 45 cm pipes. Usually, side slope risers are used for composite liner landfills.

The final cover (Fig. 7) has several layers, each with a distinct function. The grading layer, 6–24 in. (15–60 cm) thick layer of coarse-grained material, provides a stable surface for subsequent layers. The thickness depends on waste type. For unstable sludge waste surfaces a layer of bark or geotextile is used below the grading layer. The barrier layer, provides barrier for infiltration of precipitation. Clay, synthetic membrane or geosynthetic clay liner (GCL) or a combination is used for construction of barrier layer. A composite barrier layer (eg, HDPE liner over clay or GCL) is required over landfills with composite liners. If only clay is used as the barrier layer, then it must be 2 ft (60 cm) thick and have a compacted permeability of 1×10^{-7} cm/s or less. For landfills with composite barrier layers, a 2–6 in. (5–15 cm) thick layer of coarse sand, commonly known as drainage layer, is constructed above the barrier layer to provide better drainage of precipitation falling on the landfill. The protective layer (above the drainage layer – if constructed) protects the barrier layer from freeze–thaw and desiccation cracks and helps vegetation root growth. The protective layer thickness varies between 1 and 3.5 ft (30–105 cm); the most preferred material for this layer is silty loam. A 6 in. (15 cm) top soil layer is constructed above the protective layer. The topsoil layer is vegetated to reduce the amount of precipitation entering landfills. An alternative final cover may be adopted for arid regions (Fig. 8).

Two other types of cover are used in landfills: intermediate cover and daily cover. Intermediate cover must be constructed over areas below final grade that are not going to receive waste for six months or more. If soil is used as daily cover, then it must be six inches thick. Materials other than soil may be used as daily cover.

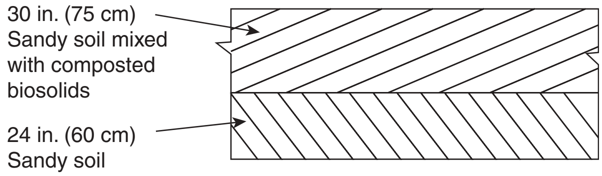

Fig. 8. Alternative final cover for arid regions.

Surface erosion must be minimized during landfill construction and also in active and closed landfills. Establishing thick and healthy vegetation is key to minimize erosion. Drainage swales and berms on and around landfills are constructed to divert surface water run-off properly. Drainage swales are lined with a minimum of two foot clay. Properly designed surface water control helps to reduce leachate production and soil erosion. Sedimentation basins are constructed to trap eroded soil and thus help to reduce surface water pollution. Drainage ditches, berms around landfills, and sedimentation basins are important for surface water control at landfills.

Biological activities within a landfill lead to the generation of gas. The quality, quantity, and chemical characteristics of landfill gas depends on the type of solid waste placed in landfills. Mainly methane and carbon dioxide gases are generated in municipal and paper mill sludge landfills. Landfill gas may also contain several other gases, like nitrogen, oxygen, hydrogen sulfide, and hazardous air contaminants. In general, an active gas extraction system (that uses pumps or blowers to remove gas) is required for all big municipal waste landfills. Passive gas vents (that do not use pumps or blower) are installed in some C&D, and paper mill sludge landfills where the gas generation is relatively low.

5.2. Landfill Operation. Proper operation of a landfill is essential to minimize odor, noise, insect and rodent problems, wind blown paper, and dust. While operating a landfill, it is also essential to address concerns regarding surface water and air emission. Odor from a municipal landfill can be minimized by using daily cover, proper collection and treatment of landfill gas, and correcting leachate seeps. If clay is used for daily cover, then the daily cover must be scarified or removed before placing the next lift of waste. To control dust in ash or foundry sand landfills, waste should be dumped in areas sheltered out of wind, constructing paved or graveled roads inside landfills, and by not disturbing crusted compacted waste. Unstable waste slope is a problem in sludge landfills. Slope stability of sludge landfills can be improved by disposing low moisture sludge with a 6–8% waste slope.

Materials containing friable asbestos containing materials must be covered with three feet of waste after disposal and the disposal location must be recorded. Every precaution must be taken to prevent a landfill fire. In most cases landfill fires are started by hot waste loads.

A landfill must be secured properly using fences, gates or other physical barrier. Surveillance of site visitors and site users is needed for site security and to prevent dumping of unauthorized materials.

Leachate lines must be cleaned with a high pressure water jet immediately after construction and annually there after. Eroded landfill surface areas must be repaired immediately to prevent erosion from spreading. An effective maintenance program for landfill structures and equipment minimizes costly repairs.

Although waste oil, yard waste, lead acid batteries, major appliances, infectious waste, and recyclable plastics may not be allowed to be disposed in landfills, usually disposal of household hazardous wastes are allowed. Only disinfected infectious waste is disposed in landfills.

Random load inspections are done in MSW landfills to eliminate dumping of unapproved waste. All landfills should have a contingency plan for injuries, illness, spills, and releases.

5.3. Landfill Monitoring. Monitoring wells are installed around landfills for groundwater monitoring. Leachate head monitoring wells are installed within landfills. In addition, if required by regulatory agencies, other monitoring devices, eg, gas probes are installed on or around landfills. Required monitoring program for a landfill is included in regulatory agency approvals. In general, the following items may need to be monitored: groundwater, surface water, leachate, ambient air, landfill settlement, stability of berm, side slope and final cover, structures related to surface water control and gradient control, and vegetative growth.

5.4. Financial Issues. Sufficient funds for design, construction, operation, monitoring, and long-term maintenance must be allocated for a successful landfill project. Proper cost analysis must be done to ensure cash flow for performing all the above tasks. Currently, monitoring and long-term maintenance of landfills are required for 40 years. Regulatory agencies require proof of financial responsibility for closure and long-term care of landfills. Effect of inflation on money value is taken into consideration for calculating the future funds requirement for performing these tasks. Of the several mechanisms available for establishing these proofs, usually escrow funds, bonds, and letter of credit are used. Many industries use the company net worth to establish these proofs for their landfills.

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