Solid Waste Management
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1. Introduction. Solid wastes are those waste materials that are not easily carried by water or air flows (solid or semisolid). The Federal Government defines a solid waste as any discarded material that is not specifically excluded (40 CFR 261.2). Hazardous wastes are a subset of solid waste. Discarded means that the material is either abandoned, recycled, or considered inherently wastelike. Excluded wastes are excluded from the legal definition of a solid waste by Congress and the U.S. Environmental Protection Agency (40 CFR 261.2 or 261.1(4)(a)).

In this section, we will just focus on municipal solid waste. Municipal solid waste (commonly referred to as trash or garage) consists of items such as: packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. You can learn more about solid waste by going to the web site of the U.S. Environmental Protection Agency's Office of Solid Waste and Emergency Response (http://www.epa.gov/epaoswer).

Civil and environmental engineers are faced with the problem of collecting these discarded wastes from municipalities and industry and disposing them in a manner that is safe and acceptable to society.

2. Solid Waste Production. USEPA has determined that in 1998, homeowners, businesses, and institutions (universities, schools, and hospitals) produced more than 220 million tons of municipal solid waste. This number has increased by about 4 million tons from 1997. This equates to approximately 4.46 pounds of waste generated per person per day. In 1960, this value was approximately 2.7 pounds per person per day.

Table 1 shows the breakdown of this waste production on a weight basis. Note that these numbers would change if the percent composition was reported on a volume basis. These percentages are also highly variable and are a function of items such as geography, season, and wealth.. In general terms, wealthier communities and nations tend to produce more solid waste (they consume more and utilize commercial establishments and packaged food more), total solid waste production and the type of material produced is a function of the time of the year, and also urban households tend to produce more waste than rural households. The production and composition of municipal solid waste also varies by country. For example, the United States is the clearly the world leader in solid waste production on a per capita basis. In Japan, there is little glass and metal produced but a large amount of paper and cardboard usage. Ireland tends to have a relatively larger usage of plastics.

Table 1. Municipal solid waste generation by percentage of total generated (total generated in 1998 was 220 million tons) (data is from 1998 and was obtained from USEPA).

Item	Percent by Weight
Paper and paperboard	38.2%
Yard trimmings	12.6%
Plastics	10.2%
Food wastes	10.0%
Metals	7.6%
Rubber, leather, textiles	7.0%
Glass	5.7%
Wood	5.5%
Other	3.2%

3. Components of a Solid Waste Management Plan. The six components of a successful solid waste management plan are:

1) Source reduction, recycling, composting

2) On-site storage

3) Collection

4) Transport and transfer

5) Processing

6) Disposal

3-1. Source Reduction, recycling, composting.

The U.S. Environmental Protection Agency (USEPA) estimates that in 1996, recycling, including composting of yard trimmings and food wastes, diverted 57 million tons of solid waste away from landfills and incinerators. This was an increase from 34 million tons in 1990. In 1998, 28.2 percent of the total refuse was recycled. Table 2 shows the recycling rates of some common materials. However, while recycling rates are increasing, solid waste production is still high relative to other parts of the world. Accordingly, source reduction (that includes reuse) should always be the preferred method to reduce the amount of solid waste that must be managed, followed by recycling and composting, and, finally, disposal.

By carefully studying Table 2, one can see why many municipalities and state governments will encourage recycling by providing households with composters or perhaps encouraging the use of mulching lawn mowers. In additions, some government entities have simply mandated recycling or banned certain items from disposal in landfills.

Table 2. Recycling rates of some common materials found in municipal solid waste (from USEPA).

Item	**Approximate Percentage Recycled in 1996**
Auto batteries	94
Steel cans	58
Aluminum packaging	52
Paper and paperboard	41
Yard wastes	39
Glass containers	29
Plastic containers	23
Tires	19

We can not stress the importance of source reduction, recycling, and composting in designing and implementing a "successful" "sustainable" solid waste management plan. Needless to say, a successful solid waste management plan requires that the engineer discuss various options with members of the community, local government, and state government, then implement programs in source reduction, recycling, and composting.

Recycling is important because it has been shown to prevent the emission of many greenhouse gases and water pollutants, saves energy, recycled materials provide raw materials back to industry, it creates jobs, conserves resources and habitat, and reduces the need for additional landfill space and incinerators. USEPA states that in 1996, recycling of solid waste in the US prevented the release of 33 million tons of carbon into the air that is equal to the amount emitted annually by 25 million cars.

3-2. On-site Storage. Storage of solid waste on-site is usually the responsibility of the homeowner, tenant, or business. Wastes are most commonly stored in cans or plastic bags with the use of bags gaining popularity. In fact, some communities now require the homeowner to purchase a special bag so the cost of disposal is distributed more towards individuals who produce more solid waste. In some communities, individuals now purchase special bags and pay for disposal on a per-bag basis. Larger generators store waste in dumpsters or waste compactors to reduce storage area. The best place to separate wastes for recycling is at the point of generation; however, the collection of separated solid wastes is more expensive.

3-3. Collection. Several decisions must be made by the solid waste engineer. These include:

1) Type of service (e.g., curbside pickup (most common), alley pickup, set out or set back, backyard carry (most expensive). Nowadays, engineers may also develop local household hazardous waste pickup days that allow homeowners to safely dispose of their hazardous wastes (e.g., paints, solvents, oil, pesticides) so they are not improperly disposed of in the environment, landfills, or the wastewater treatment plant.

2) Frequency of collection. This is typically once per week (most common in northern states) or twice per week (most common in southern states). Collection frequency is also greater for larger generators.

3) Type of collection vehicle. Engineers make selection of the type of collection vehicle. For example, packer trucks can increase the mass of collection. Decisions are also made in regard to rear, side, or front loading vehicles; manual or mechanically loaded vehicles, or the use of smaller satellite vehicles that can maneuver better around crowded streets.

4) Crew size. This is typically 1 to 3 individuals. Note that increased frequency of collection does not significantly reduce the required crew size because container-handling time is approximately the same, whether a container is full or partially full.

5) Collection route design. Collection routes are designed after equipment and labor decisions are made. An engineer can obtain valuable advice on designing a collection route by first talking to workers who are familiar with the collection route. Also, because there are no fixed-rules for designing a collection route, worker input is even more valuable. Obviously waste generated in crowded areas should be picked up before traffic and pedestrian congestion is at its peak and collection points that generate a large volume of daily waste should be serviced earlier in the day.

3-4. Transport and Transfer. Once the waste is collected, it must be transported to the processing and/or disposal sites. Usually the collection vehicle is also used for the long distance transport of refuse though it is becoming more common to transport refuse to a local "transfer station" where the waste is then transferred to a larger vehicle. Thus, it must be large enough to minimize the number of trips to the processing site, yet small enough to be maneuverable during collection. Packer trucks range in size from 10 to 35 cubic yards (18-20 is the most common). The density of the refuse is typically doubled (from about 300 lbs/cubic yard to 500 lbs/cubic yard) by the packer truck. If the distance to the disposal site is large, then the waste is typically transferred to a larger vehicle such as truck trailer, rail car, or barge.

One reason for use of transfer stations is that the U.S. no longer supports a large network of small, community landfills. In fact, the number of landfills operating in the U.S. has been steadily decreasing. For example, in 1988 there were 8,000 landfills in the U.S. and in 1996 there were only 2,314. And because the capacity has remained relatively constant, one can see that these new landfills are larger than in the past. Another reason that transfer stations are important is because solid waste is currently shipped across county and state boundaries for final disposal. This event is partially driven by a U.S. Supreme Court ruling in 1992 that stated that refuse is a commodity protected by interstate commerce statutes. Thus, states such as Ohio, Pennsylvania, and West Virginia have not been able to legislate the ban of imported refuse from states such as New York and New Jersey (e.g., New York exports more than 2.7 million tons of refuse to Pennsylvania on an annual basis which accounts for 15% of New York's solid waste production). Imagine how this event might influence a community's support for your proposed solid waste management plan when individuals in your community perceive that they are being forced to accept additional risk associated with some other group's waste.

3-5. Processing. Processing is intended to improve disposal options, recover valuable resources, and prepare materials for recovery as new products or energy. Obviously an engineer would want to evaluate various processing options for the system's impact on the local and global environment, reliability, safety to workers and the local community, ease of operation, efficiency, economics, and, aesthetics (noise, odors, litter, increased traffic). Some of the objectives of solid waste processing include:

1) Volume reduction (baling, shredding, incineration). Incineration may reduce volume by more than 90%. However, engineers should realize that incineration is not a popular option by many local communities. However, a community may be more acceptable to unpopular alternatives such as incineration if they are combined with an aggressive source reduction/recycling program that eliminates the potential production of hazardous air emissions, and the risk associated with these emissions is equally shared between wealthy and poor residents. And , in 1996, 110 incinerators with energy recovery existed with the capacity to burn up to 100,000 tons of solid waste per day.

2) Size reduction (Shredding, grinding)

3) Component separation (hand sorting, screening, magnetic separation, air classification for lighter materials such as paper and plastic). Remember though, as stated earlier, it is much more efficient to separate wastes at the source.

4) Resource recovery (composting, energy recovery, material recovery)

A number of processing technologies have been developed for solid waste management and one of the jobs of the engineer is to select and design the most sustainable and cost effective for a given community. And of course, the engineer needs to listen to the input of local residents. It should be noted that a lot of good ideas for solid waste processing have proven to be inadequate when built to full-scale.

3-6. Disposal. No matter what source reduction/recycling plan and processing option is developed, there will always be some residue that must be disposed of. Currently, the only acceptable method of disposal is to dispose of this residue in a landfill and approximately 55% of the U.S. solid waste production is land disposed. The goal of landfilling is to compact the waste as much as possible and place it in an environmentally safe location.

The practice of open dumping of refuse (in dumps) has been replaced by the sanitary landfill. In fact, a large percentage of our federal hazardous waste sites (i.e., CERCLA or Superfund sites) were past dumps where solid and hazardous wastes were improperly codisposed, resulting in soil and groundwater contamination. In a modern sanitary landfill, the refuse is dumped, compacted, and covered with soil on a daily basis. While this is more expensive than the dump, it reduces the nuisances and health hazards associated with decaying and burning refuse. However, the potential for groundwater contamination still remains as we will discuss later.

Under the Resource Conservation and Recovery Act (RCRA), landfills that accept municipal solid waste are primarily regulated by state, tribal, and local governments. However, USEPA has established national standards that these landfills must meet in order to remain in operation. Also, municipal landfills can accept household hazardous waste.

3-6a. Landfill design, construction, and operation

The problem of managing the increased volume of solid waste is compounded by rising public resistance to siting new landfills. USEPA developed regulations that govern landfills with the attempt that the new or expanded landfills would not contaminate groundwater and thus become community burdens and drive down property values. Remember, nearly 50% of the country's population obtains its drinking water from groundwater and landfills can contribute to the contamination of this valuable resource if they are not designed to prevent waste releases into ground water or detect them when they occur. Also, remediation of contaminated groundwater is a long and costly process and in some cases may not be totally successful.

There are five general phases of landfill construction: 1) site selection; 2) site investigation; 3) design; 4) daily operation; and, 5) landfill completion or closure. These stages are discussed in further detail below.

Site selection criteria include items such as availability of land, good drainage, availability of suitable soil for daily and final cover, visually isolated, access to major transportation routes, certain distance away from a airport, not located in wetlands, and out of a floodplain. The engineer should also consider what the final use of the site will be and how long-term management of the site will impact this final use. Below are six criteria that federal law governs when siting a landfill.

Airports Federal law specifies that "the owner/operator of a municipal landfill located within 10,000 feet of the end of any airport runway used by turbojet aircraft, or within 5,000 feet of any airport runway used only by piston-type aircraft, must demonstrate that the unit does not pose a bird hazard." And "if an owner/operator plans to build a new unit or laterally expand an existing unit within 5 miles of any airport, the airport and the Federal Aviation Administration must be notified."

Floodplains Federal law specifies that "landfills located in 100-year floodplains cannot restrict the flow of the 100-year flood, reduce the temporary water storage capacity of the floodplain, or allow the washout of solid waste."

Wetlands Federal law specifies that in general, owners/operators of new or expanding municipal landfills may not build or expand in wetlands. However, states or tribes with USEPA-approved permitting programs can make exceptions for units able to show: no siting alternative is available; construction and operation will not: 1) violate applicable state/tribal regulations on water quality or toxic effluent; 2) jeopardize any endangered or threatened species or critical habitats; or 3) violate protection of a marine sanctuary; the unit will not cause or contribute to significant degradation of wetlands; and, steps have been taken to achieve no net loss of wetlands by avoiding effects where possible, minimizing unavoidable impacts, or making proper compensation (e.g., restoring damaged wetlands or creating man-made wetlands).

Fault areas Federal law specifies that "new units or lateral expansions are generally prohibited within 200 feet of fault areas that have shifted since the last Ice Age. However, the director of an approved state or tribal program may allow an alternative setback distance of less than 200 feet if the owner/operator can show that the unit will maintain structural integrity in the event of a fault displacement."

Seismic impact zones Federal law specifies that "when a new or laterally expanding unit is located in a seismic impact zone, its containment structures (liners, leachate collection systems, surface-water control systems) must be designed to resist the effects of ground motion due to earthquakes."

Unstable areas Federal law specifies that "owners/operators must show that the structure of their units will not be compromised during "destabilizing events," including: debris flows resulting from heavy rainfall; fast-forming sinkholes caused by excessive ground-water withdrawal; rockfalls set off by explosives or sonic booms; and, the sudden liquidfication of the soil after a long period of repeated wetting and drying."

After a suitable site is identified, a **site investigation** is then performed. The site investigation includes items such as performing: 1) a topographic survey for surface contours and features (used also to estimate amount of available soil), 2) a hydrologic survey that looks at how the local hydrology will impact drainage requirements, and 3) a hydrogeologic survey that will determine underlying geological formations and soil types, the depth to the groundwater table, the direction of groundwater flow, and the current quality of the groundwater (so one can determine whether the landfill is adversely impacting groundwater quality).

Landfill design and operation is the next step in the engineering process. Engineers have to consider the method of landfilling (described in more detail below) and design the landfill interface (soil foundation, liners), leachate collection and treatment systems, and gas collection and venting system. The engineer also has to consider the selection of equipment that is used for hauling, excavating, and compaction; access to haul roads, fencing, and the storage and use of soil that is used for daily and final cover.

During daily operation, topsoil is removed and stored; refuse is transported into the site, dumped, and compacted (final density about 1,000 lbs/cubic yard); daily soil cover is placed over the refuse (this ends up occupying 10-25% of the total landfill volume); groundwater is monitored; and, leachate is collected and treated.

Federal law also requires that the owner/operator of a municipal solid waste landfill "must set up a program to detect and prevent disposal of regulated quantities of hazardous wastes and polychlorinated biphenyl (PCB) wastes. The program must include procedures for random inspections, record keeping, training of personnel to recognize hazardous and PCB wastes, and notification of the appropriate authorities if such waste is discovered at the facility."

The primary methods used for landfilling are called: 1) the area method; 2) the trench method; and, 3) the depression method.

The *area method* is used when the site conditions do not allow the excavation of a trench. Typically an earthen levy is constructed and refuse is placed in thing layers against this levy and compacted. In a day, the compacted waste will reach a height of approximately 2-3 meters and at the end of the day, a minimum of 6 inches of daily soil cover is applied as a barrier to disease vectors (e.g., it prevents the hatching of flies and the burrowing of rodents) and also prevents fires, odors, scavenging, and blowing litter. When the final design height is reached, a final soil cover is placed on top of the material. Each of the days worth of refuse is entombed in a "*cell*."

The *trench method* is most suitable in locations where the depth to the groundwater table does not prevent one from digging a trench in the ground. In this method, a trench is excavated with a bulldozer. Refuse is then placed in the trench and placed in thin layers that are compacted. The operation continues for the day until the desired daily height is reached. Again, daily cover is placed over the refuse to produce a "cell."

The *depression method* occurs at sites where natural features such as canyons, ravines, dry borrow pits, and quarries are available that can be filled in. Care is given to the hydrology of the site. For example, canyons are filled from the inlet to the outlet to prevent backing up of water behind the deposited refuse.

When the landfill has exhausted its life, a final cover is placed on top of the landfill; topsoil is replaced on the site and the site is landscaped; groundwater is continuously monitored; leachate is continuously collected and treated; and, gases are continuously collected and vented.

Leachate production and groundwater monitoring Leachate is the liquid that percolates through a landfill. It is very high in concentration of water quality parameters that have been discussed elsewhere (e.g., TDS, BOD, COD, N, P, etc) and the composition of leachate was described in detail in your *Fundamentals of Environmental Engineering* textbook (page 34, Table 2-6). An engineer designs a landfill to minimize movement of water into the mass of refuse and thus attempts to minimize the production of leachate. This is discussed in depth in your *Fundamentals of Environmental Engineering* textbook (pages 277-279) and an example problem that shows how to quickly estimate the volume of leachate production on an annual basis is provided (Example 5.18)

Federal law typically results in a design that consists of a composite liner and a leachate collection system. In general, landfills in states or tribal jurisdictions without USEPA-approved programs must use this design. The composite liner system combines an upper liner of a synthetic flexible membrane and a lower layer of soil at least 2-feet thick with a hydraulic conductivity of no greater than 1x10-7 cm/sec.

The leachate collection system must be designed to keep the depth of the leachate over the liner to less than 30 cm.

Landfills are lined with either compacted clay or some type of geosynthetic liner. The purpose of these systems is to greatly reduce the hydraulic conductivity in the liner that minimizes the flow of leachate through the liner. You can use Darcy's law to estimate the maximum amount of leachate that can potentially move through a liner (see your textbook, pages 194-197, for discussion of Darcy's law and hydraulic conductivity). This calculation assumes the soil directly beneath the liner is saturated with moisture that is not always the case.

If compacted clay is used, it is typically 0.5 to 4 feet thick and it is very important that the clay liner be compacted properly and not be allowed to dry out or crack. Geosynthetic liners are gaining widespread popularity and their installation is extremely important so that seams are sealed properly. Lying on top of this liner system is a leachate collection system, and on top of this is the compacted solid waste.

Generally, ground-water monitoring is conducted at all landfills. In fact, USEPA requires that owners/operators install enough ground-water monitoring wells in the appropriate places to accurately assess the quality of the uppermost aquifer 1) beneath the landfill before it has passed the landfill boundary (to determine background quality) and 2) at a relevant point of compliance (downgradient). Owners/operators should consider the specific characteristics of the sites when establishing their monitoring systems, but the systems must be certified as adequate by a qualified ground-water scientist or the director of an USEPA-approved state/tribal program.

Gas production Gases found in landfills include air, ammonia, carbon dioxide, carbon monoxide, hydrogen sulfide, and methane. Because landfills are designed to minimize the influx of oxygen and moisture, anaerobic biological processes (discussed in your textbook, pages 237-2421) occur that lead to the production of carbon dioxide and methane. The rate of decomposition in a landfill usually reaches a peak in about 2 years, then slows down and continues for 25 years or longer. Besides being a nuisance, methane production at a landfill can lead to fire and explosions if the gas migrates through the subsurface into a neighboring home's basement. Methane concentrations as high as 40% have been detected at lateral distances up to 120 m from the edge of a landfill (Peavy, Rowe, Tchobanoglous, Environmental Engineering, McGraw-Hill Book Company, New York, 1985). See your textbook, pages 281-283, for an example problem looking a gas production at a landfill. Gas movement is controlled by constructing vents and barriers and also by recovering the gas. Thus, landfills are designed to either vent the gases to the atmosphere or at larger landfills, the gases are collected and used to produce energy.

Remember that both carbon dioxide and methane are greenhouse gases and methane traps over 21 times more heat per molecule than carbon dioxide. Thus, this phenomenon plus the large amount of methane production from a landfill means that the contribution to the greenhouse effect from landfills is primarily due to methane releases. In fact, landfills are the largest single anthropogenic source of methane emissions in the U.S. Methane emissions from U.S. landfills in 1998 were 58.8 million metric tons of carbon equivalents. This accounts for approximately 60% of the anthropogenic methane emissions (in comparison, wastewater plants account for approximately 0.9% of the anthropogenic methane emissions). This percentage did not change much in the 1990s and is a result of two offsetting trends: 1) the amount of solid waste in landfills contributing to methane emissions has increased (thereby increasing the potential for emissions); and 2) the amount of landfill gas collected and combusted by landfill operators has also increased (thereby reducing emissions).

Emissions from U.S. municipal solid waste landfills accounted for 93 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 26 percent of the methane generated in U.S. landfills in 1998 was recovered and combusted, often for energy. A regulation promulgated by the federal government in 1996 requires the largest landfills in the U.S. begin collecting and combusting their landfill gas to reduce emissions of non-methane VOCs. It is estimated that by the year 2000, this regulation will have reduced landfill methane emissions by more than 50 percent.

Management of municipal solid waste thus presents many opportunities for greenhouse gas emission reductions. For example, source reduction and recycling can reduce greenhouse gas emissions at the manufacturing stage, increase forest carbon storage, and avoid landfill methane emissions. Landfill methane emissions can also be reduced by using gas recovery systems and by diverting organic materials (e.g., food wastes, yard wastes) from the landfill.

Closure When a landfill has reached its capacity, it is ready for closure. Federal law requires that owners/operators must install final covers that meet the federal criteria within six months of the last receipt of waste. The final cover must be designed and constructed to have a permeability less than or equal to the bottom liner system or natural subsoils, or a permeability no greater than 1x10-5 cm/sec, whichever is lower. The final cover must be constructed of an infiltration layer composed of a minimum of 18 inches of earthen material to minimize the flow of water into the closed landfill. The cover must also contain an erosion layer to prevent the disintegration of the cover. The erosion layer must be composed of a minimum of 6 inches of earthen material capable of sustaining plant growth.

When a landfill's bottom liner system includes a flexible membrane or synthetic liner, the addition of a flexible liner in the infiltration layer cover will generally be the only design that will allow the final cover design to achieve a permeability less than or equal to the bottom liner.

In addition, for 30 years after closure, the owner/operator is responsible for maintaining the integrity of the final cover, monitoring ground water and methane gas, and continuing leachate management. The federal government allows that approved states and tribes may vary this interval.

4. Other sources of Information. USEPA’s web site (www.epa.gov) has many publications to assist the engineer in developing and designing all or parts of a solid waste management plan. For example, the *Decision-Maker’s Guide to Solid Waste Management, Volume II*: contains technical and economic information to assist solid waste management practitioners in planning, managing, and operating municipal solid waste programs and facilities.

5. Example Problems (Note, other practice problems are available in your textbook that investigate estimating leachate and gas production, as referred to in the text of this supplement).

Problem 1. Using information on solid waste characterization and recent recycling rates (provided in Tables 1 and 2), what items would you set up an aggressive source reduction/recycling program for if your objective was to increase the life of your local landfill?

Problem 2. Determine the area required for a landfill that services 100,000 individuals, has a design life-span of 15 years, and local zoning restrictions require that the landfill can only be 20 feet (6.67 yards) in height. Use 1998 solid waste generation data supplied by the USEPA and assume no recycling occurs and the solid waste is compacted to a density of 1,000 lbs/cubic yard at the landfill.

Solution:
100,000 x 4.46 lbs solid waste/person-day x 15 years x 365 days/year = 2,441,850,000 lbs over design life.

2,441,850,000 lbs / 1,000 lbs/cubic yard = 2,441,850 cubic yards / 6.67 yards = 366,000 square yards required (this equals 76 acres).

76 acres is required for the actual area under the refuse. Add an additional 25-50% for storage of soil, location of roads, fencing, etc.

Answer: 95-114 acres of land is required.

Problem 3. Determine the total area required (in acres) for a new solid waste landfill site with a projected life of 15 years that serves a population of 50,000 generating 1.6 kg solid waste/person-day. An aggressive recycling program results in 20% of the solid waste being recycled. Assume the density of the solid waste is 200 kg/cubic meter when it is picked up at the curb, the density in the truck is 400 kg/cubic meter, and after compaction at the landfill the density is 600 kg/cubic meter. In addition, the landfill height is restricted to 12 m by a local zoning ordinance.

Solution:
50,000 x 1.6 kg/person-day x 15 years x 365 days/yr x 0.80 = 350,400,000 kg require landfilling

350,400,000 kg / 600 kg/cubic meter = 584,000 cubic meters / 12 m = 49,000 square meters

49,000 square meters equals 12 acres (add an additional 25-50% for storage of soil, location or roads, fencing, etc).

Answer: 15-18 acres