# Chapter 5

# Solid waste Disposal - Landfill

# 1. Introduction

- Regardless of how much reuse, recycling, and energy recovery is achieved, some fraction of the MSW must be returned to the environment.
- A landfill is an engineered method for land disposal of solid or hazardous wastes in a manner that protects the environment.
  - biological, chemical, and physical processes occur
  - production of *leachate* (polluted water emanating from the base of the landfill) and gases.

# 2. Planning, siting, and permitting of landfills

- A solid waste engineer, when asked to take on the job of managing the solid waste system for a major city, had only one question: “Do the existing landfills have enough remaining capacity to last until I retire?”
- No essential public facility, with the possible exception of an airport, is more difficult to plan, site, and permit than a landfill.

- In USA
  - the number of operating landfills has decreased from about 8000 to under 1700, primarily due to stringent requirements in the last 20 years
  - It takes over ten years to go through the process of opening a new landfill.
  - During the ten-year process, many of the rules will change, including regulations, permits, and approval requirements.
  - In addition, public opposition and even lawsuits during the process are more than likely.

- The difficulty of siting landfills makes disposal in outer space appear to be a more attractive alternative!?
- ???

  Why not we send our waste to space  ???????
- One quality that is needed when siting a landfill is perseverance

- **Planning**
  - Communities must look many years into the future.
  - **Thirty years** seems to be an appropriate time frame

- **The first step in planning for a new landfill**:
  - to establish the requirements for the landfill site
  - sufficient landfill capacity for
    - the selected design period and
    - support any ancillary solid waste functions
    - house facilities for handling recyclable materials (material recovery facilities) and composting green waste.

- To determine landfill capacity, the disposal requirements for the community or communities must be estimated.
- Data
  - Population growth and per capita disposal rate for last 5 to 10 years
  - the annual amount of waste landfilled for the last 5 to 10 years
  - Estimate of in-place density (the density once the refuse has been compacted in the ground)
  - An in-place density of 1200 lb/yd3 (700 kg/m3) is typical
- Bulk densities of the components can be used in estimation of the average density of the landfill.

- Volume, mass, and density calculations for mixed materials
  - can be simplified by considering a container that holds a mixture of materials, each of which has its own bulk density.
  - Knowing the volume of each material, the mass is calculated for each contributing material, added, and then divided by the total volume.

- In equation form,

$$\frac{(\rho_A \times V_A) + (\rho_B \times V_B)}{V_A + V_B} = \rho_{(A+B)}$$

where

$\rho_A$ = bulk density of material A
$\rho_B$ = bulk density of material B
$V_A$ = volume of material A
$V_B$ = volume of material B

- When there are more than two different materials, this equation is extended.
- If the two materials at different densities are expressed in terms of their weight fraction, then the equation for calculating the overall bulk density is

$$\frac{M_A + M_B}{\left[\frac{M_A}{\rho_A}\right] + \left[\frac{M_B}{\rho_B}\right]} = \rho_{(A+B)}$$

where

$M_A$ = mass of material A
$M_B$ = mass of material B
$\rho_A$ = bulk density of material A
$\rho_B$ = bulk density of material B

If more than two materials are involved, this equation is extended.

- The volume reduction achieved in refuse baling or landfill compaction is an important design and operational variable.
- The volume reduction is

$$\frac{V_c}{V_o} = F \qquad \text{or} \qquad \frac{\rho_o}{\rho_c} = F$$

where

$F$ = fraction remaining of initial volume as a result of compaction
$V_o$ = initial volume
$V_c$ = compacted volume

$\rho_o$ = initial bulk density
$\rho_c$ = compacted bulk density

- **Siting**
  - Once the size of the landfill has been determined, it is necessary to find an appropriate site.
  - While the concept is simple, the execution is far from easy.
  - Challenges
  - NOPE—Not On Planet Earth
  - NIMTO—Not In My Term of Office.

- Historically,
  - an appropriate landfill site is within the geographic boundary of the agency.
  - However, in reality, few local communities can site new landfills
    - Lack of political support, high development costs, and public disclosure laws.
- For a private company, the geographic location is not as critical.

- **Example**
  - both Seattle, Washington, and Portland, Oregon ship waste to a private regional landfill in eastern Oregon.
  - New York City exports to states such as Ohio and West Virginia.

- **A *fatal flaw analysis***
  - *Selected potential site should be analyzed for flaw*
  - *This includes:*
    - The site is too small.
    - The site is on a flood plain.
    - The site includes wetlands.
    - A seismic zone is within 200 ft of the site.
    - An endangered species habitat is on the site.

- The site is too close to an airport
  - Not within 5000 ft for propeller aircraft or
  - Not 10,000 ft if turbine engine aircraft
- The site is in an area with high population density.
- The site includes sacred lands.
- The site includes a groundwater recharge area.
- Unsuitable soil conditions (e.g., peat bogs) exist on the site.

- **Permitting**
  - Fulfilling government standards
    - Design requirements, operating conditions, groundwater monitoring, landfill closure and post-closure, and financial assurance.
    - A design standard specifies a specific design, for example, a requirement for a composite liner.
    - Landfills are usually subject to permitting for land use conformance, air emissions, groundwater and surface water discharge, operations, extraction for cover material, and closure.

# 3. Landfill Types

- Moisture
  - Dry LF - keep waste dry to limit biological activity
  - Wet LF - leachate recirculation used to moisten waste, bioreactor
- Use
  - Municipal (sanitary)
  - Hazardous
  - Controlled LF - co-disposal
- Configuration
  - Above ground LF - catch pan design - 3:1 or 4:1 slope
  - Under ground LF - valley or depression used

- Special LF
  - Conventional
  - LF for milled (shredded) SW (35% greater in place density, daily cover not required)
  - ”Mono-fill” LF - specialized cells –
    - Aesbestos, incinerator ash, anaerobic decomposed yard waste

# 4. Construction Techniques

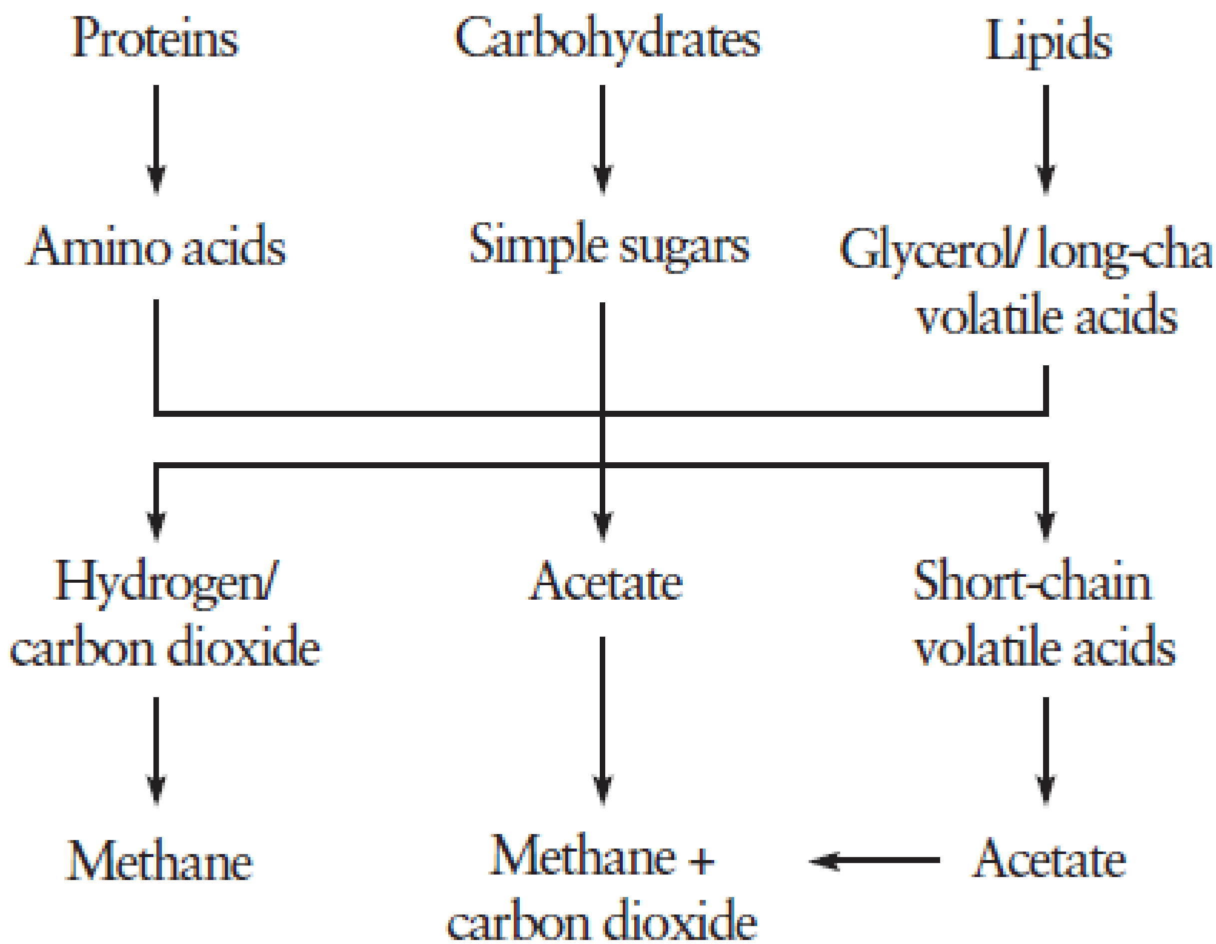
- Excavation method - ground water table (GWT) is distant from surface
  - Trenches are excavated, L=100-400ft, W=15-25ft, D=10-15ft
  - SW is dumped into trenches
  - Tractors/compactors spread & compact refuse by pushing it up the working face - multiple passes are made to maximize compaction
  - Soil cover is placed on refuse, obtained from excavation

- **Above ground method** - used when excavation method is not feasible
  - SW is unloaded and spread in long narrow strips (15-30 in thick)
  - Step 1, above, is repeated multiple times until a predetermined cell thickness is reached (usually 5-20 ft)
  - Cover soil is applied (6-12in) at end of day (geotextiles, foams, ground tires, compost, and other materials are often used)
  - Embankment slope - 3:1 or 4:1

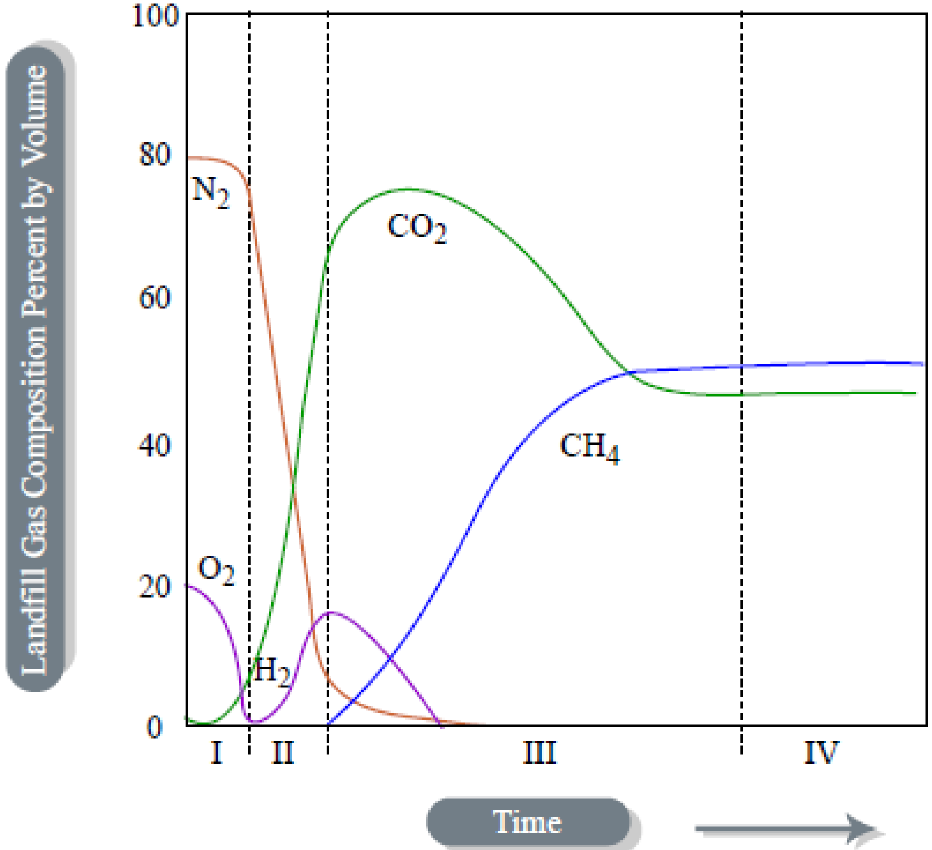
- **Canyon/depression method**
  - Similar operational technique to Above Ground Method
  - Used in areas where depressions (natural or artificial) exist, (canyons, valleys, ravines, borrow pits

# 5. Landfill processes

- **Biological Degradation**
  - Refuse is approximately 75 to 80% organic matter composed mainly of proteins, lipids, carbohydrates (cellulose and hemicellulose), and lignins.
  - Approximately two thirds of this material is biodegradable, while one-third is recalcitrant
  - the stabilization of waste proceeds in five sequential and distinct phases.


Proteins
Carbohydrates
Lipids
Amino acids
Simple sugars
Glycerol/ long-cha
volatile acids
Hydrogen/
carbon dioxide
Acetate
Short-chain
volatile acids
Methane
Methane +
carbon dioxide
Acetate

# Landfill Gas Production Pattern Phases




| Phases | Condition |
|---|---|
| I | Aerobic |
| II | Anoxic |
| II | Anaerobic, Methanogenic, Unsteady |
| II | Anaerobic, Methanogenic, Steady |

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Upper Saddle River, New Jersey: Prentice Hall PTR, 1995.

- **Phase I—Initial Adjustment Phase**
  - placement of solid waste
  - accumulation of moisture within landfills.
  - An acclimation period
- **Phase II—Transition Phase**
  - Transformation from an aerobic to an anaerobic environment occurs,
  - the depletion of oxygen trapped within the landfill media.
  - shifting of electron acceptors from oxygen to nitrates

- **Phase III—Acid Formation Phase**
  - The continuous hydrolysis of solid waste,
  - the microbial conversion of biodegradable organic content, results in the production of intermediate volatile organic acids at high concentrations throughout this phase.
- **Phase IV—Methane Fermentation Phase**
  - intermediate acids are consumed by methane-forming consortia (methanogenic bacteria) and converted into methane and carbon dioxide. Sulfate and nitrate are reduced to sulfides and ammonia, respectively.
  - The pH value is elevated, being controlled by the bicarbonate buffering system and, consequently, supports the growth of methanogenic bacteria.

- **Phase V—Maturation Phase**
  - During the final state of landfill stabilization, nutrients and available substrate become limiting, and the biological activity shifts to relative dormancy.
  - Gas production dramatically drops, and leachate strength stays steady at much lower concentrations.

- **Leachate Production**
  - **Leachate Quantity**
    - The total quantity produced can be estimated either by using empirical data or a water balance technique that sets up a mass balance among precipitation, evapotranspiration, surface runoff, and soil moisture storage.
    - A water balance uses site-specific data to track water volumes

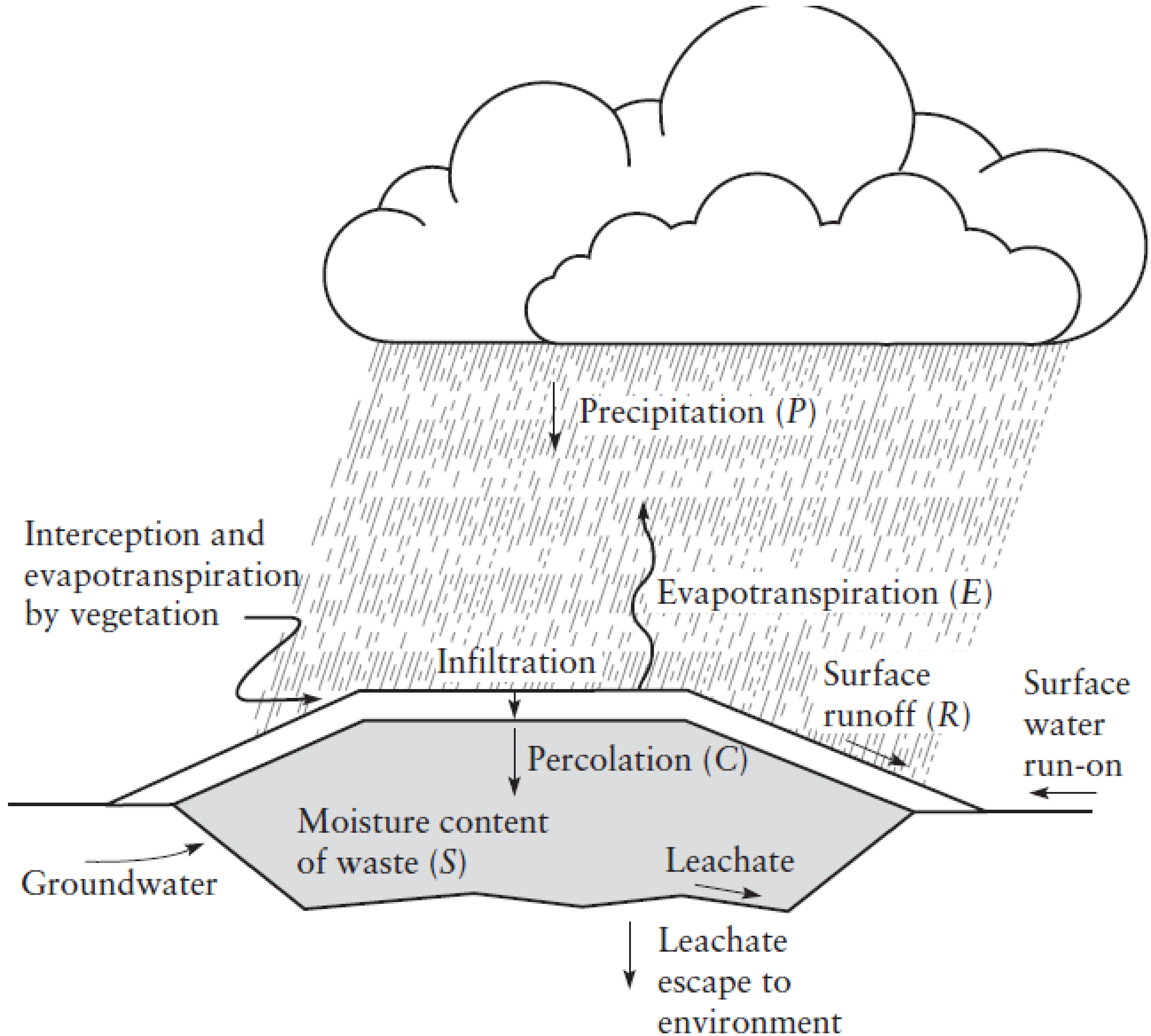



**Figure 4-4** Schematic of components of water balance within a landfill.

**Table 4-5 Field Capacities of Various Porous Materials**

| Material | Field capacity, as mm water/m of soil |
|---|---|
| Fine sand | 120 |
| Sandy loam | 200 |
| Silty loam | 300 |
| Clay loam | 375 |
| Clay | 450 |
| Solid waste | 200–350 |

Source: [7]

- The actual calculations of leachate production
  - involve a one-dimensional analysis of water movement through soil and the compacted refuse

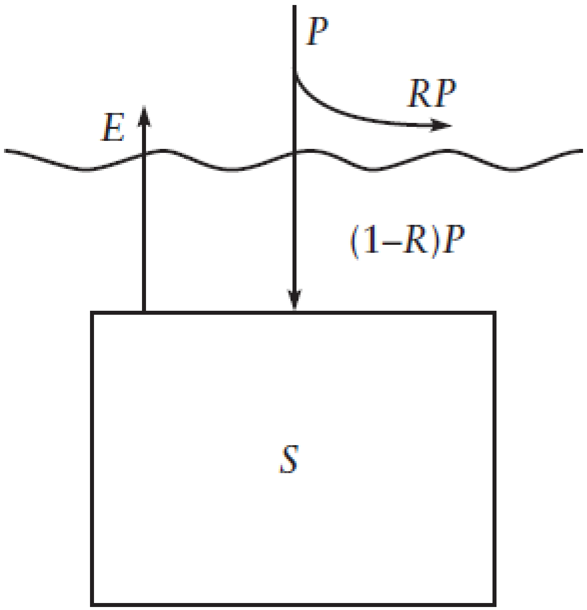



Figure 4-6 Mass balance of moisture in a landfill.

$$C = P(1 - R) - S - E$$

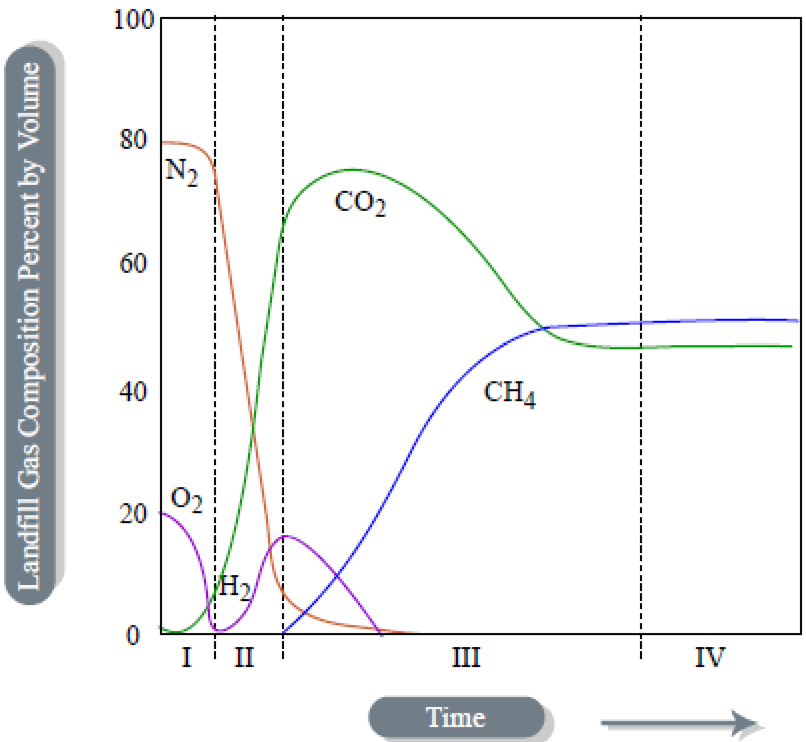
where

- $C$ = total percolation into the top soil layer, mm/yr
- $P$ = precipitation, mm/yr
- $R$ = runoff coefficient
- $S$ = storage within the soil or waste, mm/yr
- $E$ = evapotranspiration, mm/yr

- **Leachate Quality**
  - The characteristics of the leachate produced are highly variable, depending on the composition of the solid waste, precipitation rates, site hydrology, compaction, cover design, waste age, interaction of leachate with the environment, and landfill design and operation.
  - The quality of leachate directly affects viable leachate treatment alternatives.

# ➢ Gas Production

**Landfill Gas Production Pattern Phases**

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– **Gas Quantity**

- Landfill operators, energy recovery project owners, and energy users need to be able to project the volume of gas produced and recovered over time from a landfill.
- Recovery and energy equipment sizing, project economics, and potential energy uses depend on the peak and cumulative landfill-gas yield.
- The composition of the gas (percent methane, moisture content) is also important to energy producers

# Typical Landfill Gas Composition

| Component | Source | Typical concentration (% by volume) | Concern |
|---|---|---|---|
| Methane ($CH_4$) | B[a] | 50-70 | Explosive |
| Carbon Dioxide ($CO_2$) | B | 30-50 | Acidic in groundwater |
| Hydrogen ($H_2$) | B | <5 | Explosive |
| Mercaptans (CHS) | B | .1-1 | Odor |
| Hydrogen Sulfide ($H_2S$) | B | <2 | Odor |
| **Solvents** | | | |
| Toluene | C[b] | .1-1 | Hazardous |
| Benzene | C | .1-1 | Hazardous |
| Disulfates | C | .1-2 | Hazardous |
| Others | B and C | traces | Hazardous |

[a]B = Product of biodegradation [b]C = A contaminant in the MSW

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR, 1995.

- **Gas emission estimation**

US EPA has published a model called Land GEM based on the following equation:

$$Q_T = \sum_{i=1}^{n} 2kL_oM_ie^{-kt_i}$$

where

$Q_T$ = total gas emission rate from a landfill, volume/time
$n$ = total time periods of waste placement
$k$ = landfill gas emission constant, $time^{-1}$
$L_o$ = methane generation potential, volume/mass of waste
$t_i$ = age of the ith section of waste, time
$M_i$ = mass of wet waste, placed at time $i$

**Example**

A landfill cell is open for three years, receiving 165,700 tonnes of waste per year (recall that 1 tonne=1000 kg). Calculate the peak gas production if the landfill-gas emission constant is 0.0307 $yr^{-1}$ and the methane generation potential is 140 m3/tonne.

- **Solution**

For the first year,

$$Q_T = 2\,(0.0307)\,(140)\,(165{,}700)(e^{-0.0307(1)}) = 1{,}381{,}000 \text{ m}^3$$

For the second year, this waste produces less gas, but the next new layer produces more, and the two are added to yield the total gas production for the second year.

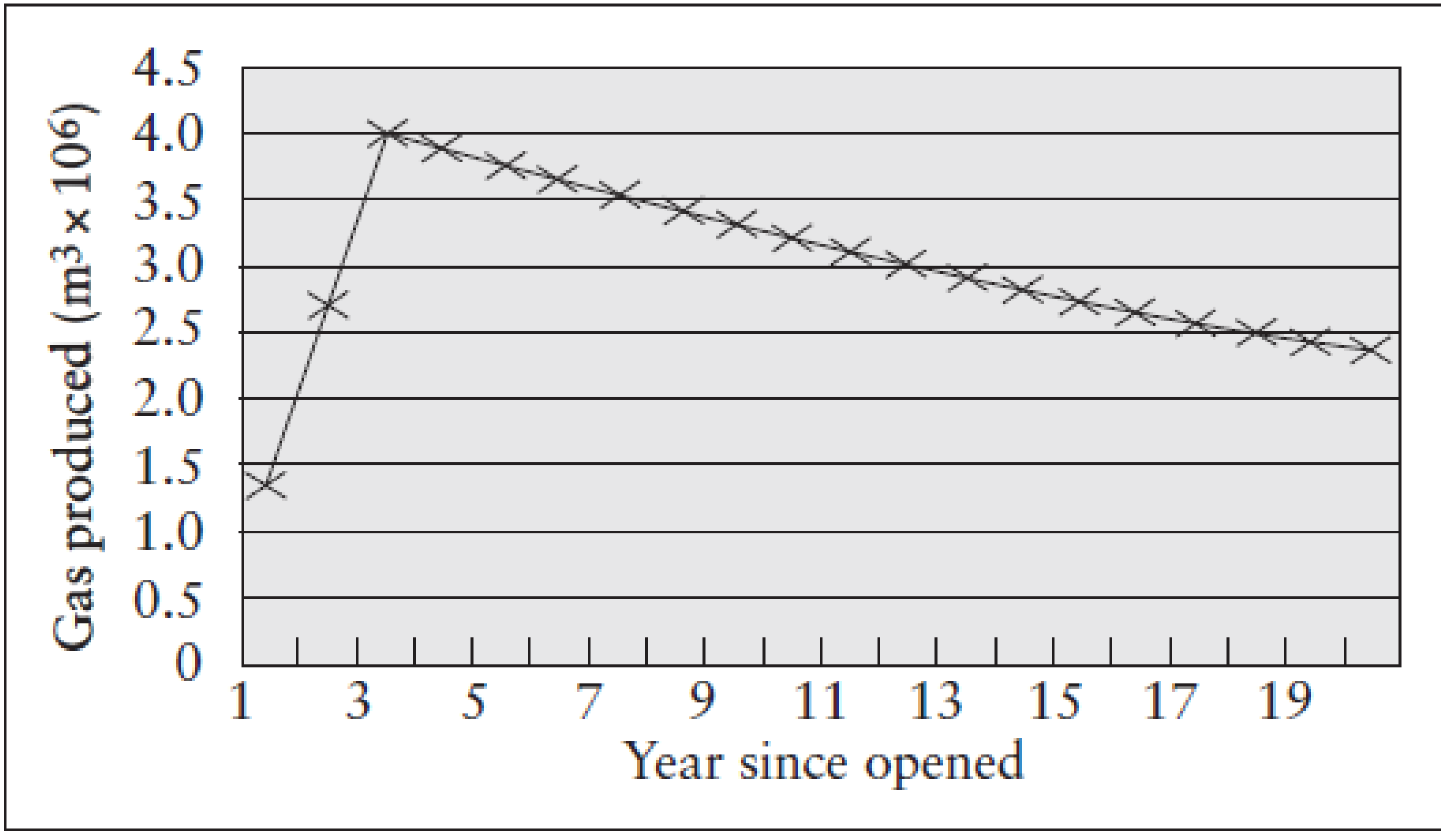



**Figure 4-7** Landfill gas generated in a landfill. [See Example 4-4.]

- These results are plotted as Figure 4-7. The annual peak gas production is found from this figure as about 4,000,000 m3/yr.
- The duration of decomposition of solid waste and gas production are influenced by environmental conditions within the landfill.
- The lag period prior to methane generation may range from a few weeks to a few years, depending on landfill conditions.

- A practical guide to forecasting of yield—based on waste generation, the ability of wastes to decompose, and the efficiency of collecting gases from that decomposition— uses the following assumptions:
  - 80% of the MSW generated is landfilled.
  - 50% of the organic material will actually decompose.
  - 50% of the landfill gas generated is recoverable.
  - 50% of the landfills are operating within a favorable pH range.

- **Gas Quality**

**Table 4-8 Typical Constituents of MSW Landfill Gas**

| Component | % by volume (dry) |
|---|---|
| Methane | 45–60 |
| Carbon dioxide | 40–60 |
| Nitrogen | 2–5 |
| Oxygen | 0.1–1.0 |
| Ammonia | 0.1–1.0 |
| Hydrogen | 0–0.2 |

Source: Integrated solid waste management : engineering principles and management issues by Tchobanoglous, G., H. Theisen, and S. Vigil. 

# 6. Landfill design

- The major design components of a landfill include the liner, the leachate-collection and management system, gas management facilities, storm water management, and the final cap.

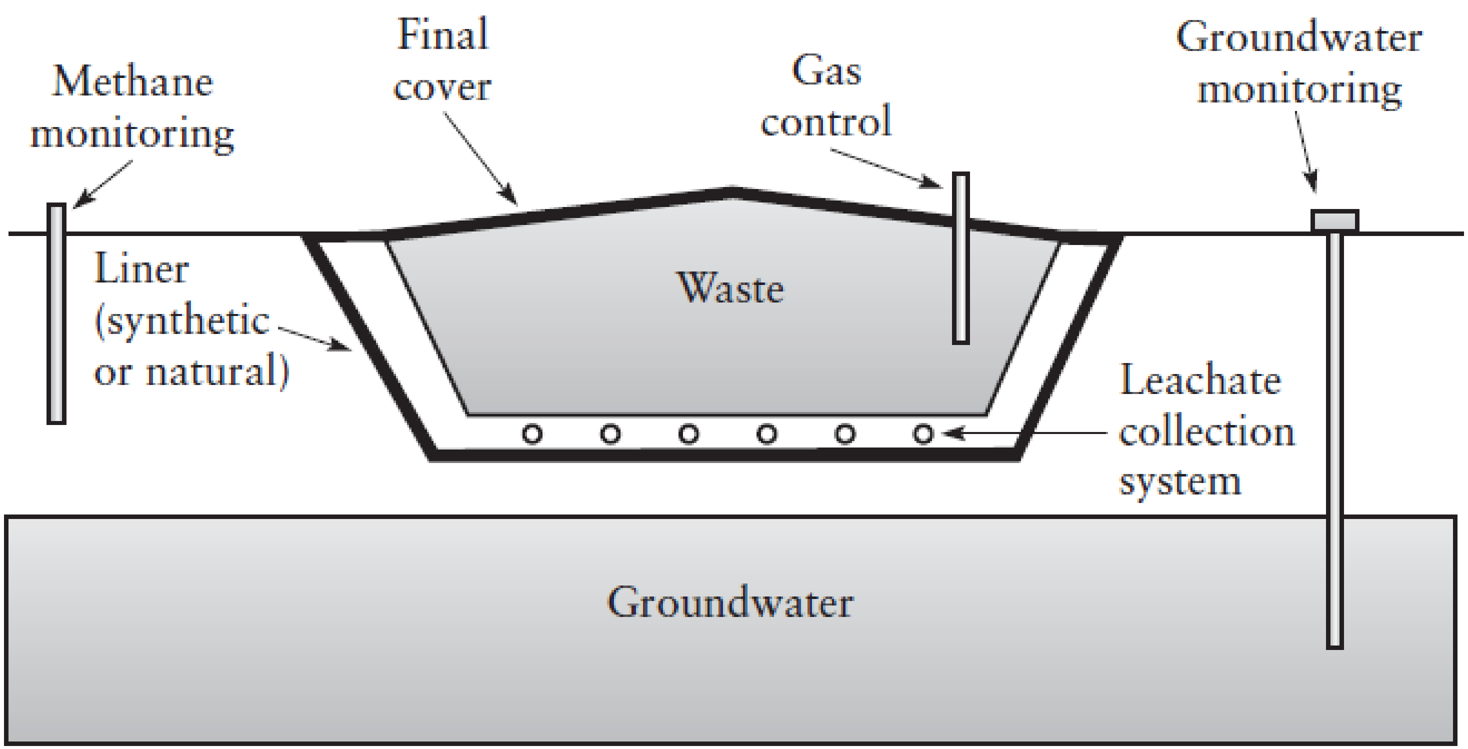
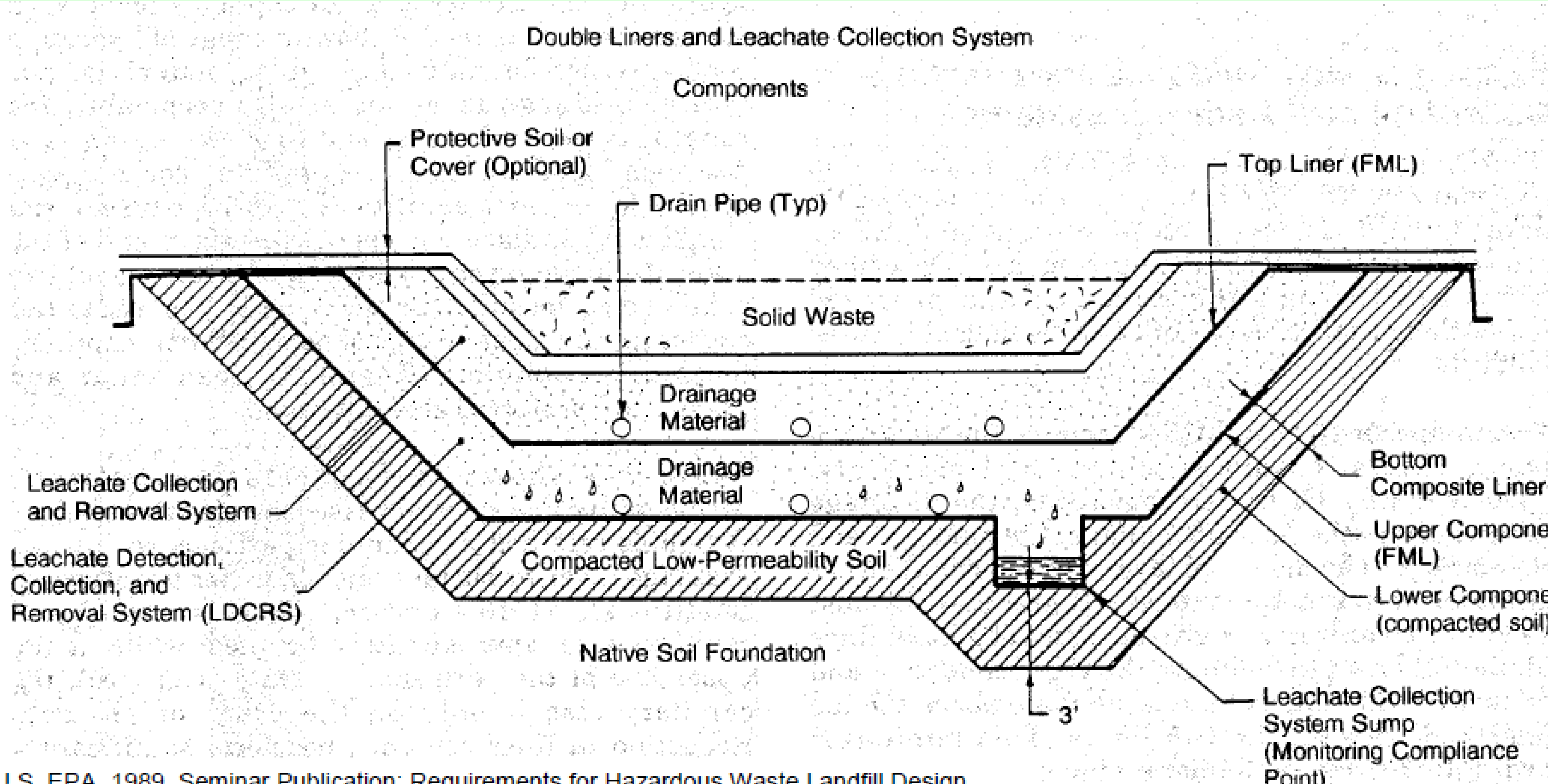



**Figure 4-8** Design components in a Subtitle D landfill.




U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

- **Liners**
  - The liner system is required to prevent migration of leachate from the landfill and to facilitate removal of leachate.
  - It generally consists of multiple layers of natural material and/or geomembranes selected for their low permeability.
  - Soil liners usually are constructed of natural clays
  - If natural clay materials are not readily available, commercial clays (bentonite) can be mixed with sands to produce a suitable liner material.
  - Geomembranes are impermeable thin sheets made from synthetic resins, such as polyethylene, polyvinyl chloride, or other polymers.

- Landfills may be designed with single, composite, or double liners, depending on the applicable local, state, or federal regulations
- A single liner is constructed of clay or a geomembrane.
- A composite liner, which is the minimum liner consists of two layers:
  - The bottom is a clay material and the top layer is a geomembrane.
  - The two layers of a composite liner are in intimate contact to minimize leakage.
  - A double liner may be either two single liners or two composite liners (or even one of each).

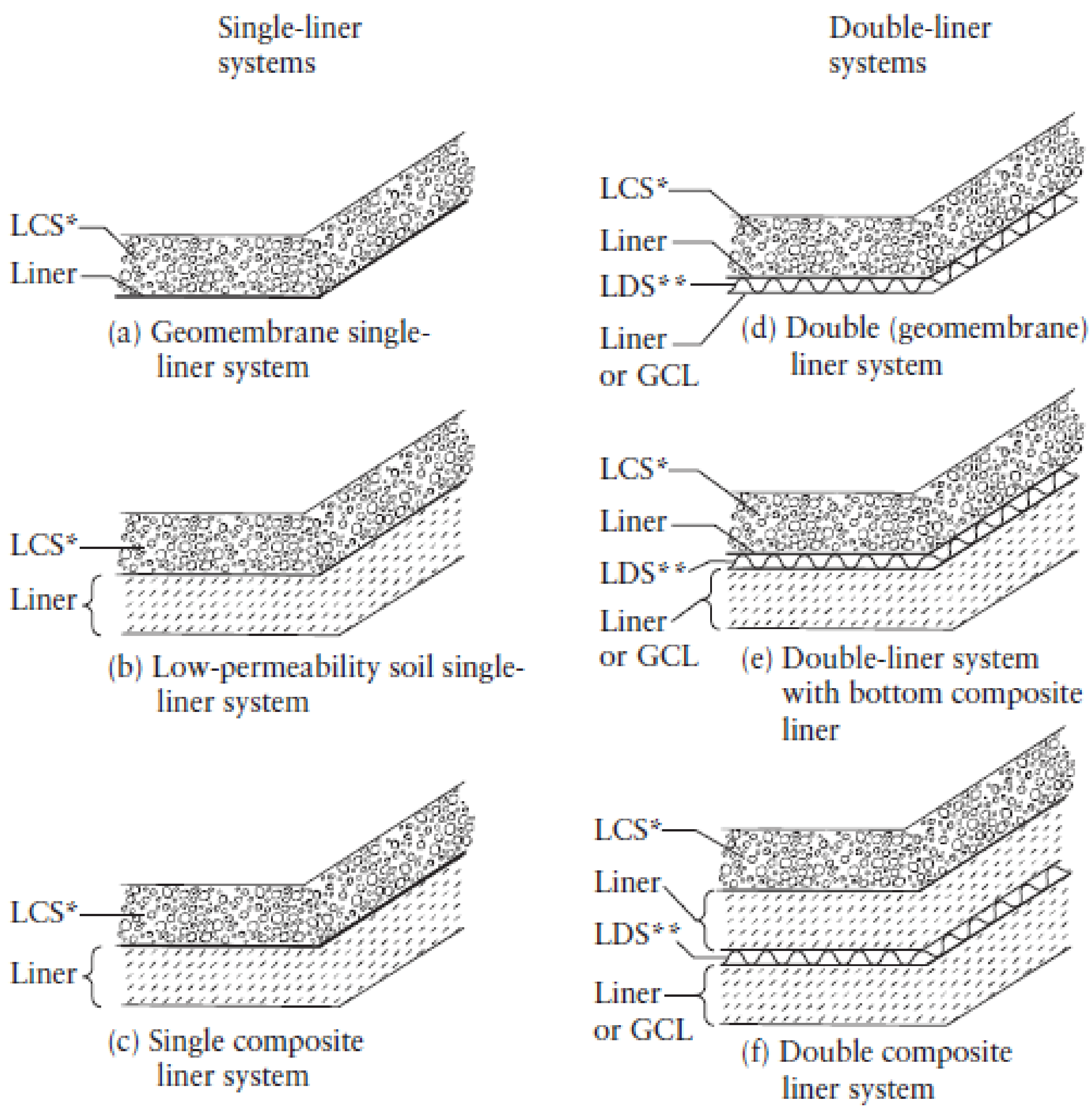
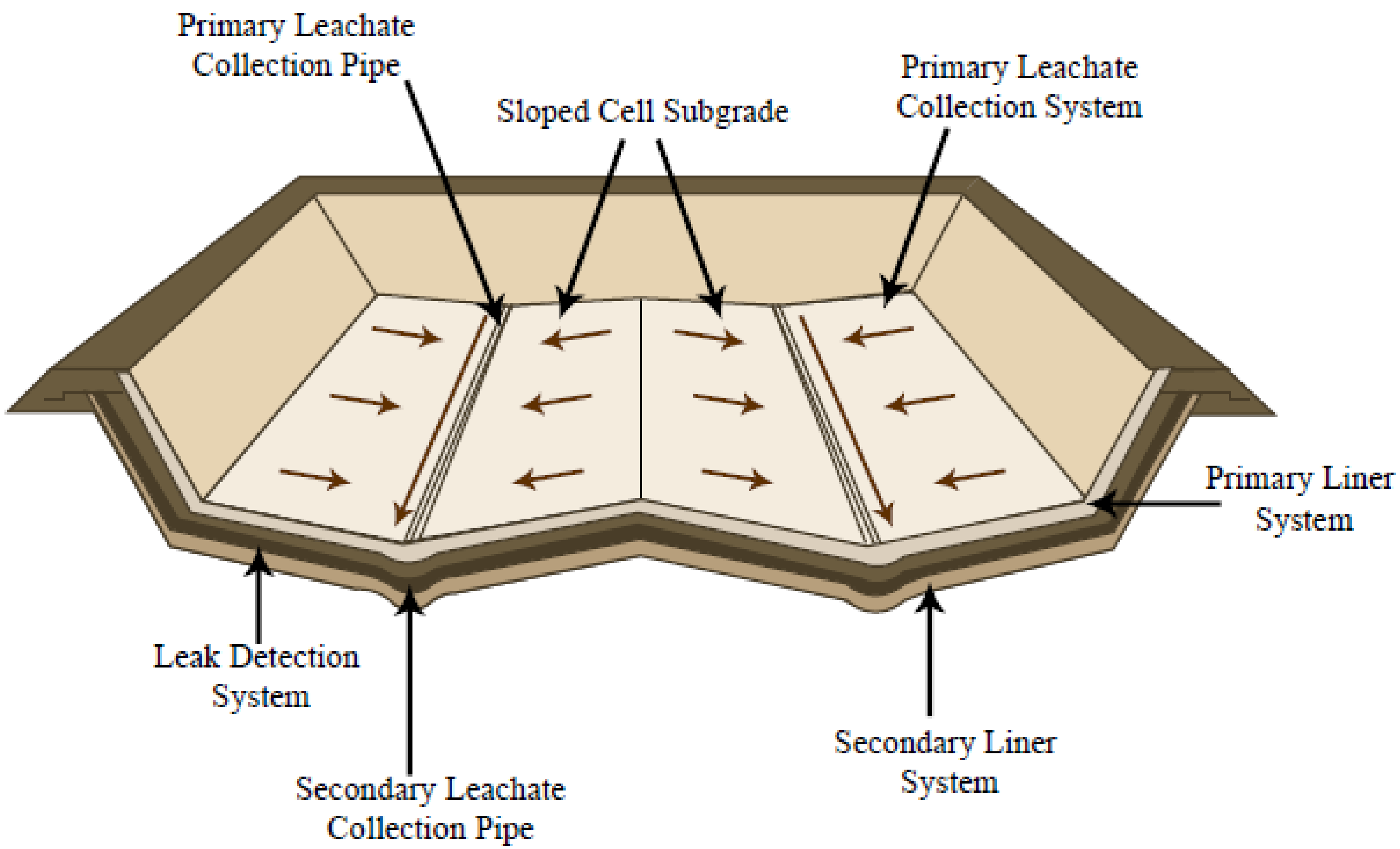



**Figure 4-9** Examples of liner systems in municipal solid waste landfills. LCS = leachate-collection system, GCL = geosynthetic clay liner, and LDS = leachate-detection system.

**Figure 4-10** Synthetic liner on slope, ready for earth cover. (Courtesy William A. Worrell)

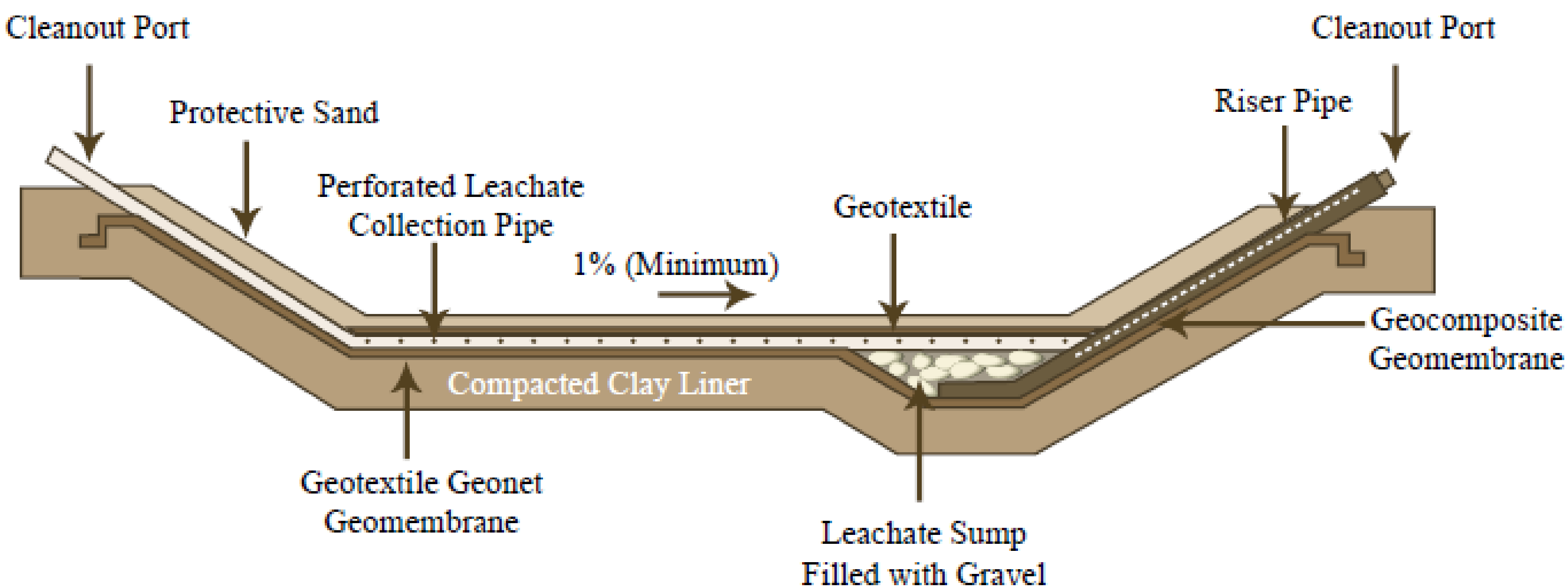
- **Leachate Collection, Treatment, and Disposal**
  - Leachate is directed to low points at the bottom of the landfill through the use of an efficient drainage layer composed of sand, gravel, or a geosynthetic material.
  - Perforated pipes are placed at low points to collect leachate and are sloped to allow the moisture to move out of the landfill.




Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

- **Leachate Collection and Storage**
  - The primary purpose of lining a landfill cell is to minimize the potential for groundwater contamination.
  - The liner serves as a barrier between the buried waste and the groundwater and forms a catch basin for leachate produced by the landfill.
  - the head of leachate (free liquid depth) should be lower than on a liner system to 30 cm (USA EPA).
  - Leachate is typically removed by two means: gravity flow or pumping.

- The various components of a leachate collection system for an MSW landfill typically include the following.
  - Protective and drainage layers
  - Perforated collection lateral and header pipes
  - Pump station sump
  - Leachate pumps
  - Pump controls
  - Pump station appurtenances
  - Force main or gravity sewer line

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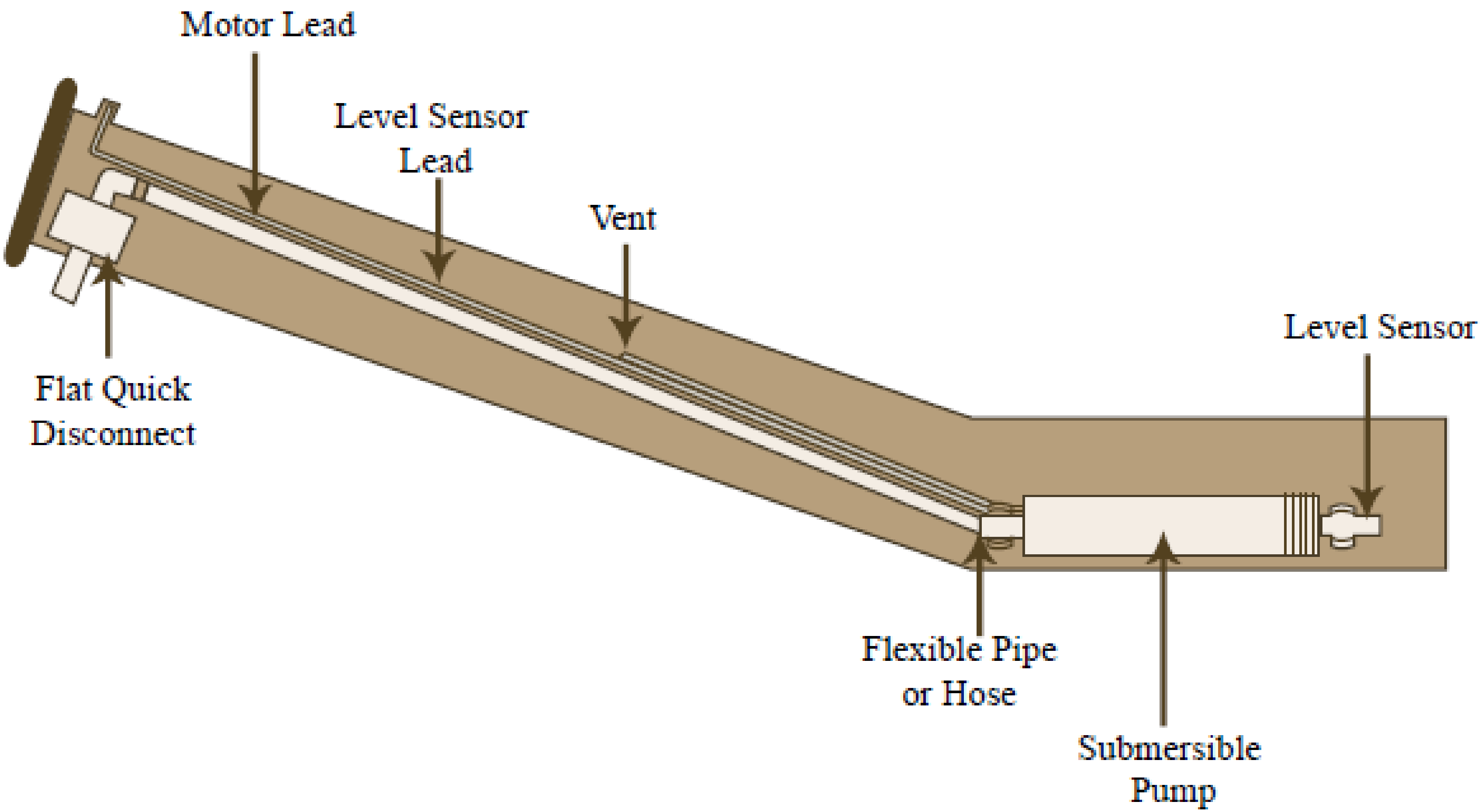


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**Table 4-10 Design Guidance for Leachate-Collection System Components**

| Parameter | Range | Median |
|---|---|---|
| Leachate loading rate (gpd/ac) | 600–1000 | 750 |
| Maximum leachate head (in.) | 9–12 | 11 |
| Pipe spacing (ft) | 60–400 | 180 |
| Collection pipe dia. (in.) | 6–8 | 8 |
| Collection pipe material | PVC or HDPE | HDPE |
| Pipe slope (%) | 0.5–2 | 1 |
| Drainage slope (%) | 0.2–2 | 1 |

Source: Reinhart, D. R., and T. Townsend. 1998. "Assessment of Leachate Collection System Clogging at Florida Municipal Solid Waste Landfills." Report to the Florida Center for Solid and Hazardous Waste Management (April).

- Leachate removed from the landfill cell(s) is temporarily stored on site until it can be treated, recirculated, or transported off site for final treatment and disposal.
- Storage of leachate is also important for equalization of flow quantities and constituent quality to protect downstream treatment facilities.

- **Leachate Collection System Design Equations and Techniques**
  - The drainage length, drainage slope, permeability of the drainage materials, and the leachate impingement rate control the depth of leachate on the liner.
  - Darcy’s law (in conjunction with the law of continuity) can be used to develop an equation to predict the leachate depth on the liner based on anticipated infiltration rates, drainage material permeability, distance from the drain pipe, and slope of the collection system

For $R < 1/4$,

$$Y_{max} = (R - RS + R^2S^2)^{1/2}\left[\frac{(1 - A - 2R)(1 + A - 2RS)}{(1 + A - 2R)(1 - A - 2RS)}\right]^{1/2.4}$$

For $R = 1/4$,

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

For $R > 1/4$,

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

where

$R = q/(K \sin^2\alpha)$, unitless

$A = (1 - 4R)^2$, unitless

$B = (4R - 1)^2$, unitless

$S = \tan \alpha$, slope of liner, unitless

$Y_{max}$ = maximum head on liner, ft

$L$ = horizontal drainage distance, ft

$\alpha$ = inclination of liner from horizontal, degrees

$q$ = vertical inflow (infiltration) per unit of horizontal area, ft/day

$K$ = hydraulic conductivity of the drainage layer, ft/day

- Proposed less cumbersome, far-easier-to-use equation:

$$Y_{max} = \frac{P}{2}\left(\frac{q}{K}\right)\left[\frac{K\tan^2\alpha}{q} + 1 - \frac{K\tan\alpha}{q}\left(\tan^2\alpha + \frac{q}{K}\right)^{1/2}\right]$$

where

$Y_{max}$ = maximum saturated depth over the liner, ft

$P$ = distance between collection pipes, ft

$q$ = vertical inflow (infiltration), defined in this equation as from a 25-year, 24-hour storm, ft/day

- This equation can be used to calculate the maximum allowable pipe spacing based on the maximum allowable design head, anticipated leachate impingement rate, slope of the liner, and permeability of the drainage materials.

- **Example**

Determine the spacing between pipes in a leachate collection system using granular drainage material and the following properties. Assume that in the most conservative design all stormwater from a 25-year, 24-hour storm enters the leachate collection system.

Design storm (25 years, 24 hours) = 8.2 in = 0.00024 cm/s

Hydraulic conductivity = 102 cm/s

Drainage slope = 2%

Maximum design depth on liner = 15.2 cm

- **Solution**

$$P = \frac{2Y_{\max}}{\left(\dfrac{q}{K}\right)\left[\dfrac{K\tan^2\alpha}{q} + 1 - \dfrac{K\tan\alpha}{q}\left(\tan^2\alpha + \dfrac{q}{K}\right)^{1/2}\right]}$$

$$P = \frac{2(15.2)}{\left(\dfrac{0.00024}{0.01}\right)\left[\dfrac{0.01(0.02)^2}{0.00024} + 1 - \dfrac{0.01(0.02)}{0.00024}\left((0.02)^2 + \dfrac{0.00024}{0.01}\right)^{1/2}\right]} = 1428 \text{ cm}$$

- Geosynthetic drainage materials (geonets) have been introduced to increase the efficiency of the leachate collection systems over such natural materials as sand or gravel.
  - A geonet consists of a layer of ribs superimposed over each other, providing highly efficient in-plane flow capacity (or transmissivity).
  - If a geonet is used between the liner and drainage gravel, the spacing between the collection pipes can be estimated from

$$\theta = \frac{qP^2}{4Y_{\max} + 2P\sin\alpha}$$

where $\theta$ = transmissivity of the geonet, $ft^2$/day

- **Leachate Treatment and Disposal**

**Table 4-11 Summary of Leachate Treatment Options**

| Treatment Option | Removal Objective | Comments |
|---|---|---|
| **Biological** | | Best used on "young" leachate |
| Activated sludge | BOD/COD | Flexible, shock resistant, proven, minimum SRT increases with increasing organic strength, > 90% BOD removal possible |
| Aerated lagoons | BOD/COD | Good application to small flows, > 90% BOD removal possible |
| Anaerobic | BOD/COD | Aerobic polishing necessary to achieve high-quality effluent |
| Powdered activated carbon/activated sludge | BOD/COD | > 95% COD removal, > 99% BOD removal |
| **Physical/Chemical** | | Useful as polishing step or for treatment of "old" leachate |
| Coagulation/Precipitation | Heavy Metals | High removal of Fe, Zn; moderate removal of Cr, Cu, or Mn; little removal of Cd, Pb, or Ni |
| Chemical oxidation | COD | Raw leachate treatment requires high chemical dosages, better used as polishing step |
| Ion exchange | COD | 10–70% COD removal, slight metal removal |
| Adsorption | BOD/COD | 30–70% COD removal after biological or chemical treatment |
| Reverse osmosis | Total dissolved solids (TDS) | 90–96% TDS removal |

Source: Reinhart, D. R., and C. J. Grosh. 1997. "Analysis of Florida MSW Landfill Leachate Quality Data." Report to the Florida Center for Solid and Hazardous Waste Management (March).

- **Leachate Recirculation**
  - Landfills can be used as readily available biological reactors for the treatment of leachate.
  - The landfill can be essentially transformed into an engineered reactor system by providing containment using liners and covers, sorting and discrete disposal of waste materials into dedicated cells, collection and recirculation of leachate, and management of gas.
  - Such landfills are capable of accelerated biochemical conversion of wastes and effective treatment of leachate

# 7. Landfill Gas Collection and Use

- Gas generated within a landfill will move by pressure gradient, following paths of least resistance.
- Uncontrolled migrating gas can collect in sewers, sumps, and basements, leading to tragic consequences if explosions occur.
- To prevent gas migration, gas vents or wells must be provided.
- There are two basic systems for gas emissions control:
  - passive collection and
  - active extraction.

- *Passive collection systems*
  - Collect landfill gas using vent collectors and release the gas to the atmosphere without treatment or conveyance to a common point.
  - Passive vents are often provided using natural convective forces within the landfill to direct gas to the atmosphere.
  - Passive vents may reach only a few feet below the cap or may reach up to 75% of the landfill depth,
  - Designed in a similar manner to the active extraction well described next.
  - Typical spacing for a passive vent is one per 9000 $yd^3$ (7500 $m^3$).

- *Active collection systems*
  - link collection wells with piping and extract the gas under vacuum created by a central blower.
  - Active extraction wells may be vertical or horizontal wells
    - Vertical wells are more frequently employed.
  - Vertical wells are installed in landfills using auger or rotary drills.
  - Wellheads provide a means of controlling the vacuum applied at the well as well as monitoring of gas flow rate, temperature, and gas quality.
  - Spacing of wells is a function of gas flow.
  - Table 4-12 provides general guidance on well construction.

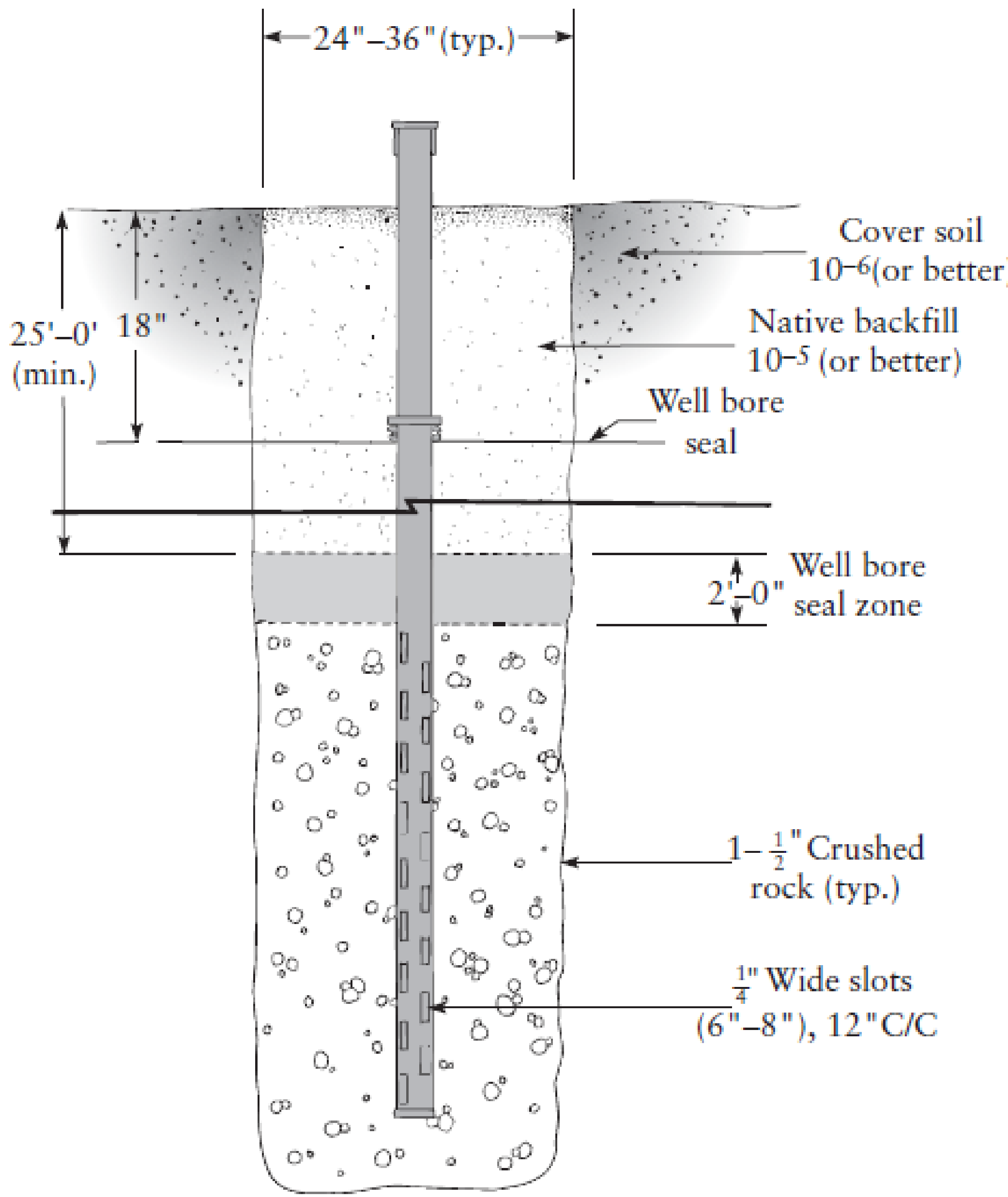



**Figure 4-11** Typical vertical gas well.

**Table 4-12 Guidelines for Construction of Vertical Gas Collection Systems**

| Parameter | Recommendation |
|---|---|
| Well depth | 75% of depth or to water table, whichever comes first |
| Perforations | Bottom 1/3 to 2/3 |
| | Minimum 25 ft below surface |
| Casing | 3–8 in. PVC or HDPE, telescoping well joint |
| Spacing (on center) | Interior collection system 200–500 ft |
| | Perimeter collection system 100–250 ft |
| Well density | One well per 1/2 to 2 acres |
| Minimum gas-collection piping slope | 3% |
| Well bore diameter | 12 to 36 in. is standard (24, 30, 36 in. most common) |

- The velocity of the flow through the piping system can be estimated using the continuity equation if compressibility is neglected.

$$Q = vA$$

where

$Q$ = landfill-gas flow rate, $ft^3/sec$

$v$ = landfill-gas velocity, ft/sec

$A$ = cross-sectional interior area of the pipe, $ft^2$

- The head loss through the pipe can be estimated using the Darcy-Weisbach equation, usually stated as

$$\Delta P = \frac{\rho f L v^2}{2gD}$$

where

$\Delta P$ = pressure drop, ft
$f$ = Darcy-Weisbach friction factor, function of pipe roughness and diameter
$L$ = length of pipe, ft
$v$ = velocity, ft/sec
$g$ = gravitational constant, ft/sec$^2$
$D$ = diameter, ft
$\rho$ = gas density, lb/ft$^3$

The Darcy-Weisbach friction factor can be read from a Moody diagram, which is found in all fluid mechanics textbooks.

- The equation gives the pressure drop in feet of water if all length units are in feet and the fluid is water.
- If the fluid is a gas, the equation can be modified (taking into account the density of the fluid) as

$$\Delta P = \frac{(0.0096)\rho f L v^2}{Dg}$$

where

$\Delta P$ = pressure drop when a gas is flowing in the pipe, ft of water

$\rho$ = density of the gas, $lb/ft^3$

- The density of the gas is calculated using the universal gas law:

$$\rho = \frac{MP}{RT}$$

where

$\rho$ = density of the gas, lb/ft$^3$
$M$ = molecular weight of the gas, lb/mole
$P$ = pressure, lb/ft$^2$
$R$ = universal gas constant, lb-ft/mole-°R
$T$ = absolute temperature, °R (°F + 460)

Typically, the pressure inside the collection pipes is close to atmospheric, about 30 inches of water (13.6 lb/in2 or about 1958 lb/ft2).
The molecular weight of the gas can be estimated as 28 lb/mole, with the universal gas constant then having units of lb-ft/ºR.

- Example

Calculate the pressure drop in 800 ft of 4-in.-diameter PVC pipe carrying 500 $ft^3$/min of landfill gas at 120°F. Assume the pressure in the pipeline is close to atmospheric (about 13.6 lb/$in.^2$) and the molecular weight of the landfill gas is 28 lb/mole. Assume the gas is incompressible.

The area of a 4-in.-diameter PVC Schedule 40 pipe (4.026 in. ID) is 0.0884 $ft^2$.

- Solution

From the continuity equation:

$$v = (500/60)/0.0884 = 94 \text{ ft/sec}$$

The roughness, $\epsilon$, for PVC pipe is 0.000005 ft. Thus, $\epsilon/D = 0.000005/(4/12) = 0.000015$. From the modified Moody diagram, the friction factor is read as $f = 0.016$.

The gas density is estimated assuming the pressure at 1958 lb/ft$^2$, the molecular weight at 28 lb/mole, the universal gas constant at 1543 lb-ft/°R, and the absolute temperature at 120°F + 460. Thus,

$$\rho = \frac{(28)(1958)}{(1543)(120 + 460)} = 0.0613 \text{ lb/ft}^3$$

The pressure drop is then calculated as

$$\Delta P = \frac{(0.0096)(0.0613)(0.016)(800)(94)^2}{(4.026/12)(32.2)}$$

$$= 6.2 \text{ ft of water}$$

Repeating the calculations for 6- and 8-in. pipes, the pressure drops are 0.8 ft and less than 0.1 ft, respectively, of water column.

Assuming head loss in the valves and fittings at 20% of the total pressure drop and adding an additional 10 in. of water column to maintain negative pressure at the wellhead, the 4 in. pipe requires a negative blower pressure at the suction side of the blower at a 84-in. water column. The 6 in. pipe requires about a 20-in. water column, and the 8 in. pipe requires less than a 12-in. water column.

# 8. Geotechnical Aspects of Landfill Design

- Landfill stability is normally analyzed using readily available computer software.
- This analysis requires knowledge of properties of waste, materials used in the liners and caps (synthetic and natural), and foundation soils.
- Waste properties are often difficult to determine because of waste heterogeneity, changes in properties with time, and the difficulty in collecting samples necessary to evaluate these properties.
- The operation of the landfill as a bioreactor can create unique geotechnical conditions.
- Increased moisture content leading to waste saturation can result in positive internal pore pressure and reduce occurs at an interface) angle of friction (angle at which slope failure

- To minimize the probability of landfill failure
  - side slopes of completed and capped landfills be no greater than 1:3, with 1:4 being preferable.
  - Shallow slopes mean reduced air space for waste disposal;
    - the reduced risk of slope failure outweighs economic advantages of increased disposal volume.
  - Use of textured geo-membranes can also reduce slippage along interfaces.
  - proper drainage and gas-pressure relief in the cap will reduce pore pressure and reduce the probability of failure.
  - Given the uncertainties of design, significant factors of safety are highly recommended.

- **Storm-water Management**
  - Many operating and design controls are available to minimize leachate production, including control of the size of the working face, placement of interim cover on the waste, and use of proper stormwater runoff and run-on controls.
  - Run-on control prevents the introduction of stormwater to the active area of the landfill, thus minimizing the production of leachate, erosion, and contamination of surface water.
  - Reducing run-on also limits the production of runoff from the landfill surface.

- **Landfill Cap**
  - The purpose is to prevent the production of leachate that can contaminate groundwater.
  - The effect of keeping water out of the landfill is to maintain dry conditions and hinder the process of biodegradation, making most landfills merely storage facilities.

- Slope stability and soil erosion are critical concerns for landfill caps.
- Typical side slopes are 1:3 to 1:4, and the interface friction between adjacent layers must resist seepage forces

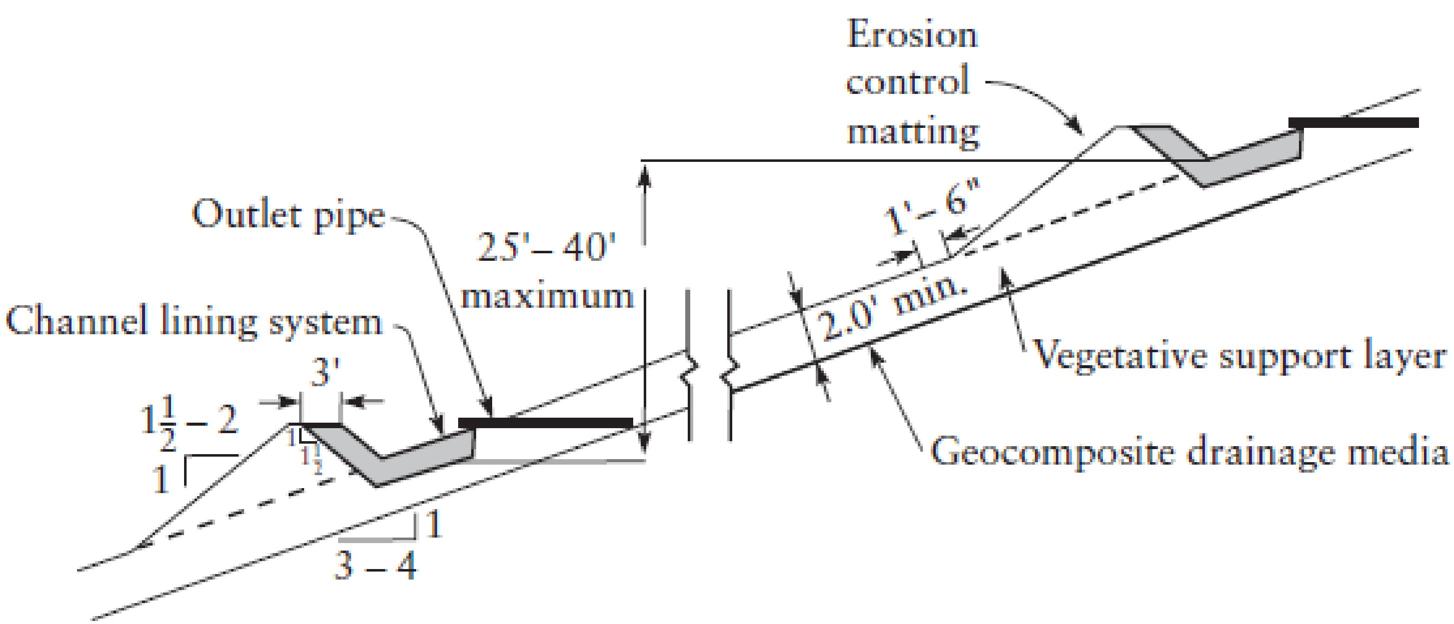
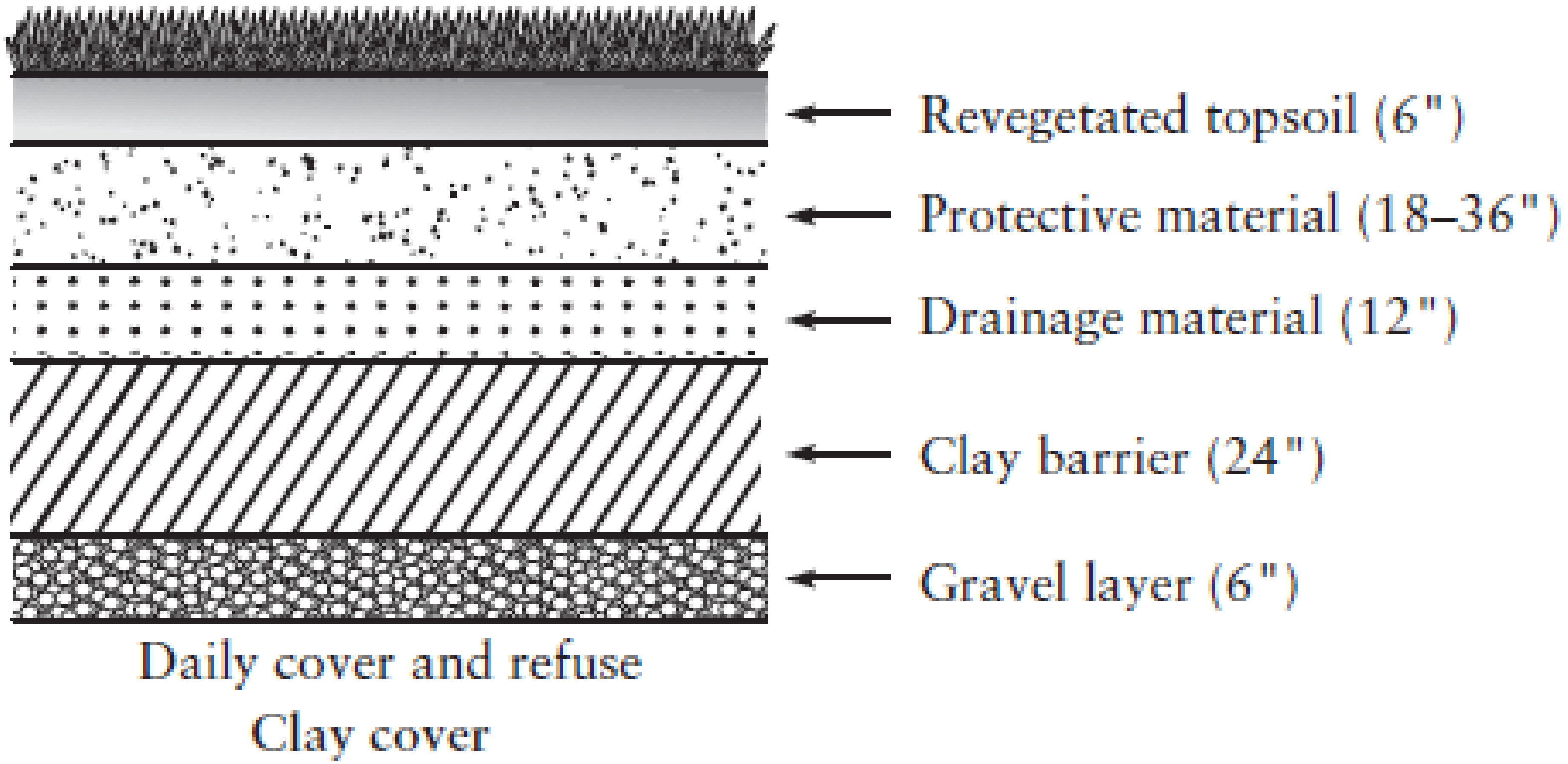
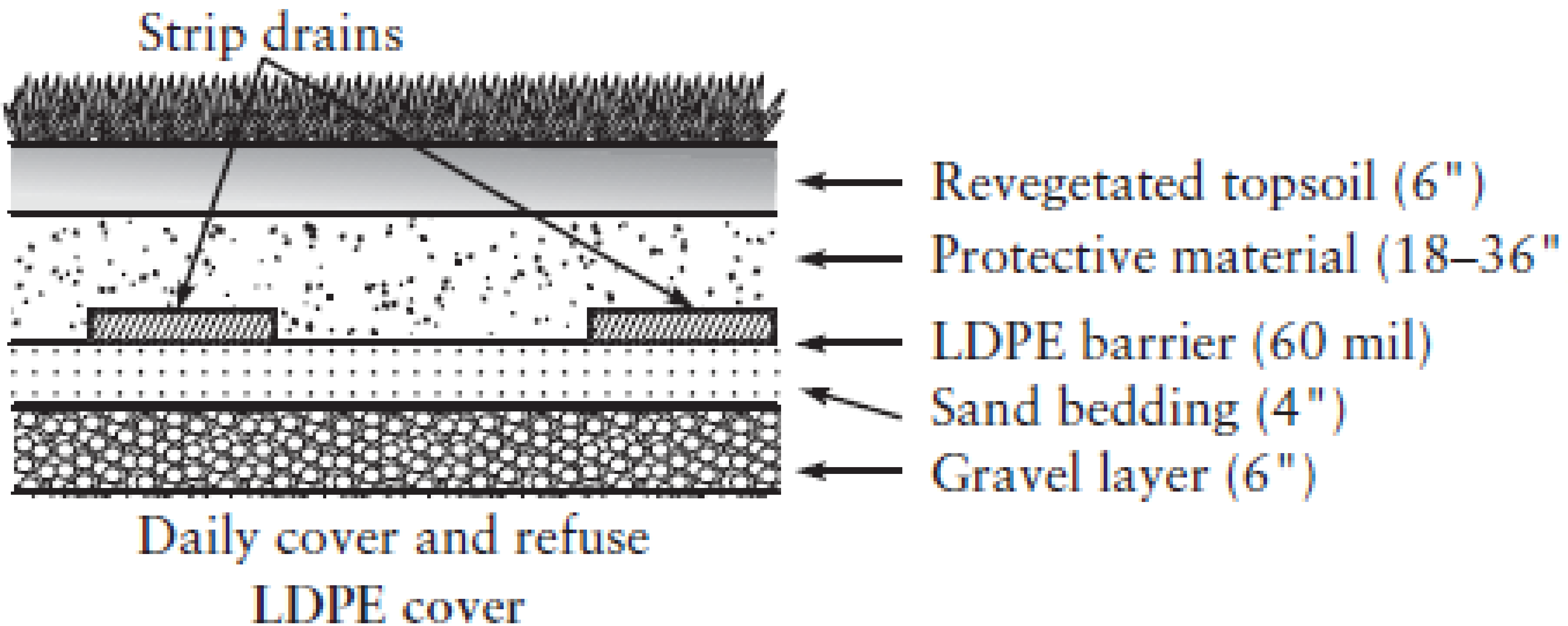



Figure 4-12 Side slope swale in a landfill final cover.

Figure 4-13 Typical caps used for closing landfills.




Strip drains
Revegetated topsoil (6")
Protective material (18–36")
LDPE barrier (60 mil)
Sand bedding (4")
Gravel layer (6")
Daily cover and refuse
LDPE cover

# 9. Landfill operations

- **Landfill Equipment**
  - The movement, placement, and compaction of waste and cover in a landfill require a variety of large machines, including tractors, loaders (track and wheel), and compactors.
  - In addition, a variety of support equipment is needed, including motor graders, hydraulic excavators, water trucks, and service vehicles.
  - Specially built landfill compactors (Figure 4-15a) are now almost universally used.
  - They are effective in spreading and compacting large quantities of waste, are quite heavy (exceeding 25 tons), and are equipped with knobbed steel wheels capable of tearing and compacting waste to densities of 1200 to 1600 lb/yd3 (710 to 950 kg/m3).
  - Daily dirt cover is excavated and placed on the operating face of a landfill using pans or scrapers (Figure 4-15b).

- The type and quantity of landfill vehicles are determined by:
  - the amount and type of waste handled,
  - the amount and type of soil cover,
  - distance of moving waste and cover,
  - weather requirements,
  - compaction requirements,
  - landfill configuration,
  - budget,
  - expected growth, and
  - supplemental tasks anticipated.


(a)

**Figure 4-15** (a) Landfill compactor used to compact waste placed in a landfill.


(b)

**Figure 4-15** (b) A pan scraper used to haul and spread daily dirt cover. (Courtesy P. Aarne Vesilind)

- **Filling Sequences**
  - At an active landfill, daily deliveries of waste are placed in *lifts* or layers on top of the liner and leachate-collection system to depths of 20 m (65 ft) or greater
  - Typical waste placement methods used for landfill construction are shown in Figure 4-16.
  - The area or mound type of landfill construction is commonly used in areas with a high groundwater table or subsurface conditions that prevent excavation.
  - The excavation or trench technique provides waste placement in cells or trenches dug into the subsurface.
  - The removed soil is often used as daily, intermediate, or final cover.

- The leachate-collection system should be protected during landfill operations,
  - waste in the first lift is selected to avoid heavy and sharp objects
  - This layer is often called the *operational layer*.
  - The waste also must be placed in a manner to keep compactor wheels away from the leachate-collection system.
  - Filling then begins in subsequent lifts, generally in a corner and moving outward to form the next layer.
  - The filling sequence is established at the time of landfill design and permitting.
  - The working face must be large enough to accommodate several vehicles unloading simultaneously, typically 12 to 20 ft (4 to 6 m) per vehicle.

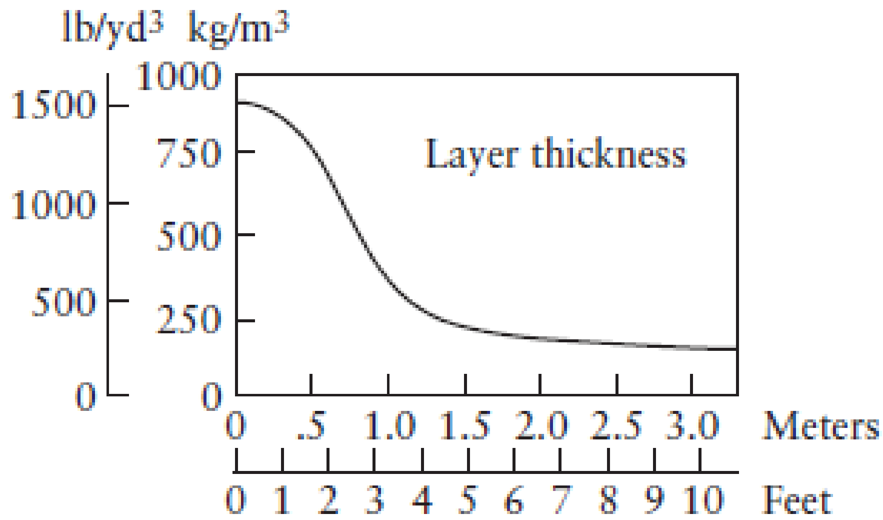



**Figure 4-17** Waste density of a landfill as a function of layer thickness.

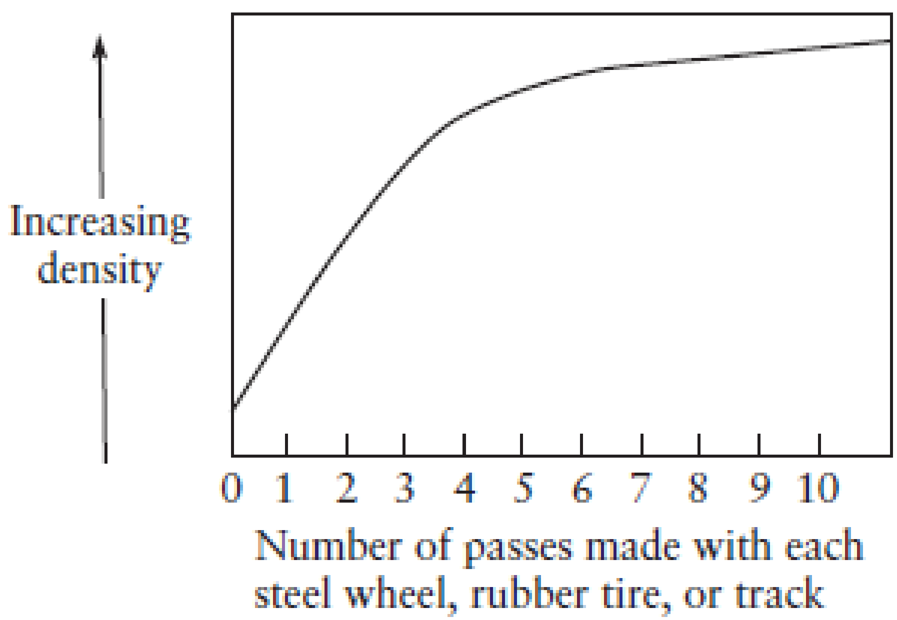



**Figure 4-18** Waste density of a landfill as a function of the number of compactor passes.

- **Daily Cover**
  - Waste is covered at the end of each working day with soil (typically 6 inches) or alternative daily cover (such as textiles, geomembrane, carpet, foam, or other proprietary materials).
  - Daily cover is required to control disease vectors and rodents; to minimize odor, litter, and air emissions; to reduce the risk of fire; and to minimize leachate
  - production.
  - The landfill sides are sloped to facilitate maintenance and to increase slope stability; generally, a maximum slope of 1:3 is maintained.