Solid Waste Management:

Landfills

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General

- Regardless of how much reuse, recycling, and energy recovery is achieved, some fraction of the MSW must be returned to the environment.
- The only two locations for the ultimate disposal of wastes are (1) in the oceans and other large bodies of water or (2) on or in land.
- With rare exceptions, most solid waste may no longer be legally dumped into oceans.

- A landfill is an engineered method for land disposal of solid or hazardous wastes in a manner that protects the environment.

- Modern sanitary landfills are carefully engineered structures designed to isolate garbage from nearby water, soil, wildlife, and people.

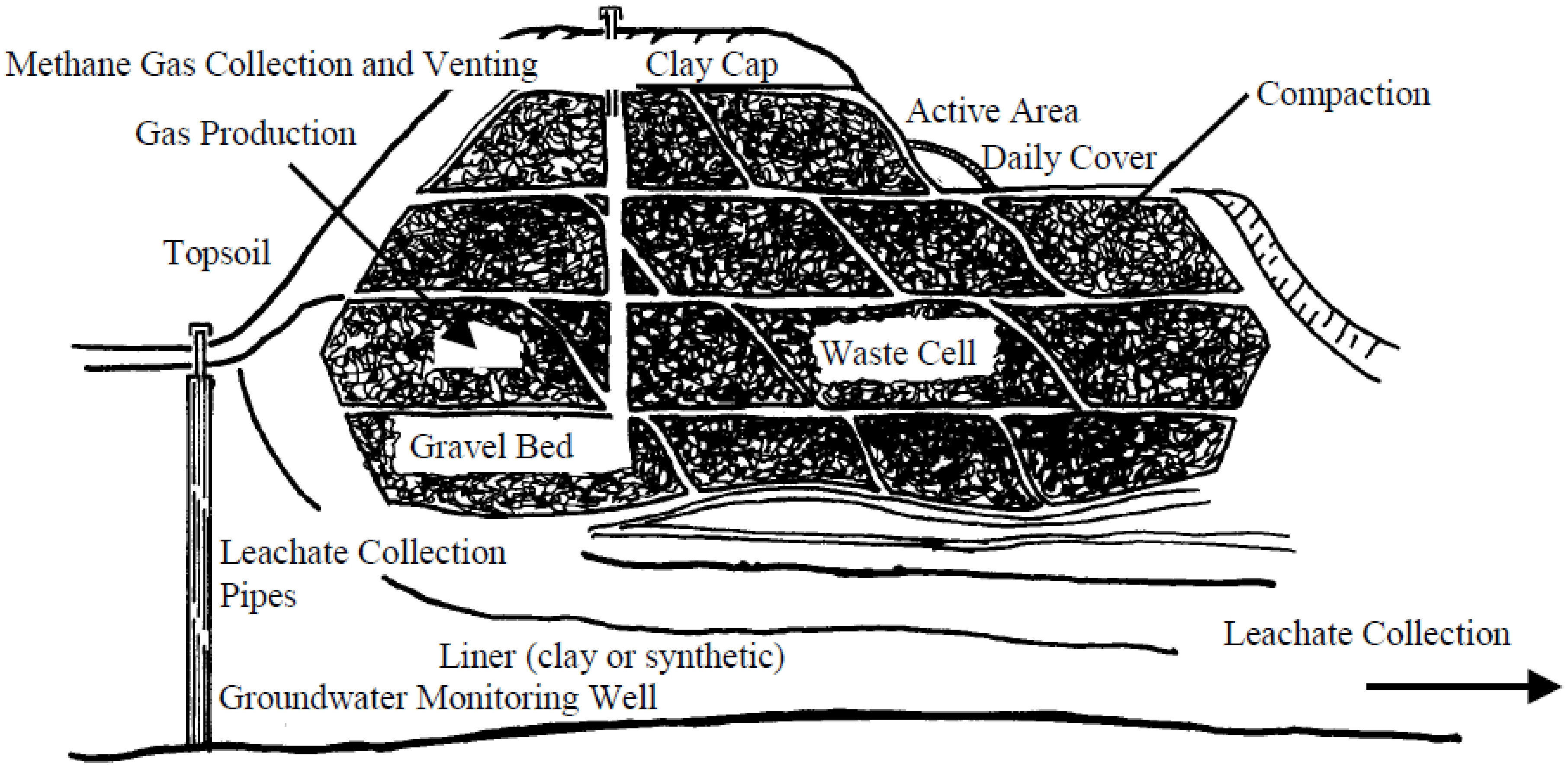
Rubbish Pit vs. Landfill

Sanitary Landfill

How sanitary landfill is made?

- The cavities are dug out of the ground and then the walls are *sealed* with layers of clay and coated with plastic to prevent groundwater contamination from wastewater that accumulates.
- Today's landfills are designed to stay dry inside, except for liquids that ooze from some garbage, and rainwater that trickles through. As water trickles through a landfill, it dissolves chemicals and other particles, creating a liquid called "leachate."
- Within the landfill biological, chemical, and physical processes occur that promote the degradation of wastes and result in the production of leachate (polluted water emanating from the base of the landfill) and gases.
- In order to be designated a sanitary landfill, a disposal site must meet the following three general but basic conditions: 1) compaction of the wastes, 2) daily covering of the wastes (with soil or other material) to remove them from the influence of the outside environment, and 3) control and prevention of negative impacts on the public health and on the environment (e.g., odors, contaminated water supplies, etc.).

Schematic diagram of basic aspects of a sanitary landfill



Planning for Landfills

- Planning involves the collection of information on type, amount, generation rate, and characteristics of the wastes to be accepted for landfilling. Acquisition of this information is a prerequisite to rational design and efficient and effective development of a landfill.

- A ten-year time frame is considered short-term planning. Thirty years seems to be an appropriate time frame, because after thirty years, it becomes difficult to anticipate solid waste generation and new disposal technology.

- The first step in planning for a new landfill is to establish the requirements for the landfill site. The site must provide sufficient landfill capacity for the selected design period and support any ancillary solid waste functions, such as leachate treatment, landfill gas management, and special waste services (i.e., tires, bulky items, household hazardous wastes).

- If possible, in-place density (the density once the refuse has been compacted in the ground) should be estimated. If an existing landfill is available, density can be easily determined by routinely conducting aerial surveys of the landfill and then calculating the volumes. This method includes the volume of cover material in the calculation. If dirt is used as daily and final cover, 20 to 50% of the volume of the landfill may be cover material. An in-place density of 1200 lb/yd3 (700 kg/m3) is typical.

Overall bulk density

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,

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

Example 4-1, page 106

where

ρ_A = bulk density of material A
ρ_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
ρ_A = bulk density of material A
ρ_B = bulk density of material B

The volume reduction achieved in refuse baling or landfill compaction is an important design and operational variable. If the original volume of a sample of solid waste is denoted by V_o, and the final volume, after compaction, is V_c, then the calculation of the volume reduction is

$$\frac{V_c}{V_o} = F$$

where

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

Landfill capacity for a community

EXAMPLE 4-2

Calculate the required 20-year landfill capacity for a community with the population projection, per capita waste generation rate, and diversion rate shown in the following table. Note that the waste generation is expected to increase at approximately 3% per year through 2015 and then remain constant. Note also that the community is expected to increase its rate of waste diversion to 35% in 2014 through an aggressive recycling and yard waste composting program. Assume a soil daily cover is used that accounts for 25% of the landfill volume.

		Per Capita Generation			
Year	Population (000)	Rate, lb/cap/day	Diversion, Fraction	Waste to Landfill, tons	Waste to Landfill, cu yd
2011	105.4	5.6	0.25		
2012	108.6	5.8	0.28		
2013	109.8	6	0.3		

Solution

Year	Population (000)	Per Capita Generation Rate, lb/cap/day	Diversion, Fraction	Waste to Landfill, tons	Waste to Landfill, cu yd
2011	105.4	5.6	0.25	8.08E+04	1.35E+05
2012	108.6	5.8	0.28	8.28E+04	1.38E+05
2013	109.8	6	0.3	8.42E+04	1.40E+05
2014	112.2	6.2	0.35	8.25E+04	1.38E+05
2015	115.2	6.4	0.35	8.75E+04	1.46E+05
2016	117.7	6.4	0.35	8.94E+04	1.49E+05
2017	121.1	6.4	0.35	9.19E+04	1.53E+05
2018	124.7	6.4	0.35	9.47E+04	1.58E+05
2019	128.4	6.4	0.35	9.75E+04	1.62E+05
2020	133.4	6.4	0.35	1.01E+05	1.69E+05
2021	139.1	6.4	0.35	1.06E+05	1.76E+05
2022	144.5	6.4	0.35	1.10E+05	1.83E+05
2023	150.7	6.4	0.35	1.14E+05	1.91E+05
2024	155.6	6.4	0.35	1.18E+05	1.97E+05
2025	163.1	6.4	0.35	1.24E+05	2.06E+05
2026	169.4	6.4	0.35	1.29E+05	2.14E+05
2027	175.3	6.4	0.35	1.33E+05	2.22E+05
2028	181.4	6.4	0.35	1.38E+05	2.30E+05
2029	187.7	6.4	0.35	1.43E+05	2.38E+05
2030	194.3	6.4	0.35	1.48E+05	2.46E+05
Total				2.15E+06	3.59E+06

A typical calculation for one year's volume is

$$\frac{(\text{population}) \times (\text{per capita generation rate}) \times (1 - \text{diversion}) \times (365\ \text{days/yr})}{1200\ \text{lb/yd}^3}$$

Total landfill waste volume is 3.59×10^6 yd^3. To account for the volume requirement for the cover soil,

$$0.25(T) + 3.59 \times 10^6 = T$$

$$T = 4.79 \times 10^6\ \text{yd}^3$$

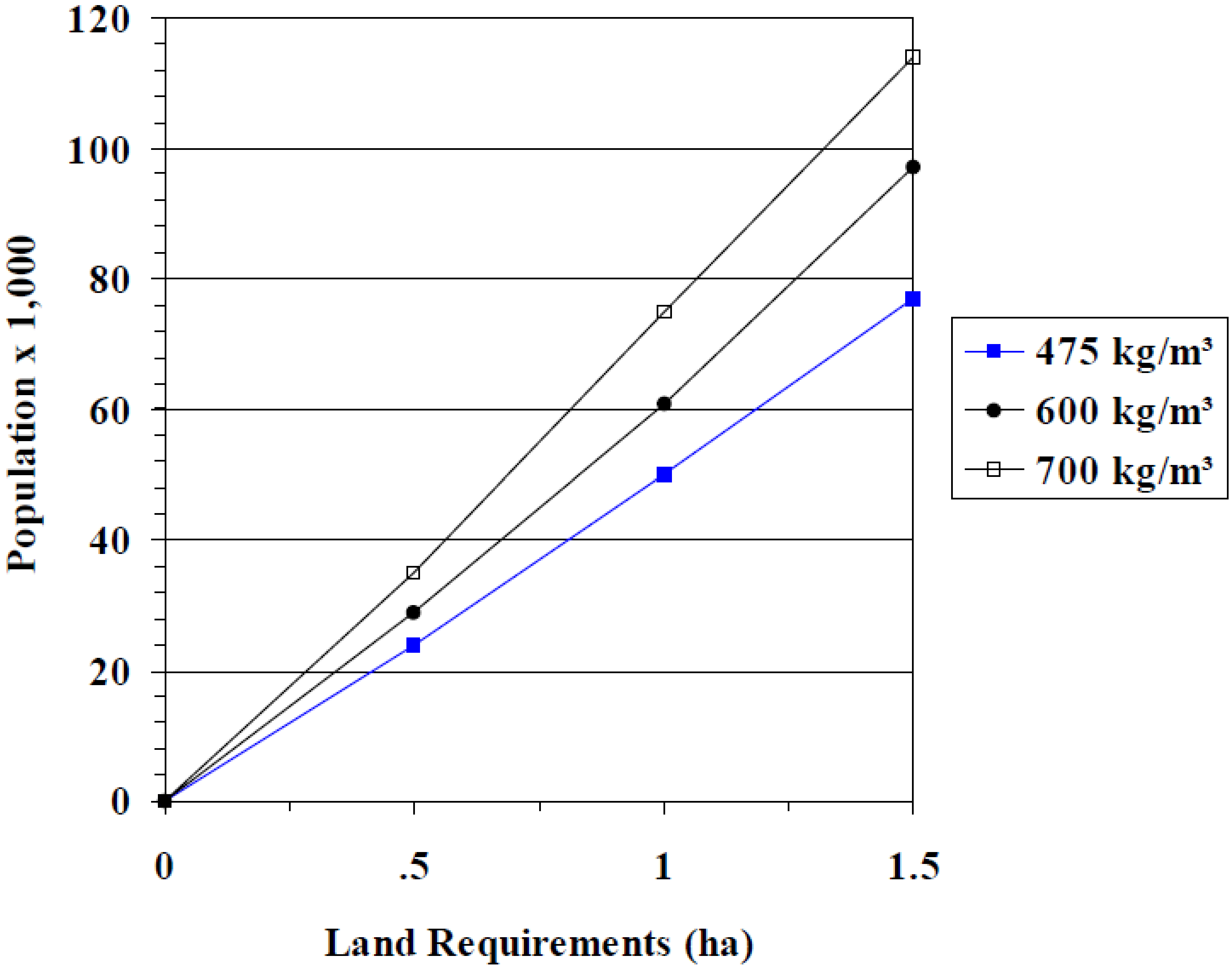
Siting of Landfills

- Once the geographical boundary of the potential site has been determined, unsuitable locations should be identified.

fatal flaw analysis

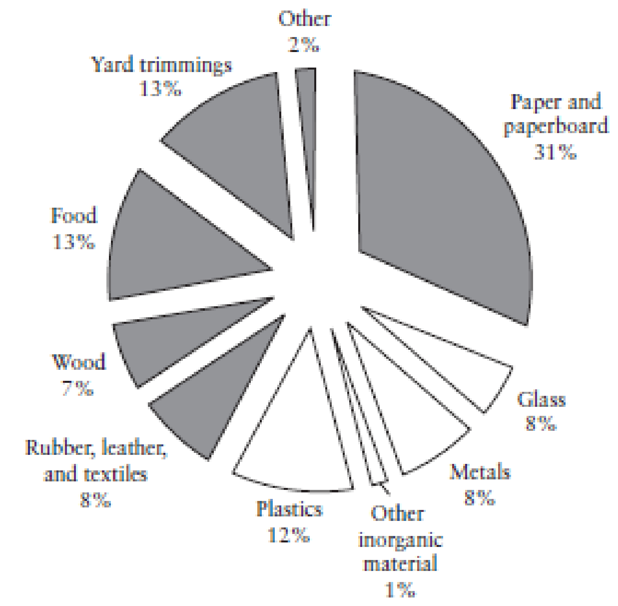
- The site is too small.
- The site is on a flood plain (the 100-yr flood plain area).
- The site includes wetlands.
- A seismic zone is within 200 ft of the site.
- An endangered species habitat is on the site.
- The site is too close to an airport (not within 5000 ft for propeller aircraft or 10,000 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.

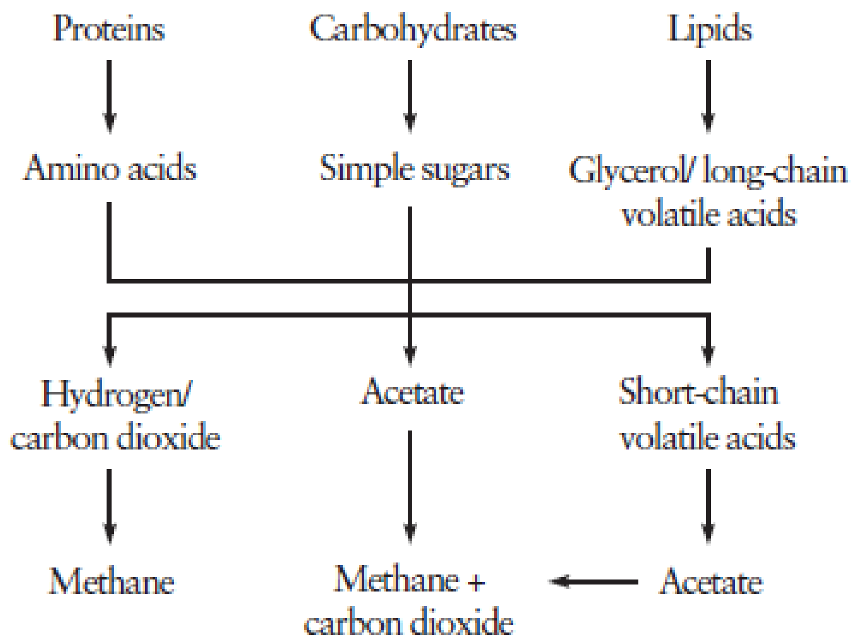
Land requirements for a landfill as a function of compaction



Landfill Processes

1. Biological degradation
2. Leachate production
3. Gas production





Biological Degradation

Phase I—Initial Adjustment Phase

This phase is associated with initial placement of solid waste and accumulation of moisture within landfills. An acclimation period (or initial lag time) is observed until sufficient moisture develops and supports an active microbial community. Preliminary changes in environmental components occur in order to create favorable conditions for biochemical decomposition.

Phase II—Transition Phase

In the transition phase, the field capacity is often exceeded, and a transformation from an aerobic to an anaerobic environment occurs, as evidenced by the depletion of oxygen trapped within the landfill media. A trend toward reducing conditions is established in accordance with shifting of electron acceptors from oxygen to nitrates and sulfates and the displacement of oxygen by carbon dioxide. By the end of this phase, measurable concentrations of chemical oxygen demand (COD) and volatile organic acids (VOAs) can be detected in the leachate.

Phase III—Acid Formation Phase

The continuous hydrolysis (solubilization) of solid waste, followed by (or concomitant with) the microbial conversion of biodegradable organic content, results in the production of intermediate volatile organic acids at high concentrations throughout this phase. A decrease in pH values is often observed, accompanied by metal species mobilization. Viable biomass growth associated with the acid formers (acidogenic bacteria), and rapid consumption of substrate and nutrients are the predominant features of this phase.

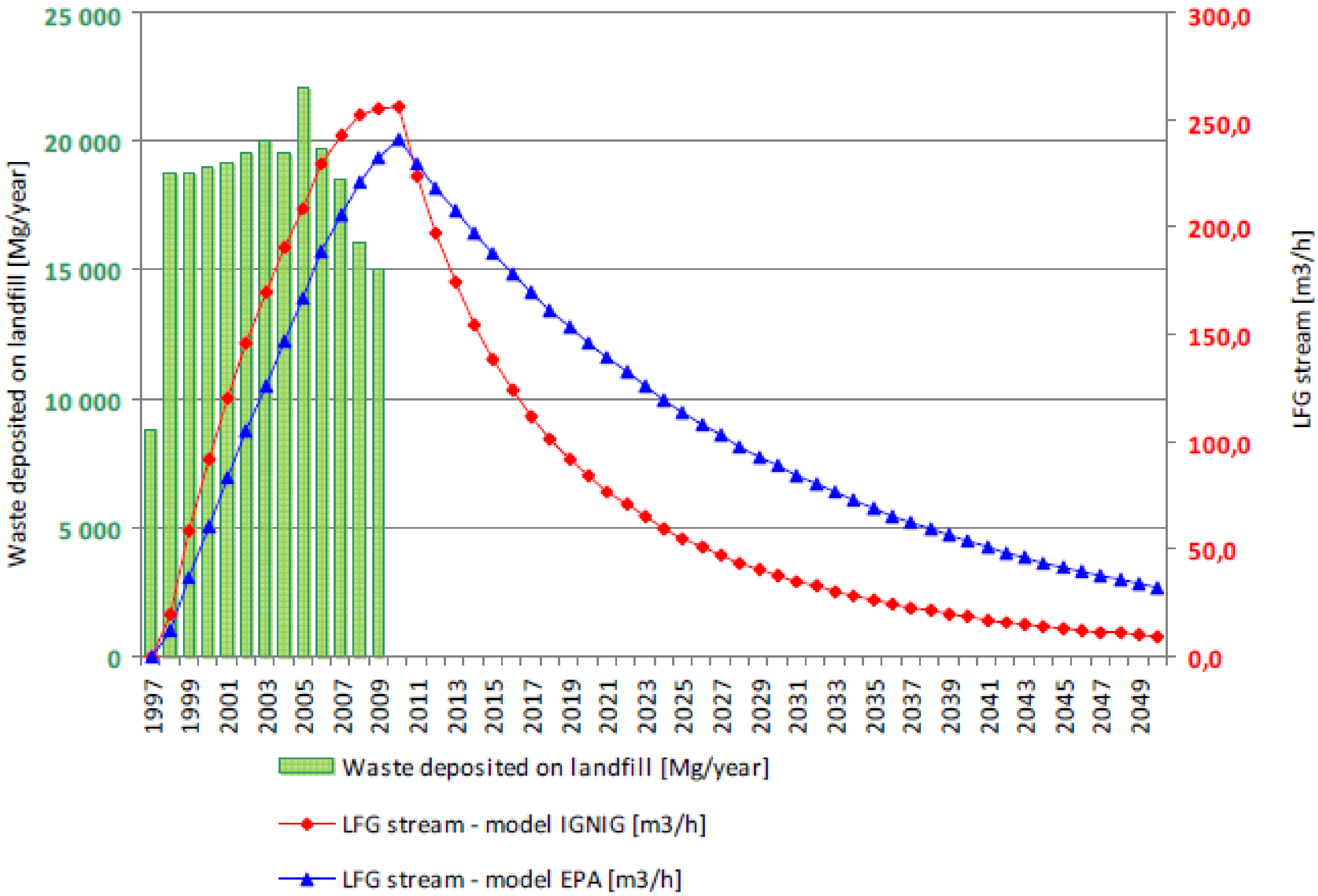
Phase IV—Methane Fermentation Phase

During Phase IV, 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. Heavy metals are removed from the leachate by complexation and precipitation.

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. Reappearance of oxygen and oxidized species may be observed slowly. However, the slow degradation of resistant organic fractions may continue with the production of humic-like substances.

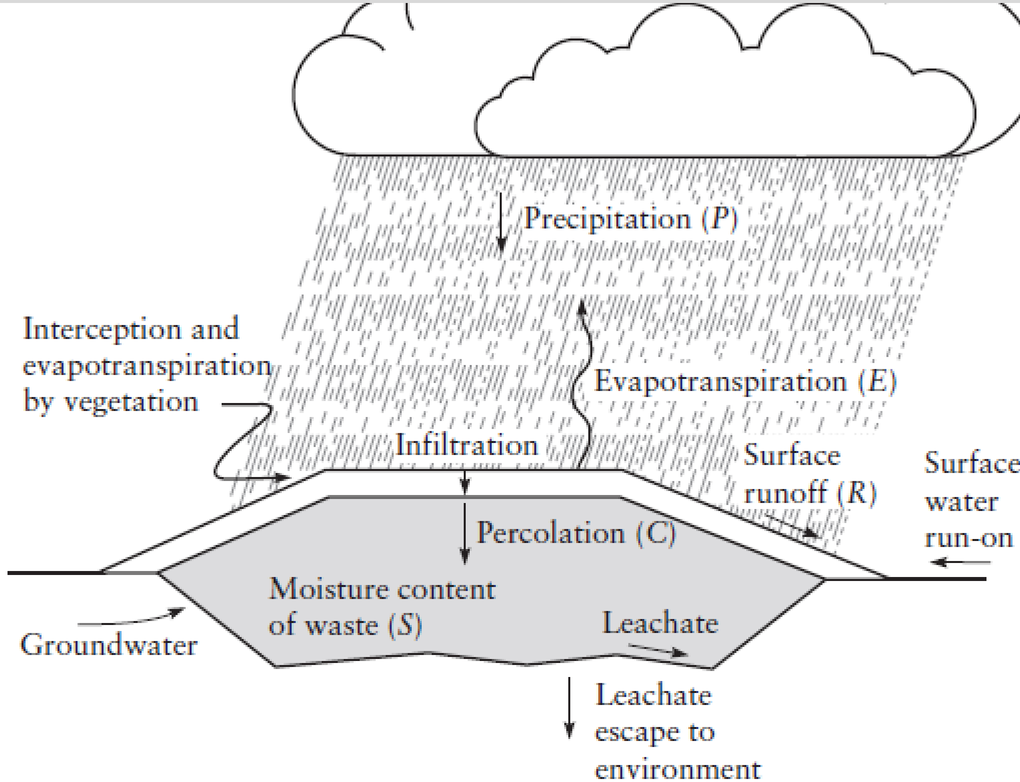
The progress toward final stabilization of landfill solid waste is subject to the physical, chemical, and biological factors within the landfill environment, the age and characteristics of landfilled waste, the operational and management controls applied, as well as the site-specific external conditions.


25 000
20 000
15 000
10 000
5 000
0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Waste deposited on landfill [Mg/year]
LFG stream [m3/h]
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
Waste deposited on landfill [Mg/year]
LFG stream - model IGNIG [m3/h]
LFG stream - model EPA [m3/h]

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.
- The field capacity is the maximum moisture the soil (or any other material such as refuse) can retain without a continuous downward percolation due to gravity.
- Field capacity is the ability to retain moisture.



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

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

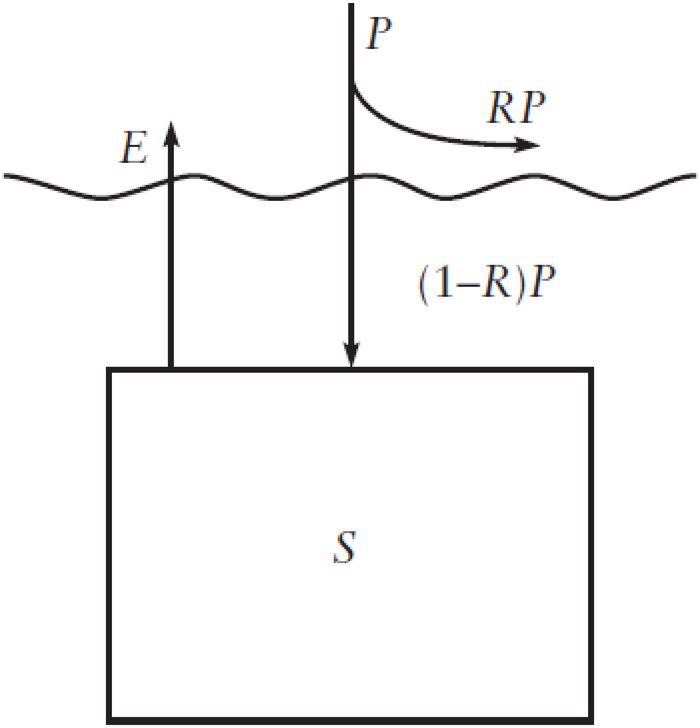


Table 4-6 Percolation in Three Landfills

	Precipitation (mm/yr) P	Runoff coefficient R	Evapotranspiration (mm/yr) E	Percolation (mm/yr) C
Cincinnati	1025	0.15	658	213
Orlando	1342	0.07	1173	70
Los Angeles	378	0.12	334	0

Example

EXAMPLE 4-3

Estimate the percolation of water through a landfill 10 m deep, with a 1 m cover of sandy loam soil. Assume that this landfill is in southern Ohio, and that

$P = 1025$ mm/yr

$R = 0.15$

$E = 660$ mm/yr

Soil field capacity, $F_s = 200$ mm/m

Refuse field capacity, $F_r = 300$ mm/m, as packed

Assume further that the soil is at field capacity when applied, and that the incoming refuse has a moisture content of 150 mm/m and therefore has a net absorptive capacity of 150 mm/m. Percolation through the soil cover is

$$C = P(1 - R) - S - E = 1025(1 - 0.15) - 0 - 660 = 211 \text{ mm/y}$$

SOLUTION

The moisture front will move

$$\frac{211 \text{ mm/y}}{150 \text{ mm/m}} = 1.4 \text{ m/y}$$

or it will take

$$\frac{10 \text{ m}}{1.4 \text{ m/y}} = 7.1 \text{ y}$$

to produce a leachate that will be collected at a rate of (211 mm × area of landfill) per year.

Leachate Quality

Parameter	Ehrig 1989	Qasim and Chiang 1994	Florida landfills Grosh, 1996 (mean value)	National database (mean value)
BOD (mg/L)	20–40,000	80–28,000	0.3–4660 (149)	0–100,000 (3761)
COD (mg/L)	500–60,000	400–40,000	7–9300 (912)	11–84,000 (3505)
Iron (mg/L)	3–2100	0.6–325	—	4–2200
Ammonia (mg/L)	30–3000	56–482	BDL–5020 (257)	0.01–2900 (276)
Chloride (mg/L)	100–5000	70–1330	BDL–5480 (732)	6.2–67,000 (3691)
Zinc (mg/L)	0.03–120	0.1–30	BDL–3.02 (0.158)	0.005–846 (0.23)
Total P (mg/L)	0.1–30	8–35	—	0.02–7 (3.2)
pH	4.5–9	5.2–6.4	3.93–9.6	6.7–8.2
Lead (mg/L)	0.008–1.020	0.5–1.0	(29.2 ± 114)	0.00–2.55 (0.13)
Cadmium (mg/L)	< 0.05–0.140	< 0.05	(7.52 ± 23.9)	0.0–0.564 (0.0235)

BDL = below detection limit
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).

The quality of leachate directly affects viable leachate treatment alternatives. Because leachate quality varies from site to site and over time, neither biological treatment nor physical/chemical treatment processes **separately** are able to achieve high treatment efficiencies. A combination of both types of treatment is one of the more effective process trains for the treatment of leachate.

Gas production

- Proper landfill management can enhance both yield and quality of gas.
- 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 and users.
- Mathematical and computer models for predicting gas yields are based on population, per capita generation, waste composition and moisture content, percent actually landfilled, and expected methane or landfill-gas yield per unit dry weight of biodegradable waste.
- **Four parameters must be known if gas production is to be estimated with any accuracy**: gas yield per unit weight of waste, the lag time prior to gas production, the shape of the lifetime gas production curve, and the duration of gas production.

In theory

- The biological decomposition of one ton of MSW produces 15,600 ft3 (442 m3) of landfill gas containing 55% methane (CH_4) and a heat value of 530 Btu/ft3 (19,730 kJ/m3).

- Since only part of the waste converts to CH_4 due to moisture limitation, inaccessible waste (plastic bags), and non-biodegradable fractions, the actual average methane yield is closer to 3,900 ft3/ton (100 m3/tonne) of MSW.

- Theoretical landfill gas production potential for the United States is estimated at 1.4 trillion ft3/y (33×10^{12} m3/y). However, a more conservative estimate would put the figure at roughly 500 billion ft3/y (14 billion m3/y) with an annual oil equivalent energy potential of 5.6 million tons/y.

Gas production pattern over time.

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

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

http://www.epa.gov/ttn/catc/products.html#software

EXAMPLE 4-4

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 m^3/tonne.

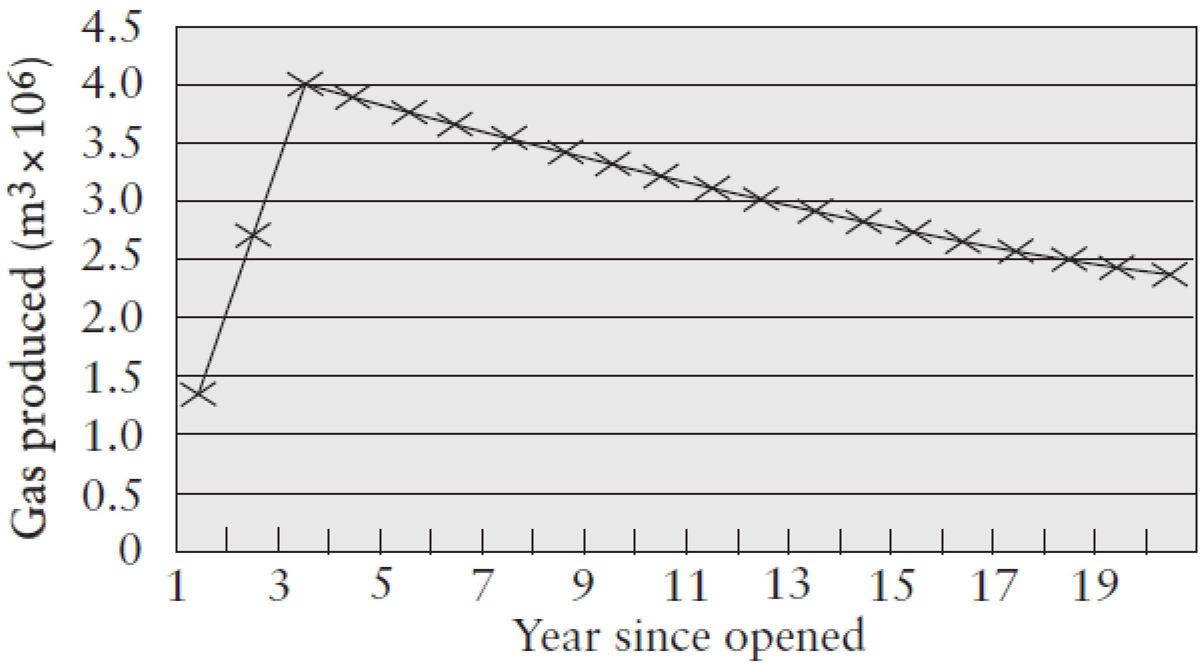
SOLUTION

For the first year,

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

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.

These results are plotted as Figure 4-7. The annual peak gas production is found from this figure as about 4,000,000 m^3/yr.



Case Study

Parameters	L_o [m^3/t]	K [1/rok]	Methane concentration [%]
CAA	170	0,05	50
AP 42	100	0,04	50

Mass of solid waste deposited in the landfill in years 1997-2009 [1].

Year	Annual solid waste mass [Mg/year]	Total solid waste mass (sum) [Mg]
1997	8 769	8 769
1998	18 716	27 485
1999	18 716	46 201
2000	19 020	65 221
2001	19 142	84 363
2002	19 522	103 884
2003	20 018	123 903
2004	19 551	143 453
2005	22 078	165 531
2006	19 661	185 192
2007	18 538	203 730
2008	16 087	219 817
2009	15 039	234 856