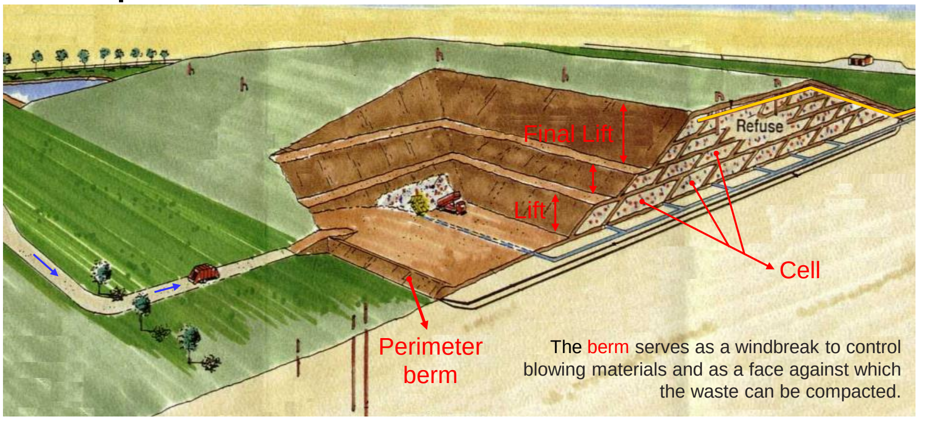
Chapter 11

Disposal of Solid Wastes and Residual Material

Landfilling Process

- *Landfills* are physical facilities used for the disposal of residual solid wastes in the surface soils of earth.
- *Sanitary landfill* is an engineered facility for the disposal of MSW, designed and operated to minimize public health and environmental impacts.
- *Landfilling* is the process by which residual solid waste is placed in a landfill. It includes;
  - Monitoring of the incoming waste stream
  - Placement and compaction of waste, and
  - Installation of landfill environmental monitoring and control facilities.

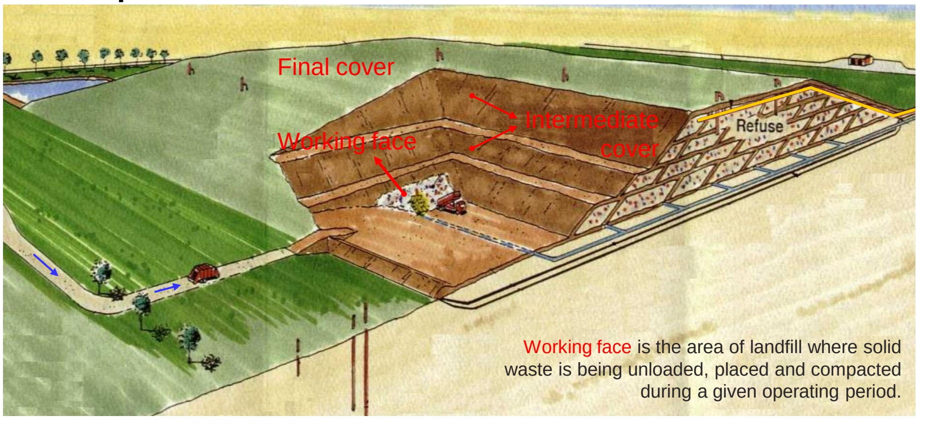
Landfilling terms



Cell is the volume of material placed in a landfill during one operating period.

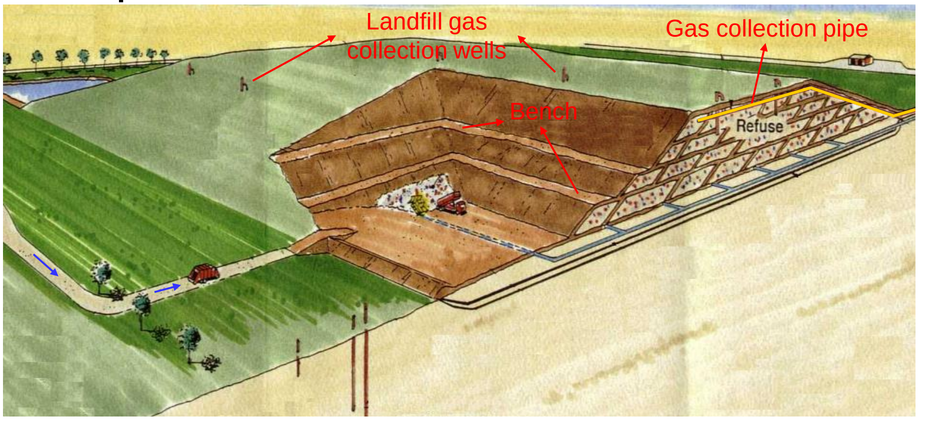
Lift is a complete layer of cells over the active area of landfill.

Landfilling terms



Intermediate cover is the soil or alternative materials such as compost that are applied to the working faces of the landfill at the end of each operating period.
Final cover is the entire landfill surface after all landfilling operations are complete.

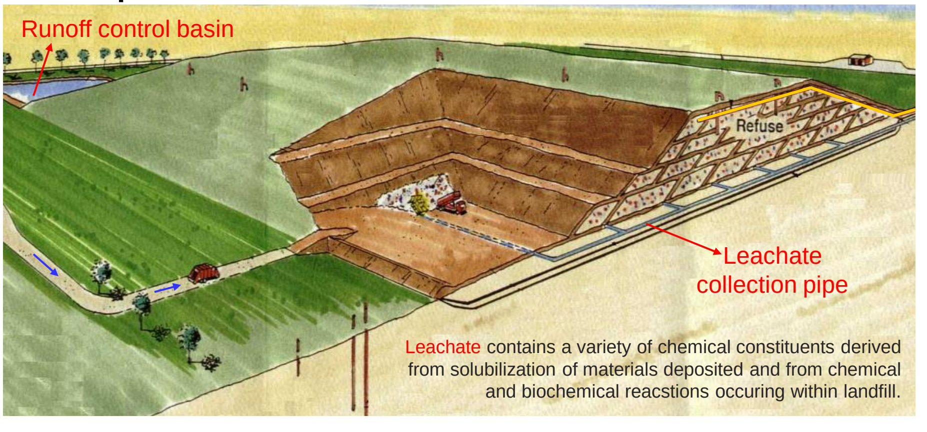
Landfilling terms



Bench (or terrace) is used to maintain the slope stability of the landfill, for placement of surface water drainage channels and for the location of landfill gas recovery piping

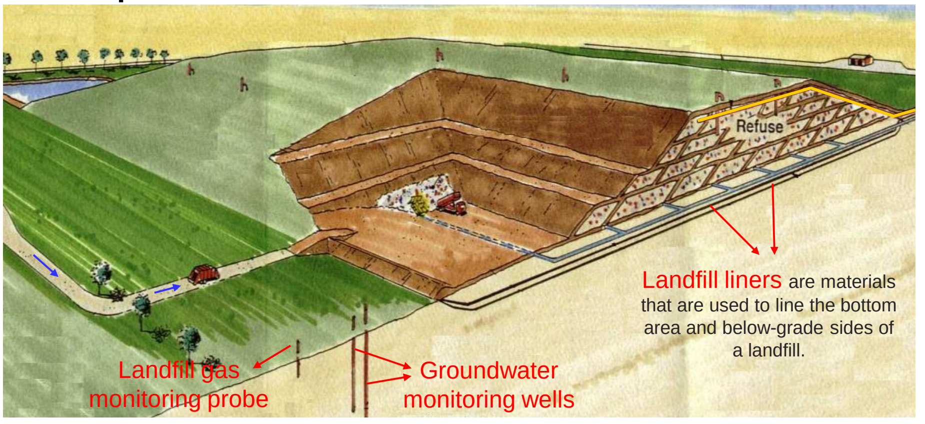
Landfill gas is mixture of gases found within landfill. It mainly consists of CH_4 & CO_2

Landfilling terms



Liquid that collects at the bottom of a landfill is known as *leachate*. It is a result of percolation of *precipitation* and uncontrolled *runoff*. It can also include water initially contained in the waste as well as infiltrating *groundwater*.

Landfilling terms



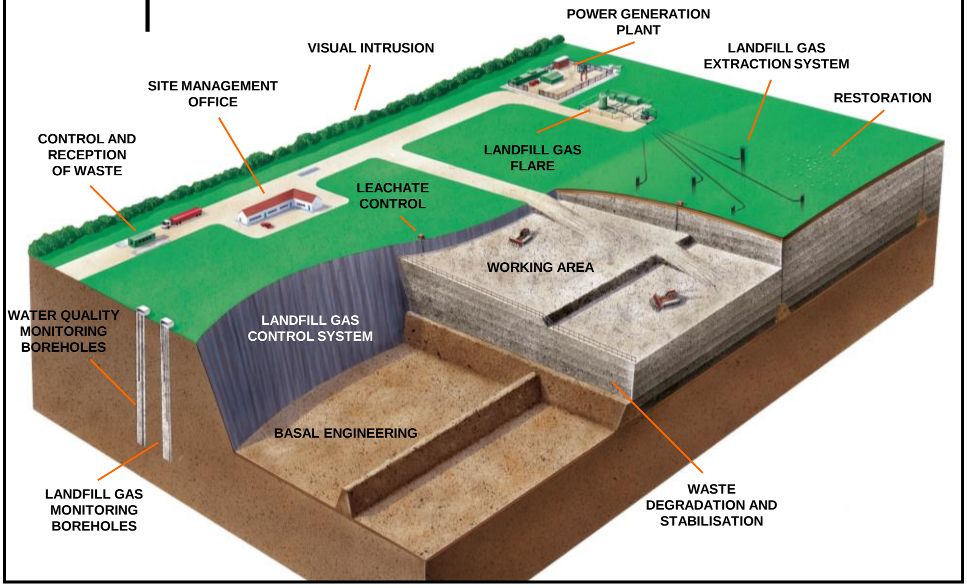
Environmental monitoring involves the activities associated with collection and analysis of water and air samples, that are used to monitor the movement of landfill gases and leachate at the landfill site.

Landfill planning, design and operation

The principle elements that must be considered;

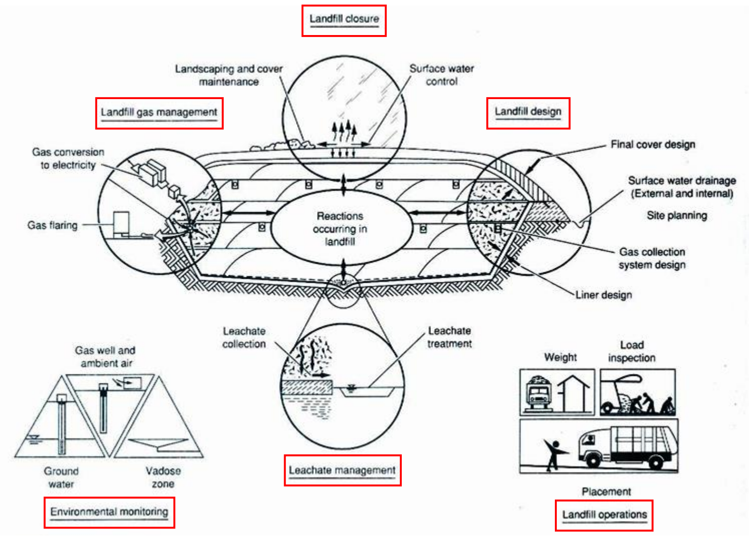
- Landfill layout and design
- Landfill operations and management
- Reactions occuring in landfill
- Management of landfill gases
- Management of leachate
- Environmental monitoring
- Landfill closure and post-closure care

Landfill planning, design and operation

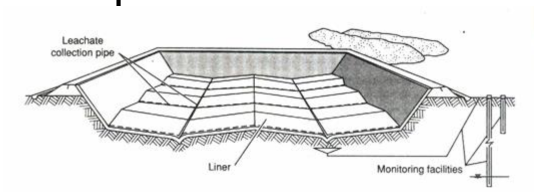


Landfill operations and processes

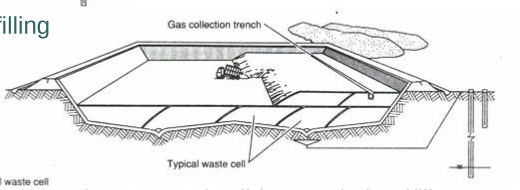
(Figure 11-3)



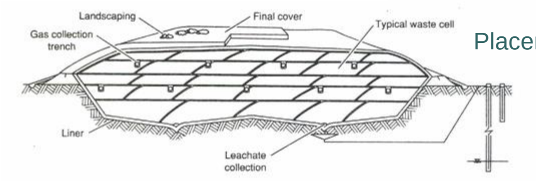
Development and completion of landfill



Preparation of the site for landfilling



Placement of solid waste in landfill



Cutaway through completed landfill

Preparation of site for landfilling

- Site drainage is modified to route any runoff away from the intended landfill area
- Access roads and weighing facilities are constructed and fences are installed
- Landfill bottom and subsurface sides are excavated and prepared. Excavations are carried out over time, rather than preparing the entire landfill bottom at once
- The bottom is shaped to provide drainage of leachate and a low-permeability (clay, geomembrane) liner is installed.
- Leachate collection and extraction facilities are placed within or top of the liner.

Preparation of site for landfilling

Placement of wastes

- Waste is placed in cells beginning along the compaction face, continuing outward and upward from the face.
- Wastes deposited by transfer vehicles are spread out in 50-60 cm layers and compacted.
- Successive lifts are placed on top of one another until the final design grade is reached.
- As organic materials within the landfill decompose, completed sections may settle. Refilling until the design grade is possible.
- Final cover is designed to minimize infiltration of precipitation and to route drainage away from the active section of landfill.
- Finally, the site is landscaped and prepared for other uses.

Placement of wastes

Reactions occuring in landfills

Biological reactions

- Organic material in MSW leads to the evolution of landfill gases and leachate.

Physical reactions

- Lateral diffusion of gases in landfill and emission of landfill gases to the surrounding environment
- Movement of leachate within landfill & into underlying soils
- Settlement caused by consolidation and decomposition of landfilled material

Reactions occuring in landfills

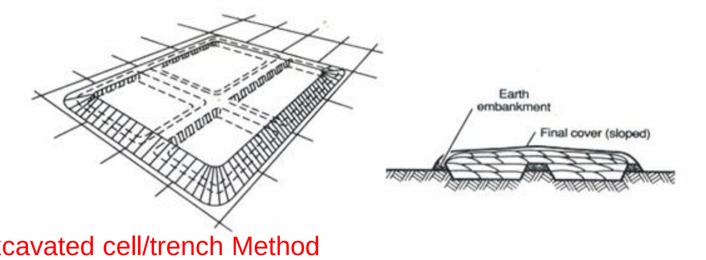
Chemical reactions

- Dissolution and suspension of landfill material and biological conversion products in leachate
- Evaporation and vaporization of chemical compounds into landfill gas
- Sorption of volatile and semi volatile organic compounds into landfilled material
- Dehalogenetaion and decomposition of organic compounds
- Oxidation reduction reactions affecting metals and solubility of metal salts

Concerns with landfilling

- Uncontrolled release of landfill gases might cause odor and other potential dangerous conditions
- Impact of uncontrolled discharge of landfill gases on greenhouse effect in the atmosphere
- Uncontrolled release of leachate might migrate down to underlying groundwater or to surface water
- Breeding and harboring of disease vectors in improperly managed landfills
- Health and environmental impacts asscociated with the release of the trace gases arising from hazardous materials placed in the landfills in the past

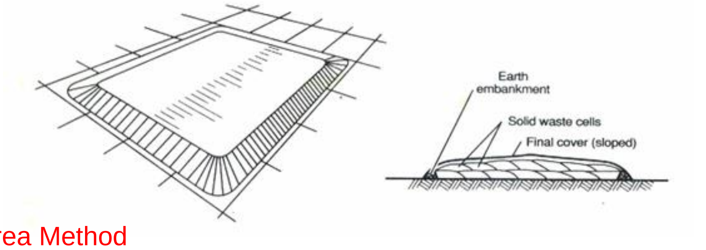
Landfilling Methods



Excavated cell/trench Method

- It is ideally suited to areas where an adequate depth of cover material is available at the site and where water table is not near the surface.
- The soil excavated is used for daily and final cover.
- Excavated cells are typically square and trenches are long ditches.

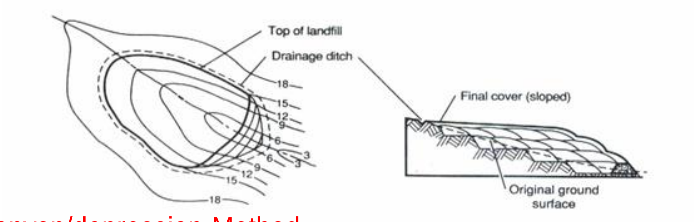
Landfilling Methods



Area Method

- It is used when the terrain is unsuitable for excavation.
- High-groundwater conditions necessitate the use of this type.
- Cover material must be hauled by truck or earthmoving equipment from adjacent land or from borrow-pit areas.
- Compost produced from MSW can be used as intermediate cover material.

Landfilling Methods



Canyon/depression Method

- Canyons, ravines, dry borrow pits, and quarries are used.
- Control of surface drainage often is critical factor in the development of canyon/depression sites.
- Filling for each lift starts at the head end of the canyon and ends at the month, so as to prevent the accumulation of water behind the landfill.
- Cover material is excavated from the canyon walls or floor before the liner is installed.

Landfill Siting Considerations

- Haul distance
- Location restrictions
- Available land area
- Site access
- Soil conditions and topography
- Climatologic conditions
- Surface water hydrology
- Geologic and hydrogeologic conditions
- Local environmental conditions
- Ultimate use of completed landfills

Example 11.1 Estimation of required landfill area

Estimate the required landfill area for a community with a population of 31000. Assume that the following conditions apply:

- Solid waste generation = 2.9 kg/ca.d
- Compacted specific weight of MSW in landfill = 475 kg/m^3
- Average depth of compacted solid wastes = 6 m

Solution

1. Determine the daily solid wastes generation rate in tons/day.

   Generation rate = (31000 ca * 2.9 kg/ca.d) / (1000 kg/ton)

   = 89.9 ton/d

Example 11.1 Estimation of required landfill area

Solution

2. Computationally, the required area is determined as follows:

   Volume required = (89.9 ton/d * 1000 kg/ton) / (475 kg/m^3)

   = 189.3 m^3/d

   Area required/d = (189.3 m^3/d) / (6 m)

   = 31.5 m^2/d

   Area required/yr = (31.5 m^2/d * 365 d/yr) / (10000 m^2/ha)

   = 1.14 ha/yr

Example 11.1 Estimation of required landfill area

Comment

- The actual site requirements will be greater than the value computed because additional land is required for a buffer zone, office and service buildings, access roads, utility access, and so on.
- Typically, this allowance varies from 20 to 40%.
- A more rigorous approach to the determination of the required landfill area involves consideration of the contours of the completed landfill and the effects of gas production and overburden compaction.

Example: Estimation of required 10-yr landfill capacity

- Calculate the required 10-yr landfill capacity for a community with a population projection, per capita waste generation rate and diversion rate shown in the table.
- Note that the waste generation is expected to increase at app. 3% per year till 2020 and then remain constant.
- Note also that the community is expected to increase its rate of waste diversion from 20% to 40% (8% increase per year) through an aggresive recycling program.
- Assume a constant population growth about 0,5% per year.
- Assume a daily soil cover is used that accounts for 25% of the landfill volume.

Example: Estimation of required 10-yr landfill capacity

Solution (Compacted specific weight of MSW = 600 kg/m^3)

Year	Population	MSW generation rate, kg/ca.d	Diversion factor	Waste to landfill, tons/yr	Waste to landfill, m^3/yr
2016	400000	1,200	20,00%	140160	233600
2017	402000	1,236	21,60%	142185	236975
2018	404010	1,273	23,30%	143982	239970
2019	406030	1,311	25,20%	145330	242217
2020	408060	1,351	27,20%	146489	244148
2021	410101	1,351	29,40%	142772	237954
2022	412151	1,351	31,70%	138811	231352
2023	414212	1,351	34,30%	134195	223658
2024	416283	1,351	37,00%	129323	215539
2025	418364	1,351	40,00%	123781	206302
Total volume of MSW landfilled between 2016 and 2025 (m^3)					2311714

Required 10-yr landfill capacity = m^3 / (1-0,25) = 3082286 m^3

Composition and Characteristics, Generation, Movement and Control of Landfill Gases

- A landfill can be conceptualized as a *biochemical reactor*, with *solid waste* and *water* as the major inputs and with *landfill gas* and *leachate* as principle outputs.
- Material stored in the landfill includes partially degraded *organics* and other *inorganic wastes* originally placed in landfill.
- Landfill gas control systems are employed to prevent unwanted *movement* of landfill gas into the *atmosphere* or the lateral and vertical movement through the *surronding soil*.
- Recovered *landfill gas* can be used to produce *energy* or can be *flared* under controlled conditions to eliminate the discharge of harmful constituent to the atmosphere.

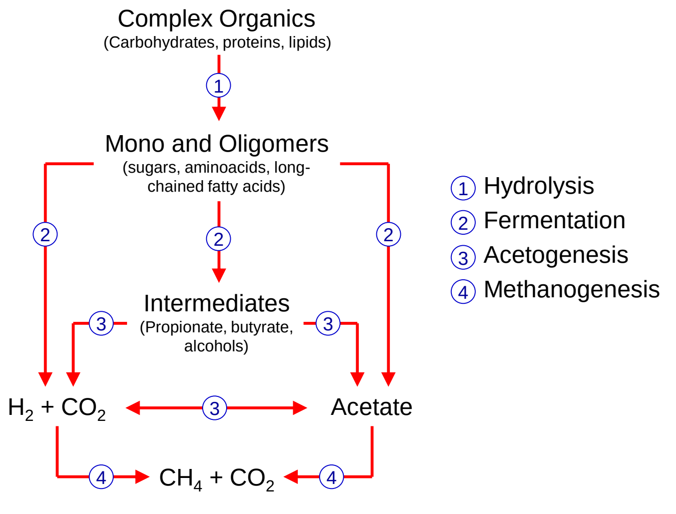
Typical composition of landfill gas

Table 11-2

Component	Percent (dry volume basis)
Methane	45-60
Carbon dioxide	40-60
Nitrogen	2-5
Oxygen	0,1-1,0
Sulfides, disulfides, mercaptanes, etc.	0-1,0
Ammonia	0,1-1,0
Hydrogen	0-0,2
Carbon monoxide	0-0,2
Trace constituents	0,01-0,6
Characteristics	
Temperature, ºC	38-76
Specific gravity	1,02-1,06
Moisture content	Saturated
High heating values, MJ/m^3	15-20

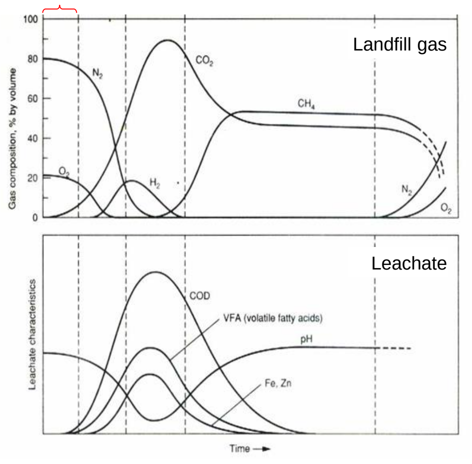
CH_4 and CO_2 are the principle gases produced from anaerobic decomposition of biodegradable organic waste components in MSW

Anaerobic decomposition in landfill



Generalized Phases of A Landfill: I. Initial adjustment phase

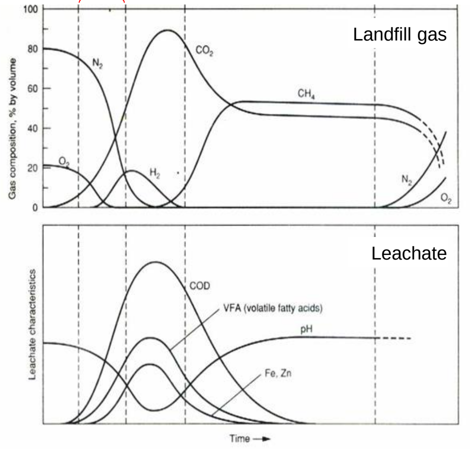
Phase I
Initial adjustment



- Biological decomposition occurs under *aerobic* conditions, because a certain amount of *air* is trapped within the landfill.
- The principle *source* of aerobic and anaerobic m.o.'s responsible for waste decompostion is the *soil* material used as intermediate *cover*.
- Wastewater treatment plant *sludges* disposed of to landfills and *recycled leachate* are other sources of m.o.'s.

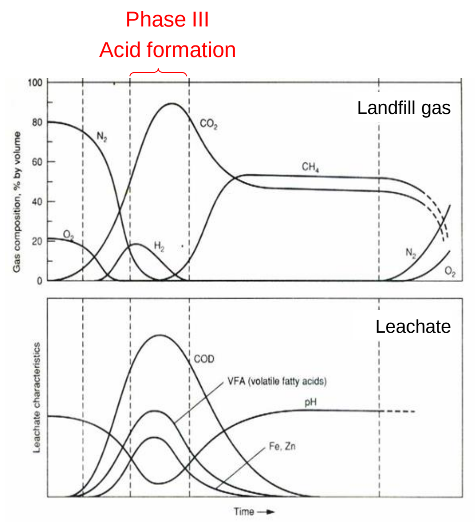
II. Transition phase

Phase II
Transition



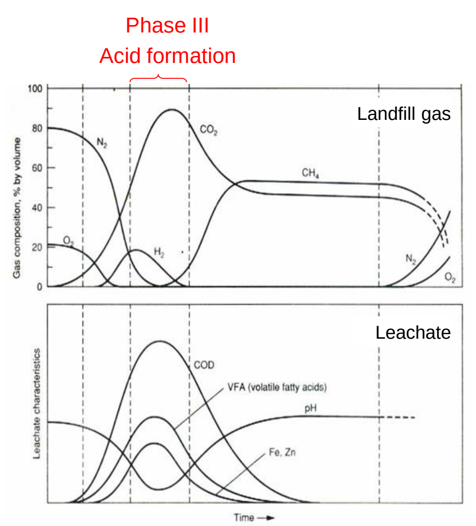
- *Oxygen* is *depleted* and anaerobic conditions begin to develop.
- As landfill becomes anaerobic, *nitrate* and *sulfate* (e- acceptors) are often reduced to N_2 and H_2S gases.
- Reduction of *nitrate* and *sulfate* occur at *-50* to *-100* mV (ORP).
- *pH* of leachate starts to *drop* due to the presence of *VFAs* and effects of elevated CO_2 concentrations within the landfill.

III. Acid formation phase



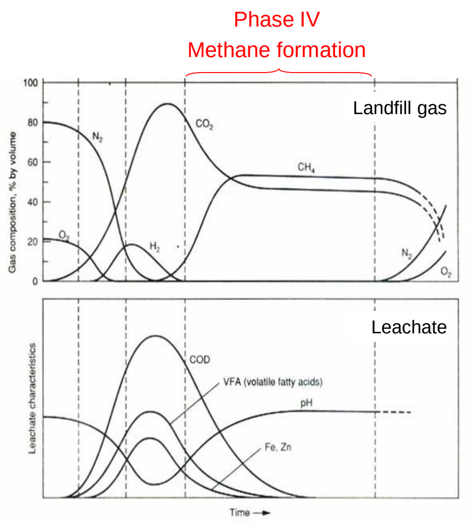
- Complex organics (*lipids*, *proteins*, *carbohydrates*) are first *hydrolyzed* to simpler compounds (long-chain *fatty acids*, *amino acids* and *sugars*) and then fermented to intermediate products (*VFAs*, *alcohols*).
- Significant amounts of *VFAs* and small amount of H_2 are produced.
- CO_2 is the principle gas generated.
- M.o.'s are facultative and anaerobic *acidogens* (fermentative bacteria)

III. Acid formation phase



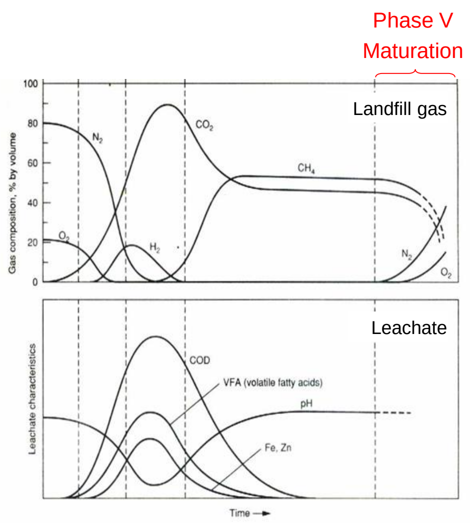
- *pH* of leachate often drops to *5* or *below* because of high concentrations of *VFAs* and CO_2.
- Due to the *dissolution* of VFAs in leachate BOD_5, *COD* and *conductivity* increase significantly.
- Because of *low pH* values, *heavy metals* are solubilized.
- If leachate is not recycled, essential *nutrients* are *lost* from the system.

IV. Methane formation phase



- *Acetic acid* and H_2 formed by acidogens are converted to CH_4 and CO_2 by strict anaerobes called methanogens.
- Because the *acetic acid* (VFAs) are consumed, *pH* rises to *6.8-8*.
- Concentration of *COD* and BOD_5 and *conductivity* are reduced.
- With *higher pH values*, fewer inorganic constituents (*heavy metals*) remain in leachate

V. Maturation phase



- Occurs after the *readily* available *biodegradable* organic material has been converted to CO_2 and CH_4.
- Landfill gas generation diminished significantly. Small amounts of O_2 and N_2 may found in landfill gas as well as CO_2 and CH_4.
- Leachate often contains *humic* and *fulvic acids*, which are difficult to process further.

Example 11-2

Example 11.2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW

- Determine the chemical compostion and the amount of gas that can be derived from the rapidly and slowly decomposable organic constituents in MSW as given in Table 3-4. Assume that 60% of the yard waste will decompose rapidly.

Solution

1. Set up a computational table to determine the percentage distribution of the major elements composing the waste. The necessary computations for the rapidly and slowly decomposable organic constituents are presented below. The moisture content of the waste constituents is taken from Table 4-1.

Example 11.2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW

Moisture content data from Table 4-1: = 9.0-(9.0*70%) → Food wastes dry weight 2.7

Ultimate analysis data from Table 4-4: = 2.7*48% → Food wastes C 1.30

Component	Wet weight, kg	Dry weight, kg	Composition, kg C	H	O	N	S	Ash
Rapidly decomposable organic constituents								
Food wastes	9.0	2.7	1.30	0.17	1.02	0.07	0.01	0.14
Paper	34.0	32.0	13.92	1.92	14.08	0.10	0.06	1.92
Cardboard	6.0	5.7	2.51	0.34	2.54	0.02	0.01	0.29
Yard wastes	18.5*60%= 11.1	4.4	2.10	0.26	1.67	0.15	0.01	0.20
Total	60.1	44.8	19.83	2.69	19.31	0.34	0.09	2.55
Slowly decomposable constituents								
Textiles	2.0	1.8	0.99	0.12	0.56	0.08	-	0.05
Rubber	0.5	0.5	0.39	0.05	-	0.01	-	0.05
Leather	0.5	0.4	0.24	0.03	0.05	0.04	-	0.04
Yard wastes	18.5-11.1= 7.4	3.0	1.43	0.18	1.14	0.10	0.01	0.13
Wood	2.0	1.6	0.79	0.10	0.69	-	-	0.02
Total	12.4	7.3	3.84	0.48	2.44	0.23	0.01	0.29

Example 11.2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW

2. Compute the molar composition of the elements neglecting the ash.

= 19.83*1000/12.01

	C	H	O	N	S
Atomic weight, g/mol	12.01	1.01	16.00	14.01	32.06
Total Moles					
Rapidly decomp.	1651.1	2663.4	1206.9	24.1	2.8
Slowly decomp.	319.7	475.2	152.5	16.4	0.3

3. Determine an approximate chemical formula without sulfur. Set up a computation table to determine normalized mol ratios

	Mol. Ratio (Nitrogen=1)	
Component	**Rapidly decomposable**	**Slowly decomposable**
Carbon	68.5	19.5
Hydrogen	110.5	29.0
Oxygen	50.1	9.2
Nitrogen	1.0	1.0

Example 11.2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW

The chemical formulas without sulfur are:

Rapidly decomposable = $C_{68.5}H_{110.5}O_{50.1}N$ (use $C_{68}H_{111}O_{50}N$)

Slowly decomposable = $C_{19.5}H_{29}O_{9.2}N$ (use $C_{20}H_{29}O_{9}N$)

4. Estimate the amount of gas that can be derived from rapidly and slowly decomposable organic constituents in MSW.

a) Using Eq. (11-2), the resulting equations are

i. Rapidly decomposable

$C_{68}H_{111}O_{50}N + 16H_2O \rightarrow 35CH_4 + 33CO_2 + NH_3$

1741 g/mol 288 560 1452 17

ii. Slowly decomposable

$C_{20}H_{29}O_{9}N + 9H_2O \rightarrow 11CH_4 + 9CO_2 + NH_3$

427 g/mol 162 176 396 17

Example 11.2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW

b) Determine the volume of CH_4 and CO_2 produced. The specific weights of CH_4 and CO_2 are 0.718 and 1.978 kg/m^3, respectively.

i. Rapidly decomposable

$$CH_4 = \frac{(560)(44.8kg)}{(1741)(0.718kg/m^3)} = 20.1m^3 atSTP$$

$$CO_2 = \frac{(1452)(44.8kg)}{(1741)(1.978kg/m^3)} = 18.9m^3 atSTP$$

ii. Slowly decomposable

$$CH_4 = \frac{(176)(7.3kg)}{(427)(0.718kg/m^3)} = 4.2m^3 atSTP$$

$$CO_2 = \frac{(396)(7.3kg)}{(427)(1.978kg/m^3)} = 3.4m^3 atSTP$$

Example 11.2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW

c) Determine the total theoretical amount of gas generated per unit dry weight of organic matter destroyed.

i. Rapidly decomposable

$$LFG, m^3/kg = \frac{20.1m^3 + 18.9m^3}{44.8kg} = 0.87m^3/kg$$

ii. Slowly decomposable

$$LFG, m^3/kg = \frac{3.3m^3 + 3.1m^3}{7.3kg} = 1.04m^3/kg$$

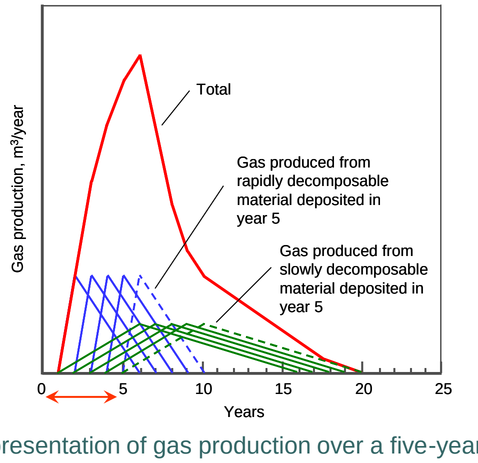
Example 11.2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW

Comment.

- The LFG generation values computed in this example represent the maximum amount of gas that could be produced under optimum conditions from the destruction of the biodegradable volatile solids (BVS) in the organic fraction of MSW.
- The range for individual organic constituents varies from about 0.128 to 0.218 m^3/kg BVS destroyed.
- LFG generation values of 0.154 m^3/kg BVS destroyed have been reported in the literature for mixed organic waste.
- The actual quantities of gas generated will be lower because not all of the BVS is available for decomposition.
- E.g., paper contained in plastic bags, while biodegradable, is typically not available for biological conversion.
- Biodegradable organic wastes that are not exposed to sufficient moisture to sustain biological activity will not be converted.

Variation in gas production with time

Figure 11-12



Graphical representation of gas production over a five-year period from the rapidly and slowly decomposible organic materials placed in landfill

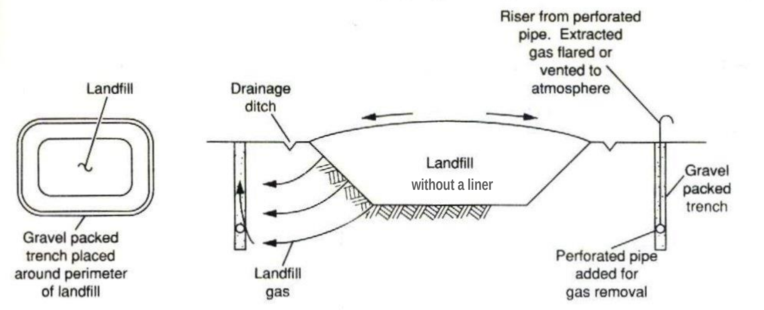
Movement of Landfill Gas

- In an active landfill, the internal pressure is usually greater than atmospheric pressure and landfill gas is released by;
  - Convection (pressure-driven)
  - Diffusion
- Sorption of the gasses into liquid or solid components and
- Generation or consumption of a gas component through chemical reactions or biological activity influence the movement of landfill gas.

Control of Landfill Gases

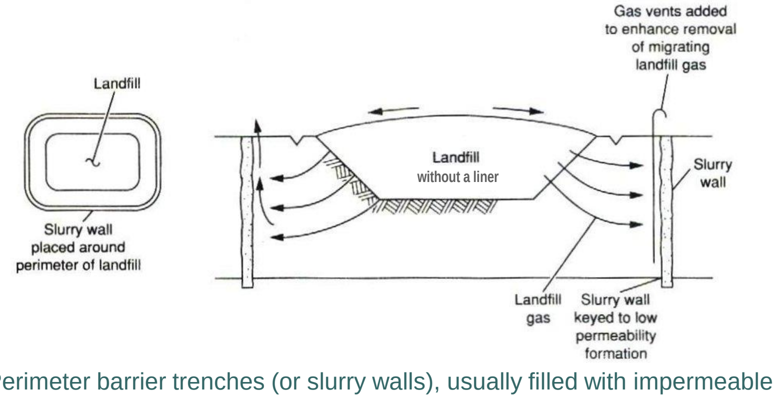
- The movement of landfill gases is controlled;
  - to reduce atmospheric emissions,
  - to minimize the release of odorous emissions,
  - to minimize subsurface gas migrations and
  - to allow the recovery of energy from methane.
- In *passive control* systems, the pressure of the gas that is generated within landfill serves as the driving force for the movement of the gas.
- In *active control* systems, energy in the form of an induced vacuum is used to control the flow of gas.

Passive control of landfill gasses



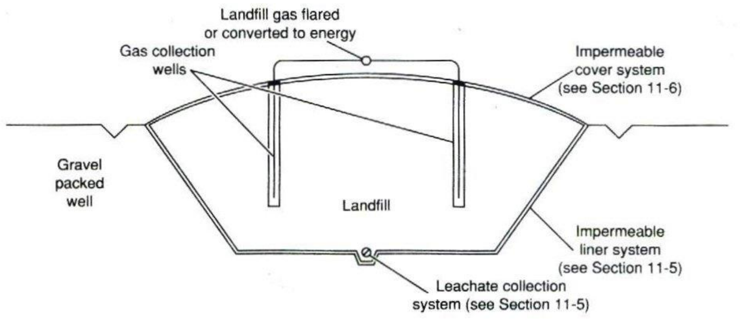
Perimeter interceptor trench filled with gravel and horizontal perforated pipes are used to intercept the lateral movement of landfill gases. Perforated pipe is connected to vertical risers through which the landfill gas that collects in the trench backfill can be vented to atmosphere

Passive control of landfill gasses



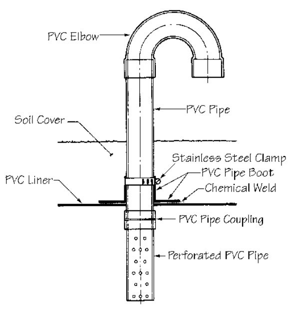
Perimeter barrier trenches (or slurry walls), usually filled with impermeable materials such as bentonite or clay slurries, are used to prevent the lateral subsurface gas movement. Landfill gas is removed from the inside face of the barrier with gas vents.

Passive control of landfill gasses

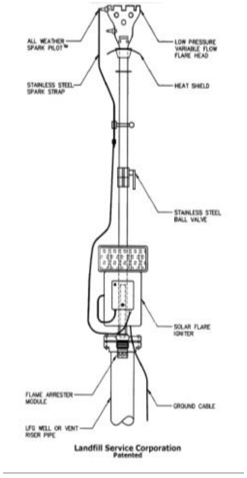


Impermeable liners (compacted clay and geomembranes) are used in modern landfills to control the movement of gases as well as leachate. Single and multilayer configurations are applicable.

Landfill gas vents and flares



Lateral migration of landfill gas can be reduced by relieving gas pressure with gas vents installed through the final cover.

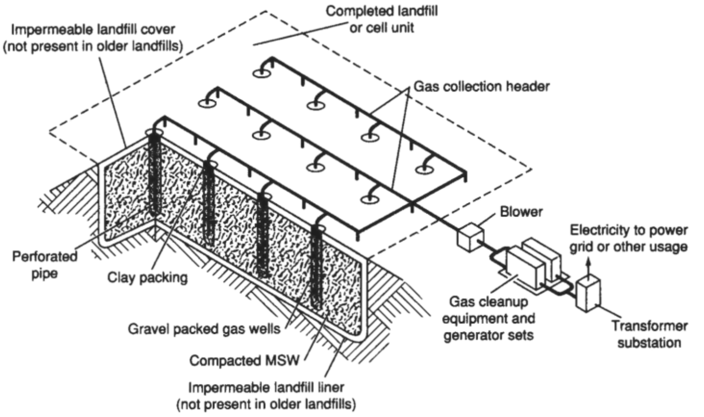


Gas vents can be connected together and equipped with a gas burner/flare

Active control of landfill gasses

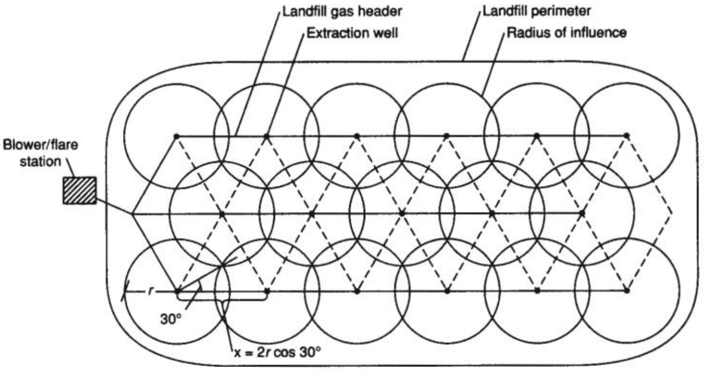
- Both vertical and horizontal gas wells are used for extraction of landfill gas from within landfill.
- The wells are spaced so that their radii of influence overlap.
- For deep landfills with a composite cover containing a geomembrane a 50-60 m spacing is common for landfill gas extraction wells.
- In landfills with clay and soil covers, a closer spacing (30 m) may be required to avoid pulling atmospheric gases in.
- Vertical gas extraction wells are usually installed after the landfill or paortion of the landfill heve been completed.

Active control of landfill gasses



Landfill gas recovery system using vertical wells

Active control of landfill gasses



Equilateral triangular distribution for vertical gas extraction wells

Management of Landfill Gas

- *Flaring (thermal desctruction)*
  - CH_4 and VOCs in landfill gas are combusted in the presence of oxygen contained in air to CO_2, SO_2, NO_x and other related gases.
- *Energy recovery*
  - Landfill gas is usually converted to electricity using internal combustion engines, gas or steam turbines.
- *Gas purification and recovery*
  - Separation of CO_2 from CH_4 can be accomplished by physical/chemical adsorption and membrane separation.

Composition, Formation and Control of Landfill Leachate

Leachate is the liquid that percolates through solid waste and extracts dissolved and suspended materials

TABLE 11-13
Typical data on the composition of leachate from new and mature landfills[a]

Constituent	Value, mg/L[b] New landfill (less than 2 years) Range[c]	Typical[d]	Mature landfill (greater than 10 years)
BOD_5 (5-day biochemical oxygen demand)	2,000–30,000	10,000	100–200
TOC (total organic carbon)	1,500–20,000	6,000	80–160
COD (chemical oxygen demand)	3,000–60,000	18,000	100–500
Total suspended solids	200–2,000	500	100–400
Organic nitrogen	10–800	200	80–120
Ammonia nitrogen	10–800	200	20–40
Nitrate	5–40	25	5–10
Total phosphorus	5–100	30	5–10
Ortho phosphorus	4–80	20	4–8
Alkalinity as $CaCO_3$	1,000–10,000	3,000	200–1,000
pH	4.5–7.5	6	6.6–7.5
Total hardness as $CaCO_3$	300–10,000	3,500	200–500
Calcium	200–3,000	1,000	100–400
Magnesium	50–1,500	250	50–200
Potassium	200–1,000	300	50–400
Sodium	200–2,500	500	100–200
Chloride	200–3,000	500	100–400
Sulfate	50–1,000	300	20–50
Total iron	50–1,200	60	20–200

Water balance and leachate generation in landfills

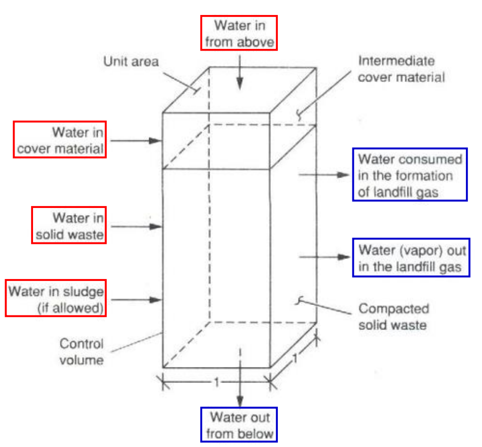
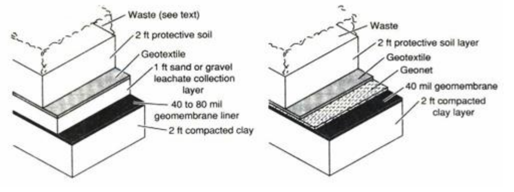
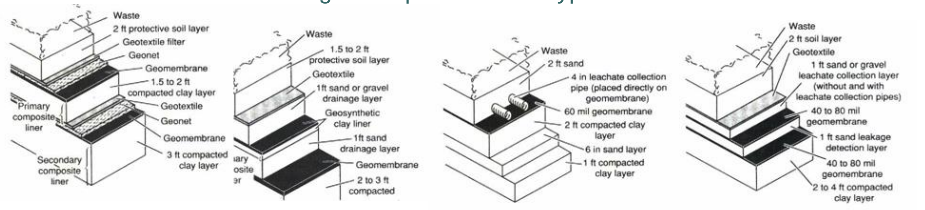


FIGURE 11-31
Definition sketch for water balance used to assess leachate formation in a landfill.

Control of leachate in landfills

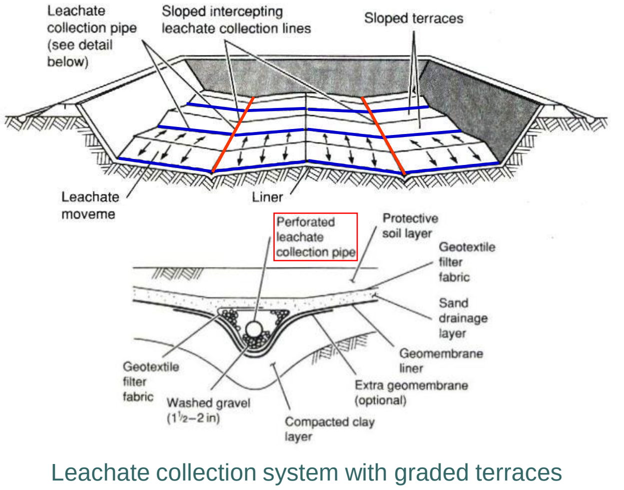


Single-composite barrier types



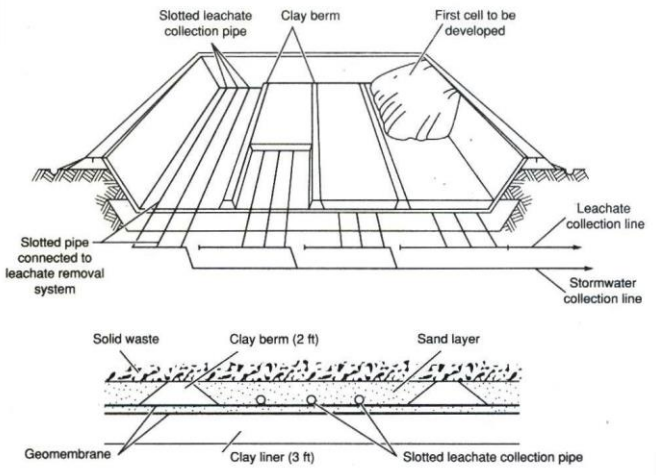
Double-composite barrier types: The first liner is the primary liner or the leachate collection system. The second liner is leachate detection layer. Leachate detection probes are placed between the first and second liner

Leachate collection systems



Leachate collection system with graded terraces

Leachate collection systems



Leachate collection system using multiple leachate collection pipes

Leachate management options

- *Leachate recycling*
  - An effective method for the treatment of leachate is to collect and recirculate the leachate through the landfill.
- *Leachate evaporation*
  - One of the simplest leachate management systems involves the use of lined leachate evaporation ponds.
- *Leachate treatment*
  - Where leachate recycling and evaporation is not used and the direct disposal of leachate to a WWTP is not possible, some form of pretreatment or complete treatment will be required.
- *Discharge to municipal wastewater collection system*

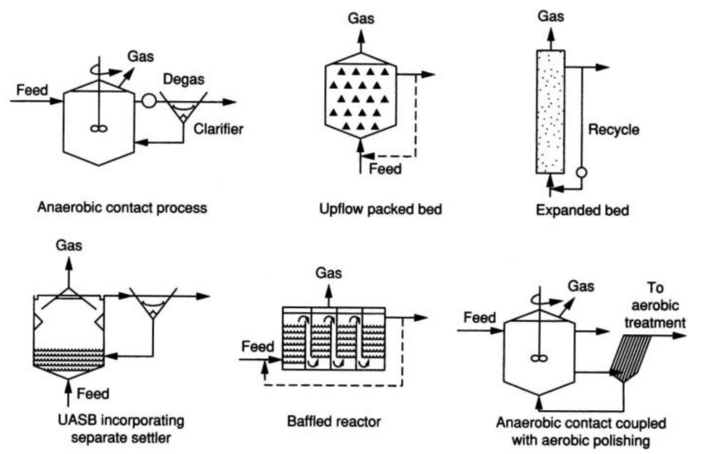
Treatment of leachate: Chemical & physical operations Table 11-18

Treatment process	Application	Comments
Chemical processes		
Neutralization	pH control	Of limited applicability to most leachates
Precipitation	Removal of metals and some anions	Produces a sludge, possibly requiring disposal as a hazardous waste
Oxidation	Removal of organics; detoxification of some inorganic species	Works best on dilute waste streams; use of chlorine can result in formation of chlorinated hydrocarbons
Wet air oxidation	Removal of organics	Costly; works well on refractory organics
Physical operations		
Sedimentation/flotation	Removal of suspended matter	Of limited applicability alone; may be used in conjunction with other treatment processes
Filtration	Removal of suspended matter	Useful only as a polishing step
Air stripping	Removal of ammonia or volatile organics	May require air pollution control equipment
Steam stripping	Removal of volatile organics	High energy costs; condensate steam requires further treatment
Adsorption	Removal of organics	Proven technology; variable costs depending on leachate
Ion exchange	Removal of dissolved inorganics	Useful only as a polishing step
Ultrafiltration	Removal of bacteria and high molecular weight organics	Subject to fouling; of limited applicability to leachate
Reverse osmosis	Dilute solutions of inorganics	Costly; extensive pretreatment necessary
Evaporation	Where leachate discharge is not permissible	Resulting sludge may be hazardous; can be costly except in arid regions

Treatment of leachate: Biological processes Table 11-18

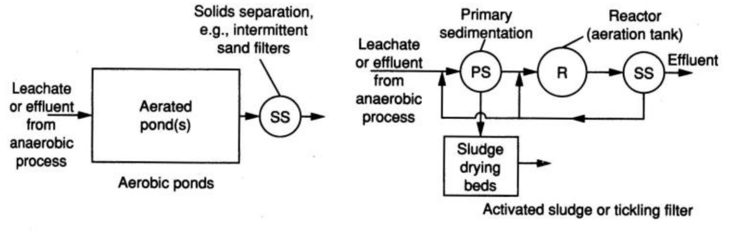
Treatment process	Application	Comments
Biological processes		
Activated sludge	Removal of organics	Defoaming additives may be necessary; separate clarifier needed
Sequencing batch reactors	Removal of organics	Similar to activated sludge, but no separate clarifier needed; only applicable to relatively low flow rates
Aerated stabilization basins	Removal of organics	Requires large land area
Fixed film processes (trickling filters, rotating biological contactors)	Removal of organics	Commonly used on industrial effluents similar to leachates, but untested on actual landfill leachates
Anaerobic lagoons and contactors	Removal of organics	Lower power requirements and sludge production than aerobic systems; requires heating; greater potential for process instability; slower than aerobic systems
Nitrification/denitrification	Removal of nitrogen	Nitrification/denitrification can be accomplished simultaneously with the removal of organics

Treatment of leachate

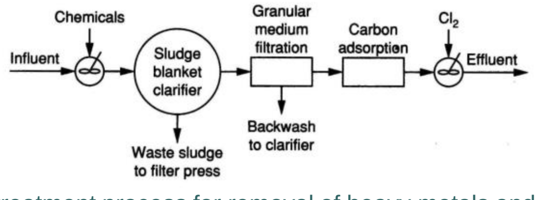


Anaerobic leachate treatment processes

Treatment of leachate



Aerobic leachate treatment processes



Chemical treatment process for removal of heavy metals and organics

Surface Water Management

- Equally important in controlling the movement of leachate is the management of all surface waters including *rainfall*, *stormwater runoff*, *intermittent streams* and *artesian springs*.
- Surface water control systems;
  - Surface water drainage facilities
  - Stormwater storage basins
  - Intermediate cover layers
  - Final cover layers

Intermediate cover layers

- They are used to cover the wastes placed each day to eliminate harboring disease, to enhance aesthetic appearance of landfill site and to limit the amount of surface infiltration.
- The greatest amount of water that enters a landfill and becomes leachate enters during the period when the landfill is being filled.
- Materials and method of placement of the intermediate cover can limit the amount of surface water that enters the landfill.

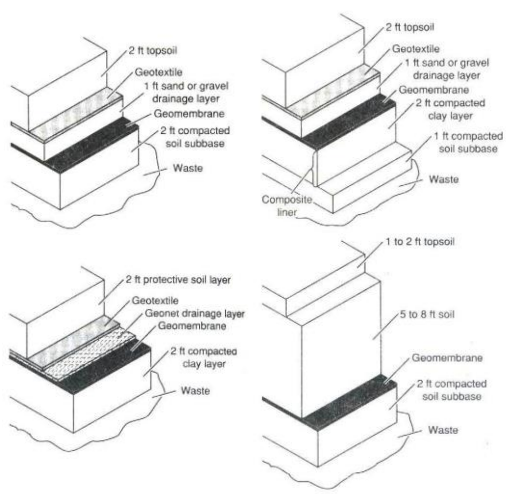
Intermediate cover layers

- If the amount of native soil available for use as intermediate cover is limited, alternative materials can be used.
- Compost produced from yard waste and MSW, geosynthetic clay liner and clay are the alternative materials effective in limiting the surface water into the landfill.
- Composted MSW need not be cured fully before being used as intermediate cover.
- Use of composted MSW increases the capacity of landfill.

Final cover layers

Surface layer	Cover soil, available locally or imported
Protective layer	
Drainage layer	Sand, gravel or geonet and geotextile separator
Barrier layer	Geomembaren
Subbase	Compacted and graded native soil

Typical components that constitute a landfill cover



Typical landfill final cover configurations

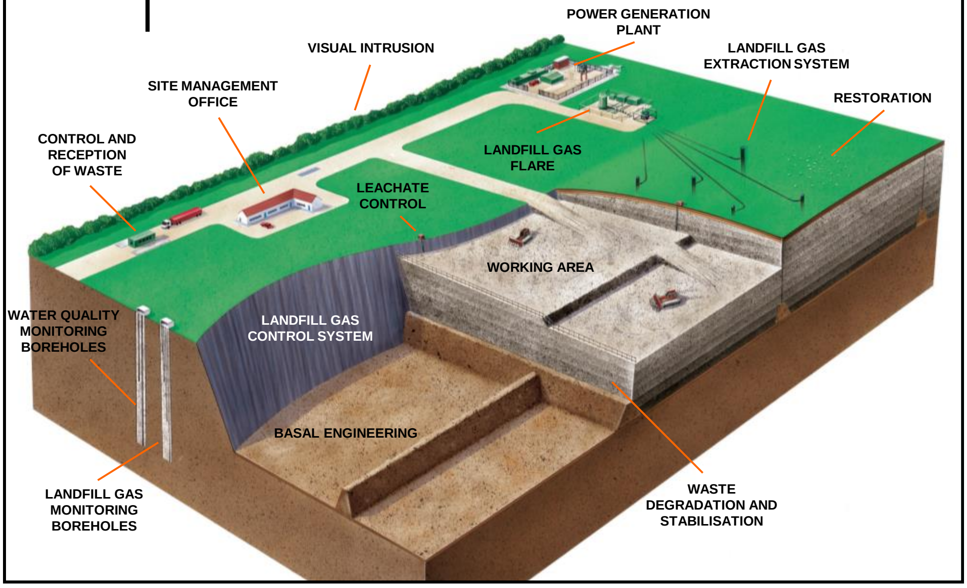
Layout & Preliminary Design of Landfills

- Important topics that must be considered in a landfill design
  - Layout of landfill site
  - Types of wastes that must be handled
  - The need for a convenience transfer station
  - Estimation of landfill capacity
  - Evaluation of the geology and hydrology of the site
  - Selection of landfill gas and leachate control facilities
  - Layout of surface drainage facilities
  - Aesthetic design considerations
  - Monitoring facilities
  - Determination of equipment requirements
  - Development of an operations plan

Layout of Landfill Sites

- In planning the layout of a landfill site, the location of the following must be determined;
  - Access roads, office space and plantings
  - Equipment shelters and (if used) scales
  - Storage and/or disposal sites for special wastes
  - Areas to be used for waste processing
  - Areas for stockpiling cover material
  - Drainage facilities
  - Location of landfill gas management facilities
  - Location of leachate treatment facilities
  - Location of monitoring wells

Layout of Landfill Sites



Design of Landfills

- Important factors to consider in the design of landfills
  - Access (roads to landfill site, temprorary roads to unloading area)
  - Land area (large enough for 10-25 years)
  - Landfilling method (excavated cell/trench, area, canyon)
  - Completed landfill characteristics (slope of final cover: 3-6%)
  - Surface drainage (to divert surface water runoff)
  - Intermediate cover material (waste to cover ratio: 5-10 to 1)
  - Final cover (multilayer design)
  - Landfill liner (multilayer design, leachate collection system)
  - Cell design and construction

Design of Landfills

- Important factors to consider in the design of landfills
  - Groundwater protection (divert any underground springs)
  - Landfill gas management (passive and active control)
  - Leachate collection (determine Q_{max} and size of collection pipes)
  - Leachate treatment (Based on expected leachate flow rate and discharge standards select the appropriate treatment process)
  - Environmental requirements (gas and liquid monitoring facilities)
  - Equipment requirements
  - Fire prevention

Typical equipment used at landfills

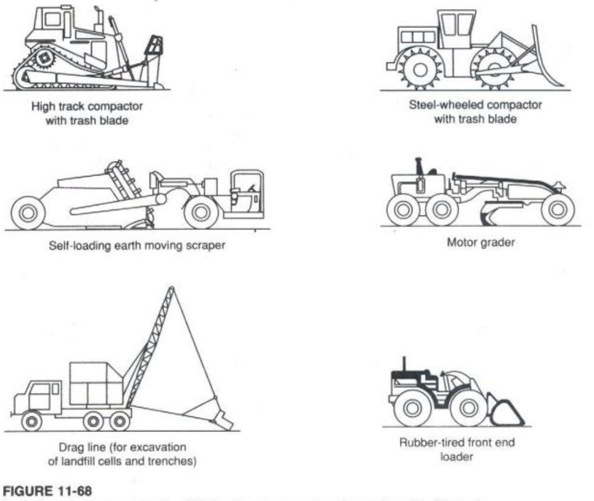


FIGURE 11-68
Typical equipment used at landfills for the placement and covering of solid waste.

Example 11.5 Determination of density of compacted MSW without and with waste diversion

- Determine the specific weight in a well-compacted landfill for MSW with the characteristics given in Table 3-4. Also determine the impact of a resource recovery program on landfill area requirements in which 50% of the paper and 80% of the glass and tin cans are recovered. Assume that the wastes have the characteristics reported in Table 3-4.

Solution

1. Set up a computation table with separate columns for (1) the weight of the individual solid waste components, (2) the volume of the wastes as discarded,(3) the compaction factors for well-compacted solid wastes, and (4) the compacted volume in the landfill. The required table, based on a total weight of 1000 kg, is given on the next slide.

Example 11.5 Determination of density of compacted MSW without and with waste diversion

Component	Weight of solid waste, kg	Specific weight, kg/m3	Volume as discarded, m^3	Compaction factor	Compacted vol. in landfill, m^3
Organic					
Food wastes	90	291	0.309	0.330	0.102
Paper	340	89	3.820	0.150	0.573
Cardboard	60	50	1.200	0.180	0.216
Plastics	70	65	1.077	0.100	0.108
Textiles	20	65	0.308	0.150	0.046
Rubber	5	131	0.038	0.300	0.011
Leather	5	160	0.031	0.300	0.009
Yard wastes	185	101	1.832	0.200	0.366
Wood	20	237	0.084	0.300	0.025
Inorganic					
Glass	80	196	0.408	0.400	0.163
Tin cans	60	89	0.674	0.150	0.101
Aluminum	5	160	0.031	0.150	0.005
Other metals	30	320	0.094	0.300	0.028
Dirt, ashes, etc.	30	481	0.062	0.750	0.047
Total	1000		9.969		1.801

Example 11.5 Determination of density of compacted MSW without and with waste diversion

Solution

2. Compute the compacted specific weight of the solid wastes.

$$\text{Compacted specific weight} = \frac{1000\,kg}{1.801\,m^3} = 555.2\,kg/m^3$$

3. Determine the compacted specific weight of the wastes in the landfill in which 50% of the paper and 80% of the glass and tin cans are recovered.

a) Determine the weight of waste after resource recovery.

Weight remaining = 1000 kg-(340 kg*0.5+80 kg*0.8+60 kg*0.8)
= 718 kg

b) Determine the volume and compacted specific weight of waste after resource recovery.

Vol. remaining = 1.801 m^3-(0.573 m^3*0.5+0.163 m^3*0.8+0.101 m^3*0.8)
= 1.303 m^3

Example 11.5 Determination of density of compacted MSW without and with waste diversion

Solution

$$\text{Compacted specific weight} = \frac{718\,kg}{1.303\,m^3} = 551\,kg/m^3$$

Comment

- The specific weight value of 555.2 kg/m^3 (computed in Step 2) would then be used to determine the required landfill area.
- Because the specific weight computed in Step 2 is essentially the same as that computed in Step 3.
- The impact of the materials recovery program can be assessed on the basis of the weight reduction alone.
- In cases where the computed compacted specific weight changes significantly as a result of a materials recovery program, the required landfill area can also be reduced by the ratio of compacted specific weights.

Example 11.6 Determination of waste to soil ratio

- Determine the ratio of waste to cover material (volume basis) as a function of the initial compacted specific weight for a solid waste stream of 70 ton/day to be placed in 3 m lifts with a cell width of 5 m. The slope of the working faces is 3:1. Assume that the waste is compacted initially to an average specific weight of 350, 450 and 600 kg/m^3. The daily cover thickness is 15 cm.

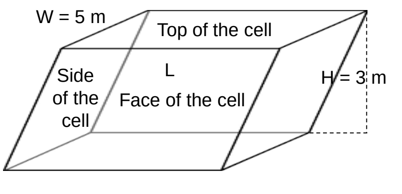
Solution

1. Determine the daily volume of the deposited solid waste.
   a) For 350 kg/m^3
      V_d = (70 ton/d * 1000 kg/ton) / (350kg/m^3) = 200 m^3
   a) For 450 kg/m^3 V_d = 155.5 m^3
   b) For 600 kg/m^3 V_d = 116.7 m^3

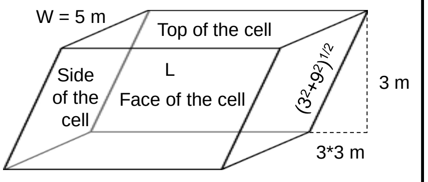
Example 11.6 Determination of waste to soil ratio

Solution

2. Determine the length of each daily cell.
   For 350 kg/m^3 L = 200 m^3 / (3 m * 5 m) = 13.3 m
   For 450 kg/m^3 L = 10.4 m
   For 600 kg/m^3 L = 7.8 m
3. Determine cell surface area
   Cells usually are parallelepiped, with cover materials on 3 of the 6 sides
   a) For the top of the cell
      A_{T-350} = 13.3 m * 5 m = 66.5 m^2
      A_{T-450} = 10.4 m * 5 m = 52.0 m^2
      A_{T-600} = 7.8 m * 5 m = 39.0 m^2



Example 11.6 Determination of waste to soil ratio



Solution

3. Determine cell surface area

   b) For the face of the cell

   $A_{F\text{-}350}$ = 13.3 m * ((3 m)^2 + (9 m)^2)$^{1/2}$ = 126.2 m^2

   $A_{F\text{-}450}$ = 10.4 m * ((3 m)^2 + (9 m)^2)$^{1/2}$ = 98.7 m^2

   $A_{F\text{-}600}$ = 7.8 m * ((3 m)^2 + (9 m)^2)$^{1/2}$ = 74.0 m^2

   c) For the side of the cell

   A_S = 5 m * ((3 m)^2 + (9 m)^2)$^{1/2}$ = 47.4 m^2

4. Determine volume of soil for daily cover

   $V_{C\text{-}350}$ = 0.15 m * (66.5 m^2 + 126.2 m^2 + 47.4 m^2) = 36.0 m^3

   $V_{C\text{-}450}$ = 0.15 m * (52.0 m^2 + 98.7 m^2 + 47.4 m^2) = 29.7 m^3

   $V_{C\text{-}600}$ = 0.15 m * (39.0 m^2 + 74.0 m^2 + 47.4 m^2) = 24.1 m^3

Example 11.6 Determination of waste to soil ratio

Solution

5. Determine ratio of waste to cover soil

   b) For 350 kg/m^3 → $R_{W:C}$ = 200.0 m^3 / 36.0 m^3 = 5.55:1

   For 450 kg/m^3 → $R_{W:C}$ = 155.5 m^3 / 29.7 m^3 = 5.24:1

   For 600 kg/m^3 → $R_{W:C}$ = 116.7 m^3 / 24.1 m^3 = 4.84:1

Comment

- Note that as the initial compacted specific weight of the waste placed in the landfill increases, the ratio of the waste to cover material decreases.
- However, the total volume occupied by the waste that has been compacted to an initial specific weight of 600 kg/m^3 is 0.58 times the volume occupied by the waste compacted to an initial specific weight of 350 kg/m^3.

Example 11.8 Landfill gas generation

Determine the distribution of gas production over time for a landfill with a useful life of 5 years based on the following data and assumptions.

- The total amount of LFG produced from the rapidly and slowly biodegradable waste (RBW and SBW) deposited each year is 0,87 and 1,04 m^3/kg dry solids, respectively (see Example 11-2)
- Time period for total decomposition of RBW and SBW is 5 and 15 years, respectively.
- 75% of RBW is available for degradation (i.e., some organic waste materials in plastic bags will not be degraded, some of the material will be too dry to support biological activity).
- 50% of SBW is available for degradation (for the same reasons cited above).

Example 11.8 Landfill gas generation

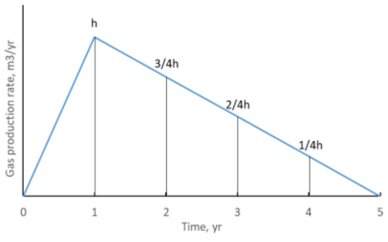
- Assume the yearly rate of decomposition for RBW and SBW is based on a triangular gas production model in which the peak rate of gas production occurs 1 and 5 years, respectively after gas production starts.
- LFG production is assumed to start at the end of the first full year operation.
- 1 ton of MSW contains 448 kg of RBW and 7.3 kg of SBW based on dry weight (See Example 11-2).

Example 11.8 Landfill gas generation

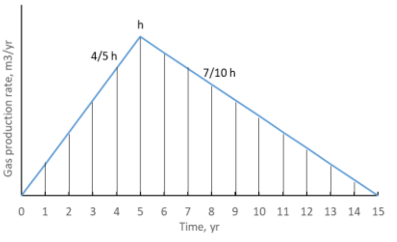
Solution

1. Determine the amount of LFG that has been produced at the end of each year from **<u>one kg</u>** of RBW and SBW as they decompose over a 5- and 15-year period, respectively.

RBW



SBW



Example 11.8 Landfill gas generation

Surface area of triangle $= \frac{time * h}{2}$

h of RBW $= \frac{0{,}87 m^3 * 2}{5\ yr} = 0{,}348\ m^3/yr$

h of SBW $= \frac{1{,}04 m^3 * 2}{15\ yr} = 0{,}139\ m^3/yr$

For RBW		
End of year	**Rate of LFG production, m^3/yr**	**LFG production, m^3**
1	0,000	
2	0,348	0,174
3	0,261	0,305
4	0,174	0,218
5	0,087	0,131
6	0,000	0,044
Total		**0,870**

For SBW		
End of year	**Rate of LFG production, m^3/yr**	**LFG production, m^3**
1	0,000	
2	0,028	0,014
3	0,055	0,042
4	0,083	0,069
5	0,111	0,097
6	0,139	0,125
7	0,125	0,132
8	0,111	0,118
9	0,097	0,104
10	0,083	0,090
11	0,069	0,076
12	0,055	0,062
13	0,042	0,049
14	0,028	0,035
15	0,014	0,021
16	0,000	0,007
Total		**1,040**

Example 11.8 Landfill gas generation

2. Determine the yearly LFG production rates from RBW and SBW (based on dry weight) **per ton of total MSW**.
   - RBW available = 448 kg * 0,75 = 336 kg/ton-MSW

     LFG prod. = 0,87 m^3/kg * 336 kg/ton = 292,3 m^3/ton-MSW

     Peak LFG prod. rate = (292,3 * 2 / 5) = 116,9 m^3/ton-MSW.yr
   - SBW available = 73 kg * 0,50 = 36,5 kg/ton-MSW

     LFG prod. = 1,04 m^3/kg * 36,5 kg/ton = 38,0 m^3/ton-MSW

     Peak LFG prod. rate = (38,0 * 2 / 15) = 5,1 m^3/ton-MSW.yr

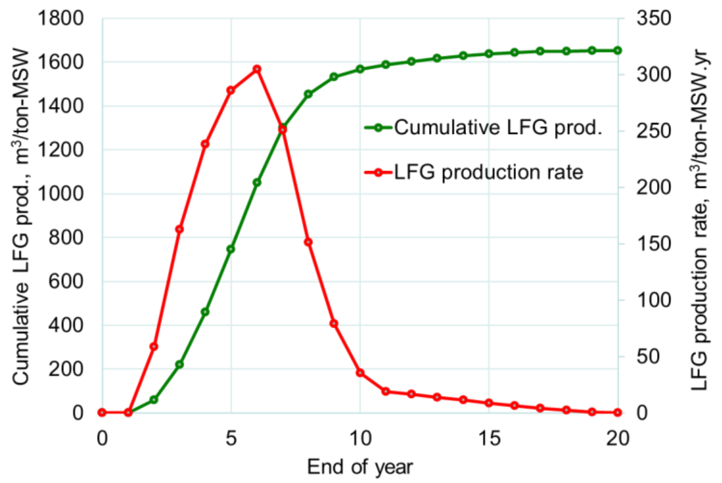
Example 11.8 Landfill gas generation

	LFG production-RBW		**LFG production-SBW**		**Total LFG production**	
End of year	m^3/ ton-MSW.yr	m^3/ ton-MSW	m^3/ ton-MSW.yr	m^3/ ton-MSW	m^3/ ton-MSW.yr	m^3/ ton-MSW
0	0,0	0,0	0,0	0,0	0,0	0,0
1	0,0	0,0	0,0	0,0	0,0	0,0
2	116,9	58,5	1,0	0,5	117,9	59,0
3	87,7	102,3	2,0	1,5	89,7	103,8
4	58,5	73,1	3,0	2,5	61,5	75,6
5	29,2	43,8	4,0	3,5	33,3	47,4
6	0,0	14,6	5,1	4,6	5,1	19,2
7			4,6	4,8	4,6	4,8
8			4,0	4,3	4,0	4,3
9			3,5	3,8	3,5	3,8
10			3,0	3,3	3,0	3,3
11			2,5	2,8	2,5	2,8
12			2,0	2,3	2,0	2,3
13			1,5	1,8	1,5	1,8
14			1,0	1,3	1,0	1,3
15			0,5	0,8	0,5	0,8
16			0,0	0,3	0,0	0,3
Total		**292,3**		**38,0**		**330,3**

Example 11.8 Landfill gas generation

	LFG production m³/ton-MSW.yr						Yearly LFG production	Cumulative LFG production
End of year	Year 1	Year 2	Year 3	Year 4	Year 5	Total	m³/ton-MSW	
0	0					0	0	0
1	0,0					0,0	0,0	0,0
2	117,9	0,0				117,9	59,0	59,0
3	89,7	117,9	0,0			207,7	162,8	221,8
4	61,5	89,7	117,9	0,0		269,2	238,4	460,2
5	33,3	61,5	89,7	117,9	0,0	302,4	285,8	746,0
6	5,1	33,3	61,5	89,7	117,9	307,5	305,0	1051,0
7	4,6	5,1	33,3	61,5	89,7	194,1	250,8	1301,8
8	4,0	4,6	5,1	33,3	61,5	108,4	151,3	1453,1
9	3,5	4,0	4,6	5,1	33,3	50,5	79,5	1532,5
10	3,0	3,5	4,0	4,6	5,1	20,2	35,4	1567,9
11	2,5	3,0	3,5	4,0	4,6	17,7	19,0	1586,9
12	2,0	2,5	3,0	3,5	4,0	15,2	16,4	1603,3
13	1,5	2,0	2,5	3,0	3,5	12,7	13,9	1617,2
14	1,0	1,5	2,0	2,5	3,0	10,1	11,4	1628,6
15	0,5	1,0	1,5	2,0	2,5	7,6	8,9	1637,5
16	0,0	0,5	1,0	1,5	2,0	5,1	6,3	1643,8
17	0,0	0,0	0,5	1,0	1,5	3,0	4,0	1647,9
18	0,0	0,0	0,0	0,5	1,0	1,5	2,3	1650,1
19	0,0	0,0	0,0	0,0	0,5	0,5	1,0	1651,1
20	0,0	0,0	0,0	0,0	0,0	0,0	0,3	1651,4

Example 11.8 Landfill gas generation



Problem 11.11

If the MSW with the composition given in Table 3-4 is to be mixed with WWTP sludge contining 5% solids to achieve a final moisture content of 55%, estimate the ultimate amount of leachate that would be produced per m^3 of compacted waste if no surface infiltration was allowed to enter the completed landfill.

Assume that the following data and information are applicable:

- Initial moisture content = 20%
- In-place specific weight of compacted mixture of solid waste and sludge = 700 kg/m^3
- Chemical formula for decomposable portion of OFMSW = $C_{60}H_{96}O_{38}N$
- 65% of OFMSW is biodegradable
- Final moisture content of wastes remaining in landfill = 35%

Problem 11.11

Solution:

- Sludge + MSW = 700 kg/m3 (based on wet weight)
- (Sludge * 0,95) + (MSW * 0,20) = (700 kg * 0,55)

  ((700 kg - MSW) * 0,95) + (MSW * 0,2) = 385 kg
- MSW = 373,3 kg → Sludge = 700 - 373,3 = 326,7 kg (wet weight)
  - MSW (dry weight) = 373,3 kg * (1-0,2) = 298,6 kg
  - OFMSW (dry weight) = 298,6 kg * (52,1 / 78,8) = 197,4 kg
  - IFMSW (dry weight) = 298,6 – 197,4 = 101,2 kg
  - bOFMSW = 197,4 kg * 0,65 = 128,3 kg → nbOFMSW = 197,4 - 128,3 = 69,1 kg
  - H_2O in MSW = 373,3 – 298,6 = 74,7 kg
  - Sludge (dry weight) = 326,7 kg * (1-0,95) = 16,3 kg
  - bSlduge = 16,3 * 0,65 = 10,6 kg → nbSludge = 16,3 - 10,6 = 5,7 kg
  - H_2O in sludge = 326,7 – 16,3 = 310,4 kg

Problem 11.11

Solution:

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3$$

$\underline{C_{60}H_{96}O_{38}N}$ + $\underline{17.75H_2O}$ → 32.125CH_4 + 27.875CO_2 + NH_3

1438 g/mol   17,75 * 18 g/mol

- H_2O consumed = (319,5 / 1438) * 128,3 kg = 28,5 kg
- Solids remaining in landfill = IFMSW + nbOFMSW +nbSlduge
  = 101,2 +69,1 + 5,7 = 176 kg
- Final moisture content = H_2O / (H_2O + Solids rem.)
- Final H_2O = 0,5385 * Solids rem. = 94,8 kg
- Leachate generated = Initial H_2O – Final H_2O – H_2O consumed
  = (310,4+74,7) – 94,8 – 28,5 = 261,8 lt/m^3

Problem 11.18

How many m^3 of waste be placed on a soccer field subject to the following constraints?

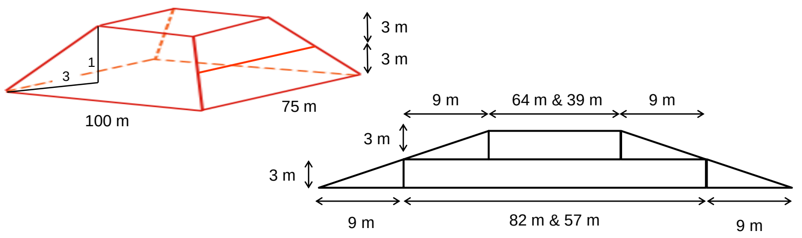
- Slope of all the landfill faces = 3 to 1
- Cover material will be excavated from the site
- Neglect cover material requirements

How many soccer fields would be required per year, assuming the in-place specific weight of the waste is 600 kg/m^3. The following conditions are applicable:

- Lift height = 3 m
- Maximum height of landfill = 6 m
- Waste generation rate = 2 kg/ca.d
- Population = 80000 person

Problem 11.18

Solution:



Lift No.	Contour elevation, m	Area at contour, m^2	Average area, m^2	Average volume, m^3	Cumulative volume, m^3
	0	7500			
1			6087	18261	18261
	3	4674			
2			3489	10467	28728
	6	2304			
				Total	28728

Problem 11.18

Solution:

- Determine MSW landfilled yearly.

  Weight = 2 kg/ca.d * 80000 ca * 365 d/yr

  = 58400 ton/yr

  Volume= $\frac{58400\ ton/yr}{0{,}6\ ton/m^3}$ = 97333 m^3/yr

- Evaluate how many soccer fields are needed per year.

  # of soccer fields = $\frac{97333\ m^3/yr}{28728\ m^3}$ = 3.4 (~ 4 soccer fields)

Landfill Closure and Postclosure Care

- They are the terms used to describe what is to happen to a completed landfill in the future.
- Development of Long-Term Closure Plan
  - Cover and landscape design
  - Control of landfill gases
  - Collection and treatment of leachate
  - Environmental monitoring systems
- Postclosure Care
  - Routine inspections
  - Infrastructure maintenance
  - Environmental monitoring systems