ABSTRACT
This module gives an overview of landfill design, with some perspective on design calculations as well.

IITM-EWRE
Solid and Hazardous Waste Management
Introduction
We have looked at Landfills in Module 1, which dealt with Municipal Solid Waste. In this module, we can look at landfills in a more detailed manner.

Operating requirements for a solid waste landfill:
- Detection and exclusion of hazardous waste from the facility
- Use of appropriate cover material for the landfill
- Disease vector control
- Control of gas production (especially those which can combust readily)
- Monitoring of air and groundwater quality
- Access to facility
- Run-on and run-off control systems
- Restricting liquids entering the landfill
- Record keeping requirements

Site selection criteria for a sanitary landfill:
- Land area and volume must be sufficient enough so that the landfill can serve for the projected number of years.
- The slope of the region should not be very steep.
- Irrigation pipelines and water supply wells should not be situated close to the boundary of the landfill.
- Residential development should be planned away from the landfill site.
- Unstable areas posing seismic risks should be avoided.
- The depth to groundwater and proximity to water wells must be thoroughly analyzed.
- The visual impact of the landfill must be minimized (landscaping, aesthetic development of landfill).
- Agricultural land should not be used for landfill development.
- The landfill must not cause flood hazard in the event of heavy rainfall.
Liner systems
Landfill liners are designed to create a barrier between the waste and the environment, and to drain the leachate to collection and treatment facilities. Liners may be single, composite, or double. Selection of liner is based on chemical compatibility, stress-strain characteristics, survivability and permeability.

I. Single liner
Single liners consist of a clay liner, a geosynthetic clay liner or a geomembrane. Single liners are sometimes used in landfills containing construction debris. Clay liner is easily available and is durable. Synthetic geo-membranes are composed of polymers such as: Thermoplastics (PVC); crystalline thermoplastics (HDPE, LDPE); thermoplastic elastomers (chlorinated polyethylene, chlorylsulphonated polyethylene); elastomers (neoprene, ethylene propene diene monomer).

Fig. 2: Single liner system
Source: The Ohio State University Extension Factsheet. Landfill Types and Liner Systems.

II. Composite liner
A composite liner consists of a geomembrane in combination with a clay liner. These are more effective at limiting leachate migration into the subsoil.

Fig. 3: Composite liner system
Source: The Ohio State University Extension Factsheet. Landfill Types and Liner Systems.
III. Double liner

A double liner consists of either two single liners, two composite liners, or a single and a composite liner. The upper (primary) liner collects the leachate, while the lower (secondary) liner acts as a leak detection system. Double liners are to be used in MSW landfills, and especially in hazardous waste landfills. A double liner is more resistant to stress cracking and increased strain due to tensile yield.

Definitions:

- Geotextile: A permeable fabric made of plastic threads that separates the base of the landfill from the underlying soil. It allows water to pass through it but prevents soil from coming into the base.
- Geomembrane: A synthetic membrane with very low permeability that controls the movement of fluid in any engineering structure or system.
- Landfill cover: A daily cover of compacted soil or earth is applied on top of the waste deposited in a landfill. This cover minimizes the interaction between waste and the surrounding environment. It also reduces odours.

*Fig. 4: Double liner system*

*Source: The Ohio State University Extension Factsheet. Landfill Types and Liner Systems.*
Leachate generation and control

Integrated into all liner systems is a leachate collection system. This collection system is composed of sand and gravel, or a geo-net. A geo-net is a plastic net like drainage blanket. In this layer is a series of leachate collection pipes to drain the leachate from the landfill – to holding tanks for storage and eventual treatment. In double-liner systems, the upper drainage layer is the leachate collection system, and the lower drainage layer is the leak detection system. The leak detection layer contains a second set of drainage pipes. The presence of leachate in these pipes serves to alert landfill management if the primary liner has a leak. The leachate collection and removal system (LCR) also contains a sump (which is the lowest point in the composite liner system) in addition to the parts mentioned above.

The rate of percolation of leachate through the liner is controlled by the hydraulic activity of the liner, the head of the leachate on top of the liner, and the total area of the liner. The leakage through a composite liner can be described the following equation (Darcy’s Law):

\[ Q = KA \frac{dH}{dL} \]

Where \( Q \) is the volume of flow per unit time through a column of cross-sectional area \( A \); the flow occurs under a pressure gradient \( dH/dL \); change in water level happens over a length \( L \); \( K \) is the saturated hydraulic conductivity which depends on grain size for saturated soils and on grain size as well as water content of pores for unsaturated soils.

Fick’s First Law describes the leakage through a synthetic liner:

\[ J = -D \frac{dC}{dx} \]

Where \( J \) is the flux (mol/cm\(^2\)/s), \( D \) the diffusion coefficient (cm\(^2\)/s), \( C \) the concentration (mol/cm\(^3\)) and \( x \) the length in the direction of movement (cm). The diffusion process is similar to the rate of flow governed by Darcy’s Law, except that the latter is driven by hydraulic gradient as opposed to concentration gradient.

Bernoulli’s Equation can be used to estimate the flow rates through pores in geo-membranes, assuming that shape and size of pores are known.

\[ Q = C_b a [2gh]^{0.5} \]

Where \( Q \) is the flow rate through a geo-membrane (cm\(^3\)/s), \( C_b \) the flow coefficient with a value of about 0.6 for a circular hole, \( a \) the area of circular hole (cm\(^2\)), \( g \) the acceleration due to gravity (cm/s\(^2\)), and \( h \) the liquid head acting on the liner (cm).
Generation of landfill gases

The Landfill Gas Emission Model (LandGEM) developed by USEPA describes gas production from a landfill using the following equation:

\[ Q_T = \sum_{j=1}^{n} 2kL_oM_ie^{-kt_i} \]

Where \( Q_T \) = Total gas emission rate \( \left( \frac{\text{volume}}{\text{time}} \right) \)

\( L_o \) = Methane generation capacity of waste \( \left( \frac{\text{volume}}{\text{mass}} \right) \)

\( n \) = Total time period of waste placement

\( k \) = Landfill gas emission constant \( \left( \frac{1}{\text{time}} \right) \)

\( t_i \) = Age of \( i^{\text{th}} \) section of waste (time)

\( M_i \) = Mass of wet waste placed at time ‘i’

It has been observed that production of gases from landfill occurs in five phases. CH\(_4\) and CO\(_2\) are the most common gases produced; with other gases being CO, H\(_2\), H\(_2\)S, NH\(_3\), N\(_2\) and O\(_2\) in smaller quantities.

\[
C_aH_bO_cN_d + \frac{4a - b - 2c + 3d}{4} H_2O \rightarrow \frac{4a + b - 2c - 3d}{8} CH_4 + \frac{4a - b + 2c + 3d}{8} CO_2 + dNH_3
\]

The organic component of MSW is of two types: rapidly decomposing (3 months – 5 years) and slowly decomposing (more than 50 years).
Phase I
This is an aerobic phase. Biodegradable components of MSW undergo microbial decomposition immediately after placement in landfill cell. Initially, $O_2$ is present in sufficient amounts. Organic matter present in waste and the soil material used as daily cover are degraded by aerobic bacteria. Once the volume of oxygen available drops to less than 15%, anaerobic organisms are cultivated.

Phase II
Phase I and Phase II together take up to a few weeks. Phase II is an anaerobic (or anoxic) phase. Organic matter acts as the electron donor, while nitrate and sulphate ions act as electron acceptors.

\[
\frac{1}{5} NO_3^- + \frac{1}{4} (CH_2O) + \frac{1}{5} H^+ \rightarrow \frac{1}{10} N_2 + \frac{1}{4} CO_2 + \frac{7}{20} H_2O
\]

\[
SO_4^{2-} + 2(CH_2O) + 2H^+ \rightarrow H_2S + 2CO_2 + 2H_2O
\]

$CH_2O$ is the representation of organic content in a generic form.

During this phase, the pH of landfill cells drops down. This is due to the formation of organic acids and elevated levels of $SO_2$ within voids.

\[H_2O + CO_2 \rightarrow H_2CO_3\]

Phase III
This is the second anaerobic phase (acid phase). Anaerobic microbial activity is much higher, resulting in higher amount of organic acids and production of some hydrogen gas (due to enzyme mediated hydrolysis). The pH of landfill liquids drops to around -5 due to presence of these organic acids and there is an increased amount of $CO_2$ within voids. However, there is no production of methane gas as methanogenic bacteria cannot tolerate acidic conditions. As a result of the low pH values, metals and other inorganic constituents are solubilized. BOD$_5$, COD, and conductivity of leachate show a sudden increase due to dissolution of organic acids in leachate.

Phase IV
This is the methane fermentation phase.

Organic acids + $H_2 \rightarrow CH_4 + CO_2$

$CH_4$ and organic acids formation proceed simultaneously. pH increases and stabilizes around 6.8-8. BOD$_5$, COD, and leachate conductivity reduce. Metals which were soluble previously begin to precipitate.

Phase V
This is the maturation phase. Rate of gas generation decreases as most of the available nutrients have been removed with the leachate, and substrates that remain are highly stable. Principal gases evolved are methane and carbon dioxide.

The occurrence of these phases depend on distribution of organic components in landfill cell, availability of nutrients, moisture content of waste, and degree of initial compaction. Higher moisture content results in lower production of gases.
In theory, biological decomposition of MSW produces 442 m$^3$ of landfill gas containing 55% CH$_4$ and a heat value of 19730 kJ/m$^3$. Actual average yield of CH$_4$ is closer to 100 m$^3$/MT of waste. Gas yields based on waste generation have been predicted using the following assumptions:

- 50% of organic material placed in landfill will actually decompose
- 50% of landfill gas generated in recoverable
- 50% of landfills operate within favourable pH range

The Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL) must be continuously monitored, keeping in mind the safety of workers and residents in and around the landfill area. The range for explosive gases in air on a volume basis should be contained within 5-15%.

**Closure and post-closure care**

The closure standards for a landfill require that a final cover be installed to minimize infiltration of liquids and soil erosion. The permeability of the final cover must be less than that of the underlying liner system. The final cover must consist of an infiltration layer of at least 18 inches of earthen material covered by an erosion layer of at least 6 inches of earthen material that is capable of sustaining plant growth.

Post-closure care deals with monitoring the effectiveness of the:

- Final cover system
- Leachate collection system
- Groundwater monitoring system
- Methane gas monitoring system
Treatment, Storage and Disposal Facilities (TSDF)

TSDF is a facility that is permitted to treat, store and dispose hazardous wastes in special hazardous waste management units. TSDFs can be commercial or private – i.e., they may accept hazardous waste from outside generators for a fee, or they may be set up for a manufacturing facility (in which case they do not accept waste from other generators).

Definitions:
- **Treatment** – Incineration or oxidation are commonly used to alter the chemical properties of the incoming hazardous waste. Other chemical processes seen in Module 6 may be applied here too. Incineration is detailed in the sections below.
- **Storage** – Storage units are used for temporary storage of hazardous wastes until they are completely treated or disposed of.
- **Disposal** – Hazardous waste landfills or deep underground injection wells are used for this purpose.

In Tamil Nadu, three commercial TSDFs are located across the state – in Gummidipoondi, Karur and Tiruppur. The Gummidipoondi TSDF has a capacity of 3,00,000 tons and is designed to incinerate 1 ton per hour.

I. Waste Analysis

The incoming waste is first analyzed in order to verify the composition – the hazardous components are characterized. This is done by thorough physical and chemical analysis in a laboratory. The waste analysis must have rules for the following:

- Parameters to be analyzed
- Safe sampling methods
- Labelling
- Repeatability of tests
- Standardized tests for physical and chemical properties
- Trained personnel to handle equipment and hazardous substances

II. Hazardous Waste Landfills

A hazardous waste landfill must fulfill the following design requirements:

- Double liner
- Double leachate collection removal systems
- Leak detection system
- Monitoring storm water run-on and run-off
- Monitoring wind dispersal
- Absence of liquid wastes
- Cover system in place

Post-closure care includes: frequent groundwater monitoring, continuous operation of leachate collection and removal systems until leaks are no longer detected, maintaining final cover.

In some instances, underground repositories are used for storage and disposal of hazardous waste. These must be chosen keeping in mind the potential damage that can be caused to human health and environment.
III. Incineration of hazardous wastes

The definition of an incinerator is “any enclosed device that uses controlled flame combustion and does not meet the criteria for classification as a boiler, sludge dryer, carbon regeneration unit, or industrial furnace”. Typical incinerators include rotary kilns, liquid injectors, controlled air incinerators, and fluidized-bed incinerators. There are three factors which ensure the completeness of combustion in an incinerator:

1. Temperature of combustion chamber
2. Length of time wastes are maintained at high temperatures
3. Turbulence (degree of mixing)

During a controlled burn, wastes are fed continuously or in batches into the combustion chamber. As the wastes are heated, they are converted into liquids and gases (CO$_2$, water, SO$_x$, NO$_x$ depending on composition of waste). If combustion is incomplete, elemental carbon (C), PCBs, benzopyrenes may be emitted – known as Products of Incomplete Combustion (PICs). Ash is collected at the base of the combustion chamber; lightweight ash may be entrapped in the flue gases as particulate matter (referred to as fly-ash).

The main indicator of incinerator performance is given by Destruction Removal Efficiency (DRE). An incinerator burning hazardous waste must achieve a DRE of 99.99% for each Principal Organic Hazardous Constituent (POHC) designated in the waste stream.

\[
DRE = \frac{(W_{in} - W_{out})}{W_{in}} \times 100\%
\]

HCl is formed when chlorinated organic compounds in wastes are burned. An incinerator burning hazardous waste cannot emit more than 1.8 kg of HCl per hour or more than 1% of the total HCl in the stack gas prior to entering any pollution control equipment.

Particulate matter consists of minute particles (solid or liquid, organic or inorganic), which are part of flue gas. They are inhaled easily. An incinerator burning hazardous waste must not emit particulate matter in excess of 180 mg/dscm (milligrams per dry standard cubic metre).

\[
P_c = P_m \times \frac{14}{21 - Y}
\]

Where $P_c$ is the corrected concentration of particulate matter, $P_m$ the measured concentration of particulate.

Some reactions which take place during the incineration process:

\[
2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O \text{ [Combustion of alkane]}
\]

\[
C_6H_4(CH_3)_2 + 11.5O_2 \rightarrow 8CO_2 + 5H_2O \text{ [Combustion of aromatic hydrocarbon]}
\]

\[
2C_2H_4Cl_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O + 4HCl \text{ [Combustion of chlorinated hydrocarbon]}
\]

Air requirement (kg air/kg solid waste) for the incineration of hazardous is calculated as follows:

\[
Weight \ of \ air \ required = 0.043[2.66C + 8H + S - O]
\]
Types of incinerators

**Liquid injector**

Liquid wastes are combusted using this incinerator. It is a stationary system consisting of one or more combustion chambers operating under high temperatures and equipped with atomizing nozzles. The major units are horizontally or vertically fired. The advantages in using a liquid injector are: (1) Fewer moving parts resulting in less downtime and maintenance (2) Capability to incinerate a wide variety of wastes (3) Low maintenance costs due to few moving parts in the system. The disadvantages are: (1) Only capable of combusting liquids and slurries (2) Feed nozzles tend to clog.

**Rotary kiln**

The rotary kiln consists of a refractory-lined rotating cylinder mounted at a slight incline from ground level. Wastes in the form of liquids, slurries, or solids are fed into the entry ports and agitated under elevated temperatures for a pre-determined length of time depending on waste and kiln characteristics. Waste liquids may be pumped in through a nozzle, thereby atomizing the input. The waste is expected to burn to ash by the time it reaches the kiln exit. A long residence time is preferred because the solids bed in the kiln is not thermally uniform. The solids retention time, $\theta$ (min) is given by:

$$\theta = 0.19 \frac{L}{N D S}$$

Where $L$ is the kiln length (m), $N$ the kiln rotational velocity (r/min), $D$ the kiln diameter (m), and $S$ the kiln slope (m/m).

The gas retention time for 99.99% destruction of a compound is given by (Kiely, 1996):

$$\ln t_g = \ln \left( \frac{9.21}{A} \right) + \frac{E}{R T}$$

Where $A$ is the Arrhenius constant (s$^{-1}$), $E$ the energy of activation (J/kg mol), $R$ the universal gas constant, and $T$ the temperature (K). $A$ and $E$ are usually known for a compound.
**Moving grate incinerator**

This is also referred to as the MSW incinerator. The moving grate enables the movement of waste through the combustion chamber to allow for a more efficient and complete combustion. A single moving grate incinerator can handle up to 35 metric tons of waste per hour, and can operate for ~8000 hours per year.

![Fig. 8: Moving grate incinerator](www.nett21.gec.jp/waste/data/waste_K-1.html) Mitsubishi-Martin Refuse Incineration System

**Fixed hearth incinerator**

These are extensively used for combustion of bulk solid and liquid wastes from medical or municipal facilities. A controlled flow of “under-fire” combustion air (70-80% of required air) is introduced up through the hearth; and the bottom ash is removed by dumping the parts into a water bath.

![Fig. 9: Fixed hearth incinerator](www.news.newclear.server279.com) Incineration Policy in Australia
**Fluidized bed incinerator**

In an internal circulation type fluidized bed incinerator, the bed part is separated into combustion and heat absorption cells. Using sensible heat from the media (sand), the temperature of the boiler tubes in the heat absorption cell is increased, generating high temperature and high pressure steam. This type of incineration offers nearly isothermal combustion, with the temperature of operation being in the range of 750-1000°C.

*Fig. 10: Fluidized bed incinerator*

*Source: [www.tsk-g.co.jp/en/tech/industry/tsk_fbi.html](http://www.tsk-g.co.jp/en/tech/industry/tsk_fbi.html) TSK Fluidized Bed Incineration System*
Bioreactor Landfills

Problems identified in the operation and maintenance of a traditional municipal solid waste landfill led to the development of a bioreactor landfill. Some of these problems include: build-up of methane gas inside the landfill leading to risk of explosion, leachate draining into groundwater resulting in damage to humans and the environment. A bioreactor landfill is one which accelerates the decomposition of waste through the addition of liquid and air, thus enhancing microbial processes. The success of the bioreactor landfill depends on maintaining optimal conditions: the temperature maintained between 60 and 72°C, 60-80% moisture, and a high pH to alkalinity ratio (>0.25). Once a methane content of >40% is observed (on a volume basis), it indicates that methanogens are well established in the landfill cell.

Types of bioreactor landfills

1. **Aerobic**
   - Leachate drained from bottom layer and re-circulated to the landfill cell
   - Air circulated into waste
   - Microbial activity improved

2. **Anaerobic**
   - Moisture added to waste mass (in the form of re-circulated leachate or other sources)
   - Biodegradation of organic fraction of waste to methane occurs in absence of oxygen

3. **Hybrid**
   - Sequential aerobic-anaerobic process
   - Organic content degraded in upper sections of landfill
   - Methane gas collected from lower sections of landfill

![Bioreactor Landfill with Leachate Recirculation](image)

*Fig. 11: Bioreactor landfill with leachate recirculation*

*Source: [www.ohioline.osu.edu](http://www.ohioline.osu.edu) Bioreactor Landfills: Factsheet Extension*
Appendix

Waste acceptance in landfills


Figure 1

Continued below:
The figures above show how a decision is made regarding disposal of waste to a landfill by the UK Environment Agency.
Sources

- USEPA – Non-hazardous waste – Municipal Solid Waste – Landfills
  - [http://www.epa.gov/osw/nonhaz/municipal/landfill.htm](http://www.epa.gov/osw/nonhaz/municipal/landfill.htm)
- USEPA – Non-hazardous waste – Municipal Solid Waste – Landfills – Bioreactors
  - [http://www.epa.gov/solidwaste/nonhaz/municipal/landfill/bioreactors.htm](http://www.epa.gov/solidwaste/nonhaz/municipal/landfill/bioreactors.htm)
- USEPA – Hazardous Waste – Hazardous Waste Land Disposal Units
  - [http://www.epa.gov/wastes/hazard/td/index.htm](http://www.epa.gov/wastes/hazard/td/index.htm)
- Kerry L. Hughes, Ann D. Christy and Joe E. Heimlich. *Bioreactor Landfills*. The Ohio State University Extension Factsheet, CDFS-139-05.
  - [http://ohioline.osu.edu/cd-fact/0139.html](http://ohioline.osu.edu/cd-fact/0139.html)