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CHE 5203 - LANDFILLING/ FINAL DISPOSAL IN DC

Landfill emissions, site requirements, landfill construction, monitoring, landfill technology and operation, sitting and construction, design characteristics, life span, extraction of landfill gas – future energy production, operation and maintenance, emission control and treatment.

CONTENTS

1. INTRODUCTION

The basis of a good solid waste management system is the municipal solid waste (MSW) landfill. MSW landfills provide for the environmentally sound disposal of waste that cannot be reduced, recycled, composted, combusted, or processed in some other manner. A landfill is needed for disposing of residues from recycling, composting, combustion or other processing facilities and can be used if the alternative facilities break down. A properly designed MSW landfill includes provisions for leachate management and the possible collection of landfill gas and its potential use as an energy source. Innovative planning will also facilitate productive use of the landfill property after closure. Good design and operation will also limit the effort and cost necessary for maintaining the landfill after final site closure.

2. CONCEPTS OF SOLID WASTE LANDFILLS

2.1. Landfill design issues

A solid waste landfill is an engineered facility that requires detailed planning, careful construction, and efficient operation. In a landfill, solid wastes are disposed of by spreading in thin layers, compacting to smallest practical volume, and covering each day, or periodically, with soil or suitable substitute material in a way that minimises environmental problems. A landfill's design life extends many years beyond the time when it is closed. Waste stabilisation begins shortly after it is placed in the landfill, but will not be completed until years after closure.

Modern MSW landfills differ greatly from simple land disposal. Today's MSW landfills which have evolved in design and operating procedures over the last 20 years, are very different from landfills of even 5 or 10 years ago. Design improvements have reduced environmental impacts and improved the efficient use of resources. In the completed landfill, the waste is enclosed by cover material at the top and by a liner system at the bottom. Appropriate systems are in place to control contaminated water and gas emissions and reduce adverse impacts on the environment.

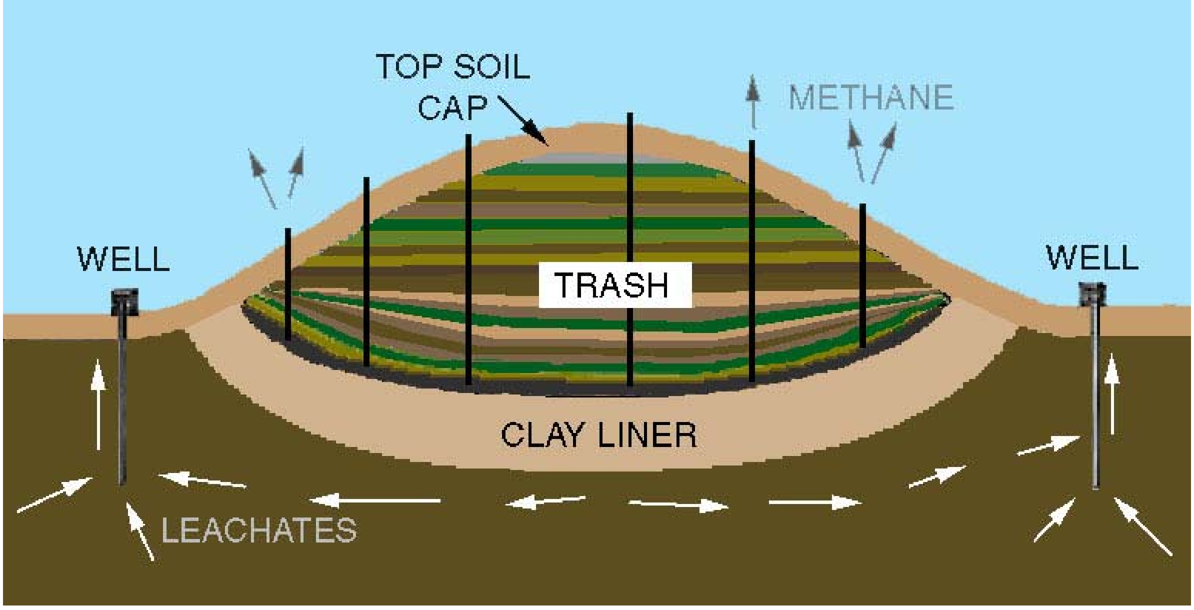


Figure 1: Typical landfill.

Some of the key terms used in MSW landfill design include the following:

- **Waste management boundary:** The waste management unit boundary is the boundary around the area occupied by the waste in a landfill. It is measured in square meters.
- **Liner:** The liner is a system of clay layers and/or geosynthetic membranes used to collect leachate and reduce or prevent contaminant flow to groundwater.
- **Cover:** A typical MSW landfill has two forms of cover consisting of soil and geosynthetic materials: (1) a daily cover placed over the waste at the close of each day's operations and (2) a final cover, or cap, which is the material placed over the completed landfill to control infiltration of water, gas emission to the atmosphere, and erosion. It also protects the waste from long-term contact with the environment.
- **Leachate:** Leachate is a liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from such waste. Leachate typically flows downward in the landfill but may also flow laterally and escape through the side of the landfill.
- **Leachate collection system:** Pipes are placed at the low areas of the liner to collect leachate for storage and eventual treatment and discharge. Leachate flow over the liner to the pipes is facilitated by placing a drainage blanket of soil or plastic netting over the liner. An alternative to collection pipes is a special configuration of geosynthetic materials that will hydraulically transmit leachate to collection points for removal.
- **Landfill gas:** Generated by the anaerobic decomposition of the organic wastes, landfill gas is a mixture of methane and carbon dioxide, plus trace gas constituents.
- **Gas control and recovery system:** A series of vertical wells or horizontal trenches containing permeable materials and perforated piping is placed in the landfill to collect gas for treatment or productive use as an energy source.
- **Gas monitoring probe system:** Probes placed in the soil surrounding the landfill above the groundwater table to detect any gas migrating from the landfill.
- **Groundwater monitoring well system:** Wells placed at an appropriate location and depth for taking water samples that are representative of groundwater quality.

The goal of MSW landfilling is to place residuals in the land according to a coordinated plan designed to minimize environmental impacts, maximize benefits, and keep the resource and financial cost as low as possible. To achieve these ends, the solid waste manager and the landfill owner and operator must carefully plan the development of new facilities and optimize the performance of existing facilities.

2.2. New landfills siting

Careful planning by the developers of new or expanding landfills is important. A large amount of money and a long period of time are required to build a landfill. Some of the cost elements and time periods are listed below:

- Siting, design, and construction: 3-10 years
- Operation, monitoring, and administration: 15-30 years
- Closure: 1-2 years
- Monitoring and post-closure maintenance: 30 or more years
- Remedial actions: unknown.

Numerous technical details, significant public involvement, and extensive regulations all present challenges to the new landfill developer. The steps outlined below should be considered:

- Estimating landfill volume requirements.
- Investigating and selecting potential sites.
- Determining applicable regulatory requirements.
- Assessing landfill options for energy and materials recovery.
- Considering the site's final use.
- Determining the suitability of sites.

- Designing the fill area to satisfy plan/permit requirements.
- Establishing a leachate management plan.
- Instituting groundwater monitoring.
- Setting up a gas management plan.
- Preparing landfill final cover specifications.
- Obtaining plan and permit approvals.
- Establishing financial assurance for closure and post-closure care.
- Operating the landfill.
- Closing the landfill.
- Providing post-closure care.

These steps may be organized into four phases. The first phase (steps 1-6) involves developing an information base and making some preliminary site decisions. The second phase (steps 7-12) includes making a detailed design for the landfill and for managing related issues such as groundwater monitoring and leachate and gas management. In the third phase (steps 13-14) financial assurance is established and actual operation begins. The fourth phase (steps 15-16) includes closure and post-closure care. More info on landfill siting in Chapter 5.

Figure 2: landfill site location.

2.2.1. *Developing an Information Base and Making Initial Site Decisions*

The specific approach followed in designing an MSW landfill will vary from project to project, but certain preliminary information must be gathered and initial site decisions must be made for any project. Landfill volume is the first consideration to be made in the design process. Initial investigations should focus on locating potential sites, determining the applicability of federal, state and local requirements, and identifying the environmental impacts of the landfill. The end use of the site should also be considered during the initial site decision phase. The landfill could be closed with restricted access, or it may be feasible to design systems for productive site end use and energy and materials recovery. These initial design considerations must be addressed before a more detailed design can be developed.

2.2.2. *Estimating Landfill Volume*

Landfill volume estimates are necessary to determine the dimensions for the landfill. An adequate prediction of landfill volume requirements can be made by projecting records of past landfill volume consumption, refuse weight, or gate volume. Such projections must be made in light of population growth estimates and anticipated changes in commercial or industrial wastes. Depending on the accuracy of previous records, especially with regard to the volume filled per year over the period of record, such a projection can be reasonably reliable and can be used to estimate the landfill volume requirements for a design period of perhaps seven to ten years of site operation. Accurate tonnage estimates of waste to be received at the site will be necessary. Such estimates can range in complexity from simple projections using national or regional data to detailed weighing programs and sophisticated population projections.

Once general projections have been made for the amount of waste to be landfilled, the next step is to estimate any anticipated increase or decrease in the diversion of material to waste-to-energy facilities, composting, recycling, reuse efforts, or waste minimization efforts. Other units in this study guide deal with the amount of waste that can potentially be diverted from the landfill by these different options and the amount of materials the landfill can expect to get back from them as residuals requiring disposal. Reusable items such as clothes, doors, windows, appliances, and miscellaneous household items can be separated at the gate and sold. Waste-to-energy plants typically reduce incoming volume by 90 percent and weight by 75-80 percent.

To estimate landfill capacity, one needs density figures for the waste. Density figures at the level of compaction obtained in the typical collection vehicle. If the composition of the waste is known, it can be used to estimate the density in the truck, and compaction figures can be used to estimate the density to be expected in the landfill. The density of material in an MSW landfill is usually 590 kg per cubic meter, but the range depends on refuse composition, moisture content, and the degree of compaction. Deeper landfills achieve higher density because the weight of the refuse compacts lower portions of the landfill. When waste is dumped from trucks at the landfill face, it loses its compaction. The load is then broken up as it is spread by the bulldozer and then re-compacted by the bulldozer/compactor.

The amount of soil necessary for daily and final cover must be added to the refuse volume data to obtain the final landfill space projection. The refuse- to-soil ratio usually ranges from 2:1 to 5:1 on a volumetric basis. Therefore, every two to five parts by volume of refuse will require one part by volume of cover soil for all of the various forms of cover in the typical landfill space.

In general, a ratio of 3:1 (refuse to soil) can be used to plan for the operation of most sites. The ratio can be modified upward or downward, depending on any special cover requirements, phasing requirements, or final cover requirements.

A final factor to consider in developing volume estimates is the amount of settlement that will take place. Settlement will occur as the refuse decomposes or becomes compacted by the weight of overlying materials. For average-to-good compaction, the surface will settle to 80 or 85 percent of the original (un-decomposed) height within five years. This probably will be 90 percent of the ultimate settlement. Some landfills have soil temporarily placed on the surface, the weight of which will promote settlement to final grades.

2.3. Existing or closed landfills issue

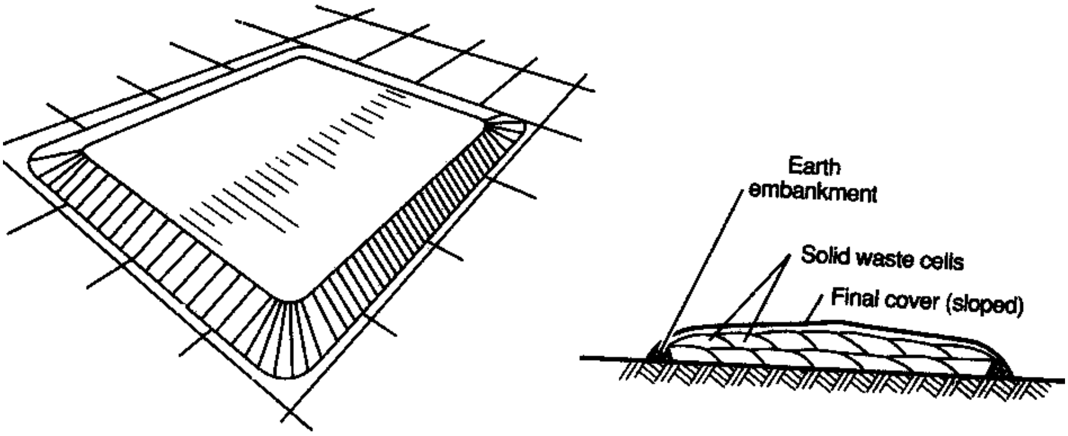
Owners and operators of existing landfills must also execute a number of these steps in order to comply with recently established regulations. Leachate and gas management, groundwater monitoring, financial assurance, operating procedures, and closure activities are among the activities described in this unit which must be carried out at existing landfills. The steps summarized below are equally crucial to existing and closed landfills as they are to new landfills.

- Establishing a leachate management plan.
- Instituting groundwater monitoring.
- Setting up a gas management plan.
- Preparing landfill final cover specifications.
- Obtaining closure plan approval.

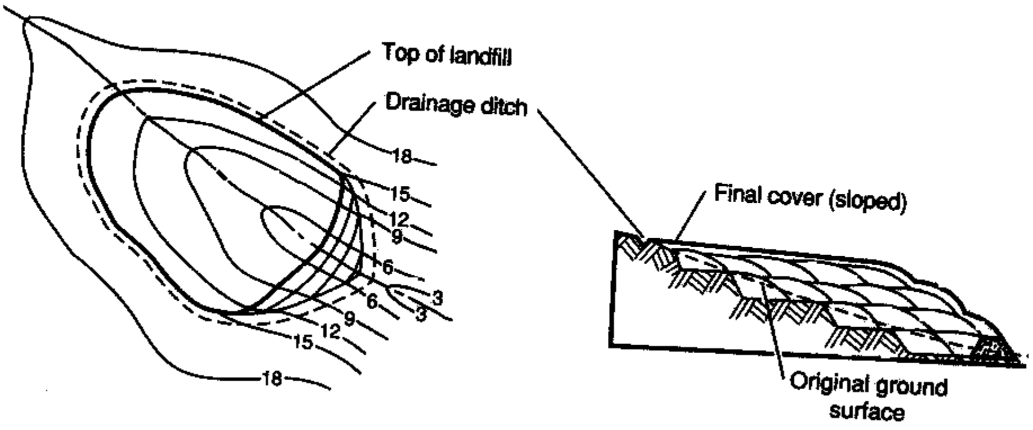
- Establishing financial assurance for closure and post-closure care.
- Operating the landfill.
- Closing the landfill.
- Providing post-closure care.

3. SOLID WASTE LANDFILL TYPES AND LANDFILLING METHODS

The three common configurations of sanitary landfills are the area method, the ramp method, and the trench method. In the area method excavation into which the landfill is placed may either be naturally occurring or excavated specifically for the purpose of landfilling. If excavation is done, the soil is temporarily stockpiled. The waste is placed on the ground surface or, more commonly, on a landfill liner, spread in layers, and driven over with compaction equipment. Successive layers are built up until a depth of 3 to 4 m is achieved. An intermediate cover material is recommended on the top and exposed sides of the compacted solid waste. The cover material may be soil or a synthetic material and is usually placed at the end of each day's operation, or more frequently. Possible exceptions to this procedure are when limited equipment availability at small sites results in less frequent covering, or when a large site operator continuously fills the area, in which case intermediate cover may not be required.

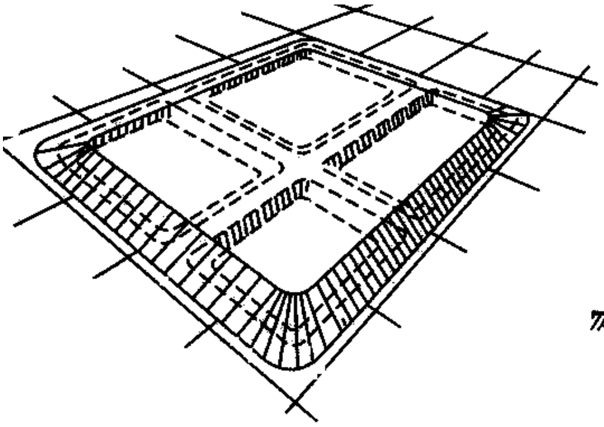


The ramp method is a variation of the area method. It is best suited to sloping land. Solid waste is spread and compacted on a slope. Cover material is obtained directly in front of the working face and compacted on the waste.



The trench method is generally used on flat or gently sloping land. The land is excavated and filled in successive parallel trenches. As soil is needed to cover a previously opened trench, a new trench is opened. Trenches should be dug at least twice as wide as the tractors which must operate in them. The depth of the trenches varies with soil and ground water conditions. Generally they are 2.5 to 3.5 m deep.

Final cover is placed over the completed cells or the landfill is extended vertically using imported soil or other materials for intermediate and final cover.



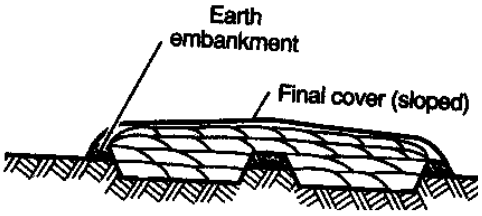


Figure 3: typical landfill during waste disposal.

4. PRELIMINARY DESIGN OF SOLID WASTE LANDFILLS

It is not possible to outline a typical landfill design process and expect a given project to follow the specified sequence. Each project presents a unique combination of timing, site restrictions, and waste characteristics, along with regulatory and political factors that force the design team to adapt as the project unfolds. Nevertheless, certain points must be covered in the, and it is helpful to have an initial outline of a logical sequence of activities to follow. Such an outline is summarized in the table 1.

Table 1: Landfill design process outline of a logical sequence of activities

Step 1	**Determine solid waste quantities and characteristics**
Step 2	**Compile information for potential sites**
2.1 Perform boundary and topographic surveys	
2.2 Prepare base maps of existing conditions on and near sites	Property boundaries
	Topography and slopes
	Surface water
	Wetlands
	Utilities
	Roads
	Structures
	Residences
	Land use
2.3 Compile hydrogeological information and prepare location map	Soils (depth, texture, structure, bulk density, porosity, permeability, moisture, ease of excavation, stability, pH, CATION exchange capacity)
	Bedrock (depth, type, presence of fractures, location of surface outcrops)
	Groundwater (average depth, seasonal fluctuations, hydraulic gradient and direction of flow, rate of flow, quality, uses)
2.4 Compile climatological data	Precipitation
	Evaporation
	Temperature
	Number of freezing days
	Wind direction
2.5 Identify regulations (federal, state, local) and design standards	Loading rates
	Frequency of cover
	Distances to residences, roads, surface water and airports
	Monitoring
	Groundwater quality standards
	Seismic and fault zones
	Roads
	Building coas
	Contents of application for permit
Step 3	**Design filling area**
3.1 Select landfilling method based on:	Site topography
	Site soils
	Site bedrock
	Site groundwater
3.2 Specify design dimensions	Cell width, depth, length
	Cell configuration
	Fill depth
	Liner thickness
	Interim cover soil thickness
	Final cover specifications

3.3 Specify operational features	Use of cover soil
	Method of cover application
	Need for imported soil
	Equipment requirements
	Personnel requirements
Step 4	**Design features**
4.1 Leachate controls	
4.2 Gas controls	
4.3 Surface water controls	
4.4 Access roads	
4.5 Special working areas	
4.6 Special waste handling	
4.7 Structures	
4.8 Utilities	
4.9 Recycling drop off	
4.10 Fencing	
4.11 Lighting	
4.12 Washracks	
4.13 Monitoring wells	
4.14 Landscaping	
Step 5	**Prepare design package**
5.1 Develop preliminary site plan of fill areas	
5.2 Develop landfill contour plans	Sequential fill plans
	Completed fill plans
	Fire, litter, vector, odor and noise controls
5.3 Compute solid waste storage volume, soil requirement volumes, and site life	
5.4 Develop final site plan showing	Normal fill areas
	Special working areas
	Leachate controls
	Gas controls
	Surface water controls
	Access roads
	Structures
	Utilities
	Fencing
	Lighting
	Washracks
	Monitoring wells
	Landscaping
5.5 Prepare elevation plans with cross-sections of	Excavation plans (including benches)
	Excavated fill
	Completed fill
	Phase development of fill at interim points
5.6 Prepare construction details	Leachate controls
	Gas controls

	Surface water controls
	Access roads
	Structures
	Monitoring wells
5.7 Prepare ultimate land use plan	
5.8 Prepare cost estimate	
5.9 Prepare design report	
5.10 Prepare environmental impact assessment	
5.11 Submit application and obtaining required permits	
5.12 Prepare operator's manual	

Data collected during site selection will be incorporated into the site design, but changing conditions and the need for more detail may require re-evaluation and adding to previously collected data.

Concurrent with the design and permitting processes, public education and participation programs must be undertaken. The final stage of site selection is gaining public approval. Projects lacking public review or input until the design is completed may face substantial delays in the approval process.

4.1. Meeting Regulatory Standards

There are generally two types of regulatory standards: engineering design standards and performance standards. Engineering design standards are essentially building codes that describe how the facility must be built. An example might be requiring that new landfills have a 2m high fence surrounding them. The regulating bodies monitor compliance with these standards by reviewing the building plans and inspecting the landfill during construction. Performance standards are applicable over a facility's life and specify that a certain level of environmental control be achieved and maintained. For example, the state agency regulating groundwater quality may specify the maximum allowable concentration of a contaminant that may be present in the groundwater below or adjacent to the site.

The site operator must incorporate the necessary control systems to achieve compliance with the groundwater standard. If the landfill as initially designed does not achieve compliance, then the operator must install additional protective systems.

The final use of the landfill must be considered during the design phase in order to provide for the best use of the property. Good planning at the earliest possible stage will minimize costs and maximize the site's usefulness after closure. The long-term alternative end uses will be limited and must be consistent with the approved closure plan.

4.2. General Design Considerations

The design package should include plans, specifications, a design report, and an operator's manual, all of which will be submitted to regulatory agencies. A cost estimate for in-house uses should also be submitted.

Plans and specifications typically include the following elements:

- Base map showing existing site conditions with contour intervals
- Site preparation plan designating fill and stockpile areas and site facilities
- Development plan showing initial excavated and final completed contours in filling areas
- Cross sections illustrating phased development of the landfill at several interim points
- Construction details illustrating detailed construction of site facilities
- Completed site plan including final site landscaping and other improvements.

A design report typically includes the following four major sections:

- Site description, which includes existing site size, topography, slopes, surface water, utilities, roads, structures, land use, soil, groundwater, exploration data, bedrock, and climatological information
- Design criteria, which include solid waste types, volumes, and fill-area dimensions and all calculations
- Operational procedures, which include site preparation, solid waste unloading, handling, and covering, as well as equipment and personnel requirements
- Environmental safeguards, including the control of leachate, surface water, gas, blowing paper, odour, and vectors.

4.3. Public Involvement

Many of the permits needed before landfill design and operating plans are approved require that a public hearing be conducted to solicit input from interested parties. The firm or agency designing the landfill should also solicit input from individuals and groups who will be directly affected by the future landfill. The mechanisms chosen to facilitate public participation must be suited to the particular group from whom input is being sought. Such techniques include advisory committees, surveys, public meetings, and tours of similar facilities. Public hearings should be conducted after the public has been provided with details about the proposed facility and any concerns voiced by representatives of the community. Some communities establish technical and citizen advisory committees that participate in establishing goals and objectives and then help prepare evaluation criteria and the final landfill design.

4.4. Developing the Site Layout

The landfill’s layout will be strongly influenced by the site’s geology. Of particular concern is the potential for gas and leachate migration and the suitability of the soil for landfill base and cover material. The site layout begins with geotechnical information, which includes data on the geology, hydrology, and soils at and around the site. These data are usually collected during the site selection process, then supplemented during subsequent site investigation. Soil-boring logs, as well as other data describing subsurface formations and groundwater conditions, are diagrammed to present an interpretation of the subsurface conditions at the planned landfill site.

4.5. Preparation of Drawings

The base map usually shows the landfill location in relation to surrounding communities, roads, and other features. A site map shows the following features:

- Contour lines drawn at intervals
- Clearly delineated property lines
- Easements and rights-of-way indicated
- Utility corridors, buildings, wells, roads, and other features identified
- Drainage ways marked
- Neighboring property ownership and land uses shown.

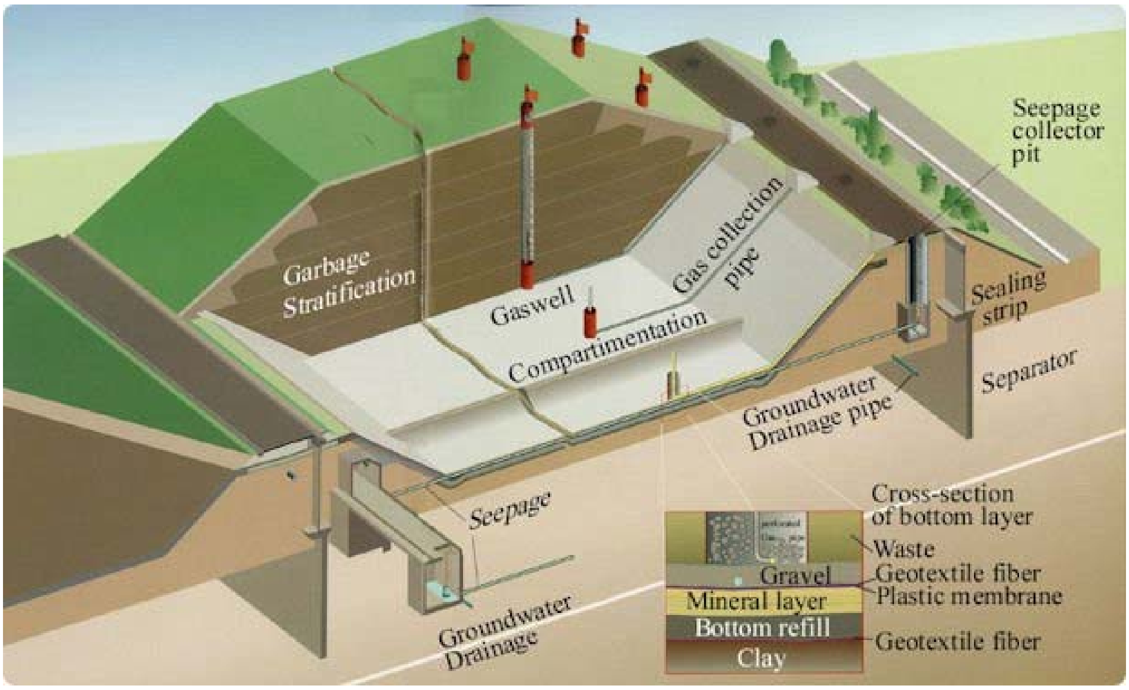


Figure 4: Landfill design.

Contour maps show drainage patterns adjacent to and through possible disposal sites. Areas with excessive slope or direct overland flow from a potential site to surface waters must be carefully evaluated. Subsurface formations and ground-water conditions will influence the landfill's design features in the leachate collection system and liner requirements. A formation's geotechnical characteristics will determine its suitability as a construction material.

The site plans should describe landfill development in sequence, showing in chronological order which features or phases are to be developed. Development is usually planned for the landfill to be constructed and operated in phases of one to two years each. Dividing the project into phases minimizes the amount of open landfill surface and reduces the potential for precipitation to accumulate in the site. As each phase is completed, that portion of the landfill can be closed and final cover material placed over the waste. A final advantage of phasing is that it makes premature closure of the landfill more practical and economical in the event of an environmental problem. In a well planned phase development, the landfill's end use can be implemented in the completed sections while other areas are still being used for disposal.

Concurrent with the development of plans for liners, covers, service roads, and embankments, soil cut-and-fill balances must be calculated. The best designs minimize the transfer of soil at the site. Substantial volumes of earth will be required for cover material and possibly for liners.

Some regulatory agencies mandate the construction of screening berms or fences around the active areas of a landfill. The extra soil needed for berm construction must be accounted for when planning excavation work. The height of the berms will depend upon the lines of sight into the landfill from adjacent areas. When practical, the phases should be laid out so that excavated soil is used immediately. When stockpiling is necessary, the work should be organized so that stockpiled soil may be left undisturbed until needed or be used to surcharge completed areas. Stockpiled soil should be covered whenever possible to prevent erosion from wind and precipitation.

After completion of the phasing diagrams and earth work balances, a table should be prepared summarizing the waste disposal and earth volumes that will be contained within each phase of the landfill.

4.6. Operating Plans

4.6.1. Determining Working Face and Phase Dimensions

The operating plan should describe, in detail, the configuration of the working face of the landfill. The "working face" is the area presently being worked, with new refuse being deposited and compacted into it. Once the working face has been completed and daily cover material provided, it is a completed cell or "daily cell." A "lift" is composed of the adjacent daily cells that form one layer of the landfill. Lift thicknesses are generally 3 to 6 m. Larger landfills that accept more refuse per day have higher lift thicknesses. "Daily cover material"is applied over the working face and can extend over the horizontal surface at the top of each daily cell, depending on how long the cover will be exposed to the environment. If the landfill is not expected to receive additional wastes, closure activities must begin within 30 days of the final receipt of waste. The requirement to begin closure ensures that a proper cover is installed at the landfill.
The minimum width of the working face or daily cell should be at least wide enough to accommodate as many trucks or vehicles as are expected to be at the landfill at a given time. Typically, 3 to 5 m per truck or vehicle is used for design purposes. Clearly, it is not a good operating practice to have extremely wide working faces to accommodate the peak flow of trucks that may occur once or twice a day. A tradeoff must be made between the width of the working face and the area needed to queue vehicles entering the site during peak hours. The working face should be kept as small as possible because it is this area that can attract birds, provide visual problems for passersby, and be a source of blowing paper. Keeping freshly deposited refuse in a well-defined and small working face is a good indication of a well-operated landfill.

4.6.2. Phase Diagrams

The site plan should illustrate the chronological order for developing the features. In a well-planned phased development, the landfill's end use can begin on completed sections while other areas in the landfill are still being used for disposal. Phasing diagrams show the evolution of the landfill at different stages through the life of the site. They should be developed for key times in sufficient detail to ensure that the operator knows what is to be done at any point. The engineers and management must be assured that the site is proceeding according to plan and contracts can be let or finances arranged for construction activities. Regulatory bodies must also be assured that landfill operators are following the plan and the site will be completed as designed at the agreed-upon time. The dimensions of each phase are determined by several factors. Generally, each phase accommodates 2 to 3 years of refuse volume.

5. SOLID WASTE LANDFILL SITE SELECTION

Landfill site selection is usually an extensive process which will likely involve public input. The community or private company developing a landfill should clearly identify project objectives; having well-defined goals and objectives makes it easier to communicate with citizens (those who support and those who oppose the project) and with political officials. Each party involved will have specific needs to address, but common factors will include the following:

- Geographic area and population to be served by the site
- Type of waste and quantity to be disposed of
- Tipping fee or cost of operation
- Unacceptable wastes
- Maximum hauling distance
- Minimum, and possibly maximum, site operating life span

- Profile of potential site users.

If the addition of a new facility means that more than one landfill or waste recycling/treatment operation will be serving the area, facility developers must determine if the new facility can compete economically with existing units. For example, there are recent indications that economies-of-scale favor large landfill sites. When planning to develop such a site, however, one must compare the cost of hauling longer distances to the large landfill with the economics of existing waste management options.

5.1. Fulfilling Land Use Goals

Potential sites must be in areas that are suitable for landfill development. Operation and end use of a landfill site should also conform to long-term land use goals. Most areas have projected land-use plans of 10 to 20 years.

Special consideration must be given when evaluating potential sites in areas with endangered plant or animal habitats, virgin timber land, wildlife corridors, unique physical features, or significant historical or archaeological sites. Developers should anticipate possible competing land use interests associated with such areas and realize that certain aspects of the siting and development process may be more complicated. A careful evaluation of possible short- and long-term environmental, political, and social impacts should be made and the anticipated benefits of developing the site must be evaluated in light of the potential impacts and the availability of alternative sites.

A site selected for a landfill will have some characteristics that are less than ideal. Engineering techniques may overcome these limitations and enable the site to meet design goals, but it is important to start with the best site possible. In selecting a site, some factors to consider include health, safety, accessibility, drainage, soils, proximity to groundwater and surface water, zoning, hauling distance, and adjacent land use. The following considerations should be key factors in locating and operating a landfill.

- A landfill must be consistent with the overall land-use planning in the area.
- The site must be accessible from major roadways or thoroughfares.
- The site should have an adequate quantity of earth cover material that is easily handled and compacted.
- The site must be chosen with regard for the sensitivities of the community's residents.
- The site must be located in an area where the landfill's operation will not detrimentally affect environmentally sensitive resources.
- The site should be large enough to accommodate the community's wastes for a reasonable time (10 to 30 years).
- The site chosen should facilitate developing a landfill that will satisfy budgetary constraints, including site development, operation for many years, closure, post-closure care, and possible remediation costs.
- Operating plans must include provisions for coordinating with recycling and resource recovery projects.

In addition to determining the suitability of a site, location restrictions must be considered. In general there are restrictions on locating landfills in the vicinity of airports, in flood plains, wetlands, fault areas, seismic impact zones, and unstable areas.

Airports: If a landfill is located within a specified distance of an airport, the owner or operator must demonstrate that the landfill will not present a bird hazard to aircraft.

Flood plains: For landfills located on a 100-year flood plain, the owner or operator must demonstrate that the landfill will not restrict the flow of a 100-year flood, reduce the storage capacity of the flood plain, or result in the washout of solid waste.

Wetlands: New landfills and lateral expansions cannot be located in wetlands except where an owner demonstrates to an approved state/ community that there is no practical alternative. The landfill must not cause or contribute to violations of any state water quality criteria, contribute to significant degradation of wetlands, cause net loss of wetlands, or violate any other federal requirements.

Fault areas: New landfills and lateral expansions must not be located within close vicinity of a fault that has experienced displacement during the past.

Seismic zones: New landfills and lateral expansions are restricted in areas susceptible to ground motion resulting from earthquakes. If the site is in an earthquake zone, investigations that demonstrate to an approved state/community the suitability of locating a landfill at the designated location must be conducted.

Unstable areas: Unless it can be demonstrated otherwise, landfills must not be located in areas susceptible to natural or human-induced events or forces capable of impairing the integrity of landfill components. Examples of unstable areas are those with poor foundation conditions, areas susceptible to mass movements (landslides, rock falls, etc.), and areas with karst terrains (sinkholes).

5.2. Tabulating Site Identification Data

Several procedures may be used to collect and tabulate the necessary data. The most informal approach is to identify a list of potential sites based on personal knowledge of the area being studied. This approach limits the area being considered but presents a major handicap because other suitable areas may be overlooked.

One way of incorporating the various siting criteria is to prepare a series of map overlays. Each overlay identifies land areas with moderate or severe limitations in regard to a particular criterion. The overlays are prepared on transparent plastic sheets placed over the base map.

The best approach for establishing the limitations ratings for each criterion is through a technical assessment conducted in combination with input from public officials, interested citizens, and regulatory officials. A unique criteria rating should be prepared for each proposed landfill development project to ensure that local concerns are addressed.

Once a map is prepared for each criteria the maps are assembled as overlays and the most suitable areas identified. Both graphical or computer techniques are available for assembling the data.

When using soil and site identification data, project developers should keep in mind that these sources do not provide absolute data, but only estimates or approximations of predominant soil types, depths, and other features. The estimates or approximations should be confirmed later by conducting soil borings if the potential site is otherwise found to be a good candidate for a landfill.

A well-planned siting program must include opportunities for public participation at appropriate times. Citizens may participate through public hearings, advisory committees, surveys, tours of established landfills, and public meetings in which small-group discussions between citizens and project planners are encouraged. The public may also be involved in publishing newsletters or issuing press releases to keep other residents informed about the program's progress.

5.3. Assess Landfill Options for Energy and Materials Recovery

Gas generated from landfills can have at least three uses: (1) as a boiler fuel, (2) as fuel for an engine-generator set to produce electricity, and (3) as a natural gas supplement, when first upgraded to pipeline quality. In industrial boilers, landfill gas is best used as a supplementary fuel. This allows the boiler to be fired continuously using other fuels if landfill gas becomes unavailable for some reason.

Specifications for boiler gas focus on the absence of air or oxygen, compression, and transporting the gas to the boiler. Dewatering may also be necessary to accommodate climate and pipeline distance and configuration. Depending on the situation, gas as low as 20 to 30 percent methane can be used in boilers.

Landfill gas is also used to generate electricity. Compressed and dewatered landfill gas can be used to fuel either gas turbines or reciprocating engines that drive electrical generators. In general, smaller plants tend to use reciprocating engines and larger plants tend to use gas turbines. To drive a generator, the gas must be at least 30 percent methane.

The third use for landfill gas is as a supplement for natural gas. This requires removing carbon dioxide and trace gases to upgrade the landfill gas to 100 percent methane. The gas is then directed into a natural gas transmission system.

The market for this gas is virtually inexhaustible and is easily accessible with natural gas transmission lines, which are often located in the vicinity of the landfills.

Difficulties in reaching markets for this use of landfill gas are usually associated with the amount and cost of processing required to upgrade the gas to pipeline quality and gaining approval of the pipeline company.

5.4. Consider Final Site Use

The final use of the landfill site should be considered during the initial site decision phase in order to provide for the best use of the property. Good planning at the earliest possible stage will minimize costs and maximize the site's usefulness after closure.

Many case studies have shown that land formerly used for solid waste disposal can be upgraded through proper design and implementation of innovative landfill concepts. An example is land that has been converted into an open-space park in a municipality where open space may be in short supply. Many landfills have been turned over to parks departments or conservation agencies for general public use after landfilling has been completed. Careful attention must be given to monitoring requirements, groundwater protection, gas migration control, and uneven settlement. If the landfill design provides for such constraints, however, the land can be turned into productive use when the landfill is completed. Improvements also need to be properly designed to avoid disturbance of design features in the closed landfill, such as leachate collection systems.

The best strategy is to plan for the eventual use of the site before the landfill is constructed and operated. An additional benefit of planning ahead is that stating a planned use during site selection may reduce possible opposition to a new landfill. Potential uses for closed MSW landfills are provided below:

- Nature park
- Recreation park
- Wilderness area
- Animal refuge
- Golf course
- Ski or toboggan hill
- Parking lot

Planning is particularly important if future construction or building on or near the landfill site is anticipated. Design features such as location of structures requiring special support, recreational facilities requiring specific topography, and gas control systems to protect future buildings can be anticipated during landfill operation.

Depending on planned site use, factors that can be modified are cover thickness, slope, cover/waste ratio, degree of compaction, use of additives and cements, selective disposal, and setting aside undisturbed areas as structural pads. The consequences of changing plans for the landfill usually include costly modifications, such as the removal of settlement-prone cover and waste layers.

When identifying potential options for final landfill use, it is important that uses under consideration be compatible with the post-closure care plan, with other nearby land uses, and with the limited ability of the landfill to support structures. Most completed landfills are used for recreational purposes, such as golf courses, nature preserves, or ski hills. Consideration must also be given to compatibility with existing land forms, settlement allowances, landfill gas protection, drainage patterns, and open-space planning.

5.5. Determine Suitability of Sites

The next step in the site selection process is to conduct a more detailed investigation of those sites designated in the site identification process as being most suitable. Site characterization studies should be conducted at sites with the most desirable characteristics. Thorough site characterizations are conducted in two phases. The first phase involves collecting and reviewing as much information as can be found about the site. The second phase involves field investigation activities. Most of the new data collected will concern the geology and hydrogeology of potential sites. Such information helps planners determine aquifer depths, geologic formations, drainage patterns, depth to groundwater, groundwater quality and flow direction, and construction characteristics of on-site soils. Data about existing land use, surrounding land development, available utilities, highway access, political jurisdiction, and land cost are also tabulated.

5.6. Conducting Site Characterizations—Information Collection and Review

Before beginning a field investigation, developers should review all available information about the site. A thorough review will include the following:

A literature review: including (1) research reports that provide findings of studies conducted on the site itself or on surrounding areas, (2) journal articles dealing with the site or surrounding areas, and (3) studies and reports from local, regional, and state offices (geological surveys, water boards,
environmental agencies, etc.).

Gathering information from file searches: Including (1) reports of previous site characterizations for the site, (2) geological and environmental assessment data from state and federal project reports, (3) previous site uses for disposal which may have resulted in contamination.

The documentation listed above is by no means a complete listing of data necessary to conduct a preliminary investigation. There are many other sources of documentation that may be available for review during the preliminary investigation. After completing the preliminary investigation, the hydrogeology of the site must be characterized.

5.7. Conducting Site Characterizations—Field Investigations

The proposed site must be characterized to determine subsurface conditions. Site characterization studies consist of geophysical investigations, soil borings and test pits below and adjacent to the proposed site. The number, location, and depth of the soil borings are dictated by the hydrogeology of the site. The number of borings needed to accurately define conditions increases with the size and geologic complexity of the site. The result of the investigations will lead to the formation of a conceptual model. This model should be a reliable estimation of geologic and hydrogeologic conditions at the site.

The borehole program usually requires more than one round of drilling. The objective of the initial boreholes is to further define the conceptual model derived from research data. The borehole program should be designed as follows:

- Determine the initial number of borings and their spacing based on the information obtained during the preliminary investigation.
- As needed, install additional borings to provide more information about the site.
- Collect samples when changes in lithology occur. For boreholes that will be completed as monitoring wells, at least one sample must be collected from the interval that will be screened. As a boring is being advanced, a soils scientist or geologist will collect samples for testing. Normally, soil samples are tested for grain size distribution and moisture content and are classified by soil type.

Soils that may later be used for liners and landfill covers will also be tested for permeability, moisture content, moisture density relationship, and moisture strength factors. This data is used to prepare a boring log.

Borings should extend below the expected base elevation of the landfill, and at least a portion of the boreholes should terminate below the water table. Selected borings should extend to bedrock unless the distances involved make it unreasonable. Monitoring wells can be constructed in the boreholes as part of the hydrogeologic study. Some states' regulations specify the minimum number of borings for each site and a minimum number per acre to reduce the chances of overlooking significant hydrogeologic features such as sand lenses or perched water.

Measuring static water elevations in wells helps to determine the horizontal and vertical groundwater gradients for estimating flow rates and flow directions. The water levels can be plotted and contoured on a map that also shows adjacent land uses. Superimposing flow lines on the contours shows where leakage from a potential landfill may migrate.

The final output of the site characterization phase of the hydrogeological investigation is a conceptual model, which consists of an integrated picture of the hydrogeologic system and the waste management setting. The final conceptual model must be a site-specific description of the vadose zone, the uppermost aquifer, and its confining units. The model should contain all of the information necessary to design a groundwater monitoring system.

Other conditions may exist at proposed landfill sites. The presence of bedrock can impede excavation and greatly complicate groundwater protection. Sites with multiple soil layers and formations will require careful characterization as the landfill is being designed. When soil and groundwater limitations must be overcome, specialized site layout must be carefully implemented.

Hydrogeologic studies are relatively expensive to conduct and should, therefore, be limited to those sites with the most promising characteristics. A further cost concern is obtaining permission to do the testing without buying the property beforehand. One alternative is to purchase an option to buy, which gives the purchaser the right to buy the land within a specified period of time for a specified price. This allows time for testing and evaluating the results without commitment to purchasing the property.

The preliminary feasibility report should contain all of the pertinent information needed for determining which site to select. The report may suggest a preferred site or may leave this decision to the governing board of the unit of government or other organization that will be operating the landfill.

Once a site has been selected, a final feasibility report can be prepared and submitted to the appropriate agencies for approval.

6. SOLID WASTE LANDFILL GAS MOVEMENT/ CONTROL AND USEPROBLEMATIC ISSUES OF LAND DISPOSAL

Uncontrolled landfill gas migration can be a major problem at a municipal solid waste landfill. The gas must be controlled to avoid explosions and vegetation damage in the vicinity of the landfill. The composition of municipal landfill gas is controlled primarily by microbial processes and reactions in the refuse. Methane is usually the gas of concern. It is produced in about a 50:50 ratio with carbon dioxide. Other compounds are also produced and additional chemicals are released into the atmosphere by volatilization.

Table 2: Typical landfill gas composition.

Component	Percent (%)
Carbon dioxide	47.0
Oxygen	0.8
Aromatic-cyclic hydrocarbons	0.2
Hydrogen sulfide	0.01
Trace compounds	0.5
Methane	47.4
Nitrogen	3.7
Paraffin hydrocarbons	0.1
Hydrogen	0.1
Carbon monoxide	0.1

The oxygen and nitrogen levels shown above are not products of decomposition; rather, they result from intrusion of air during gas sampling or analysis. On an airfree basis, and depending on the amount of dissolution of carbon dioxide and moisture in the landfill and the material being decomposed, the methane content typically ranges from 50 percent to 60 percent, the remainder being carbon dioxide and minor constituents.

The gas that is generated will either vent to the atmosphere or migrate underground. In either case, monitoring and control equipment must be used to detect and control air pollution or damage to structures or vegetation. In addition to being a hydrocarbon source and greenhouse gas, landfill gas entering the atmosphere will carry with it trace quantities of a large number of volatile organic compounds, some of which have known detrimental health effects. Landfill gas traveling underground may enter structures, where explosive concentrations may build up, or it may displace oxygen, causing a danger of asphyxiation. Landfill gas in the soil profile may damage the vegetation on the surface of the landfill or on the land surrounding the landfill.

6.1. Gas Control is Needed

Methane can quickly asphyxiate a person, and concentrations as low as 5 percent are explosive. Methane displaces oxygen from the root zone and kills vegetation. Landfill operators must receive adequate safety training, and gas monitoring equipment and other safety devices must be properly calibrated and maintained.

If methane accumulates in a building it poses a severe hazard. Methane can enter a building through cracks, construction joints, subsurface utility openings, or weak spots in the basement wall or building floor. Because it is lighter than air, methane tends to accumulate near the ceiling. If the source of methane cannot be immediately controlled, the building must be evacuated or a methane alarm system must be installed and the building must be continuously vented. Following are some of the basic safety rules for dealing with methane:

- Anyone entering a landfill vault or trench must check for methane gas, wear a safety harness, and have someone there to pull him or her to safety if needed.
- Anyone installing gas wells in a landfill must wear a safety rope to prevent falling into the borehole.
- Smoking must never be permitted while drilling or installing landfill gas wells or collection pipes, or when gas is venting.
- Gas collected from a mechanically evacuated system to minimize air pollution and reduce danger of explosion or fire must be flared.
- If it is suspected that methane gas has accumulated in a building, alert the fire department immediately. Most fire departments have equipment to detect methane and ventilate buildings.

Gas movement through refuse and soils is extremely complicated. The gas will tend to migrate from the landfill on a path through the refuse and surrounding soils that offers the least resistance. Gas will migrate farther through a highly permeable sand or gravel soil than it will through a less permeable silt or clay soil. The rate of migration will also be influenced by weather conditions. When barometric pressure is falling, gas will tend to be forced out of the landfill into the surrounding soil formations. Wet surface soil conditions and frozen ground may prevent gas from escaping into the atmosphere at the edge of the landfill; this may cause the gas to migrate even farther away from the landfill. Maximum migration distance of methane gas is difficult to predict. Migration distances greater than 300 m have been observed.

6.1.1. Controlling Gas

Controlling gas movement at a landfill begins with a study of the local soils, geology, and nearby area. For example, if the landfill is surrounded by a sand or gravel soil and if buildings are close to the landfill, the movement of gas into this area should be controlled by engineering methods. On the other hand, any landfill surrounded by clay may not require as stringent a control system. Note, however, that the clay cap installed at a completed landfill to exclude moisture infiltration and restrict leachate generation will, at the same time, tend to contain the landfill gas. The pressure gradient that results will force the gas to move laterally and into the areas surrounding the landfill. Even a narrow sand seam in a clay formation can transmit a large quantity of gas, especially if the gas cannot escape through the cover.

6.1.2. Gas Probes

Gas probes are used to detect the location and movement of methane gas in and around a landfill. The probe is installed by boring a hole into the landfill or the ground around it. If off-site migration is a concern, the hole should extend at least 150 percent of the depth of the landfill, but not below the water table. A pipe with a perforated zone at the bottom is placed into the hole and the space between the original soil and pipe is filled with sand or gravel over the perforated portion. A bentonite slurry or other impermeable material is packed around the pipe above the perforated interval to the ground surface to prevent air leaking into the probe. At some sites, multilevel probes are installed to obtain a more accurate three-dimensional picture of gas movement.

Two types of measurements are conducted. Gas pressure is measured with a gauge or manometer. Gas pressure gradients indicate landfill gas movement. The concentration of methane is also measured by using a calibrated meter on site or by taking samples for laboratory analysis.

Since the migration patterns and the methane concentrations change rapidly, frequent measurements are required to obtain an accurate picture of the gas migration pattern. At sites where there is much concern about gas migration endangering residences, daily measurements should be conducted until migration controls are put into place.

6.2. Gas Control Systems

6.2.1. Passive Gas Control Systems

Passive vents are sometimes used to control landfill gas migration. Passive systems rely on natural pressure and convection mechanisms to vent the landfill gas to the atmosphere. Research findings and field observations have confirmed that passive systems offer only limited protection. In areas where there is a significant risk of methane accumulating in buildings, passive systems may not be reliable enough to be the sole means of protection. Because of the unpredictability of gas movement in landfills, the use of passive venting is declining in modern landfill designs. Active systems are becoming more common.

6.2.2. Active Gas Collection Systems

Active gas collection systems remove the landfill gas with a vacuum pump from the landfill or the surrounding soils. These systems may provide migration control or recover methane for use as energy. In both cases, gas recovery wells or trenches and vacuum pumps are employed. A pipe network is built to interconnect wells and blower equipment. When the primary purpose is migration control, recovery wells are constructed near the perimeter of the landfill. Depending on site conditions, the wells may be placed in the waste or in the surrounding soils, if they are reasonably permeable.

At landfills where the waste has been placed up to the property line, there may not be sufficient space to put wells and collection lines outside the waste. In such cases, interior wells, especially near the waste-soil boundary, are used.

Borehole diameters for an active gas well are generally 0.3 to 1m. Larger diameter holes provide more surface area at the refuse-gravel interface, require less suction for gas removal, and are less prone to plugging. They are used if large amounts of gas are expected from each well, as in the case of gas recovery.

6.3. Collecting Gas for Beneficial Use

At some landfills, it is cost-effective to install gas recovery wells or trenches throughout the landfill and recover the gas for its energy value. In addition to the wells that may be constructed along the landfill's perimeter for migration control, wells or trenches may be placed in a grid pattern throughout the landfill to recover gas that might otherwise escape through the landfill cover. Depending on gas quality and user requirements, gas collected along the perimeter may be flared so as not to dilute the higher-quality gas typically collected from interior wells or trenches.

Wells are connected to a collection system that carries the gas to energy recovery equipment. Pipes connecting wells or trenches are called laterals or headers. The overall design must take settlement into consideration and should be sloped to drain gas condensate. The piping material must resist corrosion.

Collected landfill gas can be directly vented to the atmosphere in some locations, burned or flared, or directed to an energy recovery system. Venting is usually done through a stack, to provide atmospheric dispersion and to minimize the potential of odour problems. If odour problems or the presence of undesirable air contaminants justify it, the gas may be directed through a burner for combustion. If the methane concentration exceeds 15 percent and will support a flame, a supplemental fuel (such as natural gas) is not needed. This is important because supplemental fuel can greatly increase the operating cost of the landfill gas control system. When the methane gas concentration is greater than approximately 35 percent, it may be worthwhile to recover the energy from the gas. Landfill gas containing 47 percent methane has a heating value of ½ of natural gas.

Before constructing an energy recovery system, it is important to conduct tests to predict the quantity and quality of gas available. Testing is important because wide variations have been observed in gas generation rates and compositions. A pumping test is conducted by installing a gas recovery well and a number of monitoring probes in the landfill. The well is pumped until the gas flow stabilizes. Chemical characterizations of the gas are measured to determine methane content and the concentration of other chemicals; concurrently, the probes are monitored for pressure drop and methane content. The probes help define the volume of the landfill influenced by a well.

6.4. Methods of Energy Recovery

The method of energy recovery depends primarily on the available energy markets. If a factory or large building is near the landfill, it may be practical to pipe the gas directly into a boiler at the facility. The landfill gas typically is passed through condensate knock-out tanks designed to remove liquid droplets by a baffle system and then injected into the furnace in combination with the regular boiler fuel, which may be coal, oil, or natural gas. A blower is needed to pull gas from the landfill and transport it at the desired pressure to the user. Using landfill gas as supplementary boiler fuel is possibly the simplest approach, but a suitable boiler is seldom available near a landfill. If the gas must be transported, the cost of a pipeline between the site and the boiler must be compared to the value of the gas.

Often a boiler is not available as a feasible market for the methane gas. In this case, landfill gas can be directed to an engine/generator system for producing electricity. Almost all landfills have electrical service and the generated power can be used on site or sold to the electric grid. To produce electricity, the gas is compressed, dewatered, and possibly purged of particulates before it is used as a fuel in an internal combustion engine or a gas turbine.

Since the methane content of the gas will directly affect the performance of the engine or turbine, the site operator must closely regulate the gas collection system. The cost-effectiveness of generating electricity from landfill gas is limited by the price paid for the electricity by the utility and varies widely, depending on local power costs and generating capacity.

Figure 5: equipment for energy recovery from landfill gas.

Natural gas pipelines are located near many landfill sites. Several different methods including membranes, liquid solvent extraction, molecular sieves, and activated carbon adsorption, have been used to remove the carbon dioxide and other noncombustible constituents from methane landfill gas. The gas is thereby upgraded to pipeline quality and injected into the natural gas distribution network. The landfill operator is paid by the natural gas utility for the value of the methane. The market for such gas is generally excellent, but the cost of upgrading the gas to meet pipeline specifications presents problems. Generally, such gas treatment is feasible only with larger landfills. Operation problems and economic costs have limited the extent to which this option has been implemented.

As gas emission control becomes more common for environmental and regulatory reasons, gas use will also probably become more common even if the income, for example, from electricity sales, is too low to justify the project on a financial basis alone. Although the energy available from landfill gas represents a small fraction of the total energy usage in the area, it can be important because it is available locally and continuously. Electricity and natural gas pipeline production from existing landfill gas recovery systems can often supply the electrical needs for 5,000 to 20,000 homes.

7. SOLID WASTE LANDFILL LEACHATE CONTROL AND TREATMENT

Refuse contains decomposable matter, as well as the nutrients and organisms that promote decomposition. The limiting factor controlling the amount of decomposition taking place in municipal solid waste is usually the availability of moisture. The decomposition of solid wastes in an MSW landfill is a complex process. It may be characterized according to the physical, chemical, and biological processes that interact simultaneously to bring about the overall decomposition. The by-products of all these processes are chemically laden leachate and landfill gas.

Leachate is a liquid that has passed through or emerged from the waste in a landfill. It contains soluble, suspended, or miscible materials removed from such waste. Changes in leachate composition occur as a landfill proceeds through the various decomposition phases. It is imperative, therefore, when designing leachate collection and treatment facilities to consider the concentrations and variability of leachate with regard to its many constituents. Leachate generation rates depend on the amount of liquid originally contained in the waste (primary leachate) and the quantity of precipitation that enters the landfill through the cover or falls directly on the waste (secondary leachate).

7.1. Factors affecting leachate generation

These factors influence leachate generation at landfills:

- **Climate:** Climate at the site significantly influences the leachate generation rate. All other factors being equal, a site located in an area of high precipitation can be expected to generate more leachate.
- **Topography:** Topography affects the site's runoff pattern and the amount of water entering and leaving the site. Landfills should be designed to limit leachate generation from areas peripheral to the site by diverting surface-water "run-on" away from the site and by constructing the landfill cover area to promote runoff and reduce infiltration. All areas of a landfill should maintain at least a two percent grade over the waste at all times to prevent ponding of surface water.
- **Landfill cover:** Landfill cover at the site affects the amount of water percolating into the landfill to form leachate. As the permeability of the soil used for final cover increases, leachate production rates increase. Consequently, to reduce the amount of leachate, modern design requires the use of low-permeability clays or geosynthetic membranes in final cover configurations.
- **Vegetation:** Vegetation plays an integral part in leachate control. It limits infiltration by intercepting precipitation directly (thereby improving evaporation from the surface) and by taking up soil moisture and transpiring it back to the atmosphere. A site with a poor vegetative cover may experience erosion that cuts gullies through the cover soil and allows precipitation to flow directly into the landfilled waste.
- **Type of waste:** The type of waste and the form that it is in (bulk, shredded, etc.) affect both the composition and quantity of leachate. Wetter wastes, for example, will generate more leachate.

7.2. Predicting leachate production rates

Good landfill design requires predicting the amount of leachate that will be produced. The amount of leachate generated will affect operating costs if leachate collection and treatment are provided. The amount of leachate formed also affects the potential for liner leakage (to be calculated later) and hence to the potential for groundwater contamination. It also affects the cost of post-closure care after the landfill is closed.

Predicting leachate formation requires water-balance calculations. The water-balance equation is used for this purpose which estimates the amount of water from rain or melting snow that will percolate through the landfill cover. Over time, the volume of percolating water will nearly equal the volume of leachate produced. There may be a lag between the time percolating water enters the fill material and the time leachate emanates continuously from the base of the fill. During this lag period, the solid wastes increase in moisture content until their field capacity is reached (field capacity is defined as the moisture content of the waste above which moisture will flow under the influence of gravity). Some leachate will be generated intermittently (almost immediately in wet climates), because of water channeling through the wastes. Once field capacity is achieved, however, leachate production should be more consistent.

7.3. Landfill liner system

The purpose of lining an MSW landfill is to prevent leachate from migrating from the site and entering an aquifer. A liner is a hydraulic barrier that prevents or greatly restricts migration of liquids, thus allowing leachate to be removed from the unit by the leachate control system. Liners function by two mechanisms: (1) they impede the flow of leachate into the subsoil and aquifers, and (2) they adsorb or attenuate pollutants, thus retarding contaminant migration. This adsorptive or attenuating capability depends largely on the chemical composition of the liner material and its mass. Most liner materials function by both mechanisms, but to different degrees, depending on the type of liner material and the nature of the liquid to be contained. Liners may be grouped into two major types: synthetic (flexible membrane) liners and natural (soil or clay) liners.

There are various types of liners in use, including compacted native and imported soils, compacted mixtures of native soils and bentonite, and flexible membrane liners. Flexible membrane liners are the least permeable liners, but have little capacity to attenuate dissolved pollutants. Natural liners can have a large capacity to attenuate materials of different types, but they are considerably more permeable than flexible membrane liners. A combination of both types of liner materials is referred to as a composite liner. Composite liner systems are more effective than either a single component flexible membrane liner or a soil liner. A composite liner can provide added protection to ensure that contaminant migration is controlled. The flexible membrane liner portion of the liner increases leachate collection efficiency and provides a more effective hydraulic barrier. The soil component provides support for the flexible membrane liner and the leachate collection system and acts as a back-up in the event of a flexible membrane liner failure. Landfill liner systems consist of several components as described below that control leachate movement off site.

7.4. Clay liners

Regulatory agencies usually require that the soil liner have a permeability of less than 10^{-7} centimeters per second. To achieve final liner permeabilities that are consistently this low, tests must be conducted to determine the optimum moisture content and degree of compaction effort needed during construction of the liner. Additional specifications are designed to ensure that the landfill is successfully constructed.

7.5. Flexible membrane liners

Landfill designs may call for flexible membrane liner systems for several reasons: to overcome known leakage through clay liners, to save site volume for refuse instead of clay, and to overcome costly importation of clay if suitable clay is not locally available. Many kinds of flexible membrane liners are available for containing different kinds of liquid wastes. Design considerations include ensuring compatibility with the waste, developing a structurally sound design, providing good seaming, providing a firm base free of debris or sharp objects under the liner, maintaining construction quality control, and protecting the liner after construction. Flexible membrane liners can be used as the “impermeable” layer, and geonets can be used to facilitate drainage to a collection pipe. A typical flexible membrane liner thickness is 0.75-2.0 mm.

A concern when relying on synthetic liners is that chemical interactions may affect the liner’s integrity. Certain waste materials are known to degrade certain types of liners. Testing flexible membrane liners with MSW leachate has shown that most materials resist chemical attack under most conditions.

7.6. Leachate collection systems

The effectiveness of a leachate collection system is dependent on the design of the liner and the collection pipes. Layout of the liner and pipe network system varies, depending on the overall landfill area, phase shapes, and overall slope or topography. The slope of the liner should be at least 2 percent, and preferably 4 percent or more, to promote lateral flow of leachate to collection pipes, and pipes should be sloped at 1 percent minimum to ensure leachate flow and prevent accumulation at low spots along the pipeline.

The pipe is placed in a trench or directly on the liner at the low points. The trench should be backfilled with gravel and the pipe must be well-supported to avoid crushing. The gravel may need to be protected by a geotextile to avoid plugging by fine-grained material in any overburden layers. Access can be direct from the surface or by manholes placed in the landfill. Because all manholes accumulate gas and are subject to shifting and settling, they can pose safety and maintenance problems.

7.7. Leachate treatment processes

Leachate treatment options include on-site treatment, discharge to a municipal sewage treatment plant, or a combination of these approaches. Studies have also indicated that another method, leachate recirculation, has certain benefits, which include increasing the rate of waste stabilization, improving leachate quality, and increasing the quantity and quality of methane gas production. Leachate recirculation also provides a viable on-site leachate management method.

Leachate can be treated on or off-site but the treatment process must be carefully developed to guarantee a successful system. The most common leachate treatment option is discharge to municipal sewage treatment plants. Since leachate strengths are significantly greater than normal municipal wastewaters, care must be taken to avoid overloading the plant. Studies have shown that greater than a 2 percent hydraulic loading of a sewage treatment plant with leachate will disrupt its operations.

For a leachate of high BOD (biological oxygen demand), such as those typically found in a young landfill, anaerobic biological treatment is useful because of its energy efficiency and low sludge generation rate. A 90 percent or more reduction in BOD can be expected using this method.

Leachate of medium BOD levels or pretreated leachate may be treated in aerobic biological systems, including activated sludge, rotating biological contractors, or sequenced batch units. Reduction of 90 percent or more of BOD, suspended solids, and precipitated metals is accomplished, but energy consumption may be high and comparatively large amounts of sludge are produced.

An aeration or facultative pond can be used to polish leachate treated by other methods, if the leachate has not yet reached a contaminant level suitable for discharge. Ponds can also be used to treat relatively low-strength leachates with BOD less than 100 mg/l. Such ponds may have surface aerators depending on the BOD, retention time, and configuration.

7.8. Natural Attenuation of Leachate

Many existing landfills do not have liners or have liners that can not completely contain the leachate. The chemicals in leachate that escape from the landfill base may undergo a variety of conversion and destruction reactions as they pass through the soil and into the underlying formations (a process called attenuation). For example, as leachate moves through a clay soil, most of the heavy metals (such as lead, arsenic, zinc, cadmium, and mercury) are retained by the soil. The ability of each soil to attenuate leachate is different, and not all elements or compounds are equally removed or reduced in concentration. The unpredictable concentrations of leachate constituents, plus weather related leachate generation surges and variations in subsurface conditions make it extremely difficult to predict the degree of protection that natural attenuation will accomplish. The result is that landfills now incorporate means for containing and controlling leachate within the site, relying on natural attenuation only as a backup measure to protect groundwater quality.

7.9. Groundwater quality assessment

Groundwater monitoring systems are required for new, existing, and lateral expansions of existing landfills. The monitoring is necessary to determine groundwater quality at a facility and to determine whether there has been a release of contaminants through the base of the landfill. All new landfills must have a groundwater monitoring system installed before any wastes are placed in the landfill.

Monitoring wells must be cased in a manner that maintains the integrity of the borehole and must be maintained to meet the design specifications. The number, spacing, and depths of the wells should be based on site-specific characteristics. The wells must also be constructed to facilitate the collection of groundwater samples. These two requirements are closely related. Great care must be taken when selecting well construction materials or sampling devices. Materials that may react with groundwater or contaminate samples should not be used.

The casing, associated seals, and grout protect the integrity of a borehole and minimize the hydraulic communication between zones. Materials that are not compatible with subsurface conditions can cause false or misleading detections, or non-detections, of analytes.

The techniques used to withdraw groundwater samples from a well must be based on considerations of the parameters to be analyzed in a sample. To ensure that the sample is representative of groundwater in the formation, physical alterations of the sample must be kept to a minimum. It is important to select sampling equipment that will maintain sample integrity. The sampling equipment must be constructed of inert materials that will not alter analyte concentrations or react with, sorb, or desorb the analytes.

8. ENVIRONMENTAL QUALITY MONITORING AT SOLID WASTE LANDFILLS

Environmental quality monitoring is used to ensure that the public health and the surrounding environment is not affected by the contaminants released from the landfill. Methods used in monitoring the environmental quality aspects at a solid waste landfill include the following:

- Vadose zone monitoring of landfill gases and liquids
- Groundwater monitoring solid waste landfills
- Air quality monitoring at sold waste landfills

9. OPERATION OF SOLID WASTE LANDFILLS

The landfill operational plan should serve as the primary resource document for operating the site. It shows the technical details of the landfill and the procedures for constructing the various engineered elements. Since a landfill is constructed and operated over a number of years, it is important that personnel periodically review the plan and refresh their memories to ensure conformance with the plan over the long term. If operating procedures must be modified, the changes must be noted so that an accurate record is maintained. Documented operating procedures can be crucial if questions arise in the future regarding the adequacy of site construction. After receiving the required approvals for the site design, preparation and construction of the site can begin.

Table 3: Site preparation and construction tips lists.

1.	Clear site	
2.	Remove and stockpile top soil	
3.	Install drainage improvements	
4.	Excavate fill areas	
5.	Stockpile daily cover materials	
6.	Install environmental protection facilities (as needed)	*Landfill liner with leachate collection system*
		Groundwater monitoring system
		Gas control equipment

		Gas monitoring equipment
7.	Prepare access roads	
8.	Construct support facilities	*Service building*
		Employee facilities
		Weigh scale
		Fueling facilities
9.	Install utilities	*Electricit*
		Water
		Sewage
		Telephone
10.	Construct fencing	*Perimeter*
		Entrance
		Gate and entrance sign
		Litter control
11.	Prepare construction documents.(continuously during construction)	

9.1. Program to Detect and Exclude Hazardous Waste

The owner or operator is required to implement a program to detect and exclude regulated hazardous wastes and PCBs from disposal in the landfill. This program must include the following elements:

- Performing random inspections of incoming loads or other prevention methods
- Maintaining inspection records
- Training facility personnel
- Notifying appropriate authorities if hazardous wastes or PCB wastes are detected.

An inspection is typically a visual observation of the incoming waste loads by an individual who is trained and qualified to identify regulated quantities of hazardous waste or PCB wastes that would not be acceptable for disposal at an MSW landfill. An inspection is considered satisfactory if the inspector knows the nature of all materials received in the load and is able to discern whether the materials are potentially regulated hazardous wastes.

Random inspections provide a reasonable means to adequately control the receipt of inappropriate wastes. The frequency of random inspections may be based on the type and quantity of wastes received daily, and the accuracy and confidence desired in conclusions drawn from inspection observations. A random inspection program may take many forms, such as inspecting every incoming load one day out of every month or inspecting one or more loads from transporters of wastes of unidentifiable nature each day.

Inspection frequency also can vary depending on the nature of the waste. For example, wastes received exclusively from commercial or industrial sources may require more frequent inspections than wastes collected exclusively from households. Priority can also be given to inspecting haulers with unknown service areas, to loads brought to the facility in vehicles not typically used for disposal of municipal solid waste, and loads transported by known previous offenders.

To provide the facility owner or operator the opportunity to refuse or accept wastes, loads should be inspected before actual disposal of the waste at the working face of the landfill. Inspections can be conducted on a tipping floor of a transfer station before transferring the waste to the disposal facility. Inspections may also occur at a tipping floor located near the facility scale house, inside the site entrance, or near, or adjacent to, the working face of the landfill.

9.2. Access control

Public access to landfills must be controlled by use of artificial barriers, natural barriers, or both to prevent unauthorized vehicular traffic and illegal dumping of wastes. These barriers can include fences, ditches, berms, trees, etc. Access should be controlled by gates that can be locked when the site is unsupervised.

9.3. Run-on and runoff control systems

Site drainage is always critical in a good sanitary landfill design. As much water as possible should be diverted off the landfill to minimize operational problems and the formation of leachate. Landfill operators are required to have a run-on control system to prevent flow onto the active portion of the landfill during the peak discharge from a 25-year storm event. The goal of the run-on system is to collect and redirect surface waters entering the landfill boundaries. A runoff control system from the active portion of the landfill must be able to control at least the volume of water that results from a 24-hour, 25-year storm. The runoff control system should be designed to collect and control any water that may have contacted any waste materials.

Small Vehicles and Safety

Many landfill operators find that allowing public access at the disposal face interferes with site operation and can lead to unsafe conditions. Separate waste collection facilities can be located near the site entrance for private citizens. Such facilities provide disposal service to the public, while eliminating possible interference with operations. On a regular basis, the area should be inspected and litter picked up to prevent unsightly conditions.

Figure 6: Trucks in landfills.

Additional Controls

Good housekeeping procedures are necessary for landfill operations. A well-planned and maintained landfill effectively controls for the following:

- **Aesthetics**: Addressing aesthetic concerns may include using fences, berms, plantings, or other landscaping to screen the landfill's daily operations from roads or nearby residents, and providing an attractive entrance with good roads and easy-to-read signs.

- **Wind-Blown Paper**: On-site litter control is accomplished by using fences to stop blowing paper and plastic. Frequent manual or mechanical litter pick up is also needed.
- **Insects:** Flies and mosquitoes are the most common insects of concern to neighbours. They are best controlled by covering the solid waste daily and eliminating any open standing water, such as in appliances stored for recycling or in surface depressions.
- **Rodents and Wildlife**: Rats were once a problem at open dumps, but at sanitary landfills, burying all food wastes with daily cover material usually eliminates rat problems.
- **Birds:** Birds can be a nuisance or even cause problems with planes if the landfill is near an airport. Methods to discourage birds include use of noise makers, wire grids, and liberal use of cover soil. The best approach is to keep the working face small and to provide adequate cover.
- **Odours and Fires**: Odours are best controlled by daily cover, as well as by adequate compaction. Daily cover also forms cells that reduce the ability of inadvertent fires to spread throughout the landfill. Any burning or smoking waste should be dumped off to the side and extinguished before placing it in the working face. Fire-fighting equipment and an emergency water supply should be available on site or arranged for with local authorities.
- **Noise:** Equipment should be operated behind berms, which shield the surrounding area from noise as much as possible. Access should be designed to minimize the impact that landfill site traffic has on nearby neighbourhoods.
- **Dust and Tracking**: Roads should be watered in dry periods to keep dust to a minimum. Roads should be crowned and well-drained to minimize mud tracking. Adequate wheel-cleaning and mud knock-off areas should be provided. Entrance roads should be paved or have all weather surface concrete or asphalt to keep mud tracking on-site and should be cleaned whenever a mud buildup occurs.
- **Scavenging**: While recycling at a landfill may be desirable, scavenging (or uncontrolled picking through waste to recover useful items) is not desirable. Because scavengers have been injured, sometimes fatally, while picking through the wastes, the practice should be prohibited. Salvaging, which is the controlled separation of recoverable items, should be distinguished from scavenging. Any salvage operations should be kept away from the landfill, usually at the gate area, and residues should not be allowed to accumulate.

Figure 7: Scavengers during work in Delhi dump site.

- **Gas and Leachate**: Particularly important to the protection of public health and the environment is the control of gas generated by the decomposition of solid wastes, and of leachates that form as water migrates through the solid wastes.

9.4. Landfill equipment

Equipment at sanitary landfills falls into three functional categories: waste movement and compaction, earth cover transport and compaction, and support functions. Selection of type, size, quantity, and combination of machines required to move, spread, compact, and cover waste depend on the following factors:

- Amount and type of waste to be handled
- Amount and type of soil cover to be handled
- The distance the cover material must be transported
- Weather conditions
- Compaction requirements
- Site and soil conditions: topography, soil moisture, and difficulty of excavation
- Supplemental tasks such as maintaining roads, assisting in vehicle unloading, and moving other materials and equipment around the site.

Figure 8: Typical vehicles-equipment in a landfill.

The amount of waste is the major variable influencing the selection of an appropriate-size machine. Heavier equipment provides more compaction, all else being equal, but also provides more flexibility in handling and compacting a variety of materials using thicker compaction lifts. The condition in which the waste is received may affect choice of equipment. For example, landfills accepting only shredded wastes are operated much like landfills handling unprocessed wastes, although there may be less need for daily soil cover, and it will be easier to compact the waste. For landfills handling baled waste, the bales are often moved with forklifts and no compaction equipment is needed.

The degree of compaction is critical to extending the useful lifetime of a landfill. For achieving high, in-place waste densities, a compactor may be necessary. The number of passes that the machine should make over the wastes to achieve optimum compaction depends upon machine wheel pressure, waste compressibility, and compaction layer thickness. In general, three to five passes are recommended to achieve optimum in-place waste densities. Although additional passes will compact the waste to a greater extent, the return on the effort diminishes beyond six passes.

The working face slope will affect the degree of compaction achieved. As the slope increases, vertical compaction pressure decreases. The highest degree of compaction is achieved with the least slope. However, the feasibility of a nearly flat working face grade has to be weighed against the larger area over which the solid wastes and cover soil must be spread.

9.5. Waste handling and compaction

There are several factors to consider when making decisions about waste handling and compaction, shredding and baling of wastes, and the types of equipment used for compacting the wastes.

9.6. Waste shredding

In shredding of solid waste, incoming refuse is mechanically processed into small uniformly sized pieces. Shredding can take place immediately before landfilling or it can be done at a transfer facility prior to transport. While shredding may be undertaken as the sole processing technique used before disposal, it also can be one step in a process that includes the mechanical separation and removal of recyclable or reusable materials from the waste stream. After compaction, shredded refuse has a greater density than compacted, unprocessed MSW. This can result in preserving landfill space and reducing the amount of required cover material. In addition, landfill settlement and stabilization may be more uniform over time in the landfilled area. These benefits must be compared with the significant capital and operating costs of the shredding equipment, the space required to process the waste, and the historically significant potential for worker injury and equipment downtime caused by explosions from crushing compressed gas containers and by the ignition of explosive gases by sparking metal.

Baling Solid Waste

The baling of municipal solid waste involves the compaction of refuse into high-density blocks that are stacked and covered with cover material in a landfill. In certain circumstances, baling municipal solid waste before disposal may result in landfill space savings as a result of increased compaction density and reduced cover material requirements. Baling wastes can also reduce the amount of blowing litter.

Landfill Handling and Compaction Equipment

Steel-wheeled compactors are designed specifically for compacting solid wastes. Wheels are studded with load concentrators of various designs. This equipment gives maximum compaction of solid wastes. Steel-wheeled compactors are best suited to medium or large sanitary landfills, which can support more than one machine, since these units are suitable only for compaction work. Track-type tractors or dozers may be used for handling and compacting waste, as well as for cover excavation and compaction. Such units can also be used for site preparation, road construction, and maintenance. These are the most versatile units and are preferred for small operations in which one unit must perform a variety of functions.

Earth Movers

Rubber-tyred loaders or dozers provide more speed and maneuverability than track-type units and can haul cover efficiently and apply it up to approximately 300 m from the working face. Rubber-tyred scrapers are efficient for excavating and transporting soil for cover when it is more than 300 m from the working face. Where the soil is hard to excavate (e.g., clay or frozen soil), scrapers can be pushed with a bulldozer. Draglines are also efficient earth movers but are only able to deposit soil within the area reached by the boom and are not suitable for transporting cover material. Backhoes are well suited for small, specialized excavation at the landfill, such as for a leachate collection system. Dump trucks can be used at landfills in conjunction with excavation equipment for moving cover material. Motor graders are useful for road construction and maintenance, for construction of berms and drainage ways, and for landscaping.

9.7. Equipment maintenance and backup

Equipment maintenance is clearly an important task. Regular maintenance reduces breakdowns and identifies equipment problems early, before more costly and time-consuming repairs are needed. Provision must also be made for backup equipment, perhaps by keeping additional equipment available.

Adverse Weather- Wet weather problems are especially serious with soils that have a high silt or clay content. When wet, these soils usually become muddy and slippery. Provision should be made to continue operating areas less susceptible to such problems. Procedures to minimize and clean mud tracking on roads are especially important during wet weather. Cold weather brings many problems in starting and operating machinery, keeping employees comfortable, and obtaining cover material. Equipment manufacturers can offer recommendations for cold weather starting and operation, and excavation of well-drained and stockpiled cover soil can improve cold weather operations.
Windy conditions can require the use of extra or specially placed fencing and use of a lower or more protected working face. Unloading wastes at the bottom of the working face can help because the wind cannot pick up materials as easily as when wastes are deposited at the top of the working face.
In addition to fencing at the perimeter of the active area, portable fences are often used to catch litter immediately downwind of the working face. Fencing and the area downwind of the working face should be cleaned at least daily.
Dust can be a nuisance at landfills, both to employees and to neighbours. Water wagons can be used to control dust. Calcium chloride is also used for dust control, because it absorbs moisture from the air.

9.8. Personnel and safety

To maintain an efficient landfill operation, employees must be carefully selected, trained, and supervised. Proper landfill operation depends on good employees. Along with equipment operators, other necessary employees may include maintenance personnel, a scale operator, labourers, and a supervisor. People will also be needed to keep financial and operating records. Good employee training and supervision must include attention to safety. Operating a landfill presents many challenges; accidents are expensive and have hidden costs often several times the readily apparent costs.
Solid waste personnel work in all types of weather, with many types of heavy equipment, with a variety of materials presenting diverse hazards, and in many different types of settings. The types of accidents possible at landfills include injury from explosion or fire, inhalation of contaminants and dust, asphyxiation from poorly vented leachate collection system manholes or tanks, falls from vehicles, injury associated with operating heavy earth-moving equipment, injury from attempting to repair equipment while engines are operating, exposure to extreme cold or heat, and traffic accidents at or near the site.

9.9. Community relations

An important and often overlooked aspect of landfill operation is sustaining good community relations. The landfill manager must maintain a dialog with neighbors, municipal leaders, community activists, and state governmental representatives in an effort to build trust through honest communications. While community relations activities do not guarantee continued support for the landfilling operation, poor relations almost certainly will result in complaints and problems.

10. SOLID WASTE LANDFILL CLOSURE AND REHABILITATION

The landfill must be closed in accordance with an approved closure plan. The goal of closure and post-closure care is to ensure the long-term protection of human health and the environment. The owner or operator must close the landfill in a manner that will minimize the need for maintenance and will be protective of human health and the environment.

10.1. Financial Assurance for Closure and Post-Closure Care

It is important that landfill owners and operators, including municipalities that operate landfills, have financial assurances in place to cover the costs of closure and post-closure. Financial assurance is also required when corrective action is necessary to clean up releases of hazardous constituents to groundwater. The closure and post-closure cost estimates used to determine the amount of coverage required must be based on the cost of closing the landfill at the point of the landfill's active life when the extent and manner of its operation would make closure and post-closure care the most expensive.

Furthermore, cost estimates must reflect the costs that a third party would incur in conducting the closure and post-closure activities. The closure and post-closure cost estimates must be updated yearly to account for inflation and updated whenever changes to the closure and post-closure plans or changes at the facility increase the cost of closure and post-closure. Whenever the cost estimates increase, the owner or operator must increase the level of financial assurance.

10.2. Procedures for Site Closure

The primary objectives of landfill closure are to establish low-maintenance cover systems and to design a final cover that minimizes the infiltration of precipitation into the waste. Installation of the final cover must be completed within six months of the last receipt of wastes. The procedures for placing the cover over the landfill are usually defined during site design. If no cover design is available, specifications must be prepared. The following is the description of:

Table 4: Procedures that could be adopted for landfill site closure.

Preplanning	3months before closure	At closure	3months after closure
Identify final site topographic plan	Review closure plan for completeness	Erect fences or appropriate structures to limit access	Complete needed drainage control features or structures
Prepare site drainage plan	Schedule closing date	Post signs indicating site closure and alternative disposal sites	Complete, as required, gas collection or venting systems, leachate containment facilities, and gas or groundwater monitoring devices
Prepare vegetative cover and landscaping plan	Prepare final timetable for closing procedures	Collect any litter or debris and place in final cell for covering	Install settlement plates or other devices for detecting subsidence
Identify closing sequence for phased	Notify appropriate regulatory agencies	Place cover over any exposed waste	Place required thickness of earth cover over

operations			landfill
Specify engineering procedures for the development of on-site structures	Notify site users by letter if they are municipalities or contract haulers; by published announcements if private dumping is allowed		Establish vegetative cover

10.3. Post-Closure Care

Post-closure care of the landfill begins upon completion of the closure process. The post-closure care period can be 30 years, but some jurisdictions can choose to shorten or lengthen the post-closure care period. During this period the landfill owner is responsible for providing for the general upkeep of the landfill, maintaining all of the landfill's environmental protection features, operating monitoring equipment, remediating groundwater should it become contaminated, and controlling landfill gas migration or emissions.

After closure, the landfill site will appear inactive, but biological activity in the landfill will continue. As a result, the landfill cover continues to settle as the waste consolidates. Poorly compacted waste will settle the most. Settlement will cause depressions in the cover and stresses on the cover. The depressions need to be filled with cover soil to limit infiltration through the top of the landfill.

Where flexible membranes are part of the cover, extensive repair work may be needed if the settlement results in the membrane tearing. A few years after closure, the settlement rate will slow, necessitating less repair work of this type.

The vegetative cover on the landfill must also be maintained. In the long run weeds and areas of dead vegetation will result in damage to the landfill cover. The grass cover should be mowed periodically. The frequency will depend on local conditions. Reseeding areas where the vegetative cover has died is also necessary. Failure to reseed may result in excessive erosion and damage to the cover.

Settlement may affect the access roads, which must be maintained so equipment can reach monitoring points on the landfill without damaging the cover. Access roads may also experience settlement and erosion problems. Periodically, the access roads should be regraded and repaired in order to maintain their long-term usefulness.

Drainage patterns on the landfill may change as settlement occurs. Channels, culverts, and risers must be annually inspected to determine their condition. Repair work should be done each year where drainage patterns have changed or erosion has damaged the structures.

Surface waters released from the closed landfill site must be properly managed. Any detention basin constructed to control peak runoff rates and sediment flow must be maintained. This may include the need to dredge the sedimentation basin.

10.3.1. Leachate Treatment

Leachate will continue to be generated after the landfill is closed. The quantity should diminish if a good cover was placed over the landfill. Providing cover maintenance will also reduce leachate generation. The chemical composition will also change as the landfill becomes more biologically stabilized with pollutant concentrations slowly diminishing. Leachate collection and treatment generally will be necessary throughout the entire post-closure care period. Pumps and other leachate collection equipment must be operated and serviced. Every few years, leachate lines must be cleaned with sewer cleaning equipment. On-site leachate treatment facilities must be maintained and operated. Where leachate is transported off-site, arrangements for trucking and treatment must be continued.

10.3.2. Groundwater Quality Monitoring

The groundwater under the landfill must be monitored during the post-closure care period. If contamination is detected it will be necessary to undertake more intensive monitoring and corrective action. The extent of groundwater contamination must be determined. Plans must be prepared and approved for the corrective action. Following implementation of the corrective action, less frequent monitoring can resume if groundwater quality improves to within specified limits.

10.3.3. Landfill Gas Monitoring

The management of landfill gas was described in a previous section. The operation of landfill gas control and monitoring systems will need to continue for many years after the landfill closes. Failure to operate and maintain the system may result in damage to the vegetative cover of the landfill and off-site migration of landfill gas. Where landfill gas migration is detected near occupied structures, more frequent monitoring is recommended. If regulatory standards for migration are exceeded, improved migration control and landfill gas recovery facilities may be necessary. At sites that do not have control systems, the landfill may need to be retrofitted for gas control.

This unit examined the following aspects related to disposal of solid waste in a sanitary landfill:

- Basic concepts of solid waste landfilling
- Types of solid waste landfills and methods
- Factors to be considered in selecting a landfill site
- Aspects of solid waste landfill gas generation and management
- Aspects of solid waste landfill leachate generation and management
- Types of solid waste cover systems
- How to monitor environmental quality at solid waste landfills
- How to perform a preliminary design of a solid waste landfill
- Aspects of operating a solid waste landfill
- Aspects of solid waste landfill closure and rehabilitation

10.4. Solid Waste Landfill Cover Systems

To close an MSW Landfill a final cover system composed of an infiltration layer that is a minimum of 450mm thick and overlain by an erosion layer that is a minimum of 150 mm thick is strongly recommended. Over the long term, the infiltration layer should minimize liquid infiltration into the waste. The infiltration layer must have a hydraulic conductivity less than or equal to any bottom liner or natural subsoils present to prevent a “bathtub” effect. In no case can the infiltration layer have a hydraulic conductivity greater than 1×10^{-5} cm/sec regardless of the permeability of underlying liners or natural subsoils.

Figure 9: Landfill operation: linners are seen on the side of the area.

To meet the infiltration layer performance standard at a landfill with a flexible membrane bottom liner, it is likely that the final cover will also need to incorporate a flexible membrane liner. As with other design features, the state may have additional requirements.

Design criteria for a final cover system should be selected to do the following:

- Minimize infiltration of precipitation into the waste
- Promote good surface drainage
- Resist erosion
- Prevent slope failure
- Restrict landfill gas migration or enhance recovery
- Separate waste from vectors (animals and insects)
- Improve aesthetics
- Minimize long-term maintenance

Reduction of infiltration in a well-designed final cover system is achieved through good surface drainage and runoff with minimal erosion, transpiration of water by plants in the vegetative cover and root zone, and restriction of percolation through earthen material. The cover system should be designed to provide the desired level of long-term performance with minimal maintenance. Surface water runoff should be properly controlled to prevent excessive erosion and soil loss. The vegetative cover should not contain deeply rooted plants that could damage the underlying infiltration layer. In addition, the cover system should be stable geotechnically to prevent failure, for example, sliding that may occur between the erosion and infiltration layers, within these layers, or within the waste.

10.4.1. Erosion Control

When designing the final cover system it is necessary to study the interrelationships between vegetation, slope, soil used, and climatic conditions. To minimize major erosion and post-closure care problems, the maximum slope is typically 4:1 (4 parts horizontal to 1 part vertical); however, 5:1 is better. A slope of 3:1 is likely to lead to long-term maintenance problems, but it may be feasible in some areas if the site is well maintained and the slope is not too long.

10.4.2. Vegetation

Selection of vegetation is important in ensuring long-term, maintenance-free operation of the cover. Good vegetation will improve erosion control through rapid growth and the formation of a complex root system. Vegetation commonly used includes vetches and fescues; however, it is a good idea to check with the local highway department for suggestions regarding vegetation for erosion control in the climate at hand.

ACRONYMS

MSW	Municipal Solid Waste