Best practice environmental management

Siting, design, operation and rehabilitation of landfills

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Contents

1 Introduction

Landfills have served a key role in the management of solid wastes and are likely to continue to be an important component of the waste management system. The implementation of the waste management hierarchy of waste avoidance, reuse, recycling, recovery of energy, treatment, containment and finally waste disposal has resulted in significant diversion of waste from landfill.

Disposal of materials to landfill is the least preferred management option; however, landfills will continue to be required in the future to manage those wastes that cannot currently be practicably removed from the waste stream.

Today's landfills must not leave an unacceptable environmental legacy for our children to address. As long as landfilling remains part of our waste management strategy, best-practice measures must be adopted to ensure that landfills are acceptable to the public.

In this context, waste management policies in conjunction with State environment protection policies (SEPPs) establish a framework to ensure that landfills are designed to minimise risks to the environment.

The key policy is the Waste Management Policy (Siting, Design and Management of Landfills) (Landfill WMP), which clarifies and strengthens the existing framework through promoting best practice and continuous improvement in the way landfills are sited, designed and managed in Victoria.

SEPPs that are particularly relevant to landfill include the SEPP (Waters of Victoria), SEPP (Groundwaters of Victoria) and SEPP (Air Quality Management).

A critical element of this policy framework is the implementation of best practice. EPA Victoria's Best Practice Environmental Management *publication Siting, design, operation and rehabilitation of landfills* (Landfill BPEM) is the source document for best-practice environmental management measures for landfills. It gives direction on the best-practice siting, design, operation, performance and rehabilitation standards for landfills in Victoria, taking into account the risk they pose to the environment, and it provides a guide for the measures required to meet legislative objectives.

Landfill owners and operators must have regard to this document in the planning for works approval or licensing of future landfill sites and design of new landfill cells. The Landfill WMP requires the objectives and required outcomes set out in this document to be met. The suggested measures should be used and are the default means of achieving the required outcomes.

The first and most important consideration in the prevention of environmental impacts from landfill is selection of an appropriate landfill site. Once an appropriate site has been selected, landfill operators must adopt best practice in:

- the assessment of landfill design and its effect on the environment
- construction quality assurance systems
- landfill management
- landfill rehabilitation.

1.1 Objectives of the Landfill BPEM

These guidelines aim to provide existing and future operators of landfills, planning authorities and regulating bodies with:

- information on potential impacts of landfills on the environment and how these are to be mitigated
- a clear statement of environmental performance objectives for each segment of the environment
- information on how to avoid or minimise environmental impacts, including suggested measures to meet the objectives.

These guidelines are intended to be used as a default position for landfill siting, design, operation and rehabilitation. Landfill operators must meet the objectives and required outcomes by implementing the relevant best-practice measures, described as suggested measures, contained herein.

Where a landfill operator believes that, for a particular section of the guidelines, alternative means can achieve the objectives and required outcomes, a risk-based assessment will be required to support the proposed alternative measure. Alternatively, if EPA believes that additional requirements are needed to protect the environment, then this will also be supported by a risk-based assessment.

A range of regulatory requirements is in place to minimise the adverse environmental effects from wastes in general, and landfills in particular. The *Environment Protection (Industrial Waste Resource) Regulations 2009* define which wastes are prescribed wastes and require waste to be classified on the basis of the potential risk posed by the material.

Liquid industrial wastes not discharged to sewer and solid industrial wastes classified as Category A, B or C are prescribed industrial wastes. Their management, handling, reuse, recycling and disposal are controlled through the Environment Protection (Industrial Waste Resource) Regulations and not through the Landfill BPEM.

1.2 The Landfill BPEM's audience

The target audience for the Landfill BPEM is:

- landfill operators in the siting, design, operation and rehabilitation of landfills
- planning authorities, particularly in the preservation of planning attributes, such as buffer distances for closed, existing and designated future landfills
- regulators, to provide understanding what the expected standards are and to give some guidance on how to achieve these standards
- waste management groups, particularly in the screening and ranking of potential landfill sites.
- local government and private operators managing the rehabilitation of closed sites
- the broader community, to provide information on the standards required for landfills in Victoria.

1.3 Implementation

The requirements of the Landfill BPEM must be taken into consideration in any works approvals or licensing of existing and new sites, as well as in the design and construction of landfill cells. A summary of implementation requirements is set out in Appendix A.

2 Waste management framework

2.1 Waste management hierarchy

When making decisions regarding the management of all wastes, including municipal and industrial wastes, wastes should be managed in accordance with the following order of preference:

- avoidance
- reuse
- recycling
- recovery of energy
- treatment
- containment
- disposal.

This hierarchy is one of the eleven environment protection principles contained in the *Environment Protection Act 1970 (EP Act).*

Where a generator has exhausted all financially and technically practicable possibilities for waste avoidance and reduction, alternatives for reuse, recycling and reclamation should be investigated. The landfill operator can assist in this process by providing facilities for the sorting of waste.

Disposal to landfill should only be considered as a last resort when there are no financially and technically practicable higher-level waste management options.

2.2 Statutory framework

All landfill operations must comply with the EP Act, its Regulations, the Landfill WMP and relevant SEPPs.

The following definition of landfill scheduled premises is provided in the *Environment Protection (Scheduled Premises and Exemptions) Regulations 2007:*

> *Landfills used for the discharge or deposit of solid wastes (including solid industrial wastes) onto land except premises with solely land discharges or deposits used only for the discharge or deposit of mining wastes and in accordance with the Extractive Industries Development Act 1995 or the Mineral Resources (Sustainable Development) Act 1990.*

This Landfill BPEM applies to landfills defined above and those accepting low-hazard (Category C) prescribed industrial waste.

The Environment Protection (Industrial Waste Resource) Regulations 2009 (Regulations) define which wastes are prescribed wastes and require waste producers or EPA to classify these on the basis of the potential risk posed by the material.

Liquid industrial wastes not discharged to sewer and solid industrial wastes that are classified as Category A, B or C are prescribed industrial wastes. Their management, handling, reuse, recycling and disposal will be controlled through the Regulations. Those classified as non-prescribed industrial wastes – otherwise described as general 'industrial wastes' – are not subject to the Regulations.

At present, Category C-contaminated soils and some other low-hazard prescribed industrial wastes are managed at 25 landfills across the state, which are specifically licensed to receive one or more of these waste types. The Best practice guidelines for landfills accepting category C prescribed industrial waste (EPA publication 1208) establish clear standards for those landfills licensed to receive Category C prescribed industrial wastes.

The hazard classification of prescribed industrial wastes is defined in EPA's Industrial Waste Resource Guidelines: Solid industrial waste hazard categorisation and management (EPA publication IWRG631).

A works approval must be obtained before a landfill can be constructed except for municipal landfills serving a population of fewer than 500 people. A licence under the Environment Protection Act is required for all landfills apart from municipal landfills serving a population of fewer than 5000 people. The licence sets the performance objectives of the operating landfill, defines operating parameters and requires monitoring to check on environmental performance.

2.2.1 Environment Protection Act 1970 (EP Act)

The principle legislative vehicle for pollution control in Victoria is the *Environment Protection Act 1970.*

The EP Act regulates the discharge or emission of waste to water, land or air by a system of works approvals and licences. The Act also specifically controls the emission of noise and the transport and disposal of waste.

The acceptable environmental quality standards and conditions for discharging waste to landfill and identification of beneficial uses of the environment are specified in the relevant SEPPs and WMPs. The EP Act also allows for the development of waste management policies (WMPs).

2.2.2 State environment protection policies (SEPPs)

State environment protection policies set out policies of the government to manage environmental pollution. Policies establish the environmental quality that must be attained and maintained to protect designated beneficial uses (namely, amenity, health and ecosystem protection). Policies typically set quantitative, ambient and environmental objectives (such as for air, water and soil), and specify measures that must be implemented to minimise the risk of activities causing their ambient standards to be exceeded.

Activities that result in environmental quality objectives being exceeded cause pollution and may be subject to EPA enforcement action.

SEPPs that are relevant to landfills are:
- SEPP (Waters of Victoria)
- SEPP (Air Quality Management)
- SEPP (Control of Noise from Commerce, Industry and Trade) No. N-1 1989
- SEPP (Groundwaters of Victoria)
- SEPP (Prevention and Management of Contamination of Land).

2.2.3 Waste management policies (WMPs)

In 2002 the Environment Protection Act was amended by the *Environment Protection (Resource Efficiency) Act 2002* to allow EPA scope to develop waste management policies. This change means that policies on municipal waste can also be developed, thereby complementing existing arrangements and ensuring that a comprehensive framework of statutory policy can be maintained and strengthened.

The WMP covers:
- generation, storage, reprocessing, treatment, transport, containment and disposal, and generally the handling, of waste
- location of treatment and disposal plants.

Waste Management Policy (Siting, Design and Management of Landfills), No. S264, Gazette 14/12/2004 applies to all landfills in Victoria receiving solid non-prescribed waste and/or Category C prescribed industrial waste. The policy clarifies and strengthens the existing framework through promoting best practice and continuous improvement in the way we plan, site, design and manage landfills in Victoria. The policy also promotes waste minimisation and resource recovery infrastructure that will in turn encourage market opportunities for recycling.

2.3 Best-practice framework

This document is intended to provide guidance for landfill operators to meet the environment protection objectives of the regulatory framework. This is achieved by establishing a hierarchy of objectives, required outcomes and suggested measures for each section of the document. The objectives and required outcomes are derived directly from legislation and must be achieved. The suggested measures are provided to assist with achievement of the objectives and required outcomes.

Where a landfill operator believes that an alternative to the suggested measures will achieve the objectives and required outcomes, the operator will need to provide independently assessed evidence supporting the proposed measure with their submission to EPA.

Alternatively, if the suggested measures contained in this document are not likely to achieve the objectives and required outcomes, then EPA may require alternative measures to those suggested, which EPA will support with an assessment of why the alternative measures are required. This is most likely to occur where a landfill is located or proposed in a particularly sensitive environment.

2.4 Landfill licensing guidelines

The *Landfill licensing guidelines (EPA publication 1323)* provide guidance for licence holders on:
- the landfill licence
- environmental monitoring and auditing
- cell design and approval
- cell construction
- annual performance statements.

The guidelines are intended to aid licence holders to comply with their licence and to identify requirements for environmental auditors for conduct of audits of landfills

3 Community engagement

Community engagement is the process of working collaboratively with groups of people with a stake or interest in a situation to address issues affecting their social, environmental and economic wellbeing. Community engagement incorporates consultation and information sharing, as well as active participation between groups including industry, government and communities.

Better solutions are possible when all parties are engaged. Effective engagement practices help identify potential issues, impacts, opportunities, options and solutions for improvement and facilitate more efficient decision-making. The benefits of planned and well implemented engagement include:

- enabling the community to be better informed and encouraging local pride and active citizenship
- reducing the amount of misunderstanding and misinformation
- enabling all groups to have a better understanding of community and local needs
- enabling greater commitment to and ownership of decision-making by the community

Communities will have different needs, abilities and interests in participating in decisions about landfills. Different types of participation are needed, depending on the goals, time frames, resources, skills and levels of concern or interest from the community. Choosing the types of community engagement should balance the needs and expectations of all groups and will depend on the potential for the community to have input into a decision.

Types of community engagement participation approaches are shown in Table 3.1.

Table 3.1: Community engagement – types of participation approaches

Inform	Consult	Involve	Collaborate	Empower
Providing accurate, balanced and timely information to assist in community understanding of the issues, opportunities and solutions.	Getting public feedback on information, options, issues and opportunities.	Working directly with the community throughout the process to ensure issues, concerns, opportunities and solutions are understood and considered.	Partnering with community in each aspect of decision-making.	Delegating decision-making to the community.
		Example tools		
Fact sheets. Websites.	Public meetings. Surveys.	Workshops. Advisory groups. Wiki-based resources.	Citizen advisory committees. Community liaison committees.	Citizen jury.

4 Classification of landfills

The Landfill BPEM applies to municipal and non-hazardous waste landfills at which solid and non-hazardous waste from municipal and/or industrial sources is deposited to land.

As detailed in Table 4.1, landfills are classified according to the wastes types they accept. This guideline deals with four types of waste:

- putrescible waste
- category C prescribed industrial wastes
- solid inert waste
- fill material.

The classification given to a landfill is the most stringent based on the wastes received or proposed to be received. This classification is used throughout the Landfill BPEM to determine the design, construction, operation and maintenance of the landfill necessary to protect the beneficial uses of the environment.

Table 4.1: Classification of landfills

Type[1]	Waste accepted	Description
2	Putrescible (municipal) waste, solid inert waste and fill material. Specifically licensed sites may receive category C prescribed industrial waste (Best-practice guidelines for landfills receiving Category C prescribed industrial waste)	Reflects the best available technology for a municipal landfill in siting, design, construction, operation, maintenance and after-care. Operated in accordance with an appropriate management system that ensures adequate supervision, control on waste receipt, safe handling, record keeping and placement of prescribed waste in accordance with the requirements for that waste.
3	Solid inert waste, fill material.	Reflects commonly available technology for a municipal landfill in siting, design, construction, operation, maintenance and after-care.

1 Type 1 landfills are waste disposal facilities that could accept prescribed industrial wastes including Category B as defined in the Industrial Waste Resource Guidelines: Solid industrial waste hazard categorisation and management. Since this BPEM does not deal with such facilities, a Type 1 landfill is not included in this table.

5 Best-practice siting considerations

The appropriate siting of a landfill is the primary environmental control. A preliminary investigation of all possible landfill sites should be conducted to identify those sites with the best potential to be developed for landfilling in a manner that poses the minimum risk to the environment.

The objective of this section is to establish the means and criteria for identifying and ranking those sites for locating a proposed landfill. The more suitable sites require fewer engineering and management controls to meet the objectives of all State Environment Protection Policies.

An investigation of sites for a landfill is conducted in two steps:

- broad identification of candidate sites for a new landfill from a wider range of all possible sites
- ranking of the candidate sites in terms of their preference for use as a landfill.

The investigation is conducted by the regional waste management group (RWMG) during development of the Regional Waste Management Plan (RWMP), and results in a ranking of preferred waste disposal sites within and adjacent to the region. This ranking should be used in the development of planning strategies for municipalities within the region. The development of new landfills should be in accordance with this ranking.

EPA must refuse to issue a works approval for a new landfill site within a waste management region if the landfill is not provided for in, or is inconsistent with, the relevant RWMP.

EPA will require this section of the guideline to be implemented in each RWMP at its next review. Where a landfill is not provided in a RWMP, or is to be developed before the next review of the RWMP, this section is to be implemented by the RWMG in its assessment of the suitability of the proposed new landfill site. This section should also be implemented by planning authorities in their planning of current or future landfill sites.

5.1 Screening of potential landfill sites

Screening of potential landfill sites starts with preparing a list of all possible sites. As a minimum, this should include all extractive industry sites in the region and may include undeveloped sites that might be suitable for trench-and-fill or mound landfills (see section 5.1.2). The hierarchy of aspects to be considered when screening for candidate landfill sites is:

- community needs
- landfill type
- groundwater
- alternative potential uses for the site
- buffer distances
- geology
- flora and fauna
- infrastructure
- surface water
- land ownership.

These aspects are discussed in detail below.

Once a list of candidate landfill sites has been derived from a list of all possible landfill sites, this list should be ranked to indicate the preferred order of development of potential sites as landfills.

In addition to the screening criteria listed above, Schedule A of the Waste Management Policy contains exclusionary criteria that preclude the development or extension of landfills into certain areas.

5.1.1 Community needs

Regional waste management groups are responsible for providing a framework for the orderly development of waste management facilities for both the public and private sectors. They are intended to provide a reliable system of waste management, including landfill airspace, within the region.

The community expects the amenity and safety aspects of a landfill to be addressed during operation and post-closure period. This should be considered at a very early stage, and where necessary, particular care should be used to construct bunds for visual screening, noise barriers and landscaping and to ensure that the landfill is designed and managed taking into account environmental and safety outcomes.

It is also important to liaise with the community very early in the planning stage. Communities will have different needs, abilities and interests in participating in decisions about the siting, design, operation and rehabilitation of landfills. Effective and early engagement enables identification of the issues that are important to the local community and environment that affect siting, design and operation of the landfill.

Engagement also unlocks the significant amount of local knowledge, often providing insights into how better environmental outcomes may be achieved. There may be community driven reasons why one site may be selected above others. Full community engagement is expected for any project that may have an impact on the community. See section 3 for further information.

5.1.2 Landfill types

An important aspect of screening for potential landfill sites is the type of landfill to be developed. The four basic methods of landfilling and the hierarchy of their preference for use are discussed below:

- the area method, where an existing hole such as a former quarry is filled
- the trench-and-fill method, where a hole is dug and backfilled with waste using the excavated material as cover
- the mound method, where most of the landfill is located above the natural ground level
- the valley or change of topography fill method, where a natural depression is filled.

The most appropriate landfill type for a region will be determined based on local conditions as identified in the environmental assessment. The area method and the trench-and-fill method are, however, preferred.

The area method is preferred, as it achieves an additional outcome of rehabilitating an existing hole. It is also generally easier to manage litter and leachate (contaminated water that has percolated through or drained from a landfill) within the site.

Trench-and-fill landfills are favoured where there are no suitably located holes, or where the trench-and-fill alternative achieves better environmental outcomes. They also enable the operator to configure the excavation to provide the best possible design.

Mound landfills are to be avoided as their exposed nature requires significant litter controls and present a significant visual impact on the landscape. Further difficulties attached to these landfills are leachate seeps from the side of the landfill and the stability of the landfill cap.

Valley fill landfills are to be avoided as they have inherent environmental problems such as unstable slopes, water infiltration and leachate seepage. Due to the open nature of these landfills and shallow placement of waste, they consume a greater amount of soil for cover and capping than an equivalent volume landfill in a disused quarry.

Furthermore, because a valley fill landfill is located in a drainage line, extensive management is required to control surface run-off water ingress into the landfill, potential planes of geotechnical weakness from leachate flows within the landfill, and leachate seeping from the landfill. This type of landfill should be limited to select solid inert wastes that are part of an engineered solution for an erosion problem.

5.1.3 Groundwater

Pollution of groundwater by leachate is very difficult to remediate, and hence, landfills should be sited in areas where impacts on beneficial uses of groundwater can be minimised. In particular, landfills must not be located:

- in areas of potable groundwater, groundwater recharge areas or in areas identified by the Water Act 1989 as a Groundwater Supply Protection Area
- or
- below the regional watertable.

The Department of Sustainability and Environment administers a groundwater database containing information on locations of bore holes, water levels and some chemical analysis on groundwater quality. These data can be used to understand regional and localised groundwater characteristics and to estimate the depth to and quality of groundwater, its general flow direction and utilisation. Groundwater information for a proposed landfill site must be verified by local field testing.

A new landfill below the regional watertable should not be considered as it would place the landfill within the groundwater segment of the environment, which must be protected. The risks of significant impacts on beneficial uses of groundwater in this situation would be substantially greater.

Typically, installation of a groundwater extraction system would be required to keep the groundwater level to below the landfill (see section 6.3). Hence, below-groundwater landfills are strongly discouraged due to the continual and additional operational requirements to:

- maintain and operate pumps
- manage an increased volume of groundwater or leachate
- intensively monitor both groundwater and leachate quality and levels.
- New landfills must deposit waste at least two metres above the long-term undisturbed depth to groundwater unless:
- additional design and management practices to protect groundwater quality will be implemented
- regional circumstances exist that warrant the development of a landfill in this manner.

If the most appropriate site for a landfill is in an area where regional groundwater is elevated, the base of the landfill should be raised to a level above the watertable using a sub-base material designed to attenuate contaminants.

The sub-base material between the base of the liner and the watertable (that is, in the unsaturated zone) should be made of a natural or imported fine-grade soil with a cation exchange capacity of about 10 mEq/100g. This cation exchange capacity allows the sub-base to remove some contaminants from leachate seeping through the base of the liner, and further minimises the risk of groundwater pollution from the landfill.

Recommended minimum requirements for separation of the wastes from the long term groundwater level are tabulated in Table 5.1.

The most preferred site for a landfill is one that minimises the risk of groundwater pollution by providing a natural, unsaturated attenuation layer beneath the liner for contaminants that may leach through the liner. This means that sites with naturally attenuating soils, such as those in clayey areas, are preferred to those that do not have such soils, such as in sandy areas.

Table 5.1: Minimum separation of wastes from watertable

Waste accepted	Minimum separation of wastes to watertable
Municipal (putrescible) waste (Type 2 landfill)	2 metres
Solid inert waste (Type 3 landfill)	2 metres
Fill material and potential waste acid sulfate soil	Below watertable

5.1.4 Alternative potential uses

For sites other than former extractive sites, alternative land uses may be preferable that use as a landfill. For example, the value of the land for farming or future development may indicate that alternative sites should be considered.

For former extractive industry sites, alternative potential uses can be difficult to identify. Public open space as an end use without a need for public open space or a likely long-term custodian of the open space can be problematic as an end use. End use concepts may not be able to be adequately addressed in the landfill schedule stage and require the development of a total proposal during the works approval/planning permit stage

The rehabilitation of an extractive industry site by landfill is not in itself sufficient justification for a landfill, however, the benefits that may accrue to the community in rehabilitation should be considered.

5.1.5 Buffer distances

Appropriate buffer distance must be maintained between the landfill and sensitive land uses (receptors) to protect those receptors from any impacts resulting from a failure of landfill design or management or abnormal weather conditions. These failures might constitute discharge from the site of potentially explosive landfill gas, offensive odours, noise, litter and dust. Features that could be adversely affected by landfilling operations include surface waters, buildings and structures and airports.

Buffer areas are not an alternative to providing appropriate management practices, but provide for contingencies that may arise with typical management practices.

Table 5.2 summarises the buffer required for siting different types of landfills. Refer to section 8.2 for buffer requirements for closed landfills.

Table 5.2: Siting buffer distances required for landfill gas migration, safety and amenity impacts

	Type of landfill site	Part of site selection and during operation
Buffer distance	Type 2	100 metres from surface waters. 500 metres from building or structures. 1500 metres from an aerodrome for piston-engine propeller-driven aircraft[1]. 3000 metres from an aerodrome for jet aircraft[1].
	Type 3	100 metres from surface waters. 200 metres from buildings and structures. 1500 metres from an aerodrome for piston-engine propeller-driven aircraft[1]. 3000 metres from an aerodrome for jet aircraft[1].

1 A lesser distance may apply subject to the approval of the relevant aviation authority.

Subject to an evaluation demonstrating that the environment will be protected and the amenity of the sensitive areas will not be adversely affected, lesser buffer distances may be applied subject to a risk assessment that considers design and operational measures. As part of a risk management approach, additional design or operational measures will be required to ameliorate the risks associated with a reduction of the buffer distances identified in Table 5.2.

Buffers and measurement

Buffer distances are set to reflect the potential impacts from landfilling activities. Generally, the buffers are set to manage:

- odour, which is of most concern during landfill operation
- landfill gas impacts, including the risk of explosion and/or asphyxiation. Landfill gas potential risk remain post closure and for at least 30 years post-closure.

While other potential impacts such as fire, litter, noise and safety risks exist, the buffers required for protection from these impacts fall within the buffer required for odour and landfill gas.

Buffers are measured from the sensitive land use to the edge of the closest cell. All cells, including closed cells, need to be considered in calculating buffers. For sites where there is uncertainty in the location of landfill cells, the boundary of the landfill premises is the point of measurement.

Buffer measurement also needs to consider other activities capable of causing a nuisance, such as the leachate ponds, to the nearest sensitive land use.

Buffer distances and encroachment

Where this buffer has been or is proposed to be encroached, design and management practices need to be significantly increased to provide the same level of protection to sensitive land uses. In considering any planning scheme amendment or planning permit applications, in accordance with the *Planning and Environment Act 1987*, the planning or responsible authority must have regard for the effects of the environment, including landfill gas, on the development. Responsible planning authorities must also ensure planning scheme amendments or any review of a municipal strategic statement are consistent with the provisions of Waste Management Policy (Siting, Design and Management of Landfills) and with the relevant regional waste management plan.

Proposed developments and any works within the recommended landfill buffer can pose a safety risk by potentially providing preferential pathways for landfill gas migration, or providing an environment where landfill gases can accumulate to dangerous levels. All buildings and structures should be considered, including:

- buildings and structures used for sensitive or non sensitive uses
- change of use
- infrastructure installation
- installation of pipelines.

Responsible planning authorities need to be provided with sufficient information by the proponent to satisfy them that the proposed development or rezoning will not be adversely impacted by its proximity to the landfill site.

Where the proposed development or planning scheme amendment would have the effect of allowing development that encroaches into the recommended landfill buffer area or increases the extent of development within the already encroached buffer area, EPA recommends that the planning or responsible authority require an environmental audit be conducted under Section 53V of the EP Act. The audit must assess the risk of harm to the proposed development posed by the potential offsite migration of landfill gas and amenity impacts resulting from the landfill. Where a planning or responsible authority has relevant and sufficient information from previous assessments or audits, then this may be relied on in making a decision

Land within buffer areas may be used for non-sensitive uses provided that the use is not adversely affected by landfilling. Therefore, it is better that this land is owned or at least under the control of the landfill operator, maximising control over the maintenance of an appropriate buffer. Landfill operators should develop contingency plans to show how the landfill could be developed and operated to ensure that the safety and amenity of the affected land would still be preserved, should the buffer be encroached. Encroachment may affect the future development of the landfill.

For landfills with an anticipated lifespan exceeding 10 years, an analysis should be conducted of the anticipated changes in the zoning or land use of the surrounding area during the life of the facility. Guidance on future land use intentions can often be found in the municipal strategic statement prepared by the local municipality.

Failure to preserve an appropriate buffer and maintain compatible land uses within the buffer may result in unacceptable offsite impacts that limit future development of the landfill.

Buffer distances – buildings and structures

The buildings and structures buffer distance applies to any building or structure (including subsurface structures such as stormwater drains or service trenches) located near a landfill and is there to provide a protection zone around a landfill for subsurface landfill gas migration.

In the event that a building or structure is located within the recommended buffer, monitoring will be required in accordance with EPA landfill gas risk assessment requirements. An environmental audit is recommended where buildings with enclosed spaces that people will enter are proposed to be constructed within the buffer.

5.1.6 Geological setting

As the decomposition and stabilisation of waste may take many decades, landfills should be constructed in areas where the landform is stable, thereby enabling the long-term integrity of the landfill cap and liner system.

One potential impact on this stability is that of earthquakes. While Australia is considered a seismically stable continent, earthquakes do occur, albeit infrequently.

A reasonable degree of assurance of the long-term protection of the landfill from an earthquake is to avoid sites within 100 metres of a fault line displaced in the Holocene period (the most recent epoch of the Quaternary period, extending from the end of the Pleistocene Epoch – about 10,000 to 12,000 years ago – to the present). Maps are available that show the location of fault lines throughout Victoria.

A further part of the assessment of the suitability of a potential site is the geotechnical stability of the ground on which the landfill will be placed. This land should be capable of supporting the landfill, with or without engineering assistance. The assessment should also extend to the site embankments and slopes. In an area that has been subject to subsurface mining, it must be demonstrated that the ground will not collapse.

Where a landfill is located within a karst region, characterised by sinkholes, caves and possibly large water springs, special attention must be given to the investigation of the stability of the area and the containment of leachate. In general, karst regions are inappropriate for siting landfills.

A further factor to consider is the mineralogy of the area in which the landfill is to be built. In particular, the shrink/swell characteristics of the landfill substrate should be assessed to minimise the potential for differential movement of the liner resulting from changes in the moisture content of the substrate.

A further aspect to consider when assessing the local mineralogy is the suitability of the local material for liner construction.

5.1.7 Flora and fauna protection

Development of landfills may have an adverse impact on the flora and fauna of the local area. The potential impacts on flora and fauna are:

- clearing of vegetation
- loss of habitat and displacement of fauna
- loss of biodiversity by impacts on rare or endangered flora and fauna
- potential for spreading plant diseases and noxious weeds
- litter from the landfill detrimentally impacting on flora and fauna
- creation of new habitats for scavenger and predatory species
- increased vehicular traffic in the area
- erosion
- alteration of water courses.

Some of the areas where landfilling must not occur in relation to flora and fauna are:

- critical habitats of taxa and communities of flora and fauna listed under the Flora and Fauna Guarantee Act 1988
- state wildlife reserves listed under the Wildlife Act 1975
- matters of national environmental significance as identified in the Environment Protection and Biodiversity Conservation Act 1999.

A survey of the site and collection of comprehensive baseline environmental data are essential steps in the assessment of potential impacts from proposed landfilling operations. The nature and extent of this data should be site-specific, taking into account the size of the proposed operation and the risks posed to adjacent, sensitive areas. This includes potential impacts from scavenger birds on aircraft safety and water supplies, as well as impacts from predatory animals, such as feral cats, on surrounding native fauna.

An expert in the field should be consulted for an assessment of potential impacts from scavenger birds or predatory animals.

5.1.8 Infrastructure

Local infrastructure must be able to sustain the operation of a landfill. Landfilling requires the transportation of waste. The capacity of the road network to safely accommodate the increased traffic load, and with a minimum of disturbance to the local community, should be examined.

The preferred transportation route should minimise the transport of waste through residential and other sensitive areas. This consideration may influence the placement of the entrance to the landfill.

A transportation study may reveal the need for additional road infrastructure, such as freeway interchanges, turning lanes or signals.

The availability of services such as reticulated water, sewerage and power will influence the facilities provided for staff at the landfill and perhaps indicate a need to provide additional services, such as water storage for firefighting purposes.

5.1.9 Surface waters

Since leachate can be toxic to aquatic organisms and cause eutrophication (nutrient enrichment of a water body) in the waterways, it must be managed so that it cannot escape to surface waters. Accordingly, landfilling must not occur:

- in high-value wetlands, including wetlands of international significance listed under the convention on wetlands (Ramsar, Iran 1971) and listed in a directory of important wetlands in Australia (Environmental Australia 2001)
- in marine and coastal reserves listed in the National Parks Act 1975
- in areas identified by the Water Act 1989 as water supply protection areas
- in water supply catchments proclaimed under the Catchment and Land Protection Act 1994
- on land liable to flooding if determined to be so liable by the responsible drainage authority
- within 100 metres of surface waters (see below).

Municipal (putrescible) waste landfills must be located more than 100 metres from surface waters. A solid inert landfill may be located within 100 metres of surface waters if an assessment demonstrates that there is not a risk of contamination to surface water and protective measures are in place.

Landfills should not be located in a 1% annual exceedance probability (1% AEP) floodplain. Where landfills are within the 1% AEP floodplain, additional engineering and management controls must be in place to ensure that the facility will be protected from flooding, erosion by floodwaters and infiltration from perched watertable.

5.1.10 Land ownership

Land ownership will influence the siting of landfills. Where it is proposed that a site be on Crown land, a landfill may not be established without the written consent of the Minister responsible for the relevant Act under which the land is managed.

Landfill BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP.

SCREENING FOR POTENTIAL LANDFILL SITES

Relevant BPEM objective

To identify and rank those sites that require the fewest engineering and management controls to meet the objectives of all State environment protection policies.

Required outcomes of the BPEM

- Future landfilling sites must be listed in the landfill schedule in the regional waste management plan.
- Develop landfill sites in the sequence specified in the relevant regional waste management plan.
- Ensure that the landfill is sited to protect groundwater, surface waters, and flora and fauna.
- Ensure that sufficient buffer is available for the life of the landfill and for a minimum of 30 years following closure of the site.
- Provide buffers in accordance with Table 5.2 and Table 8.2; where these are unavailable, demonstrate that risks are mitigated to the same standard.
- Consider the most appropriate landfilling type to meet the requirements imposed by local conditions.
- All new landfills must deposit waste at least two metres above the long-term undisturbed depth to groundwater, unless the operator satisfies EPA Victoria that sufficient additional design and management practices will be implemented and EPA determines that regional circumstances exist that warrant the new landfill.

Suggested measures of the BPEM

- Consider natural features that will reduce the visual impact of the landfill.
- Commence the community consultation process early.
- Avoid valley fill landfills.
- Provide an unsaturated attenuation layer under the

6 Best-practice design

Once a landfill's site has been selected, it must be designed to ensure that it is able to protect the environment. This section sets out the objectives and required outcomes of each element of a landfill design, as well as providing suggested measures for achieving these. Where the landfill designer believes that alternative measures can achieve the objectives and required outcomes, these should be supported by a risk assessment.

The design of a landfill facility will be influenced by the existing natural environment, adjacent land uses, available infrastructure, waste to be received and the need to provide integrated waste management facilities for both disposal and recycling options. It must be based on a thorough understanding of the existing environment and address each of the site-specific circumstances of each site.

This section must be implemented for all landfills and any new cells.

6.1 Environmental assessment

To gain a thorough understanding of the existing environment at the site, in order to develop a sound landfill design, an environmental assessment of the site is required. This assessment must examine the impact of the landfill on the air, groundwater, surface water and noise environments, and should be based on at least two to three years of data. These data may need to be compiled from recent, targeted data sets and existing, less targeted data.

If, following an environmental assessment, the site is identified as unsuitable for a landfill, the proposal should not proceed any further.

An environmental assessment should contain:

- meteorological data, including monthly rainfall, monthly evaporation, seasonal wind strength and direction
- hydrogeological assessment in accordance with Hydrogeological assessments (groundwater quality), EPA publication 668
- water management information, including –
- water balance for the site and estimated volume of leachate to be generated
- leachate collection, storage facilities, treatment and disposal
- stormwater diversion banks and/or cut-off drains and storage dams
- fire-fighting equipment and water supply
- wheel washes
- landfill gas and odour control in accordance with landfill gas management requirements (section 6.7)
- noise assessment.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

ENVIRONMENTAL ASSESSMENT

Relevant BPEM objective

To gain a thorough understanding of the environment where the landfill is to be sited in order to design the landfill to minimise impacts on the environment.

Required outcomes of the BPEM

- Assess metrological data
- Conduct a hydrogeological assessment to assess the potential for impacts on local groundwater quality.
- Investigate water management requirements.
- Investigate landfill gas and odour control options.

6.2 Site layout

The landfill and associated facilities should be designed to:

- minimise potential environmental impacts
- minimise health and safety risks for landfill operators and the public
- encourage recycling
- make the most efficient use of resources on site.

Best-practice operation is to fill the landfill site as a series of independent tipping areas, each taking less than two years to fill, after which they are immediately rehabilitated. Large area fill landfills will require the establishment of independent cells. In the case of trench-and-fill landfills, each trench should be sized to ensure that it is filled within two years. Larger excavations for trench-and-fill landfills must be filled on a cellular basis.

Where an area fill or large trench-and-fill excavation is to be filled as a series of cells, prudent location of these cells may help to:

- stabilise a batter or embankment
- screen the landfill operation from view
- reduce groundwater flow into the site
- shed clean stormwater into the stormwater system
- reduce the need to relocate facilities such as leachate dams
- minimise the need to constantly construct roads within the site
- avoid active landfilling near areas being developed for residential purposes.

For a trench-and-fill landfill, the trenches should be:

- aligned perpendicular to the prevailing wind, to reduce litter
- use excavated soil to create windbreaks.
- aligned perpendicular to the prevailing wind to reduce litter
- use excavated soil to create windbreaks.

Where required, a transfer station with recycling and drop-off areas should be provided so that the public has no need to unload their vehicles at the tipping area. This reduces the mixing of both private and commercial vehicles at the tipping face thereby minimising safety risks to the public. In turn, this means that less supervision of the tipping area is required and that waste sorting is also encouraged.

The gradient of internal haul roads, the external road network and availability of services will influence the positioning of the transfer station, recycling facilities, site office, weighbridge, gatehouse, staff facilities, plant maintenance or storage area and the vehicle wash.

Best practice for a landfill is to have a gatehouse at the entrance to the site or at a point that cannot be bypassed when travelling to the landfill. The gatehouse is the first line of active measures to check the incoming waste stream to detect non-conforming wastes and divert materials to the recycling area. There should be facilities such as a viewing platform, elevated mirrors or video camera which allows the gatehouse attendant to readily scrutinise the incoming waste load.

A weighbridge is required at landfill sites in Municipalities listed in Schedule C of the EP Act to facilitate accurate record keeping for the purposes of invoicing clients, landfill levy documentation and monitoring waste disposal rates.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

SITE LAYOUT

Relevant BPEM objective

To ensure that the site layout minimises environmental and health and safety risks, encourages recycling and makes the most efficient use of onsite resources.

Required outcomes of the BPEM

- Site layout and filling sequence planned to ensure that landfill cells are open for the shortest period of time and site operations are optimised.
- Minimisation of public access to the tipping face and, where appropriate, assurance that waste received at the landfill can be vetted and recycled.

Suggested measures of the BPEM

- Each independent tipping area to be sized so that it can be filled within two years for subsequent rehabilitation.
- Landfills to install and operate a gatehouse, weighbridge and waste transfer station for the public.
- Position site facilities to take into account haul-road gradients, the external road network and the availability of services.
- Design the gatehouse to facilitate the auditing of the incoming waste stream.

6.3 Liner and leachate collection system

The principal functions of a landfill liner system are to limit contaminant migration to groundwater and to control landfill gas migration. This is achieved by the landfill liner slowing the vertical and lateral seepage of leachate to allow its collection and removal by the leachate collection system and to contain landfill gas within the landfill for appropriate collection. The liner may also attenuate contaminants in leachate seeping through the liner. A further function of the liner is to control infiltration of groundwater.

The design objective of the liner and leachate collection system is to protect the beneficial uses of all groundwater, including that directly beneath the landfill.

In accordance with SEPP (Groundwaters of Victoria), if EPA is satisfied that all practicable measures have been taken to prevent pollution of groundwater, EPA may designate an attenuation zone where some or all of the water-quality objectives are not required to be achieved. Implementing all of the required outcomes within the Landfill BPEM may be considered by EPA to constitute 'all practicable measures'. If an attenuation zone is declared, it must not extend beyond the boundary of the premises.

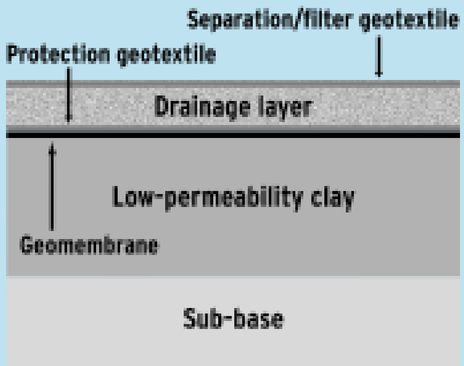
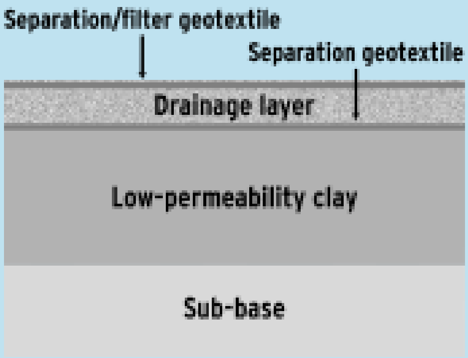
Table 6.1 shows indicative best-practice landfill liner performance standards, which would generally provide a high level of protection to the environment.

Liners comprise up to five components:

- sub-base
- clay or geosynthetic clay layer
- geomembrane and protection layer
- drainage layer/leachate collection system
- geotextile.

In designing a landfill liner, the landfill designer must ensure that the liner system is geotechnically stable between components and as a total system.

Table 6.1: Landfill liner performance standards and indicative liner design

Type	Liner performance	Indicative liner designs
2	Uses best available technology to control seepage to an amount not exceeding 10 L/ha/day.	
3	Uses commonly available technology to control seepage to an amount not exceeding 1000 L/ha/day.	

6.3.1 Sub-base

The integrity of the landfill liner and leachate collection system is fundamentally reliant upon the integrity of the underlying sub-base. The sub-base must be well-consolidated, with minimal settlement, in order to supply a firm platform for the compaction of the clay layer, to protect the geomembrane from excessive strains and to ensure that the drainage system drains effectively throughout the life of the landfill. The sub-base should also offer the capacity to further attenuate contaminants seeping through the liner.

Where the sub-base is undisturbed material (rock or soil) at the base of a quarry, it is likely to be well consolidated. Where the sub-base has been installed prior to the liner and leachate collection system, it needs to be installed in such a manner that it is geotechnically stable. One method of providing this stability is to install and compact the sub-base in thin layers.

Using solid inert waste or slimes (washings from sand-mining operations) for a sub-base is not best practice, due to the inherent problems in constructing a stable liner on such a sub-base. These problems, which include the very high moisture content and the acid-generating properties of many slimes, result in a sub-base that is difficult to travel across, much less compact a liner upon.

These problems may be resolved by drying the slimes to the point where the material is stiff enough to support compaction. In drying slimes, any potential for acid generation must be addressed.

All plans for the construction of a sub-base must be verified and approved by a geotechnical engineer. The geotechnical engineer may be an environmental auditor or part of the team providing information to the environmental auditor. To provide assurance of the quality of construction of the sub-base, construction of the sub-base must be included in the construction quality assurance (CQA) plan (see section 6.4), verifying that it is fit for its intended purpose.

6.3.2 Clay liner

The ability of clay to retard water movement and absorb exchangeable cations makes it a suitable natural material for a low-permeability liner. To meet the performance standards of the whole liner, the clay component needs to be at least one metre thick, with a hydraulic conductivity of less than 1×10^{-9} m/s using both fresh water and 50,000 ppm NaCl solution. Australian Standard AS 1289.6.7.1–2001 gives details on how hydraulic conductivity testing should be performed.

Some of the properties of the soil measured to determine its suitability as a low-permeability liner are particle size distribution and plasticity (described by the soil plasticity index) and cation exchange capacity. Properties for clays suitable for a low-permeability liner are discussed further in Appendix B, 'Clay properties'.

A key consideration is the potential for desiccation and subsequent cracking. Montmorillonite clays, found in the northern and western suburbs of Melbourne and the western district, are high-plasticity clays and can form good liners; however, they are susceptible to desiccation and subsequent cracking during the time between liner construction and placement of waste.

Clay liners are constructed in series of lifts compacted to the specifications detailed in a CQA plan prepared by the landfill designer (see section 6.4). To achieve bonding between each lift, the thickness of each lift must permit the compaction equipment, typically a sheepsfoot roller, to penetrate the top lift and knead the previous lift. To improve bonding, scarification of the previous lift may also be required. Bonding is required to overcome the effects of the imperfections within individual lifts.

Another consideration is the thickness of the liner and the number of lifts used, with a greater number of lifts and greater total thickness minimising the probability that preferential flowpaths will align. Best practice for minimising the probability that preferential flowpaths align and thus minimise the hydraulic conductivity of the liner, is to bond each successive lift with the preceding lift, construct the liner at least one metre thick, and use a minimum of four to six lifts.

During the installation of the clay liner, continual testing needs to be conducted to ensure that the hydraulic conductivity of the liner is less than 1×10^{-9} m/s. The landfill designer must provide details of how performance requirements of the liner, including the hydraulic conductivity, are to be met in a CQA plan. Section 6.4 gives more detail on the development of CQA plans.

The final surface of a compacted clay liner should be finished to a smooth surface. This promotes the rapid drainage of leachate on top of the liner, minimises the surface area of the liner thereby reducing the loss of moisture from the liner and allows the installation of a geomembrane liner.

6.3.3 Geosynthetic clay liner

Geosynthetic clay liners (GCLs) are often used as an element of composite base and side liners, and capping systems in landfills because of their very low hydraulic conductivity. Their main function is to limit contaminant migration, to reduce water ingress into the landfill and to control landfill gas migration.

Types of GCL

GCLs consist of a thin layer of bentonite bonded on either side by a geotextile or geomembrane. The purpose of the geotextile is to protect the bentonite during transport, installation and waste placement and provide a uniform layer during hydration swelling.

GCLs are either reinforced or unreinforced – reinforced GCLs have the layers of geotextiles bonded by needle punching or stitching. Unreinforced GCLs typically consist of a layer of sodium bentonite that may be mixed with an adhesive and then affixed to geotextile or geomembrane backing components with additional adhesives. Geomembranes can also be incorporated into the GCL composite barrier.

GCL performance is influenced by the mineralogy and the form of the bentonite material, type of geotextile (woven versus non-woven), incorporation of geomembrane and type of reinforcement if used.

The suitability of GCL lining for bottom, sideslope and capping of landfills requires an assessment of water and gas flow, contaminant transport and stability. This must include considerations of hydraulic conductivity, gas permeability, chemical compatibility, diffusion and shear strength.

The advantages and disadvantages of GCLs are summarised in Table 6.2.

A construction quality assurance (CQA) plan that includes supervision by an independent third party construction quality assurance consultant is required. The third party construction quality assurance consultant can be part of the geotechnical team for the environmental auditor. However, if this consultant is part of the auditor's team, that consultant can not provide advice to the owner or the contractor on any construction or design issues. Technical specifications and a CQA plan are required to be submitted for EPA approval prior to the installation of any GCLs.

Refer to Appendix E for minimum requirements for GCLs to be used in various landfill applications.

Table 6.2: Advantages and disadvantages of geosynthetic clay liners (GCLs) (modified from Bouazza, 2002)

Advantages	Disadvantages
· Ease of installation (manageable rolls, less skilled labour needed, lower costs). · Very low hydraulic conductivity to water if properly installed and pre-hydrated. · Mass per unit area of bentonite is relatively uniform if good quality control is provided during manufacture. · Can withstand relatively large differential settlement (compared to compacted clay). · Some self-healing characteristics. · Not dependent on availability of local clayey soils. · Lower repair costs and relatively easy to repair compared to compacted clay. · More landfill space from smaller liner thickness provided there is an adequate attenuation layer (for applications at the base). · Field hydraulic conductivity testing not generally required. · Hydrated GCL is effective gas barrier.	· Possible loss of bentonite during placement. · Possible increase of hydraulic conductivity due to incompatibility with leachate if not pre-hydrated with compatible water source. · Low shear strength of hydrated bentonite for unreinforced GCLs. · Possible post-peak shear strength loss. · GCLs can be punctured after installation. · Prone to desiccation and/or panel shrinkage (with consequent possible panel separation) if not properly selected, installed and/or protected from hydration/dehydration cycles. · Greater diffusive flux unless there is also an adequate attenuation layer. · Prone to ion exchange (for GCLs with Na+-bentonite) that may affect hydraulic performance under low compressive stresses. · Permeable to gases at low bentonite moisture content.

6.3.4 Geomembranes

Geomembranes are often used as an element of a composite base and side liners and capping system in landfills. Their main function is to limit contaminant migration, to reduce water ingress into the landfill and to control landfill gas migration.

Geomembrane properties

The key properties of geomembranes are the thickness, strength, the ability to resist or accept stress and deformation, tensile strength, puncture resistance, slope stability-interface friction, long term mechanical performance, durability and resistance for degradation.

Geomembrane selection

There is a range of geomembranes available with differing properties such as strength, flexibility and durability. Geomembrane materials should be selected due to their overall performance with respect to chemical resistance, mechanical properties, temperature resistance, thermally induced stresses (expansion/contraction), weathering resistance, product life expectancy, installation factors, cost effectiveness, and the type of application.

Selection of a geomembrane liner should consider:

- the hazard posed by the contained material and leachate
- susceptibility of the liner material to chemical attack or deterioration
- tensile strength and elasticity;
- thermal stability
- puncture, tear and shear resistance
- anticipated operational life required for effective containment
- local environmental conditions, including subsoil stability.

The fundamental requirement that can be applied to all geomembranes is that they must be fit for purpose. No single type of geomembrane will be suitable for all applications. The requirements for basal liners are different to capping liners.

For example, high-density polyethylene (HDPE) is expected to have an excellent ability to reduce advective and diffusive flow of contaminants out of the landfill and relatively high chemical resistance to leachate components, and hence, is used in basal and side liners.

However, for capping, the focus is more on the ability to deform with minimal impact on its integrity rather than on chemical compatibility, and hence, flexible geomembranes such as linear low-density polyethylene (LLDPE) are more suited for capping applications.

Stress on geomembranes

The strength of geomembranes relates to the behaviour of the membrane under a variety of applied stresses. A key design criterion for use of geomembranes is that they are used only as a barrier and not to serve any load-bearing or structural function. While the elimination of stress on a liner in practical terms is impossible, landfill design should place minimising stress as a key design consideration.

Stress is applied to membranes in a number of ways including:

- thermally induced stresses
- stresses during installation and handling
- stresses due to waste settlement on side liners
- stresses from differential settlement
- stress from point loads (such as stones)
- strains from long steep side slopes.

Geotextile protection layers

Geotextiles are employed to protect the integrity of the geomembranes. The purpose of the protective layer is:

- to minimise the risk of geomembrane damage/puncture during construction and during the subsequent operation of the landfill
- to minimise the strains in the geomembrane and hence the risk for future punctures forming due to environmental stress cracking.

Non-woven needle punched geotextiles have been widely used as a protection material. Selecting an adequate geotextile protection for geomembranes is a fundamental aspect of landfill barrier design if the robustness and integrity of these systems is to be ensured in the long term. Guidance on the selection and use of geotextiles is provided in Appendix F.

Installation and testing of geomembranes

Proper installation and testing of geomembranes and their geotextile protection layers is required in order to meet the performance requirements of the system design. Installation procedure for membranes must minimise wrinkling, buckling and tensioning. Wrinkling is undesirable as it increases the potential for failure at the wrinkle point and reduces the close contact between the underlying clay and geosynthetic clay liner.

A construction quality assurance (CQA) plan that includes supervision by an independent third party construction quality assurance consultant is required. Technical specifications and a CQA plan are required to be submitted for EPA approval prior to the installation of any geomembranes.

Refer to Appendices D and F for minimum requirements for geomembranes and geotextiles to be used in various landfill applications.

A leak detection survey should be undertaken once the geomembrane is installed and the drainage material (see section 6.3.5) is placed to ensure that the geomembrane has not been damaged during its installation and placement of the drainage material.

6.3.5 Leachate collection system

The leachate collection system is an integral component of the overall landfill liner system. The design objectives of the leachate collection system are to ensure that it is:

- able to drain leachate sufficiently that the leachate head above the liner is minimised
- appropriately sized to collect the estimated volume of leachate (predicted by water balance models)
- resistant to chemical attack, and physical, chemical and biological clogging
- able to withstand the weight of waste and the compaction equipment without crushing
- able to be inspected and cleaned by readily available video inspection and pipe-cleaning equipment.

The maximum leachate head on the liner (as measured at the lowest point of the liner surface) for a landfill situated above the watertable is 0.3 metres. The leachate head in the sump may exceed 0.3 metres as the sump is generally recessed below the level of the liner; some liquid is usually necessary to protect the pump in the sump.

A leachate collection system typically comprises a high-permeability drainage layer, perforated collection pipes, a sump where collected leachate is extracted from the landfill, and geotextiles to protect any geomembrane and prevent clogging of the drainage layer. The liner is sloped into the leachate collection pipes which in turn are sloped to the leachate collection sump. These slopes should be a minimum three per cent to the pipes and one per cent to the sump.

The drainage layer is a high-porosity medium providing a preferential flow-path to the leachate collection pipes and/or sump. To avoid clogging and capillary action holding water in the drainage layer, coarse material is used, so that there is space within the drainage layer for leachate to drain freely. Using coarse material also ensures leachate flow in the event of some clogging within the leachate collection pipes. The hydraulic conductivity of the drainage layer must be greater than 1×10^{-3} m/s.

The drainage layer must be across the entire landfill base and comprise at least 0.3 metres of coarse aggregate or a geosynthetic drainage material with the equivalent performance. This ensures that leachate is contained within the drainage layer, thus minimising the potential for clogging of the drainage layer. Properties of aggregate used in the drainage layer can be found in Appendix B, ‘Drainage aggregate properties’.

In designing the leachate collection system pipes, the key factors are the spacing between the pipes and the sizing of the pipes. Placing collection pipes close together minimises the head on the liner. The recommended maximum pipe spacing is 25 metres. Giroud's equation can be used to design the liner slope and pipe spacing to ensure the maximum design leachate head is not exceeded (see Appendix B, 'Giroud's Equation', for more detail on the equation and its use).

The sizing of leachate pipes is based on leachate flow rates within the pipe and the diameter required for the passage of remote inspection and cleaning equipment. This equipment typically requires pipe diameters greater than 15 to 20 centimetres.

Manning's equation is used to derive the required pipe size based on leachate flow rate and pipe slope. For landfills located above the watertable, the leachate flow rate is derived from a water balance estimation using a model such as the HELP model. For landfills located below the watertable, inflows of groundwater into the landfill must also be incorporated into the calculations. For landfills below the watertable, groundwater inflows will typically dominate calculations of the volume of leachate generated. For landfills above the watertable, the volume of leachate generated should be based on a 1-in-20 year storm event after one lift of waste has been placed in the landfill. In designing the slope of the leachate collection pipes, a minimum pipe slope of one per cent should be used, though greater slopes will minimise the sedimentation in the pipe.

Leachate collection systems can fail in less than a decade, in several known ways:

- they clog with silt or mud
- micro-organisms clog the pipes
- precipitation from chemical reactions block the pipes
- the pipes are damaged during installation or early in the filling of the landfill

or

- the pipes become weakened by chemical attack (acids, solvents, oxidising agents, or corrosion) and are crushed.

To reduce the risk of mechanical failure of the leachate collection pipes, they should be:

- flexible rather than rigid
- placed on evenly prepared bedding material and be protected with adequate surround material.
- protected by a traffic-control program minimising the movement of heavy vehicles across them until sufficient waste has been placed over the drainage layer to avoid crushing pipes.

The installation of the leachate collection system must be included in the CQA plan (see section 6.4).

Geotextile filter layers

A geotextile filter must be placed over the drainage layer to protect it from clogging as a result of solids transport, chemical precipitation and growth of biofilm.

Non-woven geotextile filters provide a greater level of protection of the leachate drainage layer than woven geotextiles. This protection is due to the greater particle retention in the non-woven filter.

Leachate collection pipes must not be wrapped in a filter geotextile, as this has been demonstrated to clog rapidly, rendering the collection pipes ineffective.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

LINER AND LEACHATE COLLECTION SYSTEM

Relevant BPEM objective

To maintain groundwater quality as close as practicable to background levels.

Required outcomes of the BPEM

- Design and construction of the best liner and leachate collection system practicable to prevent contamination of groundwater.
- Design and construct the landfill liner such that the appropriate maximum seepage rate shown in Table 6.1 is not exceeded.
- Implementation of the best practicable measures to meet all groundwater quality objectives contained in SEPP (Groundwaters of Victoria) below the landfill liner.
- Where an attenuation zone has been designated, assurance that all groundwater quality objectives contained in SEPP (Groundwaters of Victoria) are met at the boundaries of the premises.
- Geotechnically stable sub-base and liner.
- Design and construction of the most robust liner and leachate collection system to ensure that the system will continue to achieve the objective in the event of several components of the system failing.
- Maximum head of leachate on the liner surface not to exceed 0.3 metres.
- Drainage layer to be at least 0.3 metres thick with a hydraulic conductivity of not less than 1×10^{-3} m/s.
- Drainage layer extending over the entire base of the landfill.
- Geomembrane liner must meet the minimum requirements specified in section 3 of Appendix D.
- Geosynthetic clay liner must meet the minimum requirements specified in section 3 of Appendix E.
- Geotextile cushion layer must meet the minimum requirements specified in section 3 of Appendix F.
- A geotextile filter layer must be placed between drainage layer and waste

Suggested measures of the BPEM

- Avoid using slimes as a sub-base.
- Clay liner to be not less than one metre thick and

compacted to a hydraulic conductivity less than 1 x 10^{-9} m/s.
- Utilise clay with the following properties:
  - no rock or soil clumps greater than 50 mm in any dimension
  - 70 per cent passing through a 19 mm sieve
  - 30 per cent passing through a 75 mm sieve
  - 15 per cent passing through a 2 mm sieve
  - soil plasticity index > 10
  - CEC > 10 mEq/100g
  - minimal long-term degradation with exposure to leachate.
- Ensure clay liner is placed in at least four to six lifts, and each lift is bonded.
- Installation procedures to minimise tensile stress on geomembranes due to thermal expansion or contraction of installed components.
- Drainage layer aggregate size is required to be less than 50 mm and greater than 20 mm having:
  - fines content less than 1 per cent
  - containing no limestone or other calcareous material that would be subject to chemical attack.
- Low-permeability liner sloped at not less than 3 per cent into the collection pipes.
- Leachate collection pipes sloped at not less than 1 per cent, towards the leachate sump.
- Collection pipes with high resistance to chemical attack, able to withstand anticipated vertical loading stresses and able to be inspected and cleaned.
- Use an environmental auditor to review the environmental risk associated with use of any alternatives to the Landfill BPEM suggested measures.

6.4 Construction quality assurance

The development and implementation of a construction quality assurance (CQA) plan provides a means of demonstrating to the public and regulating authorities that the landfill being constructed meets its design requirements.

The CQA plan must be able to verify that:
- materials used comply with specifications
- method of construction/installation is appropriate and, as a result, design requirements have been met.

The CQA plan must contain the material/construction specifications, testing methods, testing frequency, corrective action and provide for appropriate documentation procedures.

CQA documentation will be verified by an environmental auditor and the plan will be used by the environmental auditor as part of auditing cell construction. More information is provided in *Landfill Licensing Guidelines* (EPA publication 1323).

6.4.1 Sub-grade and clay liners

Because of the importance of the sub-grade and clay liner in the overall liner performance, construction of these components must be accompanied by Level 1 geotechnical testing as set out in Appendix B of AS 3798–2007, Guidelines on earthworks for commercial and residential developments. This entails, among other requirements, full-time testing and inspection of all earthworks by the geotechnical testing authority, a geotechnical engineer independent of the liner constructor. The geotechnical testing authority must provide a report of all testing and, prior to the liner being accepted as appropriately constructed, must express the opinion that the works comply with the requirements of the specifications and drawings.

If necessary, this independent testing can be undertaken by the auditor’s geotechnical team. However, this team can not provide any advice on construction or design issues.

For any landfill it must be demonstrated that the natural sub-grade and/or a constructed sub-base is able to support the landfill without affecting the integrity of the liner system as a result of differential settlement.

In the case of a clay liner, the key parameter that must be met is the hydraulic conductivity. It is dependent upon many factors, including clay composition, moisture content, compaction, field placement techniques and liner thickness.

The CQA plan must specify how the materials used to construct the liner will be tested to ensure that the hydraulic conductivity of the liner meets the specification. One means of doing this is to regularly sample the clay liner and test the samples for dry density and moisture content. The results of this testing are then compared with the required zone for dry density and moisture content necessary to ensure that the clay meets the specified hydraulic conductivity. This is discussed in more detail in Appendix B, ‘Installation of clay liners’.

Where this method is to be adopted, dry density and moisture content tests need to be quick procedures with a one to two-hour turnaround time for results. Timely feedback and instructions can then be given to rework any areas not meeting compaction standards.

The minimum test frequencies are:
- properties of the clay (grain size distribution, plasticity index and moisture content) tested once every 5000 m^3
- field testing for liner density and moisture content at a frequency the greater of –
- one test per 500 m^3 of soil
- one test per 2500 m^2 area per clay lift
  or
- three tests per site visit.

Following field compaction work, direct permeability testing in the laboratory and/or in the field should be undertaken on undisturbed clay liner samples.

Suitable laboratory permeability testing procedures are described in AS 1289.6.7.1–2001, Soil strength and consolidation tests – Determination of permeability of a soil – Constant head method for a remoulded specimen.

Laboratory permeability testing has some advantages over direct field measurement methods because factors such as evaporation and soil saturation can be controlled in the laboratory to minimise discrepancies. However, only small samples can be tested in the laboratory, which can affect the accuracy and applicability of the permeability results.

Field permeability measurements can represent larger volumes/areas of soil, using a device such as a sealed double ring infiltrometer (SDRI). As an SDRI should run for at least four months to ensure that the flow through the material being tested is a long-term steady state flow rather than a transient flow (Parker et al. 1997), this test should be conducted on a test pad that is not part of the liner but is subject to the same construction activities.

In addition to this physical testing, visual inspections should check for the presence of oversized clods of clay, poorly compacted or dry areas and the homogeneity of the clay. The CQA plan may also need to specify the measures to be taken to protect the clay liner from desiccation and erosion.

Further to the testing of the quality of the installed clay, the CQA must also address the quality assurance with respect to the thickness of the constructed liner. In particular, the liner should be surveyed at the completion of construction to confirm that the correct grades have been attained.

Geomembranes, GCLs and geotextiles

The CQA plan for a geomembrane, geosynthetic clay liners and geotextiles must meet the requirements set out in appendices D, E and F.

A leak detection test should be carried out to ensure that the geomembrane is not damaged.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

CONSTRUCTION QUALITY ASSURANCE

Relevant BPEM objective

To ensure that materials, construction methods and installation procedures deliver a landfill meeting design criteria.

Required outcomes of the BPEM

- Development and implementation of a Construction Quality Assurance (CQA) plan to ensure that the liner and leachate collection system meets the requirements of the specifications and drawings.
- A statement from an accredited testing authority be obtained stating that the installed liner and leachate collection system meet the requirements of the specification and drawings.
- Development and implementation of a CQA plan to ensure that the stability of sub-base and liner are achieved.
- The installation of geomembranes must meet the requirements of section 5 of Appendix D.
- The CQA plan for geomembranes must address the issues raised in section 6 of Appendix D and should follow the suggestions unless an alternative provides an equivalent or better outcome.
- The installation of geosynthetic clay liners must meet the requirements of section 5 of Appendix E.
- The CQA plan for geosynthetic clay liners must address the issues raised in Section 6 of Appendix E and should follow the suggestions unless an alternative provides an equivalent or better outcome.
- The installation of geotextiles must meet the requirements of section 4 of Appendix F.
- The CQA plan for geotextiles must address the issues raised in section 5 of Appendix F and should follow the suggestions unless an alternative provides an equivalent or better outcome.

Suggested measures of the BPEM

- Perform leak detection test to verify the integrity of the geomembrane or geosynthetic clay liner after placement of the drainage layer.
- Undertake Level 1 geotechnical testing as set out in AS 3798-2007 for landfill sub-base and liner.
- Visually inspect each compacted lift of clay for impurities, poor compaction, cracking and dry areas.
- Survey liner to confirm correct grades.
- Inspect base for the geomembrane for sharp objects that may puncture the geomembrane or areas of roughness that may prevent the direct contact of the geomembrane on the low-permeability base.

6.4.2 Leachate collection system

The CQA plan must be able to demonstrate that the drainage layer materials have been placed in a manner that avoids damage to the low-permeability liner and have the following properties:

- appropriate particle size to provide design hydraulic conductivity
- placed so that no damage occurs to the landfill liner
- avoid trafficking with heavy machinery after placement
- correct grades on all surfaces achieved
- correct thickness of material
- pipes placed on an even bed
- proper joining of pipes.

6.5 Water management

Water management relies upon the management of three water streams with the intention of minimising the volumes to be managed and avoiding mixing the streams. The three components to be kept separate are:

- stormwater
- leachate
- groundwater.

When considering means of managing water on the site, reusing water onsite is always preferred to discharging the water to the environment.

6.5.1 Stormwater management

Good stormwater management design incorporates interception drains that direct stormwater away from the areas where waste is to be landfilled.

Storage ponds and other drainage measures should be designed to contain and control rainfall run-off for a 1-in-20-year storm event for a putrescible landfill or a 1-in-10-year storm event for a solid inert landfill. Storm events up to 1-in-100-year recurrence intervals should also be considered to ensure that they do not result in any catastrophic failures such as flooding of the landfill or failure of dams or leachate storage ponds.

Stormwater can also contribute sediment to the environment if the catchment area is erodible due to a lack of vegetative cover. By retaining and re-establishing as much vegetative cover in the catchment area as possible, this potential for erosion is minimised.

Other means for minimising the potential for erosion are to have water flow over flat slopes, or to spread the water across the slope. By minimising erosion the need for a settlement pond is reduced.

Sediment control features may be required where there are large stockpiles of earth or expanses of cleared land in the catchment area. Sediment control features should be designed to enable both silty sediments (able to settle out under gravity) and clayey sediments (will not settle out without flocculating agents) to be removed from the water. Typical features that may remove silty and clayey sediments include shallow, heavily vegetated stormwater control ponds and swales. The need for sediment control features will depend on:

- the topography and how this will influence water velocity
- the nature of the water environment into which the eventual discharge from the site will flow
- the typical intensity of storm events
- the extent of vegetative cover on the catchment area.

Construction techniques for sediment pollution control (EPA publication 275) and Environmental guidelines for major construction sites (EPA publication 480) provide further guidance on sediment control.

Where a water supply dam is constructed to provide water for firefighting, dust suppression or irrigation purposes, water from sediment control features should be channelled into the water supply dam. This places an additional control on the discharge of potentially turbid water, thus ensuring that the environment is better protected; it also maximises the use of this water.

All dams should have spillways with erosion-control measures such as rocks and erosion-resistant vegetation.

The discharge of stormwater from the site should only occur from dams, and only after confirmation that the water is not contaminated. This confirmation should at least be visual where the only possible contaminant source is sediment, but where other contaminants are possible, the water should be tested prior to discharging. The degree of testing will be determined by the risk of contamination and the sensitivity of the receiving environment. Water is not to be discharged if it is suspected or found to be contaminated. The maximum permissible turbidity for stormwater is contained in Table 6.3.

Where water does not meet these standards or shows other signs of contamination, the source should be found and actions taken to prevent a recurrence.

Table 6.3: Stormwater turbidity limits

	Maximum NTU	Median NTU
Dry weather	50	25
Stormwater flows	100	50

6.5.2 Leachate management

As leachate contains high levels of nutrients and salts, it requires treatment before it can be discharged to the environment. Prior to and during treatment, leachate must be stored and managed in a manner such that it will not escape into surface water or groundwater, will not cause offensive odours and will minimise human contact with the leachate.

Water used in vehicle and wheel washing should also be managed as leachate.

Management options for leachate are:

- evaporation
- discharge to sewer, with or without pretreatment
- treatment
- surface irrigation of treated leachate on capped areas of the landfill subject to salinity management
- dust suppression in the landfill
- or
- providing moisture for a bioreactor landfill (see section 6.8).

In deciding on any of the above management options, a water balance should be modelled over at least two consecutive wet years (90th percentile) to ensure that the proposed system has sufficient capacity to deal with all leachate generated over the operational life of the landfill.

Any ponds containing leachate should have a freeboard of at least 0.5m to guard against wave action causing leachate to overtop the banks, as well as to provide capacity for any unforseen events. The freeboard area should be protected from wave action by use of riprap or other suitable materials.

To prevent seepage from the treatment system into groundwater, ponds should be lined to the equivalent performance standard as the landfill (see section 6.3 for performance standards).

If leachate ponds become anaerobic, or where odour is a particularly critical issue due to surrounding sensitive land uses, leachate odours can become an issue. Where odour is an actual or potential issue, then the leachate pond may need to be covered or mechanically aerated.

Where leachate is to be evaporated, it should be within a closed system where no leachate is able to escape to the environment. Ponds are typically used to evaporate leachate (the formula for calculating the pond surface area required to evaporate the required volume of leachate is in Appendix B).

Evaporation is enhanced by increasing the evaporative surface area using measures such as microsprays in the evaporation pond or devices such as the leachate evaporation pyramid in Figure 6.1. At the end of the useful life of the evaporation pond, salt that has accumulated in the pond will need to be disposed of.

Figure 6.1: Leachate evaporation pyramid at Hogbytorp landfill, Sweden

The disposal of leachate to sewer requires the approval of the local sewerage authority, which may impose restrictions on the quality of leachate permitted to be discharged. Restrictions are typically placed on the salinity and ammonia content of leachate disposed of to sewer and, as a result, some pre-treatment of leachate may be required prior to disposal to sewer.

The principal method of treating leachate is degradation by aerobic bacteria. The efficiency of this treatment method depends upon keeping the bacterial floc in suspension and being able to inject sufficient oxygen for the needs of the bacteria.

A further element of effective leachate treatment in aerobic ponds is the avoidance of large fluctuations in leachate quality and volume. The design and management of an aerobic leachate treatment system is discussed in Appendix B, ‘Aerobic leachate treatment systems’.

A wide range of alternative leachate treatment methods have been developed, ranging from full physico-chemical treatment where the treated leachate is of an extremely high quality, to thermal treatment where leachate is evaporated by the combustion of landfill gas. Where other alternatives are not feasible or sufficiently protective of the environment, these need to be investigated on a case-by-case basis.

Where treated leachate is to be irrigated over land that has not received waste, it must be of a standard suitable for land irrigation. In particular, saline water (TDS > 3000 mg/L) should not be irrigated to land as, in general, it is unsustainable and is likely to result in long-term salinisation of the land. Guidelines for wastewater standards and the design, construction and management of a wastewater irrigation system are detailed in Guidelines for wastewater irrigation (EPA publication 168) and Guidelines for wastewater reuse (EPA publication 464).

Spraying or otherwise disposing of leachate over any part of the site that has received waste is only to be considered if it forms part of the essential operation of a bioreactor landfill or dust-suppression operations. Further details on bioreactor landfills are provided in section 6.8.

6.5.3 Groundwater management

Sites that extract groundwater (such as sites below the watertable) must manage that water so that it does not cause soil or water pollution.

Many areas of Victoria contain groundwater that is more saline than the local surface water system. The artificial or accelerated natural discharge of such saline groundwater into a fresh surface water system is likely to adversely affect that ecosystem.

Landfills below the watertable should also ensure that groundwater is segregated from leachate and stormwater. This can be achieved by groundwater interception drains surrounding the landfill where groundwater is shallow, or deep bores or sumps for deeper groundwater. Groundwater will need to be pumped from the vicinity of the landfill until the waste has stabilised – this can be assumed to be 30 years from the cessation of waste disposal.

A further impact that may need to be considered is that of rising watertables. This may manifest itself through groundwater rising to flood a landfill, or alternatively landfill operations causing a localised increase in groundwater recharge leading to a rise of a saline watertable, which impacts on surrounding land uses.

6.5.4 Water discharge

Wastewater discharge (excluding uncontaminated stormwater) from landfill sites into receiving waterways requires an EPA works approval and a waste discharge licence. State environment protection policy (Waters of Victoria) specifies requirements for physical and chemical water quality and toxicity, and these requirements are used to determine the discharge limits from the site.

Water management options, such as reducing the volume of water requiring disposal and examining alternatives for reuse onsite or offsite, should all be evaluated prior to seeking approval for an offsite discharge to the environment.

If a discharge of groundwater or treated leachate is necessary, the wastewater should be treated to the advanced level expected of treated effluent.

In considering a discharge to the environment, the existing environment of the receiving waters, such as flow rates, water chemistry, turbidity and biology, should be determined, with this information being used to design the location, volume and quality of any discharge in order to minimise impacts on water quality and ecology in the receiving waters. It is not best practice to discharge leachate to surface waters; the need to discharge groundwater to surface waters should be avoided.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

WATER MANAGEMENT

Relevant BPEM objectives

To protect beneficial uses of receiving waters and to avoid any adverse environmental impact on surface and ground waters.

Required outcomes of the BPEM

- Segregation of stormwater, leachate and groundwater.
- Wherever practical, reuse of water onsite.
- Management and treatment of leachate to:
  - Prevent it from escaping into surface waters or groundwater
  - Prevent offensive odours offsite
  - Minimise human contact with the leachate.
- Assurance that waste discharges to surface waterways are minimised and do not cause water quality objectives to be breached.

Suggested measures of the BPEM

- Use drains or bund walls to direct clean stormwater away from the landfill activities.
- Design drainage measures to contain and control rainfall run-off for a 1-in-20 year storm event for a putrescible landfill or 1-in-10 for a solid inert landfill.
- Control erosion by minimising disturbed land, treating disturbed land as soon as practical, establishing flatter slopes or spreading the flow of water.
- Where sediment cannot be controlled at the source, install sediment control features.
- Manage water from vehicle-washing areas (manual or automatic) as leachate.
- Model leachate treatment facilities to ensure that they have sufficient capacity to store and treat all leachate generated over two consecutive wet years.
- Use interception drains to intercept surface water or shallow groundwater.
- Assess potential impacts of rising watertables.
- Prevent the discharge of turbid stormwater to the environment by maintaining turbidity levels within those outlined in Table 6.3.

6.6 Groundwater

Since a landfill must not impact on beneficial uses of groundwater, the design of the landfill must consider the local hydrogeological environment. Issues to be considered include:

- liner uplift;
- groundwater monitoring bores
- groundwater recovery bores.

6.6.1 Liner uplift

The upward or outward force of groundwater through the base or sides of a landfill can cause a structural failure of the liner. Until the loading on the landfill liner due to waste placement exceeds any inward or upward force exerted by groundwater, this risk of liner uplift needs to be managed.

The key to managing this risk is to reduce the level of groundwater beneath the landfill by extracting groundwater. Two of the strategies that will enable this reduction are groundwater underdrains beneath the liner and groundwater extraction bores surrounding the landfill. If groundwater extraction ceases, the rebounding watertable will exert a force on the landfill that will need to be balanced by the force exerted by the waste for the liner to remain intact.

6.6.2 Groundwater monitoring

Monitoring should be undertaken in accordance with the Landfill licensing guidelines (EPA publication 1323). Monitoring bores may be installed to:

- establish the groundwater background quality and levels (in mAHD)
- establish the local groundwater flow direction and rate
- act as an early indicator of leachate contamination in groundwater prior to offsite migration
- measure compliance with the site licence or notice
- provide an indication of the downstream groundwater quality that a permitted groundwater user may find.

The bore(s) to establish the background groundwater quality are placed up-gradient of the landfill, where they will not be influenced by seepage out or into the landfill or affected by surface water features, such as dams. The location of these bores should also take into account potential impacts from surrounding landfills, such as localised changes in groundwater quality or flow direction.

Monitoring should occur in all aquifers that may be affected by the landfill. The number of monitoring bores should be commensurate with the size of the facility, the risk of contamination and the nature of the groundwater environment. Further guidance on groundwater monitoring programs is contained in *Hydrogeological assessment (groundwater quality) guidelines* (EPA publication 668).

The bores established in close proximity to the landfill are screened so as to intercept any leachate-contaminated groundwater. For a landfill located above the watertable, the top three to five metres of the watertable aquifer would normally be sampled. Multiple bores screened at various depths in the aquifer may be used to establish the water quality profile.

Permission must be obtained from the appropriate regional water authority to install a groundwater bore, and all groundwater monitoring results should be forwarded to the State Groundwater Database.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

GROUNDWATER MANAGEMENT

Relevant BPEM objective

To protect the beneficial uses of groundwater and to minimise the risk posed by the landfill to those beneficial uses.

Required outcomes of the BPEM

- Implement a groundwater monitoring program in accordance with *Landfill licensing guidelines* (EPA publication 1323).
- Ensure that the landfill liner cannot be damaged through groundwater pressure.
- Minimise risk to groundwater by siting landfill in accordance with section 6.2 (site layout) and utilising a liner and leachate collection system in accordance with section 6.3 (liner and leachate collection system).

Suggested measures of the BPEM

- Where groundwater pressure poses a risk to the liner integrity, extract groundwater to minimise this risk.
- Install groundwater recovery bores if necessary.
- If beneficial use of groundwater is or is likely to be at risk, implement a risk mitigation/control program.

6.7 Air quality

Landfills can pose a risk to air quality through landfill gas, odour and dust. The objectives for air quality management at a landfill are:

- no health, safety or environmental impacts due to landfill gas and dust
- minimise greenhouse gas emissions
- the prevention of offsite nuisance odours and dust
- meet requirements of relevant SEPP and waste management policies.

6.7.1 Landfill gas

Overview

The microbial degradation of putrescible waste produces landfill gas. The composition of landfill gas varies according to conditions present within the landfill. Landfills typically pass through a number of phases of microbiological breakdown (Appendix B, Figure B.2). The onset and duration of each phase of landfill gas production varies both within and between sites. The quantity of water, nutrients and bacteria present are limiting factors in the rate of waste decomposition.

Landfill gas can impact on air quality at different phases of microbiological breakdown processes. During the anaerobic phase, where decomposition occurs in the absence of oxygen, methane and carbon dioxide are the major constituents of the gas produced. With daily covering and compaction of waste the oxygen within the landfilled waste is quickly depleted. However, the timescale for the evolution of significant quantities of methane typically varies from three to twelve months following waste deposition and can continue for in excess of 30 years.

The rate of emissions from a landfill is governed by gas generation and transport mechanisms. There are a variety of models that can be used to estimate landfill methane generation and emissions (such as the Commonwealth of Australia's Department of Climate Change NGER Solid Waste Calculator 1.3.2 model, USEPA's LandGem and Environment Agency (England & Wales) GasSim).

Landfill gas can cause health, safety, amenity and environmental impacts due to the methane and carbon dioxide. Under certain conditions trace components such as hydrogen sulfide may also pose a risk.

Under certain conditions, landfill gas can:

- be flammable and explosive
- present an asphyxiation (suffocation) hazard
- be toxic to humans, flora and fauna
- be odorous
- be corrosive
- contribute to greenhouse gas emissions
- contribute to photochemical smog.

If not appropriately managed, landfill gas can be emitted from a landfill site by a number of pathways including:

- the landfill site's surface, including penetrations
- subsurface geology
- subsurface services (man-made)
- the landfill gas management system
- leachate migration.

Due to its potentially hazardous nature, landfill gas must be appropriately monitored and managed at landfill sites.

Potential impacts from landfill gas and possible migration pathways must be identified, monitored and managed to ensure there are no detrimental effects.

This will require the collection and treatment of landfill gas using appropriate methods discussed in Landfill Gas Management.

Landfill gas risk assessment

Due to the variable nature of landfill sites, the most appropriate way to evaluate the level of risk posed by landfill gas from an individual site is to conduct a site-specific landfill gas risk assessment (LGRA). Appropriate measures for monitoring and managing landfill gas can subsequently be determined based on the findings of the LGRA. Guidance on how to complete a LGRA is provided in *the Landfill Licensing Guidelines* (EPA publication 1323).

The landfill gas risk assessment approach requires an understanding of the:

- quantity, rate and composition of the landfill gas generated

- potential landfill gas emission pathways from the landfilled waste
- potential risks/hazards presented by the landfill gas generated to all potential receptors both on and offsite.

LGRA is an ongoing process that must be reviewed and updated on a regular basis taking into account new information (for example, gas monitoring data or new receptors).

Landfill gas monitoring

Landfill gas monitoring is an integral component in landfill gas management and should be developed and implemented based on the findings of a site-specific LGRA.

The location and number of landfill gas monitoring locations is site-specific and should be based, as a minimum, on the following key factors:

- type of waste deposited at the site
- generation rate and composition of the landfill gas
- possible pathways for landfill gas (LFG) migration
- nature and location of potential receptors for LFG emissions
- possible impacts on receptors
- travel time for gas migration from source to potential receptors.

The LFG monitoring should include, as a minimum, the following locations:

- the landfill's surface
- subsurface geology
- subsurface services on and adjacent to the site
- buildings/structures on and adjacent to the site
- landfill gas treatment/management equipment (such as flares and engines).

In some cases, it may be appropriate to also monitor landfill gas present in groundwater and leachate.

Further guidance on the typical spacing and design of landfill gas monitoring bores is contained in Appendix B.

The action levels for landfill gas at different monitoring locations are set out in Table 6.4. When these action levels are exceeded, the landfill operator must notify EPA within 24 hours. The notification is also to advise what action will be taken to address the matter, what further testing will be done to demonstrate effectiveness of the works, anticipated time frame for the works, or when a detailed landfill gas remediation action plan (LFGRAP) would be prepared and forwarded to EPA.

EPA need not be advised of an excursion above an action level where only an onsite location was affected and the matter is rectified within 24 hours.

Where an action level has been exceeded at an offsite location, or the result indicates that an action level would be exceeded offsite, then the landfill operator must prepare an LFGRAP.

When buildings offsite are or may be impacted by landfill gas, the LFGRAP must be verified by an environmental auditor as taking all practicable measures in the circumstances to reduce the risks from the landfill gas to acceptable levels.

Notwithstanding the requirement for auditor verification, the draft LFGRAP is to be forwarded to the EPA as soon as practicable. Auditor verification of the draft LFGRAP is not required prior to its submission to the EPA.

Table 6.4: Landfill gas action levels

Location	Parameter(s)	Action level and unit
Landfill surface final cap	Methane concentration in air*	100 ppm
Within 50mm of penetrations through the final cap	Methane concentration in air**	100 ppm
Landfill surface intermediate cover areas***	Methane concentration in air*	200 ppm
Within 50mm of penetrations through the intermediate cover	Methane concentration in air**	1000 ppm
Biofilters	Methane flux	$1.0 g/m^2/hr$
Subsurface geology at the landfill boundary	Methane and Carbon Dioxide concentrations	1% v/v Methane or 1.5% v/v Carbon Dioxide above background
Subsurface services on and adjacent to the landfill site	Methane concentration	10,000 ppm
Building/structures on and adjacent to the landfill site	Methane concentration in air	5000 ppm
Landfill gas flares	Methane and Volatile Organic Compounds	98% Destruction efficiency

* Point of measurement is 50mm above the landfill surface.

** Point of measurement is 50mm from the point of discharge.

*** Intermediate cover areas are those that do not have an engineered landfill cap and are not scheduled to receive waste during the next three months.

The following landfill gas levels inside a building, if confirmed, should trigger advised relocation from the building:

- 1% v/v methane.

The emergency services need to be advised immediately for action consistent with Victoria's emergency management arrangements. EPA and other relevant authorities should also be advised.

Landfill gas management

In order to manage landfill gas and minimise greenhouse gas emissions, appropriate landfill gas containment (for example, landfill cap, basal and side liners) and landfill gas collection systems must be developed, implemented and monitored. Guidance on the required landfill gas containment measures are provided in other sections of this document.

The selection of an appropriate landfill gas management system (and associated monitoring program) will be based on:

- the findings of a site-specific landfill gas risk assessment
- the landfill gas management hierarchy detailed in Figure 6.2.

The highest practical order use of the collected landfill gas should be established by conducting an analysis of the relevant environmental and economic factors. This analysis should be regularly reviewed.

Untreated emissions of landfill gas via vent pipes/trenches or similar infrastructure will not be permitted, unless:

- it can be demonstrated, to EPA satisfaction, that options of the landfill gas management hierarchy are not reasonably achievable
- and/or
- venting is required as a short-term (three to six-month) emergency measure.

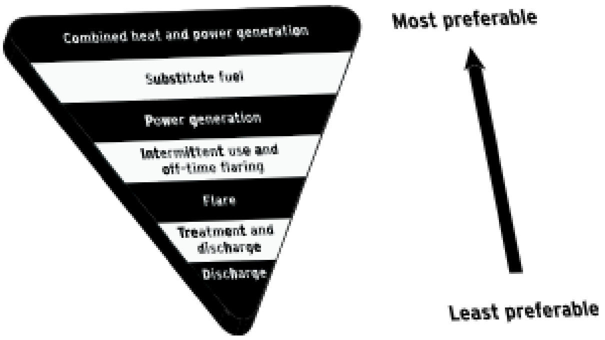


Figure 6.2: Landfill gas management hierarchy

Table 6.5 sets out potential landfill gas treatment technologies for different landfill gas generation rates.

Most of these treatment technologies adopt oxidation of methane in landfill gas to water and carbon dioxide. This reduces the health, safety, amenity and environmental impacts of landfill gas and results in a net reduction of greenhouse impacts as methane has a significantly greater greenhouse effect than carbon dioxide.

Table 6.5: Potential landfill gas treatment technologies for a range of gas generation rates

Landfill gas generation rate	Potentially suitable landfill gas treatment technologies
> 1000 m^3/hr	Combined heat and power generation Substitute fuel Power generation Intermittent use and off-time flaring High-temperature flaring
> 250 m^3/hr – < 1000 m^3/hr	Power generation Intermittent use and off-time flaring High-temperature flaring Low-calorific flaring
> 100 m^3/hr – < 250 m^3/hr	Power generation High-temperature flaring Low-calorific flaring Other oxidation and discharge (e.g. passive flares, biofilters, biocover)
< 100 m^3/hr	Other oxidation technology and discharge (e.g. passive flares, biofilters, biocover)

The landfill gas management system should be designed prior to establishing the landfill and should be progressively installed during the operational period of the landfill. Landfill gas management systems must incorporate any operational modifications required to optimise the quality and volume of gas generated.

There are, broadly, two types of landfill gas management systems:

- active systems, where the system uses a vacuum to extract the landfill gas generated
- passive systems, similar to active but with no vacuum pump.

Typically, active systems are used for moderate to large generation rates of landfill gas (> 250 m^3/hr), whereas passive systems are used for smaller rates of landfill gas (< 250 m^3/hr) generation.

As landfill gas contains water vapour, both active and passive landfill gas management systems require adequate condensate (contaminated water) collection and drainage points to prevent this water blocking and/or damaging the installed system.

Landfill gas extraction wells are a critical element of a landfill gas management system. There are two kinds of extraction wells; vertical and horizontal. A site's landfill gas management system should include one or both of these types of wells as required.

Active and passive landfill gas extraction wells are the same design and can be used interchangeably between both systems. Horizontal gas wells are used during landfilling operations and may be superseded by vertical gas wells once an area has been completely filled and intermediate and final cover materials have been placed.

Vertical wells should extend to within 3 to 5 metres of the base of the waste mass.

The design and location of the gas management infrastructure should minimise damage by settlement, vandals, animals, natural processes or operational machinery. Landfill gas extraction wells should be monitored and maintained or replaced as required.

An appropriate level of construction quality assurance (CQA) must be completed during the installation of a landfill gas management system. Any variations from the design made during the construction phase should be recorded and held by the landfill site owner/operator.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

LANDFILL GAS

Relevant BPEM objective

Ensure that no safety or environmental impacts are caused by landfill gas.

Required outcomes of the BPEM

- Undertake a site-specific landfill gas risk assessment.
- All practicable measures must be taken to achieve the landfill gas action levels detailed in Table 6.4.
- Develop and implement an appropriate landfill gas management system.
- Implement a landfill gas monitoring program in accordance with the Landfill licensing guidelines, EPA publication 1323.
- Implement a landfill gas remediation action plan acceptable to EPA if the action Levels in Table 6.4 are exceeded.
- The landfill gas management system is updated and is in compliance with the landfill gas management hierarchy.
- Notify EPA Victoria within 24 hours of detection of any exceedance of the action levels detailed in Table 6.4, except for onsite exceedance rectified within 24 hours.
- The landfill gas flares must have auto ignition and flame arrestor beneath the combustion zone.

Suggested measures of the BPEM

- Include landfill gas management systems in the landfill design.
- Install the landfill gas management system progressively during the landfilling process, to minimise uncontrolled landfill gas emissions.
- Where there are multiple landfill sites in relative proximity, examine the options for higher order measures of landfill gas utilisation of the combined landfill gas produced from the sites.

6.7.2 Air toxics

Assessment of air toxics should be undertaken as part of the landfill gas risk assessment (LFGRA). Landfill gases can contain a range of air toxics, depending on the type of waste that has been deposited.

Consistent with world best-practice and to ensure protection of public health, a monitoring plan should be developed and implemented for air toxics, where required. Advice should be sought from an environmental auditor during the development or review of the LFGRA.

The monitoring should include the bores and ambient air at the boundary of the site. The air sample should be analysed for the indicators specified in the SEPP (AQM) that are relevant for landfill gases or those contained in international guidance on monitoring of air toxics from landfills.

6.7.3 Odour

Landfill odour is a key consideration in landfill siting. Landfill odours have two main sources; odour from the aerobic decomposition of freshly deposited wastes and odour from landfill gas generated by the anaerobic decomposition of wastes. Leachate ponds can also be a source of offensive odours. Good operation and adequate buffers are essential in odour management. These buffers are set to account for upset conditions and are not a substitute for best-practice management at the landfill or for normal operating conditions.

At all times, a landfill must be managed to prevent offensive odours beyond the boundary of the premises. For existing landfills this will be assessed by community complaints that are verified by EPA officers. In particular, where surrounding land uses include residential, educational, health care or other sensitive uses, the highest degree of care must be taken to protect these areas from landfill odours.

The provision of buffers in accordance with requirements outlined in section 5.1.5 will minimise impacts of odour on surrounding areas.

While the major constituents of landfill gas, methane and carbon dioxide, are odourless, other minor constituents of landfill gases including organosulfur compounds can be very odorous. The key means of managing landfill gas odour is to manage the landfill gas in general by oxidising it through some of the measures discussed in section 6.7.1. Odour from aerobic waste deposition is managed by minimising the exposure of these wastes to the atmosphere.

6.7.4 Dust emissions

Any large area where the land has been disturbed and is subject to vehicular traffic has the capacity to generate dust. Other potential dust sources are stockpiles of earth and the delivery of dusty loads of waste.

The magnitude of the impact will depend on the:

- type and size of the operation
- prevailing wind speed and direction
- adjacent land use
- occurrence of natural and/or constructed wind breaks
- wind-abatement measures or buffers.

Dust can impact on both health and amenity, depending on the size of the particles. Reactive management strategies should put in place including real-time monitoring of PM_{10}. The monitoring may be required at the boundary of the premises both upwind and downwind of the active landfill area to assess any impact and guide mitigation actions.

An hourly trigger level of 80 $\mu g/m^3$ should be used to assess the real-time data. If exceeded additional dust management practices, such as increased water sprays and dust suppressants should be applied.

Dust suppression measures to be applied at the site include:

- vegetating or mulching of exposed areas and formation of internal roads, including sealing roads that are used regularly
- use of water or other dust suppressants on roads or stockpiles that are not sealed or vegetated
- where leachate is to be used for dust suppression it may only be applied to areas that are within the active landfill cell to ensure the leachate does not contaminate stormwater run-off.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

ODOUR, DUST AND AIR TOXICS

Relevant BPEM objective

To ensure that air quality objectives are met, and that there is no loss of amenity from odour or dust.

Required outcomes of the BPEM

- Prevention of any offensive odours beyond the boundary of the premises.
- Control all dust emissions from the landfill site.

Suggested measures of the BPEM

- Vegetate exposed areas and form internal roads.
- Ensure waste is covered appropriately and on time.
- Implement a reactive management plan including real-time monitoring for PM_{10}, where necessary.
- Monitoring of air toxics should be undertaken where required.

6.8 Bioreactor landfills

Bioreactor landfills are landfills that seek to maximise the rate of degradation of biodegradable wastes.

Generally, waste degradation in a conventional ‘dry tomb’ landfill is inhibited by the lack of moisture within the waste which impedes the rate of waste decomposition. The addition of moisture in a bioreactor landfill by way of leachate recirculation or fresh water infiltration adds moisture to the waste and promotes the conditions necessary for micro-organisms to achieve rapid rates of waste decomposition.

Bioreactor landfills seek to complete the biodegradation of the readily and moderately degradable wastes within five to 10 years of waste placement.

The enhanced degradation of waste process can be undertaken under both anaerobic and aerobic conditions. In both cases, moisture content of the waste is the most important factor in promoting decomposition of waste.

These guidelines mainly refer to anaerobic bioreactor landfills due to the beneficial use of generated methane gas while decreasing greenhouse gas emissions. Aerobic or semi-aerobic bioreactor landfills are likely to pose an unacceptable fire risk and are not recommended.

The environmental performance and required outcomes for a bioreactor landfill are the same as for a conventional landfill (refer to ‘Required outcomes’ in Section 8.1).

Bioreactor landfills have similar functional elements as conventional landfills, such as liner, capping and gas management systems; however, design, construction and operation of bioreactor landfills must take into account their different operating environments. These include:

- higher temperatures
- minimised low-permeability layers within the waste mass
- moisture addition systems
- early and progressive installation of the landfill gas extraction system
- enhanced leachate management systems
- temporary landfill capping
- additional performance monitoring
- increased waste density
- faster settlement.

Bioreactor landfills have new cells engineered to manage these different operating environments. Therefore existing landfill cells cannot be retrofitted. Accelerated rates of waste decomposition may lead to higher temperatures for sustained periods. The design and operation of the bioreactor landfills must consider the potential for higher temperatures, as they can cause degradation of both flexible membrane and clay liners.

Strategies for managing temperature effects should include placing a layer of inert waste at the base of the landfill to provide an insulation layer between the liner and the rapidly degrading wastes. Monitoring the temperature of the liner and a management program controlling the amount of water injection should also be part of the strategy.

A critical element in the effective operation of a bioreactor landfill is the minimisation of low-permeability layers within the waste mass. Low-permeability layers are typically formed by placement and compaction of clayey daily cover and laminations of plastic films contained in the waste stream.

Low-permeability layers prevent the free movement of water and gas within the waste mass. This can lead to localised zones of saturation and dry zones above and below the low-permeability layers.

Strategies to minimise the creation of low-permeability layers should include:

- removal of plastic films from the waste stream prior to landfilling; this has the additional benefit of recovering a potentially valuable resource for reuse
- minimising the use of soil as daily cover, in particular, clayey soils
- sorting for the removal of non-biodegradable (and recyclable) waste and shredding of wastes prior to landfilling
- removal of temporary caps and side barriers as wastes are deposited over existing bioreactor landfill cells.

Typically moisture levels within the waste mass are less than those required to achieve rapid rates of waste decomposition. The addition of moisture to the waste is, therefore, a key element in the successful operation of a bioreactor landfill.

Adding water to waste to achieve uniform levels of saturation may be difficult due to heterogeneity of the waste mass, which can lead to preferential flow paths and differential settlement developing in the waste mass.

Strategies employed to achieve uniform moisture content include:

- spraying of water directly onto the tip face
- wetting wastes prior to placement
- use of injector wells
- horizontal trenches.

Measuring the degree of saturation within the waste mass after placement is difficult and may be better carried out indirectly by other means, such as gas flow rates and waste temperature.

Maximising the capture of landfill gas requires that wastes are placed and contained by temporary barrier systems as soon as possible.

The used landfill cells or sub-cells must have landfill gas extraction systems installed with or as soon as possible after placement of the wastes. These sub-cells may have temporary caps that may have different performance requirements than the final landfill cap and permit the infiltration of surface water into the waste mass. Temporary caps and bunds are to be removed when additional wastes are placed against them if they are constructed of materials that will form low-permeability layers or barriers within the landfill.

Landfill gas extraction systems are commonly installed with the wastes as horizontal systems. The systems must be constructed from strong, crush-proof pipes and be installed with a slope (of three to four per cent) to prevent blockage from leachate or condensate.

Horizontal gas collection systems may also be used to introduce water into the waste mass. The basal leachate collection system may be used as an additional gas collection layer in the early stages of the operation of a cell. Vertical gas extraction systems are also used.

Leachate extraction systems of bioreactor landfills must be constructed to deliver the same level of performance as conventional landfills, allowing for the additional loadings imposed by increased levels of saturation and accelerated settlement.

Leachate collection systems must be able to deal with the high potential for system clogging from the growth of biofilms. The system is required to manage greater potential flow rates and greater densities of wastes. Geotextile filter selection in particular must consider the clogging issue; refer to geotextile section for further information.

The storage and treatment of leachate collected from the bioreactor landfill is similar to a conventional landfill, with the exception that leachate may be used to raise the moisture content of the waste in the early portion of the operation of the site. Leachate recirculation systems should allow for leachate collected from the base of the landfill to be reintroduced to the waste mass without any exposure of the anaerobic leachate to the atmosphere.

Temporary caps placed over the cells have the primary function of preventing the escape of landfill gas to the atmosphere. The temporary cap must accommodate high levels of settlement during the operation of the landfill. The prevention of infiltration of rainwater into the waste is not required during the initial active phase of operation.

Gas escape must be prevented by use of geomembranes, soil caps and biocovers. A biocover may consist of a layer of compost or wood chips that facilitate oxidation of any fugitive emissions of methane.

Once the cell has reached final design height and the rate of settlement has decreased, a final cap is to be constructed over the cell. This final cap must have the same performance characteristics as a conventional landfill cap.

Bioreactor landfills can achieve greater waste densities than conventional landfills. This increased density will create high loadings on the basal liner and leachate drainage system. Both the liner and drainage system must be designed and constructed to accommodate these higher loadings.

Smaller landfill cells are preferred for bioreactor landfills, allowing quicker completion (including completion of gas extraction equipment installation) and improved operational control.

The operation of a bioreactor landfill requires a higher degree of management skill than a conventional landfill. Constant monitoring of the operation of the leachate collection system, recirculation system and gas collection system is required. Remedial actions and performance enhancement systems are required to effectively manage the landfill.

Bioreactor landfill design and the associated application must demonstrate how all elements affecting the performance of the bioreactor landfills will be monitored and maintained.

In considering any application for a bioreactor landfill cell at an existing site, the proponent will be required to demonstrate that the proposal meets all required outcomes for siting as set out in Section 5 (‘Best-practice siting consideration’).

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

BIOREACTOR LANDFILLS

Relevant BPEM objective

To maximise the rate of degradation of biodegradable wastes and achieve the same or better levels of environmental protection as a conventional landfill

Required outcomes of the BPEM

- Protection of liners from higher temperatures that will develop in the waste mass.
- Install landfill gas collection systems progressively, and the final system is in place no later than two years after placement of waste in any cell or sub-cell.
- Design and use of monitoring systems for moisture control, gas generation and temperature.
- Avoidance of the creation of low-permeability barriers within waste mass.
- An accredited management system that provides a high level of assurance that construction and operational performance will be consistent with or better than that required of a conventional landfill.

Suggested measures of the BPEM

- Placement of solid inert waste as first lift above liner to mitigate temperature impacts.
- Progressive installation of landfill gas extraction systems.
- Installation and use of monitoring systems for gas composition and flow rates.
- Installation and use of monitoring systems for introduction and collection of leachate and temperature.
- Installation of leak detection systems within clay basal liners to monitor seepage rates.
- Removal of non-biodegradable material (plastic film, metal etc) from waste stream prior to placement of waste to reduce creation of perched zones.
- Removal of low-permeability layers used as temporary capping or covers prior to placement of wastes within a cell.

6.9 Noise

Landfill operations generally involve noisy plant and can impact detrimentally on the amenity of surrounding areas. Sources of noise at a landfill include trucks (body, engine and exhaust noise), reversing ’beepers’, external telephone bells and PA announcements, mobile machinery and equipment used for resource recovery operations such as concrete-crushing equipment.

In the Melbourne metropolitan area, industry must comply with the noise limits prescribed by SEPP (Control of Noise from Commerce, Industry and Trade) No. N-1. Outside this area, industry must comply with the guideline Noise from industry in regional Victoria, currently in draft form, which will replace N3/89 – Interim guidelines for control of noise from industry in country Victoria.

In SEPP N-1 and the EPA guidelines, noise limits are tighter outside the normal working day, such as in the evening and, especially, at night. To meet these limits, it may be necessary to avoid certain operations before 7 am and after 6 pm on weekdays, before 7 am and after 1 pm on Saturdays and throughout Sundays and public holidays.

Where noise is considered an actual or potential concern (due to changing land use), an acoustics specialist should predict the noise levels at the nearest current or future sensitive receptors, and recommend measures to control the noise.

Site operations should be set out to minimise noise impacts by using natural and/or constructed features such as earthen bunds and depressions as well as minimising steep-haul roads.

Alternative types of reversing beepers could be adopted. Broadband reversing alarms or smart beepers are less disturbing to neighbours and could meet occupational health and safety requirements.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

NOISE

Relevant BPEM objective

To ensure that policy and guideline noise requirements are achieved and that there is no loss of amenity from noise from the landfill site.

Required outcomes of the BPEM

- In the Melbourne metropolitan area, compliance with the noise limits prescribed by SEPP (Control of Noise from Commerce, Industry and Trade) No. N–1 1989.
- Outside the Melbourne metropolitan area, compliance with noise guidelines issued by EPA.

Suggested measures of the BPEM

- Set the site out to minimise noise impacts.
- Use earthen bund walls to provide an acoustic screen to homes.
- Manage operating hours.

6.10 Traffic considerations

Due to safety concerns, noise, road grime and the increased cost of road maintenance, movement of trucks on local roads may be a concern to local residents and councils.

Limiting access routes and speeds of vehicles, as well as limiting the hours of operation, can minimise noise disturbance to the local community. Another consideration is the design of the site layout to ensure that trafficked areas, such as the location of parking, the entrance gate and the weighbridge, are away from sensitive land users.

Provision of traffic control devices, such as traffic islands and merging lanes at the entrance to the landfill, may need to be considered to minimise the impact of traffic. Recessing the entrance into the landfill helps to minimise vehicles queuing along public roads, as well as assisting in the control of dirt from the site.

The accumulation of dirt on sealed external access roads can be avoided by vehicles exiting via a wheel wash or some other equivalent wheel and underbody-cleaning mechanism. The road layout within the landfill should encourage the use of wheel-cleaning devices by truck drivers, and be placed so that the gatehouse attendant can visually check that the vehicle has been cleaned.

Where external access roads are sealed, the road from the wheel wash should also be sealed and regularly cleaned to reduce the dirt re-entrained by the vehicle. Internal roads should also be sealed as far as possible into the site to reduce the amount of dirt accumulating on the vehicle and allow more time for dirt already accumulated on the vehicle to fall off before it leaves the site.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

TRAFFIC CONSIDERATIONS

Relevant BPEM objectives

To minimise nuisance from traffic movement.

Required outcomes of the BPEM

- Minimisation of safety concerns, noise and road grime on external roads.

Suggested measures of the BPEM

- Encourage trucks, where possible, to use access roads that will have the least impact on the surrounding community.
- Locate trafficked areas away from sensitive land users.
- Provide traffic-control devices and signage near the landfill entry.
- Assurance that all vehicles leaving the landfill have all soil removed from the wheels and underbody before entering public roads.
- Seal the road from the wheel wash to the public road where the public road is sealed.

6.11 Site security and fencing

Site security and fencing is a public liability issue for the landfill operator to manage. The following information is for guidance only.

Active landfill sites can present a safety risk to the public and livestock. The site should be securely fenced to prevent the unauthorised entry of people or livestock. When unattended, the gates should be securely locked. Fencing should be regularly inspected and any damage to the fence that would allow unauthorised access be repaired as quickly as possible. When designing a fence, consider the probability that unauthorised people will want to gain entry to the site.

Any particularly dangerous areas, such as disposal areas for slimes or leachate ponds, should have signs to indicate the danger posed.

The minimum recommended fencing requirements are summarised in Table 6.6..

Table 6.6: Minimum recommended fencing requirements

	Population served			
	< 5,000	5000–10,000	10,000–50,000	More than 50,000
Extractive industry sites	A	A	A	A
Trench-and-fill	B	B	A or C	A or C
Topograph y change	B	B	A or C	A or C

1 A wire mesh fence at least two metres high constructed around the landfill site perimeter.

2 A stock-proof fence constructed around the perimeter of the landfill site, and relocatable litter screens erected near the tipping area.

3 A wire mesh fence at least two metres high constructed around the tipping area only, and a stock-proof fence around the perimeter of the site.

In areas where there may be a higher risk of unauthorised people entering the site, such as where the landfill is next to a recreational area, these minimum fencing requirements may need to be upgraded.BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

SITE SECURITY AND FENCING

Relevant BPEM objective

To prevent the unauthorised entry of people or livestock.

Required outcomes of the BPEM

- Design fencing to minimise unauthorised access to the site.

Suggested measures of the BPEM

- Install and maintain fencing to the site that meets the minimum requirements summarised in Table 6.6.
- Signal any particularly dangerous areas with signs.

6.12 Low-risk rural landfills

Small rural municipal landfills that meet criteria set out below may use Type 3 landfill design criteria for capping and lining systems. This variation to requirement for Type 2 landfill containment systems is made on the basis that small, appropriately located rural landfills pose a lower risk and therefore may meet the relevant environmental protection objectives with Type 3 design.

The criteria for a site to be considered a low-risk rural landfill are that:

- it meets or exceeds the buffer requirements as set out in Table 5.2
- it receives less than 20,000 tonnes of waste per annum
- wastes are at least two metres above the long-term undisturbed groundwater level
- it is not located in Segment A groundwater
- financial assurance to the satisfaction of EPA is in place.

All the above criteria must be met for a landfill to be considered a low-risk rural landfill.

7 Best-practice operation

Protection of the environment from landfilling activities in addition to the landfill design and construction also includes operational practices which further enhance the protection of the environment.

In particular, the elements of a landfill's operations that need to be considered are:

- environmental management
- financial assurance
- waste minimisation
- waste acceptance
- waste pretreatment
- waste placement
- waste cover
- litter control
- dust and air emission control
- fires
- contingency planning
- management of chemicals and fuel
- disease vector control
- noxious weed control
- performance monitoring and reporting.

7.1 Environmental management

In accordance with the *Waste Management Policy (Siting, Design and Management of Landfills)*, the holder of a licence for a landfill site is required to develop an environment improvement plan (EIP).

The requirements of an EIP as set out in the WMP should be addressed through an environmental management system (EMS). This needs to take into consideration any relevant neighbourhood environment plan, regional waste management plan and any solid industrial waste management plan.

The EMS should be used by the landfill operator to provide clear directions and procedures for the staff at the landfill to follow to ensure the environment is protected and that appropriate records are retained. As the EMS will be influenced by site-specific circumstances and is used by the landfill operator to ensure the landfill meets the appropriate performance standards.

The complexity of the environmental management at the landfill site depends on the potential and actual environmental risks inherent in operating the landfill. The risk assessment and monitoring program described in the *Landfill licensing guidelines* (EPA publication 1323) will provide valuable guidance in managing environment at the landfill sites.

The key elements are:

- commitment from senior management to an environmental policy that is clearly communicated to all staff
- articulation of statutory requirements
- a thorough review of the actual or potential environmental impacts and preparation of plans to reduce them, which include specific objectives and targets
- mechanisms to implement improvements including the designation of responsibilities, communication processes, document control and operation procedures
- training of all relevant staff in the implementation of improvements
- mechanisms to check and review environmental performance
- management reviews of the system's performance
- commitment to continuous improvement.

International Standards ISO 14001 and ISO 9001 provide guidance on environmental management systems and quality management systems respectively.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

ENVIRONMENTAL MANAGEMENT

Relevant BPEM objective

Protect the environment by managing environmental risks.

Required outcomes of the BPEM

- Ensure that a site specific environmental management procedure is in place to manage key risks and provide for contingencies.
- Training of all relevant staff in the implementation of the site's environmental management procedure.

Suggested measures of the BPEM

- Use ISO 14001 for guidance on the development of an environmental management procedure.

7.2 Financial assurance

Financial assurance is a requirement of the EP Act and all licensed landfill are required to hold an EPA-approved financial assurance.

A financial assurance is intended to provide a guarantee that the costs of site remediation, site closure and post-closure liabilities are not borne by the State. These costs are incurred when business operators abandon their site, become insolvent, or incur clean up costs beyond their financial capacity.

All licensed landfill operators are required to develop and provide a financial assurance in accordance with the EPA method. The financial assurance will be held for the period that the landfill continues to pose a risk to the environment, and may be discharged by EPA when monitoring and regular inspection demonstrate that the landfill no longer poses a risk to the environment.

To ensure that the appropriate level of financial assurance is maintained, financial assurances are subject to review.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

FINANCIAL ASSURANCE

Relevant BPEM objective

To provide a financial assurance for environmental management costs incurred during the operation, closure and aftercare of a landfill.

Required outcomes of the BPEM

- All licensed landfill operators are to maintain a financial assurance acceptable to EPA.

Suggested measures of the BPEM

- Use an EPA-approved method to calculate an appropriate level of financial assurance.
- Progressive rehabilitation to keep financial assurance costs to a minimum.

7.3 Waste minimisation

The State Government Sustainability in Action – Towards Zero Waste (TZW) Strategy contains targets and strategies that cover all aspects of solid waste management in Victoria. The TZW strategy contains targets to reduce the volume of waste generated and increase the percentage of waste recovered for reuse, recycling or energy generation.

Regional waste management plans, including the Metropolitan Waste and Resource Recovery Strategic Plan, were developed to further deliver on key targets and intentions of the TZW strategy.

Landfilling is the least preferred option in the waste hierarchy. Every practicable opportunity should have already been taken to avoid waste production and remove recyclable material from the waste stream before it arrives at the landfill. This is particularly pertinent for wastes generated in significant volumes at a single site, such as construction and demolition waste from large projects.

Material presented at a landfill should be sorted either by the waste generator or at some intermediate facility such as a transfer station to remove and recover recyclable material prior to deposition in the landfill.

Where the landfill takes unsorted waste, infrastructure such as a transfer station or drop-off bins should be provided at the landfill to facilitate the recovery of recyclable material. The site recording system should record the waste diverted from landfill separately from waste landfilled.

In some exceptional cases it may be more efficient to sort the waste on the tipping face rather than at a transfer station. This will typically be the case at sites that only receive waste from commercial operators.

Green waste should be processed in accordance with *Environmental guidelines for composting and other organic recycling facilities* (EPA publication 508), after which it may be sold or used on the rehabilitated landfill surface to improve the quality of the topsoil and to help prevent erosion. Green waste used for this purpose should be free of noxious weed seeds.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

WASTE MINIMISATION

Relevant BPEM objective

To divert suitable wastes from landfill.

Required outcomes of the BPEM

- Removal of recyclable materials from the waste stream, where feasible.

Suggested measures of the BPEM

- Carry out a waste minimisation assessment that examines opportunities for waste avoidance, reduction, reuse and recycling.
- Where possible, ensure that waste received is sorted prior to deposition.
- Work with waste generators to ensure that the waste to be landfilled is minimised.
- Preserve topsoil for use during site rehabilitation works and use mulched green waste to improve this topsoil and help control erosion.

7.4 Waste acceptance

Signs advising which wastes may be deposited at the landfill must be provided. Signs should be provided to show where recyclable materials from waste that has not been through a transfer station or municipal recycling facility may be placed.

Landfill staff must be vigilant to ensure that only wastes specified in the EPA licence are accepted and deposited at the premises.

Loads containing non-conforming wastes can sometimes be identified by visual inspection, such as observing drums on a truck or other unusual characteristics.

Facilities such as elevated mirrors, viewing platforms or video cameras may be used to screen incoming waste loads. Random inspections of incoming loads must, however, be conducted. Records of these inspections must be kept. In particular, a random inspection program must be developed for all waste loads not from secure sources such as transfer stations. The frequency of inspection will depend on the type and quantity of waste received and whether problems have previously been identified. A typical inspection frequency is, on average, 1 in 10 vehicles being physically inspected.

There should be a communication system linking staff at the landfill tipping area to the gatehouse. Procedures must be developed to deal with the dumping of non-conforming wastes at the landfill, and must contain procedures for the identification of the waste dumper, isolation of the waste and notification of authorities.

These procedures must be contained in the site environmental management procedure and implemented where such wastes are dumped.

Where sites are licensed to accept prescribed wastes such as asbestos or Category C soils, the landfill operator is required to ensure compliance with the licence acceptance criteria. In the case of asbestos, site operators are required to ensure that asbestos transport and disposal is carried out in accordance with the Industrial Waste Resource Guideline *Asbestos transport and disposal* (EPA publication IWRG611).

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

WASTE ACCEPTANCE

Relevant BPEM objective

To ensure that only allowed wastes are deposited at the landfill.

Required outcomes of the BPEM

- Landfill operator to ensure that non-conforming waste is not disposed of at the landfill site.
- Provide signs advising the types of wastes allowed at the site.
- Implement a procedure to deal with the dumping of non-conforming waste at the landfill site.

Suggested measures of the BPEM

- Ensure that the landfill is staffed at all times it is open for the receival of waste.
- Conduct random inspections and sampling of waste loads.
- Train landfill staff to recognise conforming and non-conforming wastes.

7.5 Waste pretreatment

The pretreatment of waste prior to landfilling is intended to reduce the long-term risk posed by the waste and to improve general landfill performance.

Approaches to pretreatment include:

- recovering fractions that have high calorific value, are recyclable or are compostable
- modifying the physical form or mix of wastes going to landfill through shredding, baling or compacting.

By removing the waste that has a high calorific value or is compostable, landfills containing the residual waste stream require a shorter aftercare period and have fewer landfill gas emissions to the environment (see section 6.7 and Appendix B for more information on landfill gas generation). Best practice is to continually improve efforts to remove putrescible fractions from the waste stream.

A waste pretreatment approach that reduces the risk of landfilling waste is mechanical–biological pretreatment. This involves the mechanical separation of waste into different fractions and the biological treatment of the putrescible fraction to a relatively stable material. The gas generation potential is significantly reduced and leachate volume and strength reduced in pre-treated wastes compared with untreated wastes. This means that the aftercare period may be considerably reduced.

Besides the reduced gas and leachate generation potential, pre-treated wastes can be placed at a greater density and are subject to less settlement. Dependent upon the degree of biological treatment, the residual wastes landfilled could be considered as inert wastes.

Shredding or baling wastes may reduce some environmental effects of landfilling but do not in themselves reduce the putrescible fraction within the waste stream.

Shredding involves the ripping of waste into strips and also may entail the removal of recyclable and reusable materials still contained in the waste stream. The shredded waste is generally more homogeneous than the non-treated waste and therefore not subject to the same amount of differential settlement. After compaction, the density of shredded waste is usually greater that that of the non-shredded waste; however, shredding may result in significant litter problems.

Baling involves compacting and binding waste into solid bales. Baled wastes can be neatly stacked and may reduce the amount of litter and demand for cover material. High-density balers can also increase the quantity of waste that may be deposited in a landfill.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

WASTE PRETREATMENT

Relevant BPEM objective

To reduce the long-term risk posed by the waste and to improve general landfill performance.

Suggested measures of the BPEM

- Maximisation of the stability of waste going to landfill through pretreatment.
- Separate putrescible fractions from waste streams where possible, and continually improve the separation of putrescible wastes.
- Shred and/or bale wastes to improve landfill management and performance.

7.6 Waste placement

By maintaining tight controls on waste placement, litter and birds can be controlled and the degree of waste compaction maximised.

To contain litter and to reduce the attraction to birds and other pests at Type 2 landfills, the size of the active tipping area should be kept as small as possible. The size of the tipping face will vary according to the volume of traffic.

Waste should generally be placed at the base of the face, with a compactor pushing waste up the face and compacting it in thin layers. The thickness of the waste layer should not exceed 0.5 metres and the compactor should make three to five passes over the waste to maximise compaction and thus minimise settlement.

To minimise the quantity of cover material used, the tipping face should be kept small, ideally less than 30 metres in length. The total height of the layers combined in the lift should be less than two metres.

Wastes, particularly putrescible wastes, must be covered by the end of each day's operation. It is good practice at putrescible landfills to continually apply cover as wastes are deposited.

Operating a landfill on a cellular basis, particularly in a former extractive industry site, will often mean that at least one face or side of the cell will not be confined. In these circumstances, waste must be placed so that it is stable and can be covered by earth or other approved cover materials.

The limiting factor for the gradient of an unconfined volume of waste within a landfill will usually be governed by the stability of the cover soil placed over that exposed area. Gradients steeper than two horizontal to one vertical units should be avoided, unless it can be demonstrated that both the waste and the cover material are mechanically stable.

An initially safe, dry cover may subsequently slide down a slope due to water saturation, which increases the weight of the cover and decreases the friction resistance along the waste.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

WASTE PLACEMENT

Relevant BPEM objectives

To place waste in a manner that is mechanically stable, controls litter and birds and that maximises the degree of compaction.

Required outcomes of the BPEM

- Maintenance of an active tipping area that is as small as possible.
- Compaction of all waste deposited in the landfill.
- Assurance that waste is placed so that all unconfined faces are mechanically stable and capable of retaining cover material.

Suggested measures of the BPEM

- Keep covering waste to maintain the active tipping area at less than 30 metres x 30 metres.
- Place wastes at the base of each lift and compact wastes in layers of less than 2 metres.
- Avoid unconfined waste slopes with gradients steeper than 2 horizontal to 1 vertical unit.

The stability of waste and cover material may be further enhanced by terracing the unconfined face.

Whenever special wastes such as quarantine wastes are deposited, they should be immediately buried and covered. If trenches need to be excavated in the landfill to allow immediate burial of the waste, excavations should be made just before the arrival of the load.

7.7 Waste cover

An essential part of landfilling operations is the placement of cover over wastes.

The purpose of cover is to:

- minimise landfill odours
- control litter
- prevent the spread of fire
- control disease vectors such as birds, flies, mosquitoes and rodents
- ensure that the landfill is trafficable.

To achieve these outcomes, waste must be covered at the end of every day, though landfills that receive significant volumes of waste in a day might need to progressively cover waste during the day. Landfills that accept only solid inert or building material may not require daily cover provided that emissions (odour, dust litter and so on) are adequately controlled.

Where soil is used as cover, the soil should contain some organic matter, as this helps to attenuate landfill odours; the thickness of soil applied should be sufficient to achieve the above points. Typical cover thickness is between 0.15 to 0.3 metres for solid inert and putrescible waste landfills respectively.

Materials other than soil, such as foams, mulch, papier-mâché, gravel or cover mats, may also achieve these purposes and may meet other operational needs, including landfill gas collection and enhanced biodegradation.

Daily cover material usage should be such that the permeability of the waste and cover should (eventually) be sufficient to allow leachate to pass and gas to be extracted without creating perched conditions. If compacted, clay soils in particular can have a relatively low permeability, which results in partial containment of each layer of waste. This will make both landfill gas and leachate extraction more difficult. To avoid waste containment, low-permeability daily cover should be partially removed prior to waste placement.

Cover material with a high moisture content, such as slimes from sand mining operations, should be avoided, as such material may release water into the waste. Wet waste will decompose faster than a dry waste, producing significant quantities of gas from an open cell before a gas-extraction system can be installed.

Acid sulfate soils, as defined *by Acid sulfate soil and rock* (EPA publication 655), are not appropriate for use as cover material, as they oxidise and produce acid run-off when exposed to the atmosphere. Once started, this reaction continues in the absence of oxygen, that is, after the cover has been filled over.

As cover material may be open to the atmosphere for extended periods, acid sulfate soil in cover material would be expected to generate acid. Any site that uses acid sulfate soil, including slimes, must hold an environmental management plan from EPA, as set out *in Industrial Waste Management Policy (Waste Acid Sulfate Soils).* A landfill must not accept acid sulfate soil unless it has an environment management plan for the acceptance of the material, approved in writing by EPA.

With the lateral movement of the active tipping area across a landfill cell, it may be some time before the next lift of waste is placed over an older area. Cover material rich in clay may dry and crack during dry weather, thus releasing landfill gas and odours. It is good practice to consolidate the cover on older areas of the landfill cell by running a roller over the cover. It may also be necessary to moisten the cover to close any cracks that have formed.

Where soil is used for cover, a stockpile of soil to be used as cover material needs to be provided. Regardless of the material used as cover, sufficient material should be available at the tipping face for at least two weeks of operations.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

WASTE COVER

Relevant BPEM objective

To ensure that wastes are covered appropriately, to mitigate against any environmental or health impacts.

Required outcomes of the BPEM

- Covering of the waste, at least daily, with soil or another approved cover material for all sites that accept putrescible waste and maintain the cover.
- Close cracks in old, exposed cover layers to contain landfill gas and odour.
- No use of acid sulfate soil as daily cover.

Suggested measures of the BPEM

- No covering with wet material
- Where soil is used as cover, cover with 0.15 to 0.3 metres of soil.
- Avoid creating low-permeability confining layers in the landfill by partial removal of low-permeability cover material prior to placement of wastes in that location.
- Stockpile sufficient cover material at the tipping face for at least two weeks of operations.

7.8 Litter control

Municipal waste, especially plastic bags, can be spread over a wide area by the wind. This litter not only looks unsightly but might also foul drains and waterways, as well as interfere with neighbouring activities such as quarrying or farming.

Litter control at landfills will vary throughout the year depending on wind strength and the orientation and elevation of the tipping area. No single control option will be entirely successful for the entire life of the landfill. A litter control strategy must, therefore, be flexible and include both engineering solutions and management options.

As a minimum, a best-practice landfill will use litter screens and train staff in the appropriate placement of the screens to trap as much litter as possible. These litter screens should be portable to be able to follow the tipping area, and should be capable of withstanding wind loads when loaded with litter. Litter screens should be at least four metres high.

A best-practice landfill will also minimise the size of tipping areas and have at least a daily litter program in which fences and surrounding areas are cleaned of any litter. It will also have contingency plans for which resources are engaged to deal with extreme events that cause gross litter problems.

In areas where litter is especially problematic, this may involve a dedicated litter crew, more frequent covering and enhanced litter screens. Such landfills may also have dedicated areas for waste deposition that are more sheltered from winds from particular directions, and therefore minimise litter from the landfill.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

LITTER CONTROL

Relevant BPEM objective

To keep the landfill and surrounding environment in a litter-free condition.

Required outcomes of the BPEM

- That no litter from the landfill operations reaches beyond the boundary of the premises.

Suggested measures of the BPEM

- Minimise the size of the tipping area.
- Use litter screens at least four metres high to control litter at the active tipping area.
- Establish a program of at least daily cleaning of litter from fences and the surrounding area.
- Deposit waste in areas of the landfill that are sheltered from the wind.
- Establish contingency plans to deal with extreme events that cause gross litter problems.
- Use of appropriate daily cover to reduce litter.

7.9 Fires

Landfill fires can cause significant impacts on local air quality through odour and smoke. They can also spread outside the landfill, triggering a grass or bushfire. Subterranean landfill fires may burn for many years before they are detected. The smell of smoke or the presence of carbon monoxide in the landfill gas may be the first sign that a landfill is burning and, in some cases, the surface of the landfill may collapse as a result of the fire creating a subsurface cavity. If this collapse is triggered by the passage of a vehicle over the cavity, it could be fatal for the vehicle's occupants.

Once started, landfill fires are difficult to extinguish, so the primary objective should be to prevent a fire from starting. This is done, as far as is practical, by removing potential ignition sources, such as hot coals, from the tipping area. Other measures include not burning waste and not lighting fires on or near areas where wastes have or are being deposited.

Finally, wastes should be covered with non-combustible material.

The level of carbon monoxide in landfill gas provides some indication whether there is or has been a subsurface landfill fire. Carbon monoxide is produced when there is insufficient oxygen present, such as within a landfill, to fully burn the fuel.

Carbon monoxide levels in excess of 1,000 ppm strongly indicate that there is a fire burning within the landfill. Levels above 100 ppm are not as conclusive but should be investigated as part of the fire investigation plan with further gas and temperature measurements to determine if and where there is or was a fire.

Some field meters can provide false results for carbon monoxide due to other constituents of landfill gas such as hydrogen and hydrogen sulfide. Fitting appropriate filters or laboratory analysis of the collected landfill gas provides more accurate results.

If a fire should start, every effort must be made to extinguish it before it gets established. Equipment to extinguish a fire must be readily available at any time to enable a prompt response to any part of the premises. A water supply, either reticulated or from dams or tanks, combined with a means of delivery (pump and hoses or a tanker truck), allows prompt extinguishing of a fire on the site. Groundwater and stormwater in dams might be suitable for combating a fire. Leachate should not be used unless all parties are aware of the possible risks and adequate measures are taken to reduce human exposure. Where reticulated water is not provided, at least 50,000 litres should be stored onsite for combating small fires. For a significant fire, this volume will need to be supplemented by another source of water.

It is not usually possible to extinguish deep-seated fires using water except where the operator has sufficient plant and water to excavate and extinguish all burning waste. Where extinguishment is not possible, adding water to the landfill exacerbates the fire because the water adds oxygen to the fire. Attempts to dig out deep seated fires with inappropriate plant may exacerbate the situation by admitting air. To combat deep-seated fires, key elements are to minimise oxygen ingress to the fire by capping off the area and surcharging the area with claylike material. Landfill gas vents and extraction systems in the vicinity of the fire should be plugged.

In some areas, the local fire authority might require a firebreak to prevent the spread of fire into or out of the site. This, in conjunction with developing a fire management plan with the local fire authority, is best practice in areas where grass or bushfires might be a concern.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

FIRES

Relevant BPEM objectives

To prevent landfill fires and efficiently extinguish any that should occur.

Required outcomes of the BPEM

- Maintenance of a water supply capable of being delivered to any point on the landfill.
- No fires must be lit at the landfill or near areas where wastes have been or are being deposited.
- That all practical steps have been taken to prevent landfill fires.

Suggested measures of the BPEM

- Develop a fire-management plan in conjunction with the relevant fire authority.
- Remove ignition sources such as hot coals and car and marine batteries from the waste at the tipping area.
- Cover combustible wastes with inert material.
- Construct a firebreak around the perimeter of the landfill to the satisfaction of the relevant fire authority.
- Where the reticulated water supply is not adequate for fire fighting purposes or not available, maintain at least 50,000 litres of water onsite.

7.10 Contingency planning

To ensure that appropriate measures are taken in the event of an incident or anomaly, contingency plans must be developed for implementation to deal with such incident or anomaly.

Contingency planning should form part of the site environment management system. All staff at the landfill must be trained in the implementation of the contingency plan.

The contingency plan must consider all impacts discussed in this guideline and, in particular:

- the detection of contamination of surface or groundwaters
- detection of landfill gas
- blockage of leachate and landfill gas collection pipes

- a landfill fire
- deposit of unauthorised waste
- offensive odours or dust beyond the boundary of the premises
- litter beyond the boundary of the premises
- equipment breakdown
- flare or power outage.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

CONTINGENCY PLANNING

Relevant BPEM objectives

To ensure that all potential incidents are considered and that appropriate measures are planned to deal with them.

Required outcomes of the BPEM

- A contingency plan is in place
- All likely impacts are covered in the preparation of the contingency plan.
- All staff are trained in the implementation of the contingency plan.

Suggested measures of the BPEM

- Review the document after any incidents covered by the plan.

7.11 Management of chemicals and fuels

Landfill operations may use a variety of chemicals and fuels. If these are inappropriately managed they can impact adversely on the environment.

The storage and handling of flammable and combustible liquids should be in accordance with the provisions of AS 1940–2004 *The storage and handling of flammable and combustible liquids and Bunding guidelines* (EPA publication 347).

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

MANAGEMENT OF CHEMICALS AND FUEL

Relevant BPEM Objective

To manage the storage and handling of chemicals and fuels so as to minimise the risk of impact on the environment.

Required outcomes of the BPEM

- Storage and handling flammable and combustible liquids in accordance with the provisions of the AS 1940–2004 'The storage and handling of flammable and combustible liquids'.

Suggested measures of the BPEM

- Keep onsite chemical and fuel inventories to a minimum.
- Construct bunds for liquid storage areas in accordance with the appropriate regulatory guidelines and/or standards.
- Locate storage areas away from waterways or areas prone to flooding.
- Implement a contingency plan to handle spills to avoid environmental damage.

Particular measures include keeping inventories to a minimum, bunding liquid storage areas and locating them away from waterways or areas prone to flooding, and having a contingency plan for the management of any spills as part of the site environment management system.

7.12 Disease vector control

Flies, mosquitoes, rats, cats and birds (typical disease vectors) are attracted by food wastes and still waters at landfills. If uncontrolled, these pests can affect public health and surrounding ecosystems.

The main mechanisms for the control of disease vectors are the use of cover material to cover waste daily (see section 7.7) and eliminating any waterbodies that are not required for fire, sediment and leachate control. Other measures, such as scare devices and traps, can also be used to reduce or control infestations.

Professional pest exterminators should be employed to reduce problem infestations of vermin.

Landfills located near airports, close to a surface water supply, or industrial or residential areas that may be affected by bird droppings, need a high level of bird control.

The most successful bird-deterrent strategies rely on a variety of techniques. While the immediate spreading of cover material over the wastes may not entirely deter birds, it can be supplemented with other options, such as nets or monofilament wires over glide-paths or water dams, anti-perch strips on buildings, and active measures such as acoustic bird-scaring devices (gas guns or mimicking distress calls), predator decoys or even using dogs.

Since birds become accustomed to one particular measure, some variation in the active measures used is necessary.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

DISEASE VECTOR CONTROL

Relevant BPEM objective

To minimise disease vectors emanating from the landfill by denying pests food and shelter.

Required outcome of the BPEM

- Cover waste daily.

Suggested measures of the BPEM

- Elimination of any waterbodies at the landfill that are not required for fire, sediment or leachate control.
- Use professional pest exterminators to reduce problem infestations of vermin.
- Vary bird scare methods to avoid any patterns in methods.

7.13 Noxious weed control

Once noxious weeds become established at a landfill, they can spread through surrounding areas and adversely impact farming activities and natural ecosystems.

Noxious weeds can become established through colonisation or through introduction by contaminated seed or weed-infested mulch used to revegetate exposed areas of earth. To minimise the risk of introducing weeds through planting, only high-quality seed, free from any noxious weeds, should be used.

Where an area is to be mulched, ensure that the mulch is free of noxious weeds. Where the site accepts green waste to be subsequently used for mulching, a degree of diligence is required to prevent noxious weeds from being added to the green waste heap. Such waste should be landfilled.

Any noxious weeds onsite should be managed by regularly inspecting the site for noxious weeds and eradicating any weeds present through appropriate means.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

NOXIOUS WEED CONTROL

Relevant BPEM objective

To manage the landfill site so that it does not become a source of noxious weeds.

Required outcomes of the BPEM

- Minimise the introduction of noxious weeds to the site.
- Eradicate any noxious weeds that have established themselves onsite.

Suggested measures of the BPEM

- Ensure that all plantings from seed are from only high-quality seed. Mulch should be completely free of weeds.
- Regular inspection of the site for the presence of noxious weeds. Record their presence and, if necessary, implement a control program.
- Where pest plants need eradication, this is to be done by appropriate means. If the problem is large or current methods are not working, seek the advice of the local council or the Department of Sustainability and Environment.
- Become involved in the local Landcare group to develop regional strategies to eradicate regional noxious weeds.

7.14 Performance monitoring and reporting

In order to assess the performance of the measures taken to protect the environment from any potential environmental impacts by the landfill, monitoring, assessment and reporting of the results are required.

EPA's requirements for monitoring and auditing are detailed in *Landfill licensing guidelines* (EPA publication 1323) and submission of annual performance statements are given in *Annual performance statement guidelines* (EPA publication 1320).

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

PERFORMANCE MONITORING AND REPORTING

Relevant BPEM objective

To monitor and report on the performance of measures taken to protect the environment from potential impacts from a landfill and to identify and address any arising environmental issues.

Required outcomes of the BPEM

- Preparation of a verified monitoring program in accordance with *Landfill licensing guidelines* (EPA publication 1323).
- Monitoring of the environment in accordance with the verified monitoring program.
- Submission of an annual performance statement.

Suggested measures of the BPEM

- Develop a workplace culture of identifying any potential environmental issues and taking corrective action before any impacts occur.
- Incorporate into the environment management system both on and offsite inspections by staff to check on any emerging environmental problems or the effectiveness of existing controls.

8 Best-practice rehabilitation and aftercare

Many of the chronic impacts of landfilling occur long after the landfill has closed. While these impacts can be mitigated by good design and operation, best-practice rehabilitation and long-term aftercare of the site will further minimise the potential of any detrimental impacts from the landfill.

Best practice for rehabilitation and aftercare is considered very early in the design and operation phase of the landfill. This section of the Landfill BPEM applies to all existing landfills and closed sites.

8.1 Rehabilitation

8.1.1 Rehabilitation plan

To ensure that the objectives of rehabilitation are achieved, a conceptual rehabilitation plan must be developed as part of the initial landfill design.

The rehabilitation plan should deal with afteruse options for the site and provide a blueprint for the final surface contours and cap design of the landfill.

The rehabilitation plan should include:

- the potential afteruses of the site, taking into consideration current and likely future land use in the area surrounding the site
- operational requirements, to ensure that the capping is designed to suit the intended afteruse
- surface contours before and after settlement
- specifications and materials to be used in the final cap
- preservation/installation of environment performance control or monitoring features.

8.1.2 Progressive rehabilitation

Progressive rehabilitation of a landfill involves the closure and rehabilitation of each cell once filling has been completed during the operating life of the landfill. These works are effectively a staged closure of the landfill that occurs while the active cell is being filled.

Landfill cell rehabilitation works include:

- capping and revegetation in accordance with regulatory requirements
- installation and ongoing maintenance and replacement of gas and leachate collection infrastructure
- decommissioning of infrastructure no longer required.
- Environmental and management benefits of progressive rehabilitation include:
- collection and treatment of landfill gas during its peak generation period
- minimising the generation of leachate and offensive odours
- facilitating materials budgeting through the staged use of capping materials over the life of the landfill
- achieving cost recovery during the economic life of the landfill
- meeting financial assurance requirements.

8.1.3 Triggers for rehabilitation

Implementation of the progressive rehabilitation at a landfill should be consistent with the conceptual rehabilitation plan prepared during the initial landfill design. A landfill licence-holder should, where operationally practicable, sequence operations to complete the filling of each cell in turn, rather than leaving one or more partly filled cells inactive and not fully rehabilitated.

Where cells cannot be fully rehabilitated due to the layout of the site and the sequencing of filling, intermediate (temporary) capping must be installed.

In order to take best advantage of its inherent benefits, rehabilitation of a landfill cell should be initiated once:

- the landfill cell contents have reached the approved pre-settlement contours, allowing sufficient height to build the landfill capping within the pre-settlement contours
- further filling of the cell is operationally no longer required or feasible
- there has been a lawful direction to cease filling the cell
- the landfill is to be closed

or

- two years have elapsed since commencement of filling.

8.1.4 Site afteruse

In considering options for the use of the site after landfilling, the location of the landfill, needs of the local community, surrounding land uses and nature of the operation should all be considered. The relevant regulatory and planning authorities should be consulted, as they might have a strategic plan for the area that identifies how that land could potentially be used.

Proposals for the use of the filled landfill site should be flexible enough to allow for changes in community attitudes or planning requirements in the long period between commencement of landfilling and final rehabilitation.

Regular reviews of afteruse options are a good way of ensuring that the operation of the landfill does not alienate desired afteruses of the site. Understanding the afteruse during operation ensures that the final surface profile of the landfill is consistent with the desired afteruse.

For example, final landforms comprised entirely of steep slopes are generally inconsistent with public open-space use.

Common afteruses of landfills include sports grounds, public open space and golf courses. Closed landfill are not suitable sites for building or structures, as landfill gas emitted from the cap presents a safety risk and the capping of a landfill is not a stable platform to build on.

Historically, some landfills have been developed for commercial or industrial building development. Developments on landfill sites should only occur after an assessment that the landfill site no longer presents a risk. This will require complete risk assessment of the risks of landfill gas and the impacts of settlement on buildings and services such as water mains, gas and roads.

Closed landfills are considered to be contaminated sites and any end-use developments – including development of land in the surrounding buffer area – will require assessment by an EPA-appointed auditor.

Water features, such as ornamental lakes or ponds, should be avoided on landfills, as they may leak due to cracking of their liner from differential settlement of the landfill over time. This leakage may release significant volumes of water to the landfill, thus generating significant volumes of leachate.

8.1.5 Settlement and final surface profile

A landfill is subject to long-term settlement, as waste decomposes and consolidates. This settlement has significant impacts on the final surface profile, the landfill cap and potential afteruses for the site.

The rate and degree of settlement are dependent upon:

- proportion of putrescible wastes
- thickness of the landfill
- period over which wastes were placed in cell
- the degree of compaction
- the moisture content of the wastes
- the degree of surcharging or loading placed on the cap.

Long-term settlements for well-compacted landfills vary significantly and can range from 10 to 30 per cent.

Most of the settlement occurs within the first few years of the cell closure, the result of waste compressing under its own weight and the weight of the cap. After this initial compression, settlement will continue for many years, as a result of consolidation and biodegradation processes within the waste.

A landfill receiving largely non-putrescible wastes will have a lower range of settlement. Where landfill cells are filled rapidly, the settlement of the closed landfill will be higher than for an equivalent thickness of wastes placed over a longer period.

The landfill cap design is governed by limiting water infiltration into the landfill and gas migration through the cap; these are a function of the materials used in the cap and its shape. The gradient for a completed cap should be sufficient to prevent water ponding on the cap to minimise infiltration through the cap. Gradients of about five per cent will adequately shed water.

Where the proposed after use of the landfill require a gradient of less than 5% the cap design may need to incorporate additional levels of protection. Cap gradients of less than 1% are likely to have issues with water ponding in areas of differential settlement.

Caps should not be steeper than 20%. Caps steeper than this can have erosion problems and are more difficult to maintain than flatter caps. Steep caps will require specific engineering controls to ensure that they are stable. These controls will, typically, relate to relieving any seepage water pressures within the cap. They will also require features such as cut-off drains and rock beaching on drainage lines to control water erosion. In addition, the surface layer should be vegetated as quickly as possible to further control erosion. Until the vegetation becomes established, this revegetation program should be augmented with measures such as mulch or erosion mats to control erosion.

Since compaction of wastes along near-vertical side walls is difficult, the wastes along the walls of the landfill may exhibit the highest initial rate of settlement. The landfill cap needs to make allowance for this by providing sufficient thickness of the cap to ensure that run-off from the cap is not collected in depressions along the perimeter of the landfilled area.

The landfill aftercare program must include inspections of the cap, checking for differential settlement and indicators that the integrity of the low-permeability cap has been compromised. The frequency of the inspection program will be largely determined from the observed rate of settlement.

The use of plants on the landfill caps must consider the particular requirements of the cap design, and vegetation used must be compatible with the cap design. Conventional caps require plant roots not to penetrate the barrier layer underlying the topsoil layer. Phytocaps use different principles than conventional caps and require different vegetation strategies (see section 8.1.7 for further information).

8.1.6 Landfill cap

A key element of the rehabilitation is the capping of the landfill. The design objectives for the final landfill surface or capping are:

- minimising infiltration of water into the waste, ensuring that the infiltration rate does not exceed the seepage rate through base of the landfill
- providing a long-term stable barrier between waste and the environment in order to protect human health and the environment
- preventing the uncontrolled escape of landfill gas
- providing land suitable for its intended afteruse.

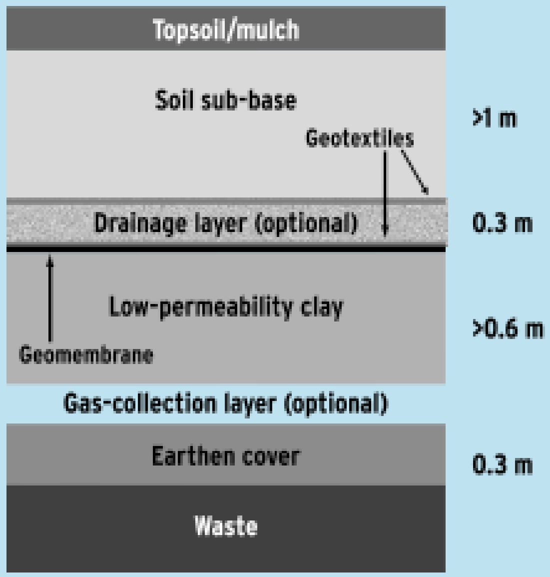
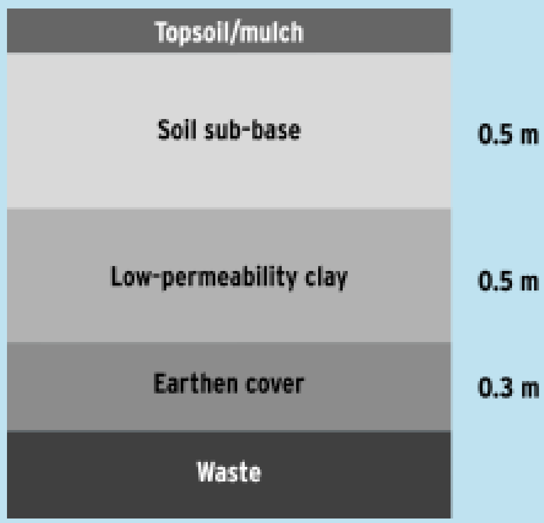
The long-term protection of the groundwater environment is provided by the landfill liner, leachate collection system and landfill cap.

Landfills are required to contain wastes for many decades after closure of the site. The landfill cap design must prevent leachate levels rising to the point where they could cause a leachate outbreak (so called bathtub effect). While the site is actively managed, leachate levels can be managed by the operation of the leachate collection system. However, eventually, leachate collection systems will either fail or no longer be operated. At this time, provided rainwater infiltration is less than seepage through the liner, leachate levels in the landfill will not rise to a level that would cause concern. To manage this concern, a required outcome is that the design seepage rate of the cap does not exceed 75 per cent of the design seepage rate of the landfill liner.

Table 8.1 indicates the required performance standards of caps, as well as indicative cap designs, which are based on preventing infiltration by providing a very low-permeability layer (clay or composite barrier).

Sites without a best-practice basal liner are still required to meet best-practice requirements for capping (in other words, the modelling must assume the basal liner was built in accordance with best-practice requirements).

Table 8.1: Indicative landfill cap designs

Type	Cap performance	Indicative landfill cap
2	75 per cent of the anticipated seepage rate through a liner that meets best-practice requirements	
3	75 per cent of the anticipated seepage rate through the liner that meets best-practice requirements	

Where the proposed afteruse of a landfill will require vegetation of the site, the topmost layer must be able to support vegetation and be of sufficient depth to ensure that roots do not penetrate the cap.

The surface layer should reflect the type and depth of topsoils normally found in the local area. Where it is not possible to duplicate the local topsoil conditions or the natural soil is too thin to support adequate vegetation for erosion control, an appropriate mix of soils 200 to 300 millimetres thick should be used. Any mulch used in the cap should be pasteurised, to remove weed seeds, plant pathogens and pests.

Introduced plantings on the landfill should not include any noxious weed variety for that area, nor should the landfill provide a haven for weeds migrating from the surrounding area (see section 7.13 for more detail on the management of noxious weeds).

Advice should be sought on species selected for planting, to prevent them from becoming local pests.

In general, EPA advises that planting be restricted to species indigenous to the area and of local provenance, in order to:

- avoid inappropriate planting
- ensure the species are adapted to the local climate
- enhance the local habitat.

To limit seepage, a layer of low-permeability clay and/or a flexible membrane liner may be required in the cap. Selection and installation of geomembranes must comply with the requirements set out in Appendix D.

- The construction and maintenance of a low-permeability clay layer for a cap is difficult for a number of reasons, including:
- the spongy foundation of waste on which it is built
- differential settlement of the waste causing cracking of the clay
- desiccation of the clay from above – due to evapotranspiration – and below – due to heat released from the landfill.

All of these significantly increase the effective hydraulic conductivity of the clay; the estimate of seepage rates through the cap should make allowance for this.

A drainage layer is sometimes placed between the soil layer and the low-permeability capping layer. The purpose of the drainage layer is to remove excessive moisture that has permeated through the soil layer and will not be removed by evapotranspiration. Due to problems with desiccation of the surface or low-permeability layer, drainage layers are generally only used in high-rainfall areas or where the cap has a very shallow gradient.

If a drainage layer is incorporated into the landfill cap, then it must be designed so that it does not dry out the surface layer, thereby killing vegetation, and does not prevent the continued hydration of the low-permeability barrier layer, which would cause it to dry and crack. The drainage layer may be a sandy soil or gravel, which conveys water to a drainage system at the toe of the landfill cap.

Care must be taken to ensure that the drainage layer is able to drain water from the landfill, as an accumulation of water at the toe of the cap may cause instability in the cap.

8.1.7 Alternative landfill cap

Alternative landfill caps, such as evapotranspiration caps (referred to as 'ET caps') or phytocaps, are increasingly being proposed in Australia and used internationally.

Phyotocaps seek to reduce the rate of infiltration into the landfill by using the water-removal capability of plants (transpiration) and water-storage capacity of the soils in the cap. Phytocaps must provide similar performance outcome as specified in Table 8.1. Similar performance in the case of phytocaps only, means that the performance requirement outlined in Table 8.1 is annualised over a climatic average year. This means that 75% of the seepage rate of 10 L/Ha/day can be interpreted as 2740 L/Ha/year for a type 2 landfill as the long term performance requirement for an established phytocap.

Proving the performance of a phytocap is more complex than for a conventional cap and, therefore, assessment of a phytocap proposal will require more detailed information on how the expected performance will be achieved.

The overall performance of the phytocap is determined by the interaction between the following three factors:

- soil properties
- climate
- vegetation.

Designing of phytocaps requires a detailed understanding of soil properties, including proposed soil source area variability, and acceptance limits for use in the cap where variability exists. This understanding of the soil must also accommodate the range of conditions in which the soil may be placed, including compaction and any conditioning requirements.

Climatic factors in Australia can vary significantly from the climates of the international studies available on phytocaps. The specific affect of climatic extreme events, including prolonged wet or dry periods, must be assessed in the evaluation of the performance of a phytocap.

A thorough understanding is required of the range of vegetation to be used on the site, including the time to maturity, regeneration, root depth, weed resistance, tolerance levels and seasonal growth patterns. The thickness of the soil layer plays a key role and hence the minimum thickness must be 1.5 m.

The long-term (20–30 yrs) survival of plants is important for phytocaps to be effective. Hence, the phytocap design must include a monitoring and maintenance program to ensure integrity of the cap and for the survival of plants.

Leachate must be appropriately monitored and managed, and refer to section 6.5.2 for further details.

Phytocaps typically do not use compacted clay layers or membranes in their construction. This must be taken into account in the design, construction and operation of the gas-management system at the site. Active gas management will be required to prevent methane and CO_2 release affecting plant growth. Once the rate of landfill gas generation has reduced to the point where active gas extraction is no longer required or feasible, phytocaps will more readily oxidise any residual methane emissions than a conventional landfill cap.

Computer models can provide an indication of the theoretical performance of a proposed design. They may provide an indication of the impact of adding or changing of elements of the cap design. However, the complexity of the behaviour of phytocaps is such that the use of a model alone is not sufficient to design a phytocap for a particular landfill site.

Use of field trials, including vegetation plots and lysimeters, are required for the purposes of cap evaluation. It is likely that a lysimeter trial will take a minimum of five years to provide data on the likely performance of a phytocap. The lysimeter trial pads must be of sufficient area to minimise edge effects and to allow techniques that will be used in the construction of the final cap.

The grade of the surface of the lysimeter must also be considered in the final cap design, if relevant.

8.1.8 Low-risk rural landfills – indicative phytocap design

Small, low-risk rural landfills that meet the criteria set out in Section 6.12 of the Landfill BPEM may use Type 3 landfill capping and lining criteria. In recognition of the level of infiltration through a Type 3 cap, as set out in Table 8.1 and Table 6.1, the lysimeter field trial is not required for the development of phytocap designs at these sites.

The required phytocap performance on a low-risk rural landfill is the performance requirement outlined in Table 8.1, annualised over a climatic average year. Therefore, the 75 per cent of the seepage rate of 1000 L/ha/day can be interpreted as 274,000 L/ha/year for a Type 3 landfill as the long-term performance requirement for an established phytocap.

Key criteria for these caps include:

- climate
- soil type
- vegetation.

Phytocaps use the soil moisture storage capacity of the capping soils to hold moisture for the months of the year when rainfall exceeds potential evapotranspiration. This stored moisture is then evapotranspired by cap vegetation in months when there is a deficit of rainfall compared to evapotranspiration. The cap is therefore required to have sufficient soil moisture storage capacity to store rainfall less evaporation over the wetter months.

The soil moisture retention capacity of the cap is determined *by Standard Test Methods for Determination of the Soil Water Characteristic Curve* (ASTM D6836–02). The total water storage capacity of the cap is determined by multiplying the soil moisture retention of a soil (expressed as a percentage) by the cap thickness.

For these low-risk rural landfills a minimum cap thickness of 1.5 metres is required, regardless of the soil moisture capacity of the proposed soils for the phytocap.

Phytocap soils are to be placed to avoid over-compaction of the soils and require a target level of compaction in the range of 75 to 80 per cent standard compaction. This low level of compaction is achieved by placing soils by bucket or loader working away from the capping area. Heavy earth-moving equipment must avoid driving over capped areas.

A vegetation establishment and maintenance scheme is required and must include the suitability of the soil for propagation of the proposed plants, types of vegetation and a maintenance and reporting program. The annual performance statement to EPA must include a report on the vegetation.

Example of how to calculate cap thickness

This example is provided for indicative purposes only. Applicants need to provide adequate justification of any proposed phytocap design.

$$Ct = \sum \frac{\text{Wet Months (Precipitation} - \textit{Evaporation})}{Smr}$$

Where:

Ct =	Cap thickness (from top of cap to top of waste)
Precipitation =	Wetter months precipitation (defined as months where rainfall exceeds pan evaporation multiplied by 0.8)
Smr =	Soil moisture capacity of cap soil

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP

REHABILITATION

Relevant BPEM objective

To ensure that landfills are rehabilitated to minimise the seepage of water into the landfill and maximise the collection and oxidation of landfill gas from the landfill.

Required outcomes of the BPEM

- Preparation, early in its design, of a rehabilitation plan for the landfill, including a detailed consideration of afteruse options for the site.
- That the seepage through the landfill cap is no more than 75 per cent of the anticipated seepage rate through a basal liner that meets best-practice requirements.
- Design and construction of the best cap practicable to prevent pollution of groundwater and degradation of air quality.
- Design and construction of the most robust cap to ensure that the system will continue to protect the environment in the event of several components of the system failing.
- Progressive rehabilitation of the landfill.
- Geomembranes to be used in landfill cover systems must meet the requirements specified in section 4 of Appendix D.
- Installation of geomembranes in the landfill cover systems must meet the requirements specified in section 5 of Appendix D.
- The CQA plan for geomembranes must address the issues raised in section 6 of Appendix D and should follow the suggestions unless an alternative provides an equivalent or better outcome.
- Geosynthetic clay liners to be used in landfill cover systems must meet the requirements specified in section 4 of Appendix E.
- Installation of geosynthetic clay liners to be used in landfill cover systems must meet the requirements specified in section 5 of Appendix E.
- The CQA plan for geosynthetic clay liners must address the issues raised in Section 6 of Appendix E and should follow the suggestions unless an alternative provides an equivalent or better outcome.
- The minimum thickness of a phytocap soil layer must be 1.5 m.
- A phytocap design must include a monitoring and maintenance program to ensure integrity of the cap and for the survival of plants.
- Design of phytocaps for a Type 2 landfill requires the use of lysimeter field trials or other approved trial.
- The site occupier must ensure that the landfill aftercare management plan is implemented until an Environmental Audit demonstrates that the site no longer poses a risk to the environment or for at least 30 years after the site stopped receiving waste.

Suggested measures of the BPEM

- Rehabilitation of a landfill cell be initiated once:
  - the landfill cell contents have reached the approved pre-settlement contours, allowing sufficient height to build the landfill capping within the pre-settlement contours
  - further filling of the cell is operationally no longer required or feasible
  - there has been a lawful direction to cease filling the cell
  - the landfill is to be closed; or
  - two years have elapsed since commencement of filling.
- Involve the community, regulatory and planning authorities in the development of the rehabilitation plan.
- Regularly review the rehabilitation plan and afteruse to ensure that changed circumstances are reflected in the plan.
- Design and operate the landfill to accommodate the desired afteruse.
- Consider impacts of settlement on any potential afteruses of the landfill.
- Design the cap gradient to be between five and 20 per cent.
- Vegetate cap or take other measure to minimise erosion as soon as possible.
- Avoid root penetration of the barrier layer of a conventional cap.
- Phytocaps should provide similar performance outcome as specified in Table 8.1.

8.2 Aftercare management

Until the waste within the landfill has sufficiently decomposed or stabilised such that it no longer presents a risk to the environment, the landfill must be managed to prevent any environmental impact.

The following areas must be considered in preparing the aftercare management plan:

- maintenance of landfill cap, in particular to –
- prevent/control erosion
- restore depressions, and seal and monitor cracks in the cap caused by settlement
- restore/maintain vegetation
- maintenance and operation of leachate collection and treatment system
- maintenance and operation of landfill gas-extraction system
- environmental monitoring of –
- groundwater
- surface water
- landfill gas
- leachate
- settlement.

As these activities will continue beyond the income-producing period of the landfill, funds should be allocated during the operational life of the landfill to provide for aftercare management. The typical period of aftercare is about 30 years for a putrescible landfill.

The aftercare management plan should address the level of monitoring and frequency of inspection of the landfill and infrastructure. These elements depend on the location of the landfill, the types of wastes and the landfill's environmental performance. Accordingly, putrescible landfills require a more extensive aftercare management plan than a solid inert landfill.

During the aftercare period, the frequency of monitoring and inspection may be decreased, frequency being based on the stability of the landfill cap and the consistency of environmental monitoring results. As most settlement occurs within the first few years after closure, the inspection program needs to be more frequent during this period.

The data and observations collected in accordance with the plan should be reviewed by an expert in the field (see section 7.14 for more information on performance monitoring and reporting; the elements discussed in this section apply to monitoring during the operation of the landfill and after its closure).

The leachate collection and treatment system will need to be inspected and maintained for as long as the landfill is actively generating leachate. This will include inspection and cleaning of leachate collection pipes, maintenance of leachate treatment plants and inspection after periods of heavy rain to ensure that the system is not overloaded. This must continue until an assessment demonstrates the landfill is no longer generating leachate able to detrimentally impact on the environment.

The landfill gas-extraction system needs to be maintained for the life of landfill's gas generation. This includes maintaining the plant, such as generation plant or flares used to combust the gas. This must continue until an assessment demonstrates that it is no longer required or that the system may be downgraded to a less intensive form of management.

In determining whether maintenance is still required, an environmental audit by an auditor is required. This audit will examine, among other things, the results of monitoring of groundwater, surface water, landfill gas and leachate.

If monitoring is conducted regularly, and the trend clearly demonstrates that leachate is clean and minimal landfill gas is being generated, then the auditor can be assured that the site no longer poses a risk to the environment and may recommend reducing maintenance requirements. Where this monitoring is patchy and trends are inconclusive, then this degree of assurance is not provided and EPA will not remove the maintenance requirements.

To ensure in the long term that prospective owners of the land are aware that it was once a landfill, measures such as a caveat on the land title or a planning overlay can alert people to the prior use of the site. EPA may also serve a pollution abatement notice on the site to ensure ongoing management of the site and place the site on the Priority Sites Register to ensure that all potential future stakeholders are aware of the ongoing management requirements of the site.

8.2.1 Buffers and measurement

Buffer distances are set to reflect the potential impacts from landfilling activities. The post-closure buffers are set to manage landfill gas impacts, including the risk of explosion and/or asphyxiation. Landfill gas potential risks remain for at least 30 years post-closure.

Buffers are measured from the sensitive land use to the edge of the closest cell. All cells, including closed cells, need to be considered in calculating buffers. For sites that cannot demonstrate the above, the premises boundary is the point of measurement.

For old landfill sites, the original plans for the development of the landfill – or, in their absence, the relevant property titles – should be used to determine the original boundary of the landfill premises.

Table 8.2 summaries the buffer required for different types of landfill.

Table 8.2: Post-closure buffer distances required for landfill gas migration

	Type of landfill site	Minimum 30 years post-closure
Buffer distance	Type 2	500 metres from building or structures.
	Type 3	200 metres from buildings & structures.

8.2.2 Buffer distances and encroachment

In considering any planning scheme amendment or planning permit applications, in accordance with the *Planning and Environment Act 1987*, the planning or responsible authority must have regard for the effects of the environment, including landfill gas, on the development.

Proposed developments and any works within the recommended landfill buffer can pose a safety risk by potentially providing preferential pathways for landfill gas migration, or providing an environment where landfill gases can accumulate to dangerous levels. All buildings and structures should be considered, including:

- buildings and structures used for sensitive or non sensitive uses
- change of use
- infrastructure installation
- installation of pipelines.

Responsible planning authorities need to be provided with sufficient information by the proponent to satisfy them that the proposed new development or rezoning will not be adversely impacted by its proximity to the landfill site.

Where the proposed development (or planning scheme amendment that would have the effect of allowing development) encroaches into the recommended landfill buffer area or increases the extent of development within the already encroached buffer area, EPA recommends that the planning or responsible authority require an environmental audit be conducted under Section 53V of the Environment Protection Act. The audit must assess the risk of harm to the proposed development posed by the potential offsite migration of landfill gas and amenity impacts resulting from the landfill.

Where a planning or responsible authority has relevant and sufficient information from previous assessments or audits, then this may be relied on in making a decision

The buildings and structures buffer applies to any building or structure (including subsurface structures such as stormwater drains) located near a landfill and is there to provide a protection zone around a landfill for subsurface landfill gas migration. In the event that a building or structure is located within the recommended buffer, monitoring will be required in accordance with EPA landfill gas risk assessment requirements – see section 6.7.

Building and structure buffer distances apply to closed landfill sites until the site has stabilised to the point where the potential for subsurface gas migration has largely ceased. Typically, this will be a period of about 30 years.

BPEM requirements to comply with clause 15 (3) and (4) of the Landfill WMP.

AFTERCARE MANAGEMENT

Relevant BPEM objective

To manage the site after closure so that environmental protection and monitoring systems are maintained until the landfill has stabilised.

Required outcome of the BPEM

- Preparation of a landfill aftercare management plan.
- No building or structures on the site of the landfill cells without an assessment of potential risks and appropriate risk mitigation measures incorporated into the design and construction of those buildings and structures.
- Provide buffers in accordance with Table 8.2, where these are unavailable demonstrate that risks are mitigated to the same standard.

Suggested measures of the BPEM

- Regularly inspect site to check the integrity of the cap and monitor the environmental impact of the landfill.
- Inspect and maintain leachate collection and treatment and landfill gas-extraction system.
- Conduct regular monitoring and analyse data for any trends.
- Ensure that any buildings at the landfill do not interfere with monitoring and maintenance of the landfill.

9 References and legislation

9.1 References

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9.2 Legislation

Environment Protection Act 1970.

Environment Protection (Scheduled Premises and Exemptions) Regulations 2007.

Environment Protection (Environment and Resource Efficiency Plans) Regulation 2007.

Environment Protection (Industrial Waste Resource) Regulations 2009.

State Environment Protection Policy (Groundwaters of Victoria).

State Environment Protection Policy (Waters of Victoria).

State Environment Protection Policy (Air Quality Management).

State Environment Protection Policy (Control of Noise from Commerce, Industry and Trade) No. N–1.

Industrial Waste Management Policy (Waste Acid Sulfate Soils).

Waste Management Policy (Siting, Design and Management of Landfills).

9.3 Codes, standards and guidelines

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Australian Standard AS 1940–2004. *The Storage and Handling of Flammable and Combustible Liquids*.

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EPA Victoria 2000. *Groundwater sampling guidelines* (EPA publication 669).

EPA Victoria 2010. *Annual performance statement guidelines* (EPA publication 1320).

EPA Victoria 2010. *Landfill licensing guidelines* (EPA publication 1323).

EPA Victoria 2009. *Solid industrial waste hazard categorisation and management* (EPA publication IWRG631).

EPA Victoria 2009. *Sampling and analysis of waters, wastewaters, soils and wastes* (EPA publication IWRG701).

APPENDIX A: Summary of implementation requirements

Section	Implementation requirements
Siting	To be implemented by the Metropolitan Waste Management Group through the implementation of Part 3 (Metropolitan Landfill Schedule) of its Metropolitan Waste and Resource Recovery Strategic Plan. To be implemented by all Regional waste management groups through the implementation of their regional waste management plans. To be implemented by all planning authorities in making their planning decisions on closed, current or future landfills.
Design of landfill liners (for the base, side walls and landfill capping systems)	All new landfills and cells to implement, except the landfill cells that are already approved and partially filled.
Design	All new landfills and cells to implement
Operation	All landfills are to implement an auditor-verified monitoring program by 30 June 2011 to enable submission of 2010–11 annual performance statement.
Rehabilitation and Aftercare	All landfills to implement during progressive rehabilitation and upon closure. Currently closed and capped landfills to implement on the basis of risk assessment by auditor, where the rehabilitation and/or aftercare is, or is likely to be, inadequate to guard against pollution.

APPENDIX B: Technical guidance

B.1 Clay properties

Clay to be used in liners should have the following properties:

- No rock or soil clumps greater than 50 mm in any direction.
- More than 70 per cent passing through a 19 mm sieve.
- More than 30 per cent passing through a 75 mm sieve.
- More than 15 per cent passing through a 2 mm sieve.
- Soil plasticity index exceeding 10.

The ability of clay to absorb exchangeable cations is measured by the cation exchange capacity, a measure of the total amount of exchangeable cations that a soil can adsorb. A cation exchange capacity (CEC) of 10 mEq/100g is a recommended level for clay to be used in a best-practice landfill.

There is a potential for the clay to degrade through clay-pollutant chemical reactions over a long period of time. To guard against this risk, long-term permeation tests should be conducted on the clay to assess any variations in intrinsic permeability over the long term. Kodikara & Rahman (1997) suggest that using a 50,000 ppm NaCl solution over two to three months should indicate any such long-term variations.

B.2 Installation of clay liners

Before a clay is used to construct a liner, samples of the clay to be used should be submitted to a laboratory for determination of the soil properties for a range of compaction efforts. This will enable the development of laboratory compaction and hydraulic conductivity curves, which should be assessed to determine the suitability or otherwise of the material as a low-permeability barrier.

The relationship between the water content and the density of the clay is the key relationship determining the suitability of the material as a low-permeability liner.

Figure B.1 shows the effect of moulding water content (moisture content of the clay when compacted) and the dry density of the clay (dry unit weight). Maximum dry density is achieved at the optimum moisture content. The lowest hydraulic conductivity of the compacted clay liner is achieved when the soil is compacted at a moisture content slightly higher than the optimum moisture content.

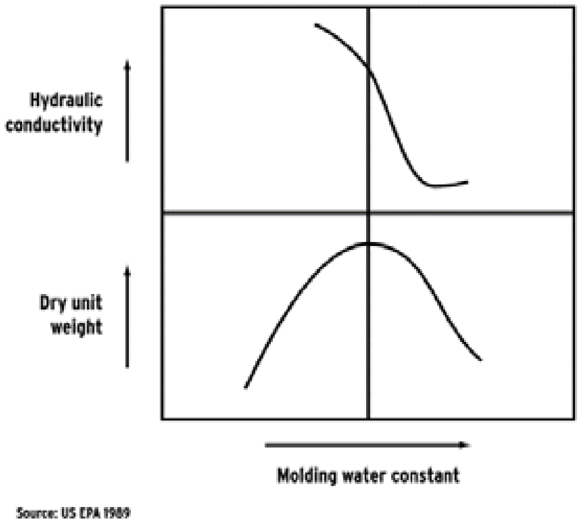

Figure B.1: Relationship between hydraulic conductivity, density and moisture content of a clay soil

By specifying compaction to be undertaken at a percentage above optimum moisture content to achieve a density defined as a percentage of maximum dry density, an envelope or 'acceptable zone' of performance criteria can be derived for undertaking quality control checks in the field both during and after construction. Best practice is to compact the clay at about two to three per cent wet of optimum moisture content to a maximum dry density of 95 to 98 per cent of Proctor Standard.

Clay liners are constructed in series of 'lifts' compacted to the required maximum dry density at the specified moisture content. To achieve bonding between each lift, the thickness of each lift must permit the compaction equipment, typically a sheepsfoot roller, to penetrate the top lift and knead the previous lift. Scarification of the previous lift may also be required to improve bonding. This bonding is required to overcome the effects of imperfections within individual lifts.

Within individual lifts of the clay liner, microscopic and/or macroscopic zones may exist of lower and higher hydraulic conductivity. These exist due to small stones or dry clods of clay within the liner material. Zones of lower hydraulic conductivity form preferential flow paths that enable rapid localised leachate flows through the lift. Where successive lifts are not bonded with the preceding lift, leachate may flow along the horizontal seams between the lifts to further preferential flowpaths. As a result, the hydraulic conductivity of the whole liner is compromised.

A further factor is the number of lifts used, with a greater number minimising the probability that preferential flowpaths will align. By bonding each successive lift with the preceding lift and using a minimum of four to six lifts, the hydraulic conductivity of the liner can be optimised.

The final surface of a compacted clay liner should be finished to a smooth surface. This minimises the surface area of the liner (thereby reducing the loss of moisture from the liner), promotes the rapid drainage of leachate on top of the liner and allows the installation of a geomembrane liner.

B.3 Drainage aggregate properties

The aggregate to be used in constructing a drainage layer should be selected to maximise drainage of leachate in the long term.

Recommended properties are:

- drainage layer aggregate size to be less than 50 mm and greater than 20 mm
- fines content to be less than one per cent
- aggregate material should not contain limestone or other calcareous material that would be subject to chemical attack.

B.4 Giroud's equation

Giroud's equation is used to derive the required spacing between subsurface drainage pipes given the maximum permissible head over the pipes and a number of physical parameters.

The equation is:

$$L = \frac{T_{max}(2\cos^2 b)}{\sqrt{\tan^2 b + 4\frac{q}{k}} - \tan b}$$

Where:

L = spacing between drainage pipes (m)

T_{max} = maximum leachate head over liner (m)

k = permeability of drainage layer (m/sec)

b = slope of the liner (radians)

q = leachate seepage rate into drainage layer (m/sec)

Since Giroud's equation assumes a constant permeability of the drainage layer, the pipe spacing may need to be less than that calculated using the equation to take into account clogging of the drainage layer. Alternatively, the permeability of the drainage layer used in the calculations could be assumed to be two orders of magnitude greater than its design permeability.

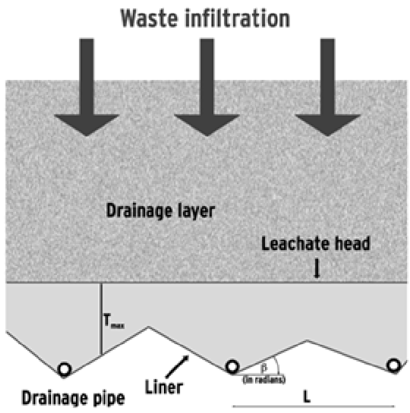

Figure B.2: Parameters for Giroud's equation

B.5 Calculation of area required for evaporation of leachate

If evaporation is to be used as the primary means of disposing of leachate, then an appropriately sized pond needs to be designed to ensure that the system can handle the volume of leachate expected to be generated over a year. This can be calculated by using the following formula:

$$A = \frac{1{,}000V}{0.8E - R}$$

Where:

A = pond surface area (m^2)

V = annual volume of leachate (kL or m^3)

E = median annual evaporation (mm class A pan)

R = median annual rainfall (mm).

B.6 Landfill gas generation

The composition of landfill gas varies according to the dominant phase of microbial degradation within landfilled waste as shown in Figure B.3.

The key phases with respect to landfill gas generation and its associated potential impacts on air quality are the anaerobic phases (phases 2 to 4). During these phases, microbial degradation of biodegradable waste occurs in low to zero oxygen conditions generating landfill gas. It can be seen from Figure B.3 that the composition of the generated landfill gas varies between the phases

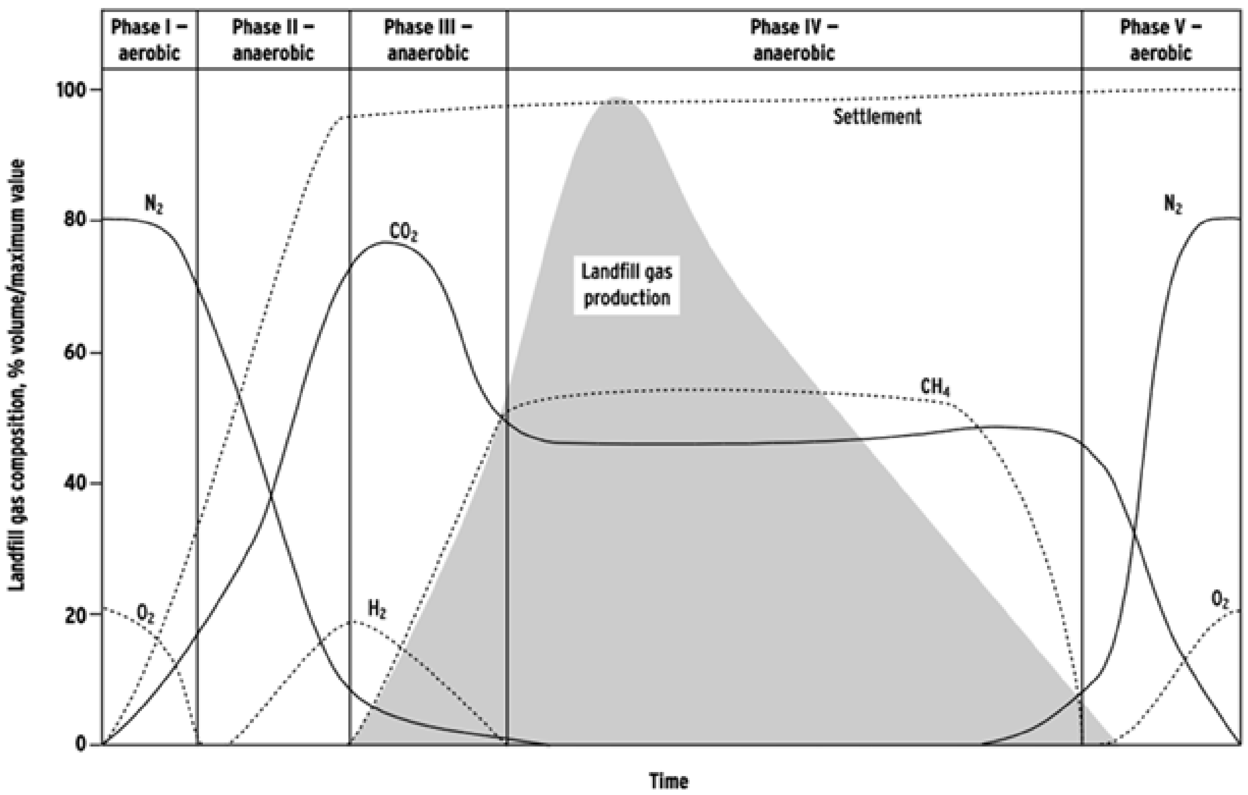

Figure B.3: Idealised representation of landfill gas generation
Note: Reproduced with permission from *Guidance on the management of landfill gas,* Environment Agency 2004.

B.7 Design of landfill gas monitoring bore systems

B7.1 Overview

The aim of a landfill gas monitoring bore system is to intercept any landfill gas escaping laterally from the site and identify its location. As such, landfill gas monitoring bores must be installed at appropriate locations, drilled to depths suitable to intercept all gas movement paths, constructed appropriately to intercept gas and should be determined based on the findings of the landfill gas risk assessment.

The following are key factors:

- bore location and spacing
- bore depth
- bore construction design
- bore installation construction quality assurance.

Typically, it is expected that a landfill gas monitoring bore system will:

- target sensitive receptors such as dwellings
- encircle the entire landfilled waste mass
- be installed into the local geology (not into waste or fill materials).

EPA recommends that landfill gas monitoring bores are sited at least 20 metres from the boundary of the landfilled waste, to ensure validity of the landfill gas monitoring data subsequently obtained.

B7.2 Landfill gas monitoring bore location and spacing

The location and spacing of landfill gas monitoring bores are site-specific requirements and governed by the findings of the landfill gas risk assessment. Table B.2 provides recommended bore spacings. The audit of the site must include a site-specific monitoring network, that has been verified by an EPA-appointed environmental auditor.

Bore spacing greater than the recommended maximum distance must be justified with valid reasons and information.

Table B.2: Recommended landfill gas monitoring bore spacing

Site description	Monitoring bore spacing – min. (m)	Monitoring bore spacing – min. (m)
Uniform low-permeability strata (e.g. clay); no development within 250 metres	50	150
Uniform low-permeability strata (e.g. clay); development within 250 metres	20	50
Uniform low-permeability strata (e.g. clay); development within 150 metres	10	50
Uniform matrix-dominated permeable strata (e.g. porous sandstone); no development within 250 metres	20	50
Uniform matrix-dominated permeability strata (e.g. porous sandstone); development within 250 metres	10	50
Uniform matrix-dominated permeability strata (e.g. porous sandstone); development within 150 metres	10	20
Fissure or fracture flow-dominated permeable strata (e.g. blocky sandstone or igneous rock); no development within 250 metres	20	50
Fissure or fracture flow-dominated permeable strata (e.g. blocky sandstone or igneous rock); development within 250 metres	10	50
Fissure or fracture flow-dominated permeable strata (e.g. blocky sandstone or igneous rock); development within 150 metres	5	20

Note: The maximum spacing given in relation to the development relate to the zone of development (location of receptor) and not the entire boundary. Table B.2 adapted from Guidance on the management of landfill gas; Environment Agency; 2004

B7.3 Landfill gas monitoring bore depth

Landfill gas monitoring bores must be drilled to an appropriate depth suitable to intercept gas movement adjacent to the landfill and should be based on the findings of the landfill gas risk assessment.

The key considerations are:

- the topography of the landfill site and the vicinity
- the hydrogeology (subsurface geology, aquifer types, watertable depths and flow direction etc.)
- the depth(s) of the landfill (waste mass)
- the construction details of landfill cells.

Bores must be designed and constructed to avoid connecting two different groundwater aquifers. Where gas monitoring is required across the depth of two aquifers, then multiple gas bores will need to be installed, with bores only open across one aquifer and sealed to prevent groundwater from the other aquifer from entering that bore.

B7.4 Landfill gas monitoring bore construction design

Landfill gas monitoring bores must be carefully designed to suit the situation and should be based on the findings of the landfill gas risk assessment.

The following aspects must be taken in to consideration in designing the bores:

- a well screen interval that intercepts as much of the unsaturated (vadose) zone as possible whilst still allowing an adequate gas tight seal to be present/ constructed at the ground's surface.
- sealing of bore so that any gas accumulating will be retained for sampling
- bore robustness and durability
- accessibility of bore to ensure its suitability for ongoing use.

Table B.3 provides typical material properties for landfill gas monitoring bores. These bores should be made of polyvinyl chloride (PVC) pipes.

Table B.3: Typical construction details for landfill gas bore construction

Component	Value
Bore and casing	
Drilled bore diameter (mm)	100–150
Pipework casing – outer diameter (mm)	50
Depth of top of bentonite seal (m)	1
Length of solid casing below ground level (m)*	1

Table B.3 continues on p.61

Table B.3: Typical construction details for landfill gas bore construction (con't)

Component	Value
Pipework design and gravel backfill	
Perforated casing pipework (% open space)	10–15
Pipework casing – size of slots / perforations (mm) (must meet % open space requirements)	2–4 but no more than 5
Size range of gravel back fill	Not greater than 10 mm Must be sufficiently larger than pipework slots/ perforations to prevent blocking.
Gravel type	Washed gravel to be rounded to sub-rounded and non-calcareous (<5% carbonate)

* To match with depth of bentonite seal used

Bores must have a suitably gastight seal to prevent any escape of landfill gas. This is normally achieved by a one-metre bentonite seal at the top of the bore. A sampling tap must be fitted to the top of the pipework casing to allow sampling of the gas. Due consideration to damage by vandals, animals, natural processes and operational machinery must be given in the bore design, and precautions incorporated as appropriate (such as by installing an appropriate security cover on the bore).

Landfill gas monitoring bores that have failed or appear to have failed must be investigated and replaced, as required.

B7.5 Bore installation construction quality assurance

A construction quality assurance (CQA) process is required.

APPENDIX C: Summary of objectives and required outcomes

5	Best-practice siting considerations
5.1 Screening for potential landfill sites	**Relevant BPEM objective** *To identify and rank those sites that require the fewest engineering and management controls to meet the objectives of all State environment protection policies.* **Required outcomes of the BPEM** · Future landfilling sites must be listed in the landfill schedule in the regional waste management plan. · Develop landfill sites in the sequence specified in the relevant regional waste management plan. · Ensure that the landfill is sited to protect groundwater, surface waters, and flora and fauna. · Ensure that sufficient buffer is available for the life of the landfill and for a minimum of 30 years following closure of the site. · Provide buffers in accordance with Table 5.2 and Table 8.2; where these are unavailable, demonstrate that risks are mitigated to the same standard. · Consider the most appropriate landfilling type to meet the requirements imposed by local conditions. · All new landfills must deposit waste at least two metres above the long-term undisturbed depth to groundwater, unless the operator satisfies EPA Victoria that sufficient additional design and management practices will be implemented and EPA determines that regional circumstances exist that warrant the new landfill.
6	Best-practice design
6.1 Environmental assessment	**Relevant BPEM objective** *To gain a thorough understanding of the environment where the landfill is to be sited in order to design the landfill to minimise impacts on the environment.* **Required outcomes of the BPEM** · Assess metrological data · Conduct a hydrogeological assessment to assess the potential for impacts on local groundwater quality. · Investigate water management requirements. · Investigate landfill gas and odour control options.
6.2 Site layout	**Relevant BPEM objective** *To ensure that the site layout minimises environmental and health and safety risks, encourages recycling and makes the most efficient use of onsite resources.* **Required outcomes of the BPEM** · Site layout and filling sequence planned to ensure that landfill cells are open for the shortest period of time and site operations are optimised. · Minimisation of public access to the tipping face and, where appropriate, assurance that waste received at the landfill can be vetted and recycled.

6.3 **Liner and leachate collection system**	**Relevant BPEM objective** *To maintain groundwater quality as close as practicable to background levels.* **Required outcomes of the BPEM** · Design and construction of the best liner and leachate collection system practicable to prevent contamination of groundwater. · Design and construct the landfill liner such that the appropriate maximum seepage rate shown in Table 6.1 is not exceeded. · Implementation of the best practicable measures to meet all groundwater quality objectives contained in SEPP (Groundwaters of Victoria) below the landfill liner. · Where an attenuation zone has been designated, assurance that all groundwater quality objectives contained in SEPP (Groundwaters of Victoria) are met at the boundaries of the premises. · Geotechnically stable sub-base and liner. · Design and construction of the most robust liner and leachate collection system to ensure that the system will continue to achieve the objective in the event of several components of the system failing. · Maximum head of leachate on the liner surface not to exceed 0.3 metres. · Drainage layer to be at least 0.3 metres thick with a hydraulic conductivity of not less than 1×10^{-3} m/s. · Drainage layer extending over the entire base of the landfill. · Geomembrane liner must meet the minimum requirements specified in section 3 of Appendix D. · Geosynthetic clay liner must meet the minimum requirements specified in section 3 of Appendix E. · Geotextile cushion layer must meet the minimum requirements specified in section 3 of Appendix F. · A geotextile filter layer must be placed between drainage layer and waste
6.4 **Construction quality assurance**	**Relevant BPEM objective** *To ensure that materials, construction methods and installation procedures deliver a landfill meeting design criteria.* **Required outcomes of the BPEM** · Development and implementation of a Construction Quality Assurance (CQA) plan to ensure that the liner and leachate collection system meets the requirements of the specifications and drawings. · A statement from an accredited testing authority be obtained stating that the installed liner and leachate collection system meet the requirements of the specification and drawings. · Development and implementation of a CQA plan to ensure that the stability of sub-base and liner are achieved. · The installation of geomembranes must meet the requirements of section 5 of Appendix D. · The CQA plan for geomembranes must address the issues raised in section 6 of Appendix D and should follow the suggestions unless an alternative provides an equivalent or better outcome. · The installation of geosynthetic clay liners must meet the requirements of section 5 of Appendix E. · The CQA plan for geosynthetic clay liners must address the issues raised in Section 6 of Appendix E and should follow the suggestions unless an alternative provides an equivalent or better outcome. · The installation of geotextiles must meet the requirements of section 4 of Appendix F. · The CQA plan for geotextiles must address the issues raised in section 5 of Appendix F and should follow the suggestions unless an alternative provides an equivalent or better outcome.

6.5 **Water management**	**Relevant BPEM objectives** *To protect beneficial uses of receiving waters and to avoid any adverse environmental impact on surface and ground waters.* **Required outcomes of the BPEM** · Segregation of stormwater, leachate and groundwater. · Wherever practical, reuse of water onsite. · Management and treatment of leachate to: · Prevent it from escaping into surface waters or groundwater · Prevent offensive odours offsite · Minimise human contact with the leachate. · Assurance that waste discharges to surface waterways are minimised and do not cause water quality objectives to be breached.
6.6 **Groundwater management**	**Relevant BPEM objective** *To protect the beneficial uses of groundwater and to minimise the risk posed by the landfill to those beneficial uses.* **Required outcomes of the BPEM** · Implement a groundwater monitoring program in accordance with *Landfill licensing guidelines* (EPA publication 1323). · Ensure that the landfill liner cannot be damaged through groundwater pressure. · Minimise risk to groundwater by siting landfill in accordance with section 6.2 (site layout) and utilising a liner and leachate collection system in accordance with section 6.3 (liner and leachate collection system).
6.7.1 **Landfill gas**	**Relevant BPEM objective** *Ensure that no safety or environmental impacts are caused by landfill gas.* **Required outcomes of the BPEM** · Undertake a site-specific landfill gas risk assessment. · All practicable measures must be taken to achieve the landfill gas action levels detailed in Table 6.4. · Develop and implement an appropriate landfill gas management system. · Implement a landfill gas monitoring program in accordance with the Landfill licensing guidelines, EPA publication 1323. · Implement a landfill gas remediation action plan acceptable to EPA if the action Levels in Table 6.4 are exceeded. · The landfill gas management system is updated and is in compliance with the landfill gas management hierarchy. · Notify EPA Victoria within 24 hours of detection of any exceedance of the action levels detailed in Table 6.4, except for onsite exceedance rectified within 24 hours. · The landfill gas flares must have auto ignition and flame arrestor beneath the combustion zone.
6.7.2–6.7.4 **Odour, dust and air toxics**	**Relevant BPEM objective** *To ensure that air quality objectives are met, and that there is no loss of amenity from odour or dust.* **Required outcomes of the BPEM** · Prevention of any offensive odours beyond the boundary of the premises. · Control all dust emissions from the landfill site.

6.8 **Bioreactor landfills**	**Relevant BPEM objective** *To maximise the rate of degradation of biodegradable wastes and achieve the same or better levels of environmental protection as a conventional landfill.* **Required outcomes of the BPEM** · Protection of liners from higher temperatures that will develop in the waste mass. · Install landfill gas collection systems progressively, and the final system is in place no later than two years after placement of waste in any cell or sub-cell. · Design and use of monitoring systems for moisture control, gas generation and temperature. · Avoidance of the creation of low-permeability barriers within waste mass. · An accredited management system that provides a high level of assurance that construction and operational performance will be consistent with or better than that required of a conventional landfill.
6.9 **Noise**	**Relevant BPEM objective** *To ensure that policy and guideline noise requirements are achieved and that there is no loss of amenity from noise from the landfill site.* **Required outcomes of the BPEM** · In the Melbourne metropolitan area, compliance with the noise limits prescribed by SEPP (Control of Noise from Commerce, Industry and Trade) No. N–1 1989. · Outside the Melbourne metropolitan area, compliance with noise guidelines issued by EPA.
6.10 **Traffic considerations**	**Relevant BPEM objectives** *To minimise nuisance from traffic movement.* **Required outcomes of the BPEM** · Minimisation of safety concerns, noise and road grime on external roads.
6.11 **Site security and fencing**	**Relevant BPEM objective** *To prevent the unauthorised entry of people or livestock.* **Required outcomes of the BPEM** · Design fencing to minimise unauthorised access to the site.
7	Best-practice operation
7.1 **Environmental management**	**Relevant BPEM objective** *Protect the environment by managing environmental risks.* **Required outcomes of the BPEM** · Ensure that a site specific environmental management procedure is in place to manage key risks and provide for contingencies. · Training of all relevant staff in the implementation of the site's environmental management procedure.
7.2 **Financial assurance**	**Relevant BPEM objective** *To provide a financial assurance for environmental management costs incurred during the operation, closure and aftercare of a landfill.* **Required outcomes of the BPEM** · All licensed landfill operators are to maintain a financial assurance acceptable to EPA.
7.3 **Waste minimisation**	**Relevant BPEM objective** *To divert suitable wastes from landfill.* **Required outcomes of the BPEM** · Removal of recyclable materials from the waste stream, where feasible.

7.4 **Waste acceptance**	**Relevant BPEM objective** *To ensure that only allowed wastes are deposited at the landfill.* **Required outcomes of the BPEM** · Landfill operator to ensure that non-conforming waste is not disposed of at the landfill site. · Provide signs advising the types of wastes allowed at the site. · Implement a procedure to deal with the dumping of non-conforming waste at the landfill site.
7.5 **Waste pretreatment**	**Relevant BPEM objective** *To reduce the long-term risk posed by the waste and to improve general landfill performance.* **No required outcomes**
7.6 **Waste placement**	**Relevant BPEM objectives** *To place waste in a manner that is mechanically stable, controls litter and birds and that maximises the degree of compaction.* **Required outcomes of the BPEM** · Maintenance of an active tipping area that is as small as possible. · Compaction of all waste deposited in the landfill. · Assurance that waste is placed so that all unconfined faces are mechanically stable and capable of retaining cover material.
7.7 **Waste cover**	**Relevant BPEM objective** *To ensure that wastes are covered appropriately, to mitigate against any environmental or health impacts.* **Required outcomes of the BPEM** · Covering of the waste, at least daily, with soil or another approved cover material for all sites that accept putrescible waste and maintain the cover. · Close cracks in old, exposed cover layers to contain landfill gas and odour. · No use of acid sulfate soil as daily cover.
7.8 **Litter control**	**Relevant BPEM objective** *To keep the landfill and surrounding environment in a litter-free condition.* **Required outcomes of the BPEM** · That no litter from the landfill operations reaches beyond the boundary of the premises.
7.9 **Fires**	**Relevant BPEM objectives** *To prevent landfill fires and efficiently extinguish any that should occur.* **Required outcomes of the BPEM** · Maintenance of a water supply capable of being delivered to any point on the landfill. · No fires must be lit at the landfill or near areas where wastes have been or are being deposited. · That all practical steps have been taken to prevent landfill fires.
7.10 **Contingency planning**	**Relevant BPEM objectives** *To ensure that all potential incidents are considered and that appropriate measures are planned to deal with them.* **Required outcomes of the BPEM** · A contingency plan is in place · All likely impacts are covered in the preparation of the contingency plan. · All staff are trained in the implementation of the contingency plan.

7.11 Management of chemicals and fuels	**Relevant BPEM objective** *To manage the storage and handling of chemicals and fuels so as to minimise the risk of impact on the environment.* **Required outcomes of the BPEM** · Storage and handling flammable and combustible liquids in accordance with the provisions of the AS 1940–2004 'The storage and handling of flammable and combustible liquids'.
7.12 Disease vector control	**Relevant BPEM objective** *To minimise disease vectors emanating from the landfill by denying pests food and shelter.* **Required outcome of the BPEM** · Cover waste daily.
7.13 Noxious weed control	**Relevant BPEM objective** *To manage the landfill site so that it does not become a source of noxious weeds.* **Required outcomes of the BPEM** · Minimise the introduction of noxious weeds to the site. · Eradicate any noxious weeds that have established themselves onsite.
7.14 Performance monitoring and reporting	**Relevant BPEM objective** *To monitor and report on the performance of measures taken to protect the environment from potential impacts from a landfill and to identify and address any arising environmental issues.* **Required outcomes of the BPEM** · Preparation of a verified monitoring program in accordance with *Landfill licensing guidelines* (EPA publication 1323). · Monitoring of the environment in accordance with the verified monitoring program. · Submission of an annual performance statement.

8	Best-practice rehabilitation and aftercare
8.1 Rehabilitation	**Relevant BPEM objective** *To ensure that landfills are rehabilitated to minimise the seepage of water into the landfill and maximise the collection and oxidation of landfill gas from the landfill.* **Required outcomes of the BPEM** · Preparation, early in its design, of a rehabilitation plan for the landfill, including a detailed consideration of afteruse options for the site. · That the seepage through the landfill cap is no more than 75 per cent of the anticipated seepage rate through a basal liner that meets best-practice requirements. · Design and construction of the best cap practicable to prevent pollution of groundwater and degradation of air quality. · Design and construction of the most robust cap to ensure that the system will continue to protect the environment in the event of several components of the system failing. · Progressive rehabilitation of the landfill. · Geomembranes to be used in landfill cover systems must meet the requirements specified in section 4 of Appendix D. · Installation of geomembranes in the landfill cover systems must meet the requirements specified in section 5 of Appendix D. · The CQA plan for geomembranes must address the issues raised in section 6 of Appendix D and should follow the suggestions unless an alternative provides an equivalent or better outcome. · Geosynthetic clay liners to be used in landfill cover systems must meet the requirements specified in section 4 of Appendix E. · Installation of geosynthetic clay liners to be used in landfill cover systems must meet the requirements specified in section 5 of Appendix E. · The CQA plan for geosynthetic clay liners must address the issues raised in Section 6 of Appendix E and should follow the suggestions unless an alternative provides an equivalent or better outcome. · The minimum thickness of a phytocap soil layer must be 1.5 m. · A phytocap design must include a monitoring and maintenance program to ensure integrity of the cap and for the survival of plants. · Design of phytocaps for a Type 2 landfill requires the use of lysimeter field trials or other approved trial. · The site occupier must ensure that the landfill aftercare management plan is implemented until an Environmental Audit demonstrates that the site no longer poses a risk to the environment or for at least 30 years after the site stopped receiving waste.
8.2 Aftercare management	**Relevant BPEM objective** *To manage the site after closure so that environmental protection and monitoring systems are maintained until the landfill has stabilised.* **Required outcome of the BPEM** · Preparation of a landfill aftercare management plan. · No building or structures on the site of the landfill cells without an assessment of potential risks and appropriate risk mitigation measures incorporated into the design and construction of those buildings and structures. · Provide buffers in accordance with Table 8.2, where these are unavailable demonstrate that risks are mitigated to the same standard.

APPENDIX D: Guidance on geomembrane use in landfills

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Executive summary

Geomembranes are nowadays extensively used in landfills as part of basal and sidewall/slope liner systems and/or in capping systems. Their main function is to limit contaminant migration, to reduce water ingress into the landfill and to control biogas escape to the atmosphere.

This document provides details on minimum standards for geomembrane liner material, thickness, quality, strength, durability, installation procedures and testing requirements. It is aimed at assisting engineers, specifiers, designers, regulators, facility owners and operators in assessing geomembranes for landfill engineering purposes.

D.1 Introduction

Geomembranes are flexible polymeric sheets mainly employed as liquid and/or vapour/gas barriers. They are designed as relatively impermeable liners for use in a variety of civil engineering applications. They are frequently used as a component of basal and side slope liners, and in capping systems for landfills.

This document covers the use of geomembrane liners in landfills. It provides details on minimum standards for liner material, thickness, quality, strength, durability, installation procedures and testing requirements. It is aimed at assisting engineers, specifiers, designers, regulators, facility owners and operators in assessing geomembranes for landfill engineering purposes.

D.2 Background

Modern municipal solid waste (MSW) facilities are typically designed with a bottom barrier system intended to limit contaminant migration to levels that will result in negligible impact. The system includes a leachate collection system (LCS), which is intended to: (a) control the leachate head acting on the underlying liner and (b) collect and remove leachate. The leachate collection system typically incorporates a geotextile filter, a granular drainage layer or geocomposite, and perforated collection pipes.

The liner may range from a thick natural clay deposit to engineered liner systems involving one or more geomembrane (GM) and/or compacted clay liner (CCL) or geosynthetic clay liner (GCL). The purpose of a composite liner is to combine the advantages of two materials, each having different hydraulic, physical and endurance properties.

Covers over municipal solid waste landfills are typically multicomponent systems that are constructed directly on top of the waste shortly after the site, or portion of a site, has been filled to capacity. The aim of the cover system is to reduce water ingress into the landfill and to control biogas escape to the atmosphere. Its design is usually driven by the landfill management approach put in place for a given site.

One approach where a geomembrane is used as part of the capping system is referred to as the passive approach. In this case, the aim is to provide a cover system as impermeable as possible and as soon as possible after the landfill has ceased operating, so as to minimise the generation of leachate (waste liquid).

D2.1 Types of geomembranes

The large number of commercially available geomembranes can make it challenging to select which geomembrane has the most appropriate combination of performance properties for a given application. Each type of geomembrane material has different characteristics that affect its installation, durability, lifespan and overall performance. It is therefore necessary to match the project performance criteria with the right combination of properties of a particular geomembrane.

Selection of a geomembrane liner should consider:

- the hazard posed by the contained material and leachate
- susceptibility of the liner material to chemical or environmental attack or deterioration while in service
- tensile strength and elasticity
- thermal stability
- puncture, tear and shear resistance
- anticipated operational life required for effective containment
- local environmental conditions, including subsoil stability.

Geomembrane materials should be selected based on their overall performance with respect to issues such as chemical resistance, mechanical properties, temperature resistance, thermally induced stresses (expansion/contraction), weathering resistance, product life expectancy, installation factors, cost effectiveness, and the type of application.

Due to the nature of the barrier system of which they will form part, geomembranes will often be subjected to coupled effects, whether they are used in bottom or side liners or in capping systems. For example, in bottom or side liners, the selected geomembrane might need to operate under the combined effects of mechanical stresses, leachate chemistry and increased temperature caused by the biological decomposition of the organic matter in municipal solid waste for short and long periods of time. Observed temperatures in different landfills reported in the literature range from 1 to 65 °C and at the liner from 7 to 60 °C (Yesiller et al. 2005, Rowe and Islam, 2009, Hanson et al., 2009, Bouazza et al., 2010).

On the other hand, in capping systems, the combined effect of the soil overburden pressure and differential settlements of the waste will tend to dominate and therefore will govern the selection of a given geomembrane.

Consequently, it is very important to recognise the difference between the lining applications and the conditions under which the geomembranes will operate for both short term and long term of applications. It follows from this that it is essential to select the geomembrane, based on scientific and technical data, such that it has the material properties required to meet the engineering requirements of the particular application.

D2.2 Selecting geomembranes

Since the engineering requirements vary depending on the specific application, the geomembrane property requirements will differ from one application to another (in other words, requirements will be different for capping and bottom lining). Because of the different magnitude of the 'stresses' (tensile, interface, thermal, chemical and so on) that may be developed in different design circumstances, a geomembrane suitable for one specific application may not be suitable for another even though, superficially, the two applications may look similar.

The majority of the geomembranes used in landfills are thermoplastics (they can be remelted) which means that they are relatively easy to weld and repair.

Polyethylene is by far the polymer most widely used to manufacture geomembranes. It can be classified into several categories based on its density and branching: high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE) are the geomembranes most used in landfills. It is important to emphasise that modern HDPE geomembranes are actually manufactured using a polyethylene resin with a density of 0.932–0.940 g/cm^3, which falls into the medium-density polyethylene (MDPE) category as defined in ASTM D833.

It is the addition of carbon black and additives that result in a final density of the geomembrane between 0.941 and 0.950 g/cm^3, which corresponds to an HDPE as defined in ASTM D833. The physical and mechanical properties of polyethylene are highly sensitive to resin density as shown schematically in Figure D1.

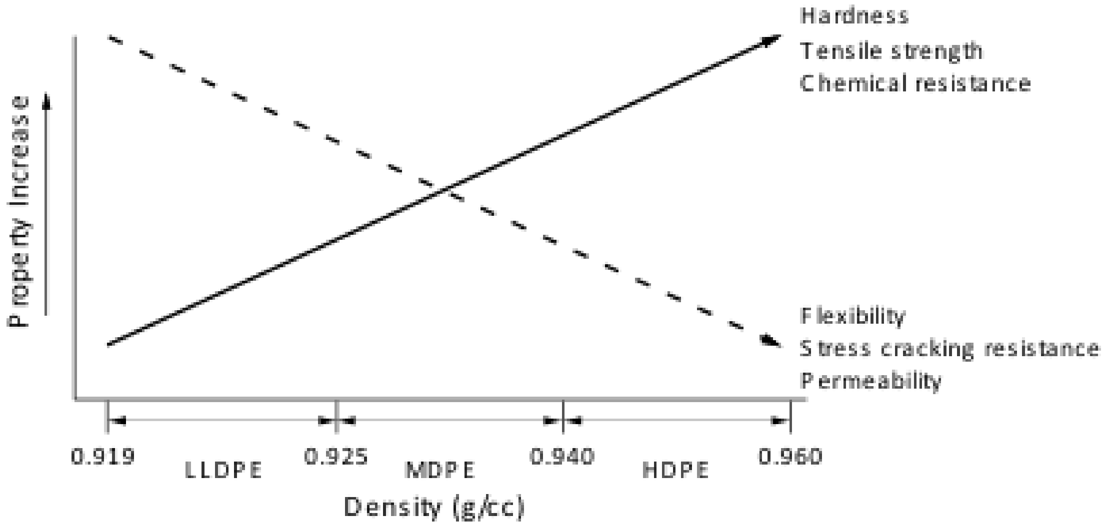

Figure D1: Generalised relationships between density of polyethylene and materials properties (from Hsuan et al. 2008).

In most cases the selection of the type of polyethylene is governed by the function of the geosynthetic product. In the case of bottom and sideslope liners, the geomembrane liner is expected to have an excellent ability to reduce advective and diffusive flow of contaminants out of the landfill and relatively high chemical resistance to leachate components. High-density polyethylene (HDPE) fulfils these conditions and it is not surprising that it is the material almost exclusively used for the geomembrane lining of the base and side slopes of landfill across the developed world in single composite or double composite liners (Giroud and Touze-Foltz 2003).

However, the requirements in a capping system are different, since the focus is more on the ability of the geomembrane to deform with minimal impact on its integrity rather than on chemical compatibility. Therefore, flexible geomembranes such as linear low-density polyethylene (LLDPE) geomembranes are often well suited to accommodate the strains and resultant stresses that arise from differential settlements of the waste.

In general, the choice of a given geomembrane should be guided by the containment application (basal liners, secondary liners, sideslope liners and capping) and the assessment of the required design life; followed by the assessment of potential physical/mechanical and chemical stresses relevant to the application and their implications on the required design life; and finally, risk assessment, including the consequence of failure.

D2.3 Material key properties

When used as part of a composite liner in the bottom or sideslope of a landfill, the HDPE geomembrane should not only have chemical resistance and low permeability to the contaminants but should also remain chemically and mechanically stable in the long-term. However, the same does not necessarily apply to LLDPE geomembranes, which are often used in landfill caps and closure of landfills, where mechanical stability is often the most important parameter governing their selection (in other words, the ability to accommodate differential settlement and localised strain while maintaining the capping liner integrity).

This section will touch on some key issues that need to be considered when selecting a geomembrane liner.

D2.3.1 Geomembrane thickness

Thickness is an important factor in geomembrane selection from a welding consideration. Geomembranes with a thickness less than 1.5 mm (0.5–1.0 mm) are more susceptible to welding problems. If welding conditions are not optimum or, if the welding machine is not set correctly it is easy for holes to be burnt in these thinner geomembranes. In general, thicknesses of 1.5–2.0 mm are preferred from a welding perspective.

The thickness of a geomembrane also dictates performance criteria such as its tear resistance, puncture resistance and its resistance to installation damage. All these properties increase with increasing geomembrane thickness. In fact the geomembrane property most involved with resistance or susceptibility to tear, puncture and impact damage; is thickness. At least a linear, and sometimes even an exponential, increase in resistance to the above properties is observed as the thickness increases. For this reason many environmental agencies require a minimum thickness under any circumstances.

For example, the US Environmental Protection Agency (USEPA) recommends that HDPE geomembrane in a basal liner be at least 1.5 mm thick (USEPA 2003). Ontario, Canada requires a minimum of 1.5 mm for a geomembrane in a primary liner and 2 mm for a geomembrane in a secondary liner (Moe 1998). South Australia requires a minimum of 1.5 mm for a geomembrane in basal liners (EPA SA 2007). In Germany a minimum thickness of 2.5 mm is required for landfill liners (Bouazza et al. 2002).

For landfill closure or cell closure, minimal thicknesses vary from 1.0 mm to 2.5 mm, depending on the regulatory agency (Zanzinger and Gartung 2002, Scheirs 2009, EPA SA 2007).

The geomembrane thickness can also affect the durability of the geomembrane due to the extent of surface exposure. Some modes of degradation, such as oxidation occur as a function of the total surface area exposed. In general, thicker geomembranes are better able to resist chemical attack, temperature fluctuations and gradients, stress corrosion cracking, environmental stress cracking and so on.

Geomembrane thickness has a significant impact on the depletion of antioxidants, with the thicker geomembrane giving the longest antioxidant depletion time (Rowe et al. 2010).

Clearly, there needs to be a trade-off between mechanical durability, ease of installation/welding and affordability. For example, a thick (3.0 mm) HDPE geomembrane will have excellent mechanical properties and durability but will be very stiff and difficult to install and, of course, more costly. On the other hand an HDPE geomembrane with thickness of less than 1.5 mm will be more economical but is more likely to present problems with extrusion welding such as 'burn through' if installation is not properly supervised. For a given resin and additive package, the thinner geomembrane will have a shorter service life.

D2.3.2 Strength

D2.3.2.1 Ability to resist/accept stress and deformation

An important aspect of geomembrane design is that the geomembrane should serve only as a barrier and not serve any load-bearing or structural function. An overriding design consideration therefore is minimizing stresses acting on a geomembrane.

Stresses that can be exerted on geomembranes include (Scheirs 2009):

- variations and discontinuities in geomembrane thickness
- thermally-induced stresses (due to thermal expansion and contraction)

- damage arising from handling and installation
- imposed and induced stress during construction (for example, wind gusting, loading of cover material by heavy vehicles)
- inadequate welding and fixing to attachments
- seaming-induced stresses (warpage, heat-affected zone).

In addition, the design of a geomembrane application needs to consider the various potential stresses imposed on the geomembrane by the in-service configuration and conditions. For instance, such stresses include the following (Scheirs 2009):

- strain imposed at the anchor trench
- strain imposed over long, steep side slopes
- differential settlement in the subgrade, foundation soils or waste
- point loading by angular or rough stones.

A geomembrane liner must maintain its integrity when subject to both short-term and long-term stresses. Short-term mechanical stresses arise from thermal expansion and contraction of the geomembrane during the construction of the installation as well as equipment traffic during the construction phase. Long-term mechanical stresses include the placement of soil or stones on top of the geomembrane and also from differential or preferential settlement of the subgrade or the waste.

Ideally, geomembrane liners are designed to be installed without stress. They are intended to act only as a barrier. In practical terms a zero stress installation is impossible to achieve since amongst other considerations, some level of wrinkles and folds are virtually unavoidable.

A geomembrane must be able to accept some deformation without excessive thinning, yielding or rupture. The ductility of a geomembrane is far more important than its ultimate strength in relation to long-term performance. Strength is of prime importance during installation of a geomembrane so it can withstand the various stresses of this phase.

Geomembranes can be subjected to uniaxial stress states from plane strain loading, such as drag-down along lined slopes and from out-of-plane loading conditions imposed by localised subsidence beneath waste containment cover and liner systems. The multi-axial tension test (ASTM D5617) is useful in evaluating the performance of geomembranes subjected to multi-axial stress states.

Note: HDPE has excellent strain capabilities under uniaxial strain (or elongation) but relatively poor multiaxial (out-of-plane) strain performance. In contrast, LLDPE exhibits excellent uniaxial and multiaxial strain behaviour.

D2.3.2.2 Tensile properties

The tensile properties are arguably the most critical mechanical properties of geomembranes since, during installation and service, there are a range of tensile forces that can act on the geomembrane. Table D1 summarises the types of tensile forces that can act on an installed geomembrane.

Table D1: Types of tensile forces that can act on an installed geomembrane (from Scheirs 2009)

Type of force	Examples
Uniaxial	'Self-weight' of the geomembrane on a slope. 'Down-drag' caused by waste settlement on side slope liners. Contraction stress on batter due to anchor trench holding liner taut.
Multiaxial	Differential settlement. Force exerted by angular or sharp projections. Multiaxial tensile stresses caused by consolidation of clay liners under compression. Thermal contraction and temperature related effects.

Minimising these tensile stresses on the geomembrane will enhance its longevity and durability as a long-term barrier. HDPE exhibits a distinct yield point in its uniaxial tensile stress/strain curve at around 12 per cent strain (elongation). Above this point further plastic deformation can occur without additional load. This arguably represents one of the main deficiencies of HDPE geomembranes. In contrast, LLDPE has a far less pronounced yield point at about 40 per cent strain.

It is misleading to assume that, since a geomembrane material has a high elongation to break, it then follows that it will have a high survivability in service.

Uniaxial tensile tests (such as those performed on dog-bone specimens in a tensile testing machine) do not represent field situations where stress states in geomembranes are biaxial (or even triaxial). Axi-symmetric multiaxial hydrostatic tests are better suited to simulate the strains found under field conditions. These tests can also simulate the out-of-plane loading that is experienced by geomembranes in service where there is subsidence of the subgrade.

D2.3.2.3 Allowable strain

The maximum allowable design strain for geomembranes is obviously far below the yield strain (12 per cent) and varies widely – ranging from quite high to very conservative values.

Some regulators in the USA have set a maximum of one per cent strain for geomembranes. The German BAM requirements allow for a maximum global strain of three per cent and maximum local strain (at individual stone protrusions) of just 0.25 per cent (Seegers and Muller 1996). To achieve such minimal strains it is necessary to use a very heavy geotextile protection layer or sand protection layers (Tognon and Rowe 2000, Bouazza et al. 2002, Brachman and Gudina 2008a, 2008b).

It is important to draw the distinction between global strain and local strain. A maximum strain of 0.25 per cent global strain (at any location) is sometimes mistakenly specified for HDPE geomembranes, which is very difficult to achieve in practice.

Based on currently available information, maximum allowable strains for various geomembrane materials are shown in Table D2.

Table D2: Maximum allowable strains for various geomembrane materials (from Peggs 2003)

Geomembrane type	Maximum allowable strain
HDPE smooth	6 %
HDPE randomly textured	4 %
HDPE structured profile	6 %
LLDPE density <0.935 g/cm^3	12 %
LLDPE density >0.935 g/cm^3	10 %
LLDPE randomly textured	8 %
LLDPE structured profile	10 %

The measurement of strain is used as an indirect measure of the stress that exists in a geomembrane that might result in stress cracking. The objective of specifying these maximum allowable strain values is to limit the in-service stress to a sub-critical value where stress cracking will not be a problem in practice (Peggs 2003).

While the control of strain is a very important consideration for HDPE geomembranes it is not as significant for other geomembranes that are not susceptible to stress cracking unless they are oxidised and embrittled.

D2.3.2.4 Puncture resistance

Puncture resistance of a geomembrane is obviously an important property, because even small punctures can reduce the effectiveness of the installed geomembrane as a containment system.

Geomembranes are often placed above or below material containing angular or sharp edges. For example, in a waste containment system, a granular drainage layer consisting of gravel may be placed above the geomembrane. Unless there is an adequate protection layer between the gravel and the geomembrane, as load is placed on the granular drainage layer (either by equipment or waste placement), the gravel may be pushed into the geomembrane, causing puncture. Puncture of the geomembrane may result in a breach of the containment system.

Puncture of geomembranes can occur when containment material such as waste containing sharp projections is placed on a geomembrane without adequate protection layers. Puncture may also occur as a result of animal damage from claws and beaks or due to sharp stones protruding from the subgrade as a result of poor subgrade preparation or, in some cases, from stones just below the surface of the subgrade.

Since puncture of the geomembrane results in leakage, it is important to select a geomembrane with adequate puncture resistance for a given particular application.

In practice there are three main ways that geomembranes can be punctured:

- Angular stones or other sharp protrusions as well as hydrostatic pressure or overburden soil pressure pushing down on the geomembrane. Also, damage can be caused by the heavy equipment itself (for example, earth movers).
- Penetration from the top where sharp or angular objects are forced into the membrane such as sharp rocks, branches or animal claws/hoofs (see Figure D2).
- Penetration from below where stones are forced into the geomembrane from the subgrade.

Damage caused by puncture will plastically deform the material up to failure and cause leaks. There are two modes of puncture. Static puncture is due to contact of stones on the geomembrane under high static load (weight of the waste or hydrostatic loading), while dynamic puncture is due to the fall of objects mainly occurring during installation. Static puncture may be reduced by using protective layers and rounded soil particles, as well as stiff and thick geomembranes. Dynamic puncture can be eliminated by considerable care in construction (good workmanship is required).

Figure D2: A kangaroo claw can be very damaging to geomembranes during the installation phase (mostly relevant to landfills in rural Victoria).

D2.3.2.5 Slope stability-interface friction

The long-term integrity of a geomembrane can depend on there being adequate friction between the various components of the liner system, in particular, between the subgrade soil or geosynthetic clay liner (GCL) and the geomembrane, as well as between the geomembrane and any adjacent layers such as geotextiles or any other ancillary material (Bouazza et al. 2002). In this respect, frictional characteristics between the different lining components are very important performance properties and represent a critical aspect of the design of geomembranes for side slopes in landfills and also steep covers.

Adequate friction is necessary to prevent slippage or sloughing on slopes of the installation. In the case of installations with sloping sides, the geomembrane must be able to:

- support its own weight on the side slopes
- withstand down-dragging during and after placement of the waste
- maintain a stable state when a soil cover or a granular drainage layer is placed on top of the geomembrane
- maintain a stable configuration when other geosynthetic components such as geotextiles or geonets are placed on top of the geomembrane.

It is important to stress the fact that published values of interface friction should not be used in detailed design. Performance tests using site-specific material and mimicking field conditions should always be conducted. In this respect, the interface shear test (ASTM 5321) is useful in evaluating the interface friction of geomembranes with soils and/or geosynthetic components.

D2.3.2.6 Long-term mechanical performance

The long-term mechanical performance of geomembranes is of primary importance in landfill design. It can be assessed through the so-called Stress Crack Resistance (SCR) test.

ASTM D883 defines stress cracking as an external or internal rupture in a plastic caused by tensile stresses less than its short-term mechanical strength. In other words it is a cracking caused by an applied stress which is lower than its tensile strength at yield.

The phenomenon occurs in crystalline polymers such as polyethylene. Thus geomembranes made from HDPE are more susceptible to stress cracking than products made from other polymers. Less crystalline geomembrane materials such as LLDPE are not susceptible to stress cracking in their new conditions. However, after oxidation they too can become susceptible to stress cracking at folds and creases.

A standard test to evaluate SCR of geomembranes is the Notched Constant Tensile Load (NCTL) test (ASTM D5397). The test measures failure times of notched specimens at different applied loads in a liquid environment at 50 °C (Hsuan and Koerner 1995).

The trend shown in Figure D3 is obtained by plotting applied stress versus failure time on a log-log scale to generate a ductile-to-ductile curve from which the transition time (T_t) and transition stress (T_s) are obtained. Material with low transition stress and long transition time, particularly the latter, indicate a high SCR.

The stress cracking resistance of polyethylene-based geomembranes is a function of the type of polyethylene resin used and thus varies widely from one geomembrane to another (sometimes even for the same manufacturer), depending on the resin used to manufacture that particular geomembrane.

Most of the geomembranes resins now have excellent stress crack resistance as a result of intensive research carried out in the 1990s. However, despite all the advances made, stress cracking can still occur due to other factors such as recrystallisation, oxidative embrittlement, sheet scoring/notching and stress rupture.

D2.3.2.7 Durability/degradation of polyolefin geomembranes

The design life of a geomembrane is defined as the minimum expected service time where a geomembrane is intended to perform a particular containment function. The survivability of geomembranes is related to the geomembrane type, the design of the installation, the MQA of the manufacture, the quality of installation (including welding), the chemical nature of the products in contact with the geomembrane and the liner temperature.

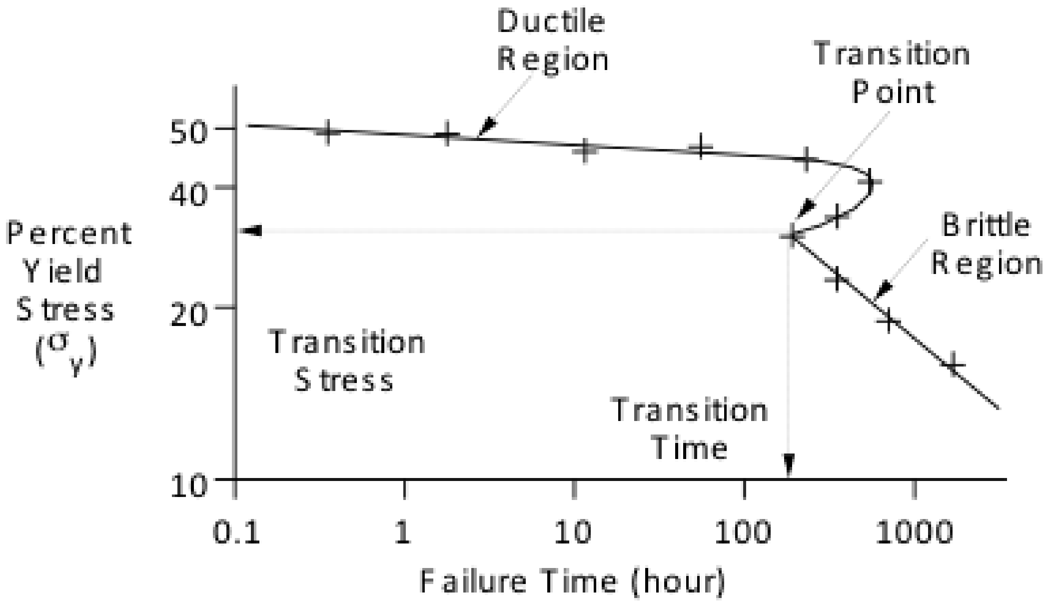

Figure D3: Ductile-to-brittle transition curve resulting from the NCTL test (from Hsuan 2000).

The durability of a geomembrane is related to the change of critical performance properties over time. The durability of geomembranes can also be influenced by the nature and quality of the additives and fillers, especially the type and level of carbon black and antioxidants used in the geomembrane sheets. In particular, the durability of geomembranes is significantly influenced by the specific type, quantity and quality of the stabilisers and the UV-screening pigments. Furthermore, it depends on the dispersion of the additives throughout the geomembrane and the ability of the additives to migrate within the geomembrane to maintain protection of the surface of the geomembrane as they are leached from the surface.

The durability of a geomembrane is a function of (Scheirs 2009):

- its base polymer
- the polymer microstructure
- its formulation (the type and amount of additives and fillers compounded in it, their level and their dispersion)
- characteristics of the containment product.

Sheet thickness is also an important factor governing the durability of geomembranes (as discussed earlier).

The following mechanical property changes are generally observed with geomembrane degradation (Scheirs 2009):

- a decrease in percentage elongation at failure
- an increase and then decrease in strength at failure (tensile stress at break)
- a decrease in impact strength
- an increase in modulus of elasticity (increasing stiffness)
- an increase in brittleness (general loss of ductility).
- An increase in susceptibility to stress cracking.

The changes in the above properties can thus be used to monitor the progressive degradation of polymeric geomembranes over time.

When examining potential degradative effects on geomembranes one has to consider synergetic factors where two or more agencies are acting simultaneously on the geomembrane (for example, chemical degradation (chemical compatibility) and mechanical stress, oxidation degradation and chemical degradation, oxidation degradation and mechanical stress).

Oxidation is generally regarded as the key degradation mechanism affecting the long-term durability of geomembranes. As oxidation proceeds the physical and mechanical properties of the polymer start to deteriorate and eventually this process leads to failure. To protect against oxidation during their service lifetime and extend their service life, antioxidants and stabilisers are added to the formulation. Conceptually, the degradation of polyolefin geomembranes is often represented as three stage process (Hsuan and Koerner 1998) as shown in Figure D4.

The first stage (Stage A) represents the period during which depletion of antioxidants and stabilisers occurs. In the second stage (Stage B), the antioxidants and stabilisers are effectively depleted but then follows the induction to the onset of polymer degradation. Finally, in the third stage (Stage C), degradation of various properties begin to gradually develop.

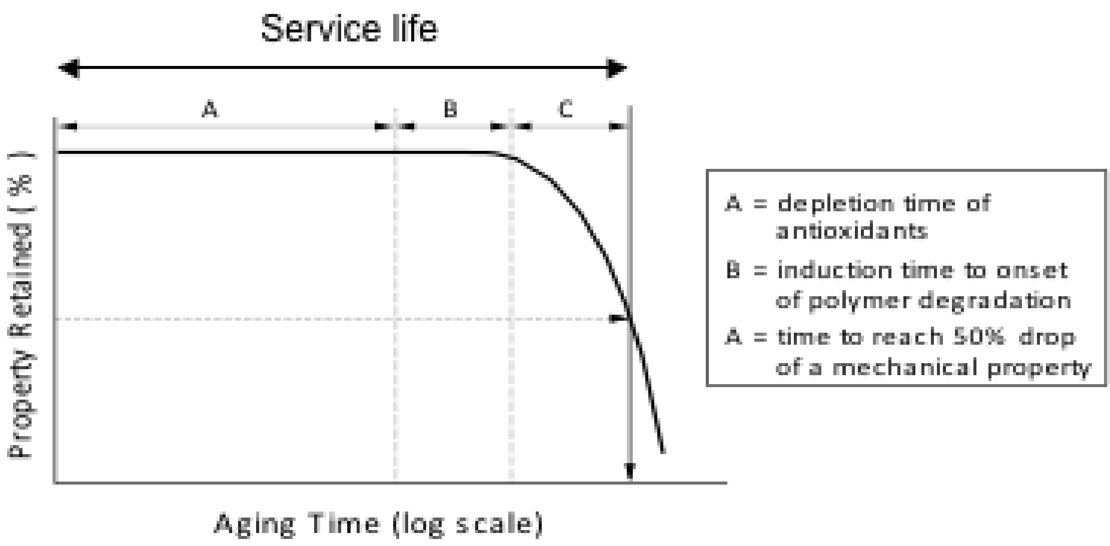

Figure D4: Conceptual stages in oxidation of polyolefin geosynthetics (modified from Hsuan and Koerner 1998).

The point of 50 per cent retention of mechanical properties is usually arbitrarily taken as the failure point and represents the limit of service life of the geomembrane (very often referred to as the 'half-life').

It should be noted that even at the half-life, the material still exists and can function, albeit at a decreased performance level with a factor of safety lower than the initial design value. Some researchers (such as Rowe 2009a, 2009b) define the limit of the service life of the geomembrane as the time to 50 per cent of the specified value of the property of interest (for example, SCR), rather than the initial values, since this is fairer to products with initial values well above the specified value and allows an increase in service life by using materials with, for example, a higher initial SCR.

The most widely used test for assessing the resistance of polyolefin geomembranes to oxidative degradation in service is the oxidative induction time (OIT) test, which evaluates the quality of the antioxidant additive package and monitors the depletion of antioxidants from the geomembrane.

This test deals only with Stage A described in the above section. Once the antioxidants are consumed then oxidation degradation starts and properties of the geomembrane will subsequently change (Stage B and C, respectively).

Common tests that can be used to detect oxidation degradation (i.e. Stage B and C) are the melt index (MI) test, tensile test, or stress crack resistance (for example, NCTL)

D.3 Minimum requirements for HDPE geomembrane for basal and sideslope liners

The following parameters are considered minimum requirements for geomembranes in basal and sideslope liners to ensure their long service life.

It should be stressed that these requirements represent a minimum expectation for 'good practice'. A higher standard might be required in certain applications and the onus is on the engineer of record to establish if a higher standard or requirement is needed.

Note that service life is considered to be the length of time the geomembrane acts as an effective hydraulic and diffusive barrier to contaminant migration (Rowe et al. 2004). In this respect, it is important to acknowledge the fact that geomembranes will have a finite service life – they should be expected to experience ageing and degradation. This aspect must be taken into account in the design of the geomembrane liner and the liner system itself.

1. The geomembrane shall be a high-density polyethylene (HDPE) geomembrane and shall have a minimum thickness of 1.5 mm.

2. It is important to select or specify high-grade polyethylene resin that has been specially formulated to meet the specific, unique demands encountered by geomembranes. Resin for the geomembrane should be virgin, first- quality HDPE resin and should not be intermixed with other resin types. Furthermore, it should not contain more than two per cent clean

recycled polymer by weight of the HDPE resin. As a minimum, the HDPE resin shall meet the specifications indicated below:

Physical property	Minimum requirement
Density* (g/cm^3)	> 0.932
Melt Flow Index (g/10 min)	< 1.0

* Base resin density without carbon black and additives added

3. The oxidative induction time of the geomembrane shall exceed both (a) 100 min, as determined by ASTM D3895 and (b) 400 min, as determined by ASTM D5885.

4. The oxidative induction time of the geomembrane after oven ageing at 85 °C for 90 days, as described in ASTM D5721, shall exceed both (a) 55 per cent of the value for the original geomembrane, as determined by ASTM D3895, and (b) 80 per cent of the value for the original geomembrane, as determined by ASTM D5885.

5. Other design requirements and technical specifications for the geomembrane (such as carbon black dispersion, tensile properties, tear resistance, puncture resistance, stress crack resistance and UV resistance).

6. The standard specification given below is intended to ensure good quality and performance of HDPE geomembranes in general applications:

Ingredients	Critical aspects	Minimum specifications to meet
97.5% polyolefin polymer	Must have the right stress crack resistance	NCTL > 300 hrs
> 2% carbon black	Must be of the right particle size	Particle size ~20 nm
At least 0.5% antioxidants and HALS stabilisers	Must have high effectiveness and permanence	HP-OIT > 400 mins

7. The design of the liner needs to consider the various potential stresses imposed on the geomembrane by the in-service configuration and conditions. It is necessary to include the calculations of the physical stresses due to:

   - strains imposed at the anchor trench
   - strains imposed over long, steep side slopes
   - differential settlement of the subgrade and foundation soils, if any
   - point loading by angular or rough stones (using ASTM D5514).

8. Provide a statement (with justification) on the chemical compatibility of the geomembrane liner and the leachate, in particular, the ability of the liner to retain adequate strength and performance after exposure to leachate.

9. A statement on the effect of thermal stresses on the liner during installation and construction, and effect of temperature during operation (effect of waste temperatures). Describe how the waste temperature and the thermal stresses will be taken into account.

10. A statement on the effect of equipment traffic during installation stresses. In particular the stresses resulting from application of the protection layer placed between the liner and the leachate collection system. Describe how these stresses will be taken into account.

11. In the case of installations with sloping sides, it needs to be demonstrated that there is adequate friction between the various components of the liner system to prevent slippage or sloughing on the slopes of the installation. In particular, the following must be assessed:

   - the ability of the geomembrane to support its own weight on the side slopes
   - the ability of the geomembrane to withstand down drag during and after waste placement
   - the suitability of the anchorage configuration for the geomembrane
   - the ability to maintain a stable state when a granular drainage layer is placed on top of the geomembrane
   - the ability to maintain a stable configuration when other geosynthetic components such as geotextiles or geocomposites are placed on top of the geomembrane
   - the ability to maintain a stable configuration when installed on top of a compacted clay liner or a geosynthetic clay liner.

12. A specification for liner strength and the calculations defining the minimum strength requirements:

   - stresses resulting from settlement, compression or uplift
   - installation stresses
   - operating stresses
   - thermal stresses
   - climatic conditions.

13. Specification for the geomembrane protection layer that will be placed between the geomembrane and the leachate collection system, including the method of placement.
14. Installation specifications should include details regarding:
    - subgrade condition (including cracking and other irregularities) and suitability
    - geomembrane labelling
    - methods of protecting the geomembrane during shipping, storage and handling
    - methods of dealing with thermal effect on geomembrane surfaces on rolls
    - methods of dealing with spotting of deployed geomembranes
    - methods of dealing with thermal expansion and contraction
    - methods of dealing with wind effects
    - panel deployment layout plan, panel identification, method of placement, seam orientation, seam preparation, seaming methods, seaming temperature constraints
    - procedures to deal with damages and defects
    - procedures to be adopted to prevent desiccation of any underlying compacted clayey liner or shrinkage of any underlying GCL (both before and subsequent to the placement of the geomembrane)
    - procedures to be adopted to protect the geomembrane from the soil backfill
    - methods of placement of the protective layer and/or leachate collection layer
    - methods of dealing with or managing wrinkles (waves), especially at the time the geomembrane is covered with soil (for example, drainage gravel).
15. Inspection activities, describe how the following will be taken into account:
    - skill of the welding crew
    - supervision of welding, welding procedure and weld preparation
    - non-destructive and destructive field testing of sheets and seams during installation of the geomembrane
    - action on test failure
    - weather and temperature conditions during geomembrane deployment and seaming
    - control of panel uplift by wind
    - wrinkles and bridging
    - inspection of the surface of the geomembrane
    - presence of damages and defects
    - repair methods.
16. CQC/CQA plan.
17. Optional requirement (specific to landfills in rural Victoria): Methods of dealing with potential damage to the geomembrane by wildlife during installation.

D.4 Minimum requirements for LLDPE geomembrane liners for landfill cover systems

The geomembrane in a final cover is not in direct contact with waste therefore chemical compatibility should not in theory be of concern, particularly if a gas collection layer is present (note: In some cases, diffusion of vapours – such as VOCs – can potentially occur from the underlying waste. In this case, this aspect needs to be considered in the design process). Focus must be on its ability to deform with minimal impact on its integrity due to settlement or subsidence of the waste. The following parameters are considered minimum requirements for geomembranes in landfill cover systems to ensure to ensure their long service life.

It should be stressed that these requirements represent a minimum expectation for ‘good practice’. A higher standard might be required in certain applications and the onus is on the engineer of record to establish if a higher standard or requirement is needed.

18. The geomembrane shall be a linear low-density polyethylene (LLDPE) and shall have preferably a minimum thickness of 1.5 mm. However, a thickness of 1 mm could be selected, provided that additional measures are taken to protect the integrity of the liner, particularly during installation. For example: extreme care is taken during installation (i.e. wedge welding of the geomembrane panels) to avoid possible burn-through, overheating, buckling and misalignment.
19. Resin for the geomembrane should be virgin, first quality LLDPE resin and should not be intermixed with other resin types. Furthermore, it should not contain more than two per cent clean recycled polymer by weight of the LLDPE resin As a minimum, the LLDPE resin shall meet the specifications indicated below:

Physical property	Minimum requirement
Density* (g/cm3)	≥0.915 and ≤0.926
Melt Flow Index (g/10 min)	<1

* Base resin density without carbon black and additives added.

20. The oxidative induction time of the geomembrane shall exceed both (a) 100 min, as determined by ASTM D3895 and (b) 400 min, as determined by ASTM D5885.

21. The oxidative induction time of the geomembrane after oven ageing at 85 °C for 90 days, as described in ASTM D5721, shall exceed both (a) 35 per cent of the value for the original geomembrane, as determined by ASTM D3895, and (b) 60 per cent of the value for the original geomembrane, as determined by ASTM D5885.

22. Other design requirements and technical specifications for the geomembrane (for example, carbon black dispersion, tensile properties, two per cent modulus, tear resistance, puncture resistance, axi-symmetric break resistance strain and UV resistance).

23. The standard specification below is intended to ensure good quality and performance of LLDPE geomembranes in general applications:

Ingredients	Critical aspects	Min. specifications to meet
97.5% polyolefin polymer	Axi-symmetric break resistance strain	>30%
> 2% carbon black	Must be of the right particle size	Particle size ~20 nm
At least 0.5% anti-oxidants and HALS stabilisers	Must be have high effectiveness and permanence	HP-OIT > 400 mins

24. The design of the liner needs to consider the various potential stresses imposed on the geomembrane by the in-service configuration and conditions. It is necessary to include the calculations of the physical stresses due to:
    - strains imposed over steep side slopes, if cover is sloped and consequently strains imposed at the anchor trench
    - differential settlement of the waste.

25. A statement on the effect of thermal stresses on the liner during installation and construction. Describe how these stresses will be taken into account.

26. A statement on the effect of equipment traffic during installation. In particular the stresses resulting from application of the top soil/cover soil/or drainage layer. Describe how these stresses will be taken into account.

27. In the case of installations with sloping sides, it needs to be demonstrated that there is adequate friction between the various components of the liner system to prevent slippage or sloughing on the slopes of the installation. In particular, the following must be assessed:
    - The ability of the geomembrane to support its own weight on the side slopes.
    - the suitability of the anchorage configuration for the geomembrane.
    - the ability to maintain a stable state if a granular drainage layer is placed on top of the geomembrane.
    - the ability to maintain a stable configuration if other geosynthetic components such as geotextiles or geocomposites are placed on top of the geomembrane.
    - the ability to maintain a stable configuration if installed on top of a compacted clay liner or a geosynthetic clay liner.

28. A specification for liner strength and the calculations defining the minimum strength requirements due to:
    - stresses resulting from differential settlement
    - installation stresses
    - thermal stresses
    - climatic conditions.

29. Specification for the geomembrane protrusions and penetrations. Describe how the geomembrane will be attached to penetrations and structures. Describe how the effect of differential settlement and/or lateral movement of the materials around the protrusions/penetrations will be taken into account.

30. Installation specifications should include details regarding:
    - subgrade condition and suitability
    - geomembrane labelling
    - methods of protecting the geomembrane during shipping, storage and handling
    - methods of dealing with thermal effect on geomembrane surfaces on rolls
    - methods of dealing with spotting of deployed geomembranes
    - methods of dealing with thermal expansion and contraction
    - methods of dealing with wind effects
    - panel deployment layout plan, panel identification, method of placement, seam orientation, seam preparation, seaming methods, seaming temperature constraints
    - procedures to deal with damages and defects

- o procedures to be adopted to prevent desiccation of any underlying compacted clayey liner or shrinkage of any underlying GCL (both before and subsequent to the placement of the geomembrane)
- o procedures to be adopted to protect the geomembrane from the soil backfill and equipment traffic
- o methods of placement of the top soil/cover soil
- o methods of dealing with or managing wrinkles (waves)
- o methods of dealing with installation around protrusions and penetrations.

31. Inspection activities – describe how the following will be taken into account:
    - o skill of the welding crew
    - o supervision of welding, welding procedure and weld preparation;
    - o non-destructive and destructive field testing of sheets and seams during installation of the geomembrane
    - o Action on failing tests
    - o Weather and temperature conditions during geomembrane deployment and seaming
    - o Control of panel uplift by wind
    - o Wrinkles and bridging
    - o Inspection of the surface of the geomembrane
    - o Presence of damages and defects
    - o Repair methods.
32. CQC/CQA plan.
33. Optional requirement (specific to landfills in rural Victoria): methods of dealing with potential damage to the geomembrane by wildlife during installation.

D.5 Requirements for the installation of liners to be used in landfills

D5.1 Geomembrane installation

In most cases the lining task involves large areas; therefore, it is important to proceed stage by stage in the geomembrane installation process. It is suggested that the installation be composed of the following phases:

1. installation planning and pre-installation conformance testing
2. construction and preparation of the subgrade
3. placement of the geomembrane including transport, unrolling and placing, anchorage
4. welding of the geomembrane panels, connection to structure penetration systems, testing of welds
5. placement of the protective layer.

D5.1.1 Planning and pre-installation conformance testing

The installation process must be preceded by a planning phase which should result in a detailed panel layout irrespective of the type of application. The layout should specify to scale the arrangement of the geomembrane panels in the area to be lined and the penetrations and connections.

Each roll of geomembrane shall be labelled to provide the following identifying data:

- name of manufacturer and type
- material thickness
- roll number
- roll length
- roll weight
- roll width
- reference numbers to raw material batch and laboratory certified reports
- the manufacturer's approved QA stamp and the technician's signature.

The geomembrane should be tested for all critical properties including stress crack resistance and oxidative resistance by a third-party accredited independent laboratory before installation.

D5.1.2 Subgrade

For a composite liner system to function optimally and efficiently the geomembrane is required to be in intimate contact with the underlying GCL or compacted clay liner (CCL). The geomembrane liner shall be placed above a smooth surface (GCL or compacted clay liner). If the material onto which the geomembrane is to be laid is a GCL then the latter needs to be placed flat on a well compact, smooth and firm foundation material. If the material onto which the geomembrane is to be laid is a CCL then the surface of the latter shall be free of any sharp objects, stones, debris, water, sudden changes in grade, and desiccation cracks. In either case, the geomembrane shall not be installed until inspection of the finished surface has been undertaken and deemed suitable by the CQA engineer.

D5.1.3 Panel placement

The geomembrane sheets shall be installed such that the panels are continuous down side walls/slopes and across the base. The arrangement of the geomembrane sheets should be according to a predetermined plan to minimise the amount of welding needed.

All panels shall be overlapped onto adjacent sheets by a minimum of 125 mm and orientated so that the lap is in the down sloping direction and across the flat base. All welds should run down a slope or be on the flat base. All primary welds used to connect panel ends to sheets shall form T-joins (tees). These T-connections must have a distance of at least 0.5 m. The welding seams of the GM cannot cross (no cruciform connections).

On slopes, the seams shall to a large extent run parallel to the line of maximum slope. Patching GM panels using transverse joints on slopes is not permitted. The connecting seam between geomembranes on the slope and the base should be located in the base at a distance of at least 1.5 m from the slope toe.

The entire surface area of each and every roll shall be inspected by the CQA engineer, prior to works commencing. The geomembrane surface inspection may occur during unrolling/installation to ensure that there are no tears, punctures, abrasions, indentations, cracks, thin spots or other faults in the material. If damages are identified, they will need to be repaired according to the specifications put in place for the site.

During installation sand bags should be placed over the panel's free edges and other areas at the end of each working day to prevent wind uplift. In expected windy conditions sandbags or similar shall be used to temporarily hold the geomembrane in position and prevent the sheet moving during welding.

Installation of a geomembrane can result in scratching or scoring which can affect the geomembrane's ability to stretch or conform. The method used to unroll and deploy the panels shall not score, scratch or crimp the geomembrane.

Wrinkles generally occur in geomembranes during installation due to temperature variations. They tend to expand when they are heated and contract when they are cooled. This expansion and contraction must be considered when placing, seaming, and backfilling geomembranes in the field. Wrinkles are undesirable as they increase the incidence of construction damage, adversely affect the durability of the geomembrane (local regions of stress concentration), and increase the infiltration beneath the geomembrane due to a lack of intimate contact between the geomembrane and the subgrade.

The geomembrane should be installed without undergoing substantial buckling, wrinkling or tensioning. In particular, care shall be taken during installation of the geomembrane to ensure that the surface of the geomembrane after installation is substantially free from buckles, wrinkles, ripples, creases and folds before the cover material is placed above it.

Geomembranes installed on slopes are required to be fixed in anchor trenches. This is done to secure the geomembrane and prevent it from sloughing or slipping down the inside side slopes during construction or service.

A normal minimum requirement is that the anchor trench must be at least one meter back from the top edge of the slope. Anchorage of the geomembrane should be carried out when the geomembrane is cool, to prevent bridging of the geomembrane at change of grade. The geomembrane should be laid on the inside wall and base of the trench only. The trench should be backfilled with low hydraulic conductivity soils and compacted as soon as after the geomembrane is laid.

Geomembranes should not be installed if it rains, hails, during periods of high wind or excessive dust, or if the subgrade is very wet.

D5.1.4 Geomembrane welding

The function of a geomembrane liner is to prevent liquid flow or gas migration into the environment, a key aspect for a successful functioning of the liner is the seaming (welding) in the field of the deployed geomembranes panels. Geomembranes can be welded by either thermal methods or chemical welding (solvent methods). The latter is not commonly used in landfills and will not be discussed further in this document. Thermal methods rely on fusion of the surfaces to be joined using applied heat (this includes wedge welding, hot air welding and extrusion welding). Only hot wedge welding and extrusion fillet welding shall be used.

The weld surfaces should be clean prior to welding. The weld area should be free of moisture, dust, dirt, debris, markings and foreign material. To minimise this problem some manufacturers apply a removable tape to the edges of the geomembranes which can be removed just prior to welding.

In the case of extrusion fillet welding, oxidation by products need to be removed from the surface to be welded by grinding/buffing. Grind marks should not be deeper than 10 per cent of the geomembrane thickness. Welding should be performed shortly after grinding so that surface oxide formation does not reform.

The contractor shall be responsible for regularly checking, calibrating and recording the following items:

- preheat air flow and temperature at the nozzle
- extrudate flow and temperature at the barrel outlet
- split copper wedge temperature on both contact points.

The contractor shall have an independently calibrated hand held temperature measuring device to confirm temperatures of each and every welding machine prior to the commencement of any test or field welds. All information regarding the results gained from the temperature device shall be recorded for each welding machine.

D5.1.5 Welding methods

Welding of all main joints between adjacent geomembrane panels (primary welds) shall be conducted using hot-wedge welding, producing two parallel seams with an air channel in between (dual-track fusion welding). The hot-wedge welding shall be conducted out using the split head wedge fusion weld method which will fuse the upper and lower overlapped geomembrane sheets.

The welding equipment shall be a fully automated device comprising of a heated copper wedge, pressure rollers and electronic controls. The copper wedge shall be controlled and constantly monitored by a programmable controller with an audible off temperature alarm and a variable speed drive unit. The copper wedge shall create two contact fusion areas of a minimum width of 15 mm and a 5 mm minimum wide void between each of the separate parallel weld zones. This void shall be created over the entire seam length to allow for field weld pressure testing.

The extrusion process is used primarily for detailed work and repair work (secondary weld) or where approved in areas that would be inaccessible to the dual track fusion weld (such as around structures, pipes and other penetrations). The extrusion welding shall be conducted using the manufacturers' surface extrusion hand welders.

The minimum width of the surface extruded bead shall be 30 mm. The surface extrusion welder shall be semi-automated and equipped with electronic controls which constantly monitor outputs for both preheat and extradite. The unit shall be capable of pre-heating the sheet just prior to the casting of the extradite over the upper and lower section of the weld zone.

The extruded granulate for surface extrusion welding shall be manufactured from the same resin type used in the manufacture of the geomembrane. All physical properties shall be identical to those possessed by the geomembrane raw material. The manufacturer shall provide certified test data with each batch of welding granulate. All granulate supplied shall be packed to prevent the ingress of moisture and other contaminants. If necessary, the contractor shall also employ an apparatus specifically built for drying granulate to ensure weld quality.

Careful control the temperature and speed of welding according to the nature and thickness of the material and the ambient temperature. Overheating during welding can lead to structural changes or melting and weakens the geomembrane. A too low temperature will result in a poor quality weld and low seam strength. Welding of any one joint should be carried out in one direction only.

All geomembrane panels subject to hot wedge welding shall be overlapped by a minimum of 125 mm and a minimum of 75 mm for extrusion welding to allow for proper construction quality assurance testing.

The contractor shall ensure prior to any primary or secondary welding that weld zones be clean, free from moisture, dust and any other foreign matter. All weld zone surfaces shall be either cleaned or abraded no more than 30 minutes prior to the commencement of welding any seam. In extremely bad conditions it may be necessary for the contractor to clean and/or abrade the weld zone areas only minutes prior to the required weld.

D5.1.5.1 Weld testing

Weld testing involves both destructive testing (field and laboratory) and non-destructive testing.

Destructive testing involves cutting out sections of the finished welds and testing them in shear and peel modes according to specific standards. Destructive testing is by its nature confined to spot checks on limited lengths of geomembrane seams and does not give adequate information on the continuity and completeness of the entire seam between sampling locations.

On the other hand, non-destructive tests aim to assess the integrity of the seam in a continuous approach with a view of validating 100 per cent of the seams.

D5.1.5.2 Destructive testing

Destructive testing is necessary to validate the strength and integrity of a weld and is part of the overall construction quality assurance programme where a sample of an installed geomembrane weld is cut out of the geomembrane and tested for shear and peel strength.

Destructive testing is required for the trial seams needed to prequalify welding personnel on a daily basis, equipment and procedures for making seams on identical geomembrane material used on site and under the site conditions.

Testing will need to be repeated if any welding stoppage exceeds one hour and if weather conditions change. The trial weld sample shall be at a minimum 1.0 m long by 0.3 m wide with the weld centred lengthways. Four 25 mm wide samples shall be cut from the trial weld sample using a calibrated die cutter and tested in shear and peel using a calibrated tensiometer to determine whether the test welds have passed or failed

Destructive seam tests shall also be performed at random locations (selected by the CQA Authority) during the installation at a minimum of one sample every 150 m of seam (for basal and sideslope liners) as per Table D3, and for capping liners in accordance with Table D4. Shorter intervals can be specified for extrusion welds. The purpose of these tests shall be to confirm and evaluate seam strength and continuity during the field seaming.

Each sample shall be cut using a calibrated due cutter into Five × two (5 x 2) 25 mm wide pieces and shall be sent to a third-party independent accredited geosynthetics laboratory for shear and peel testing. On-site testing shall also be conducted by the installer using a calibrated tensiometer. Any remaining samples shall be stored by the facility owner. In the event of a failure, all prior welds shall be tested back to the last test that passed. It will be the responsibility of the installer to repair and make good the seam/seams to the satisfaction of the CQA authority.

D5.1.5.3 Non-destructive tests

The purpose of non-destructive testing is to detect discontinuities or holes in the seam of a geomembrane. It also can indicate whether a seam is continuous and non-leaking, it is meant to verify the continuity of field seams and not to quantify seam strength. Non-destructive tests for geomembrane include air pressure testing for dual track fusion welds and vacuum testing for extrusion welds. Non-destructive testing should be performed over the entire length of the seam.

The pressurised air test is described in the standard ASTM D5820 *Standard practice for pressurised air channel evaluation of dual seamed geomembranes.* The test can begin no earlier than one (1) hour after welding.

Testing tightness of the extrusion fillet seams is more laborious. They must be tested piece by piece by applying a vacuum box. The vacuum box test is described in the standard ASTM D5641 *Standard practice for geomembrane seam evaluation by vacuum chamber.* This test should also start no earlier than one (1) hour after welding.

In addition to the above tests, the welds can also be visually inspected to assess the quality of the workmanship and the appearance of the welded seam. For wedge welds the observed needs to observe a consistent 'squeeze out' on the weld edge which is an indicator that the correct temperature and pressure were used during installation. In the case of extrusion fillet welds, the weld appearance should be smooth, uniform and free of streaks and lumps. In addition, there should be no obvious scoring, notches or deep scratches introduced by the surface grinding.

D.6 Quality

D6.1 Manufacturing specifications and quality control

The quality of the geomembranes shall be in accordance with the requirements of the Geosynthetic Research Institute (GRI) – GM13 and GM17. The minimum specifications for a quality HDPE and LLDPE geomembrane products are contained in GRI Test Method GM-13 Standard Specification for 'Test Properties, Testing Frequency and Recommended Warranty for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes' and GRI Test Method GM-17 Standard Specification 'Test Properties, Testing Frequency and Recommended Warranty for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes'.

These specifications were developed by the Geosynthetic Research Institute (GRI), with the cooperation of geomembrane manufacturers. The specifications set forth a set of minimum, physical, mechanical and chemical properties that must be met, or exceeded by the geomembrane being manufactured.

Note that, currently, there are no Australian manufacturing specifications; in this respect, GRI GM13 and GM17 represent best practice. However, it should be stressed that the GRI requirements represent a minimum. Higher requirements may be necessary in certain applications and the onus is on the engineer of record to establish if higher requirements are necessary and to specify according to the particular engineering requirements. (Further note: always refer to the latest version of both specifications).

In addition to the above, a statement on the origin of the resin, its identification (type and lot number), its production date and the maximum amount of recycled polymer material added to the raw resin must be included as well as certified copies of the quality control certificates issued by the resin supplier and reports on the tests conducted by the manufacturer to verify the quality of the resin used to manufacture the geomembrane rolls assigned to the project.

D6.2 Construction quality control (CQC)

Installation and seaming of the geomembranes must be undertaken by geomembrane installers with extensive experience in seaming the same type of geomembrane being installed and using the same seaming procedure to be used on site. They must hold a current independent certification for seaming and installation to a recognised industry standard (national or international) and must provide experience records prior to any installation.

D6.3 Third-party CQA consultant

Construction quality assurance (CQA) is defined as a planned system of activities that provide assurance that the geomembrane was fabricated and installed as specified in the design. It is an important factor in ensuring that design and installation of the geomembrane liner are done in accordance with the standards and specifications agreed with EPA.

For this purpose, an independent third-party CQA consultant with experience with geomembranes and knowledgeable of geomembrane and seam performance characteristics must be appointed to verify that the works have been carried out to the agreed standards. The duties of the third-party CQA consultant include inspections, verifications, audits and evaluation of materials and workmanship, provision of advice on installation, testing, repair, and covering of the geomembrane lining system and issuing a final CQA report documenting the quality of the constructed facility.

D6.4 CQA plan

A CQA plan shall be submitted to EPA prior to the geomembrane installation. The CQA plan needs to provide procedures for identifying non-conformance and for corrective action. The plan should cover the following:

- the nature of the non-conformance and its level of effect on the project
- determination if the non-conformance is an isolated incident or a recurring problem
- how amendments to procedures to prevent future occurrences of the non-conformance will be implemented
- the nature of corrective action to be applied to rectify that specific non-conformance
- the procedures and persons to be notified of the non-conformance and corrective measures
- procedures for reporting to the EPA major exceptions/ variations to the approved technical specifications.

It should at a minimum include the following information for each geomembrane product proposed:

1. Definitions to be used throughout the project to avoid confusion on acronyms and wording.
2. Descriptions of responsibilities, qualifications, and obligations for each party involved in the CQA plan.
3. The lines of communication and authority for the project. Identify and define the process for addressing request for information, design modifications or changes in the project specifications.
4. A formal process on handling deficiencies which defines responsibilities and the minimum documentation required to correct deficiencies.
5. A project meeting schedule.
6. The proposed level of supervision and quality control.
7. Verification process and review of the quality control certificates of the resin and the quality of the resin used to manufacture the geomembrane rolls assigned to the project. Same applies to the extrudate rod.
8. Verification process and review of the property values certified by the manufacturer. Same applies to the extrudate rod.
9. Verification process that the measurements of properties by the manufacturer are properly documented, test methods are acceptable, sampling procedure detailed and verification that the geomembrane meets the project specifications. Same applies to the extrudate rod.
10. Verification process and review of the quality control certificates of the geomembranes rolls assigned to the project (note: need to agree with manufacturer on the frequency of the tests).
11. Details of the planned geomembrane storage on site prior to installation.
12. Verification process of the geomembrane handling equipment used on the site.
13. Rejection criteria of the geomembrane sheets.
14. Details of the installation staff's accreditations and verification of their experience.
15. Details of the conformance tests the CQA consultant will undertake on the geomembrane delivered to site. Any laboratory tests must be performed at a third-party independent accredited geosynthetics laboratory.
16. Details of actions to take if geomembrane fails a conformance tests.
17. Approval procedure of the subgrade and anchor trench.
18. Establishment of a field geomembrane panel identification.
19. Details of actions to take to insure that field panels and seam orientation are as indicated in the layout plan.
20. Measures to take to protect the liner if inclement weather occurs during installation.
21. Frequency of trial welds and procedure for sampling and evaluation.
22. Procedures for inspecting seam preparation, trial welds, welds, testing and sampling welds. including the details of the nominated geosynthetic accredited laboratory for offsite testing.
23. Verification process of welding equipment, calibration and welding conditions.
24. Details of actions to take after cutting of each destructive test sample from the production seam.
25. Details of actions to take in the event of a defective weld, including retesting procedures.
26. Rejection criteria of the laid geomembrane if test results indicated failure.

27. Details of actions to take in case of defects and or damages to the surface of the laid geomembrane are identified and corrective measures.
28. Details of actions to take if geomembranes have been damaged due to shifting by wind.
29. Details of actions to take to minimise geomembrane wrinkles and bridging.
30. Verification process of the geomembrane installation around areas of protrusions and penetrations is made according to specifications.
31. Details of actions to take to protect the geomembrane following installation.
32. CQA consultant daily recordkeeping. The daily log should contain the following:
    - weather and site conditions
    - quality of subgrade
    - description of any material received at the site, including quality control data provided by suppliers
    - location of daily construction activities and progress
    - conformance to panel layout design
    - recording of installation activities consisting of panel placement, roll numbers, seam/weld locations, repairs and testing results for all works
    - records (including photos) of the wrinkling in the geomembrane at the time that cover soil is placed over the geomembrane
    - photographs of construction works and any items of specific interest. The captions of all photographs should contain the name of the project, the date on which the photograph was taken and the identity of the feature being photographed
    - type of equipment used in each work task (e.g. handling equipment, welding equipment, on-site testing equipment)
    - calibrations or recalibration of test equipment and weld equipment
    - testing conducted and test methods used
    - record of any material or workmanship that does not meet specified designs and corrective actions taken to remediate the problem
    - details of site visits
    - summaries of any meetings held and action taken
    - signature of CQA engineer.
33. Periodic acceptance reports summarising daily reports.

The contractor shall provide the CQA authority with the following listed test certificates and records prior, during and at the completion of the works as each report and record is required:

- Certification and test results of raw materials from raw material supplier.
- Certification and test results of raw materials from membrane manufacturer.
- Roll test data reports, for each roll of material.
- HDPE welding granulate test reports.
- Daily installation reports for each welder and technician:
- trial test weld record
- wedge weld records
- surface extrusion weld records
- weld peel and tensile test records
- wedge air tunnel pressure test records
- vacuum box test records
- repair records.
- Completed as-built drawing, including roll numbers, panel layout, seam locations and repair locations.

Any deviations from the approved CQA plan must be noted and explained and approved by EPA Victoria and an EPA appointed auditor.

D6.5 CQA testing

Tables D3 and D4 provide guidance on the test properties and recommended minimum testing frequencies. Higher testing frequencies might be required in certain applications (i.e. need to identify the importance of the geomembrane for the safety of the works, construction and stability included). The onus is on the engineer of record to establish if higher requirements are more appropriate.

D6.6 CQA report

A CQA report must be prepared by the CQA consultant to demonstrate that all requirements of the project specifications and CQA plan have been complied with.

Table D3: Guidance on CQA testing for HDPE geomembranes

Item	Property	Standards	Frequency
Conformance testing (upon shipment of geomembrane to the site)	Thickness	ASTM D5994	Each roll
	Density Tensile properties (yield and break stress, yield and break elongation) Puncture resistance Tear resistance Carbon black content Carbon black dispersion	ASTM D1505, ASTM D792 ASTM D6693 type IV ASTM D4833 ASTM D1004 ASTM D1603 ASTM D5596	One sample per 5000 m2, or every five rolls delivered to site whichever is the greatest number of tests
	Stress crack resistance Oxidative induction time	ASTM D5397 ASTM D3895,ASTM D5885	One sample every 10,000 m2, or resin type or manufacturing run.
Start-up test weld	Welding equipment		Checked daily at start of works, and whenever the welding equipment is shut-off for more than one hour. Also after significant changes in weather conditions
	Weld conditions		Test weld strips will be required whenever personnel or equipment are changed and/or wide temperature fluctuations are experienced. Minimum 1.5 m continuous seam
Destructive weld testing	Onsite, hand tensiometer in peel and shear	ASTM D6392	Every weld
	Offsite – weld seam strength in peel and shear	ASTM D6392	Every 150 m (if fusion weld), every 120 m (if extrusion weld)
Non-destructive weld testing		Air pressure test, ASTM D5820 Vacuum box test, ASTM D5641	All seams over full length
Visual inspection of geomembrane	Tears, punctures, abrasions, cracks, indentations, thin spots, or other faults in the material.		Every roll
Thickness of geomembrane	Onsite		Five per 100 m, 20 m apart, taken at the edge of the sheet

Note:

1 All conformance tests must be reviewed, accepted and reported by a CQA consultant before deployment of the geomembrane.

2 All testing must be performed on samples taken from the geomembrane delivered to site under the CQA consultant supervision.

3 All laboratory tests must be performed in a third-party independent accredited geosynthetics laboratory.

4 The required testing frequencies may be revised by the CQA consultant to conform with improvements in testing methods and/or in the state of the art practice and/or to account for the criticality of the application (i.e. to account for the importance of the geomembrane for the safety of works). Revisions must be approved by the relevant authorities before application.

Table D4: Guidance on CQA testing for LLDPE geomembranes

Item	Property	Standards	Frequency
Conformance testing (upon shipment of geomembrane to the site)	Thickness	ASTM D5994	Each roll
	Density Tensile properties (yield and break elongation) Puncture resistance Tear resistance Carbon black content Carbon black dispersion	ASTM D1505, ASTM D792 ASTM D6693 type IV ASTM D4833 ASTM D1004 ASTM D1603 ASTM D5596	One sample per 5000 m^2, or every five rolls delivered to site whichever is the greatest number of tests
	Axi-symmetric break resistance strain	ASTM D5617	Per formulation
	Oxidative induction time Oven ageing and oxidative induction time	ASTM D3895,ASTM D5885 ASTM D5721, ASTM D3895, ASTM D5885	One sample every 10,000 m^2, or resin type or manufacturing run
Start-up test weld	Welding equipment		Checked daily at start of works, and whenever the welding equipment is shut-off for more than one hour. Also after significant changes in weather conditions
	Weld conditions		Test weld strips will be required whenever personnel or equipment are changed and/or wide temperature fluctuations are experienced. Minimum 1.5 m continuous seam
Destructive weld testing	Onsite, hand tensiometer in peel and shear	ASTM D6392	Every weld
	Offsite – weld seam strength in peel and shear	ASTM D6392	Every 300 m (if fusion weld), every 150 m (if extrusion weld)
Non-destructive weld testing		Air pressure test, ASTM D5820 Vacuum box test, ASTM D5641	All seams over full length
Visual inspection of geomembrane	Tears, punctures, abrasions, cracks, indentations, thin spots, or other faults in the material.		Every roll
Thickness of geomembrane	Onsite		Five per 100 m, 20 m apart, taken at the edge of the sheet

Note:

1 All conformance tests must be reviewed, accepted and reported by a CQA consultant before deployment of the geomembrane
2 All testing must be performed on samples taken from the geomembrane delivered to site under the CQA consultant supervision
3 All laboratory tests must be performed in a third-party independent accredited geosynthetics laboratory
4 The required testing frequencies may be revised by the CQA consultant to conform with improvements in testing methods and/or in the state of the art practice and/or to account for the criticality of the application (i.e. to account for the importance of the geomembrane for the safety of works). Revisions must be approved by the relevant authorities before application

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(Standard Test Methods)

A list of commonly ASTM standards and GRI test specifications used in geomembrane liner design is given below for guidance. This list is not exhaustive; onus is on the project engineer, CQA consultant, Contractor and environmental authority to establish the list of standards needed for a given project.

D7.1 ASTM Standards

- ASTM D883. Standard terminology relating to plastics. ASTM, West Conshohocken, PA, USA.
- ASTM D792. Standard test method for density and specific gravity (relative density) of plastics by displacement. ASTM, West Conshohocken, PA, USA
- ASTM D1004. Standard test method for initial tear resistance of plastic film and sheeting. ASTM, West Conshohocken, PA, USA
- ASTM D1238. Standard test method for flow rates of thermoplastics by extrusion plastometer. ASTM, West Conshohocken, PA, USA
- ASTM D1505. Standard test method for density of plastics by the density-gradient technique. ASTM, West Conshohocken, PA, USA
- ASTM D1603. Standard test method for Carbon Black Content in Olefin Plastics. ASTM, West Conshohocken, PA, USA
- ASTM D3895. Standard test method for oxidative-induction time of polyolefins by differential scanning calorimetry. ASTM, West Conshohocken, PA, USA
- ASTM D4218. Standard test method for determination of carbon black content in polyethylene Compounds by the muffle-furnace technique. ASTM, West Conshohocken, PA, USA
- ASTM D4833. Standard test method for index puncture resistance of geotextiles, geomembranes, and related products. ASTM, West Conshohocken, PA, USA
- ASTM D5321. Standard test method for determining the coefficient of soil and geosynthetic or geosynthetic and geosynthetic friction by the direct shear method. ASTM, West Conshohocken, PA, USA
- ASTM D5596. Standard test method for microscopic evaluation of the dispersion of carbon black in polyolefin geosynthetics. ASTM, West Conshohocken, PA, USA
- ASTM D5397. Standard test method for evaluation of stress crack resistance of polyolefin geomembranes using notched constant tensile load test. ASTM, West Conshohocken, PA, USA
- ASTM D5617. Standard test method for multi-axial tension test for geosynthetics. ASTM, West Conshohocken, PA, USA
- ASTM D5641. Practice for geomembrane seam evaluation by vacuum chamber. ASTM, West Conshohocken, PA, USA
- ASTM D5721. Standard test method for air-oven aging of polyolefin geomembranes. ASTM, West Conshohocken, PA, USA
- ASTM D5820. Practice for pressurised air channel evaluation of dual seamed geomembranes. ASTM, West Conshohocken, PA
- ASTM D5885. Standard test method for oxidative induction time of polyolefin geosynthetics by high-pressure differential scanning calorimetry. ASTM, West Conshohocken, PA, USA
- ASTM D5994. Standard test method for measuring core thickness of textured geomembrane. ASTM, West Conshohocken, PA, USA
- ASTM D6392. Standard test method for determining the integrity of nonreinforced geomembrane seams produced using thermo-fusion methods. ASTM, West Conshohocken, PA
- ASTM D6497. Standard test method for Mechanical Attachment of Geomembrane to Penetrations or Structures. ASTM, West Conshohocken, PA, USA
- ASTM D6693. Standard test method for determining tensile properties of nonreinforced polyethylene and nonreinforced flexible polypropylene geomembranes. ASTM, West Conshohocken, PA, USA
- ASTM D7466. Standard test method for measuring the asperity height of textured geomembranes. ASTM, West Conshohocken, PA, USA

D7.2 Geosynthetic Research Institute (GRI) test methods specifications

- GRI Test Method Geomembrane 13. Standard specification for test methods, test properties and testing frequency for high-density polyethylene (HDPE) Smooth and Textured Geomembranes. Revision 9: June 1, 2009, Geosynthetic Research Institute, Folsom, PA, USA.
- GRI Test Method Geomembrane 17. Standard specification for test methods, test properties and testing frequency for linear low-density polyethylene (LLDPE) smooth and textured geomembranes. Revision 6: June 1, 2009, Geosynthetic Research Institute, Folsom, PA, USA.

APPENDIX E: Guidance on geosynthetic clay liner use in landfills

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Executive summary

Geosynthetic clay liners are frequently incorporated with other geosynthetics and soil components in basal and side slope liners, and in capping systems for landfills because of their very low hydraulic conductivity. Their main function is to limit contaminant migration, to reduce water ingress into the landfill and to control biogas escape to the atmosphere.

This document provides details on minimum standards for geosynthetic clay liner material, quality, strength, hydraulic and gas performance, installation procedures and testing requirements. It is neither a prescriptive document nor a set of specifications. It is rather aimed at assisting engineers, specifiers, designers, regulators, facility owners and operators by providing a set of minimum requirements and guidance notes in designing geosynthetic clay liners for landfill engineering purposes.

Acknowledgement

Dr WP Gates, Research Fellow, Dept. Civil Engineering, Monash University, wrote section E2.1.1, 'Bentonite used in GCLs'. His contribution is gratefully acknowledged.

E.1 Introduction

A geosynthetic clay liner (GCL) is a thin (typically 5 to 10 mm) factory-manufactured hydraulic or gas barrier comprised of a layer of bentonite supported by geotextiles (on either side) and/or geomembranes, mechanically held together by needling, stitching, or chemical adhesives. GCLs are also known as Geosynthetic Barriers-Clay (GBR-C) by the International Standards Organization. Their primary function is to act as hydraulic and/or gas barrier in a diverse range of civil engineering applications. They are frequently incorporated with other geosynthetics and soil components in basal and side slope liners, and in capping systems for landfills because of their very low hydraulic conductivity.

This document covers the use of geosynthetic clay liners in landfills. It provides details on minimum standards for liner material, quality, strength, durability, installation procedures and testing requirements. It is aimed at assisting engineers, specifiers, designers, regulators, facility owners and operators in designing GCLs for landfill engineering purposes.

E.2 Background

Modern municipal solid waste (MSW) facilities are typically designed with a bottom-barrier system intended to limit contaminant migration to levels that will result in negligible impact.

The system includes a leachate collection system (LCS), which is intended to: control the leachate head acting on the underlying liner, and collect and remove leachate. The leachate collection system typically incorporates a geotextile filter, a granular drainage layer or geocomposite, and perforated collection pipes.

The liner may range from a thick, natural clay deposit to engineered liner systems involving one or more geomembrane (GM) and/or compacted clay liner (CCL) or geosynthetic clay liner (GCL), and/or a compacted clay liner augmented with a GCL. The purpose of a composite liner is to combine the advantages of two or three materials (depending in part on their availability and cost), each having different performance characteristics as hydraulic or physical barriers and endurance properties.

Covers over municipal solid waste landfills are typically multicomponent systems that are constructed directly on top of the waste shortly after the site, or portion of a site, has been filled to capacity.

The aim of the cover system is to reduce the ingress of water into the landfill and control biogas escape to the atmosphere. Its design is usually driven by the landfill management approach put in place for a given site.

One approach, in which a GCL is used either by itself or in combination with a geomembrane as part of the capping system, is referred to as the passive approach. In this case, the aim is to provide a cover system as impermeable as possible and as soon as possible after the landfill has ceased operating, to minimise the generation of leachate (waste liquid) and gas escape into the atmosphere.

E2.1 Types of geosynthetic clay liners

Geosynthetic clay liners (GCLs) have evolved into multicomponent systems with the incorporation of a thin layer of bentonite bonded by adhesive, needling or stitching to a layer or layers of geosynthetics. GCLs come in a variety of thicknesses, have a range of bentonite mass per unit area, different geotextiles confining the bentonite, different manufacturing details and different roll sizes.

Originally the primary purpose of bonding bentonite to geosynthetics was to protect the bentonite during transport and installation and to provide a uniform layer of high swelling, low-permeability bentonite as a component of the lining system. However, research has indicated that the confining of the bentonite during initial hydration that is achieved with some methods of manufacture may improve the performance of the GCL, especially in applications where hydration may occur under low stress or where the GCL may be subject to wetting and drying cycles.

Figure E1 shows cross-sections of currently available GCLs. They offer a compromise between the hydraulic conductivity and shear strength requirements of containment projects. These products can be broadly categorised into unreinforced and reinforced GCLs.

Unreinforced GCLs typically consist of a layer of sodium bentonite that may be mixed with an adhesive and then affixed to geotextile or geomembrane backing components with additional adhesives (Bouazza 2002). For the geomembrane-supported GCL, the bentonite is bonded to the geomembrane using a non-polluting adhesive, and a thin, open-weave, spun-bound geotextile is adhered to the bentonite for protection purposes during installation.

Reinforced GCLs are geotextile-supported GCLs bonded by either needle-punching or stitch-bonding, with the bentonite contained by the geotextiles on both sides (Bouazza 2002).

Stitch-bonded GCLs consist of a layer of bentonite between two carrier geotextiles, sewn together with continuous fibres in parallel rows.

Needle-punched GCLs consist of a layer of bentonite between two carrier geotextiles, reinforced by pulling fibres from the top geotextile through the bentonite and into the bottom geotextile using a needling board. The fibres that are punched through the bottom geotextile rely on natural entanglement and friction to keep the GCL together.

However, some needle-punched GCL products are thermally treated to minimise fibre pullout. Thermal treatment involves heating the GCL surface to induce bonding between individual reinforcing fibres, as well as between the fibres and the carrier geotextiles (Lake and Rowe 2000). Thermally treated needle-punched GCLs are typically referred to as 'thermal-locked™' GCLs.

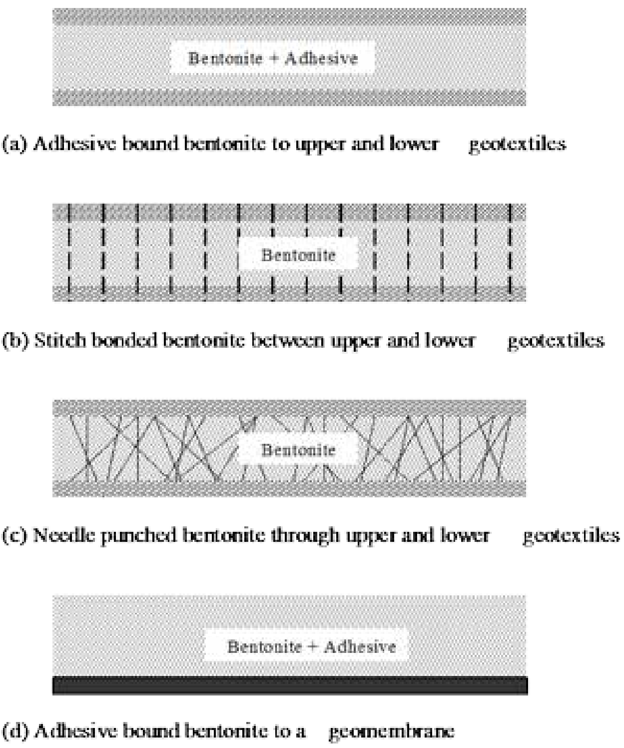

Figure E1: Cross-sections of currently available GCLs, after Koerner (2005).

Table E1: Advantages and disadvantages of geosynthetic clay liners (GCLs) (modified from Bouazza 2002)

Advantages	Disadvantages
· Ease of installation (manageable rolls, less skilled labour needed, lower costs). · Very low hydraulic conductivity to water if properly installed and pre-hydrated. · Mass per unit area of bentonite is relatively uniform if good quality control is provided during manufacture. · Can withstand relatively large differential settlement (compared to compacted clay). · Some self-healing characteristics. · Not dependent on availability of local clayey soils. · Lower repair costs and relatively easy to repair compared to compacted clay. · More landfill space from smaller liner thickness provided there is an adequate attenuation layer (for applications at the base). · Field hydraulic conductivity testing not generally required. · Hydrated GCL is effective gas barrier.	· Possible loss of bentonite during placement. · Possible increase of hydraulic conductivity due to incompatibility with leachate if not pre-hydrated with compatible water source. · Low shear strength of hydrated bentonite for unreinforced GCLs. · Possible post-peak shear strength loss. · GCLs can be punctured after installation. · Prone to desiccation and/or panel shrinkage (with consequent possible panel separation) if not properly selected, installed and/or protected from hydration/dehydration cycles. · Greater diffusive flux unless there is also an adequate attenuation layer. · Prone to ion exchange (for GCLs with Na+-bentonite) that may affect hydraulic performance under low compressive stresses. · Permeable to gases at low bentonite moisture content.

From a performance perspective, the primary differences between GCLs are the mineralogy and form of bentonite used in the GCL (for example, natural sodium versus sodium-activated calcium bentonite, powder versus granular forms, polymer enhanced or initial moisture content as it comes off the roll), the type of geotextiles (woven, nonwoven or scrim-reinforced nonwoven), the method of bonding, and the addition of a thin plastic layer.

The main advantages GCLs are limited thickness, good compliance with differential settlements of underlying soil or waste, low hydraulic conductivity if properly hydrated, easy installation and low cost. On the other hand, the limited thickness of this barrier can produce vulnerability to mechanical accidents, limited sorption capacity and an expected significant increase of diffusive transport if an underlying attenuation mineral layer is not provided. Moreover, when hydrated with some types of leachates or some mineralised pore water, bentonite will show reduced swelling and reduced efficacy as a hydraulic barrier.

Advantages and disadvantages of GCLs are summarised in Table E1.

E2.1.1 Bentonite (used) in geosynthetic clay liners

Due to the thinness of geosynthetic clay liners (GCLs) and the fact that they typically are intended to replace or augment compacted clay liners, the bentonite used in GCLs must be of high quality. Industry-driven, research-proven specifications have evolved to ensure some level of uniformity across the variety of GCLs available.

The properties of montmorillonite considered ideal for most GCL applications were reviewed by Gates et al (2009) and are summarised in Table E2. While undoubtedly circumstances may dictate deviation from these properties, the Wyoming-type montmorillonites remain the benchmark to which bentonites in GCL applications should aspire. Specifiers should be aware that, in some instances, sodium-activated calcium bentonite may be used (in whole or in part) to meet the cation-exchange capacity (CEC), free swell and hydraulic conductivity specifications but that this type of bentonite may not always perform in a manner equivalent to high-quality Wyoming bentonite.

Care is needed to adopt appropriate specification that will ensure that the engineering requirements will be met for any given application.

E2.1.1.1 Montmorillonite content

The swelling smectite clay mineral montmorillonite is the major constituent of bentonite and, because of its extremely large specific surface area and capability for both crystalline (limited) and osmotic (unlimited) swelling, brings about the desirable physical and chemical attributes that make bentonite suitable for engineering applications using geosynthetic clay liners.

The smectite (montmorillonite) content of bentonite used in GCLs should exceed 70 wt% (Egloffstein 2001) and the remaining, non-swelling mineral impurities should be limited in variety and, specifically, have limited reactivity with potential leachates (Guyonnet et al. 2005; Gates et al. 2009). Non-swelling minerals tend to reduce bentonite hydration, swelling, dispersion and gel formation.

Besides montmorillonite, other mineral constituents of bentonite typically include quartz and other silicates, feldspars and other aluminosilicates, micas and other layered aluminosilicates, as well as carbonates and other soluble mineral precipitates and/or salts.

Table E2: Most favourable bentonite properties for GCL applications

Property	Range or value
Montmorillonite content	> 70 wt%
Carbonate content*	< 1–2 wt%
Bentonite form	Natural Na-bentonite or > 80 wt% sodium as activated bentonite
Particle size	Powdered (e.g. 80% passing 75 micron sieve) or Granulated (e.g. < 1% passing 75 micron)
Montmorillonite type	Wyoming
Cation exchange capacity	70–120 meq per 100 g (or cmol per kg)
Free swell index	≥24 cm^3/2g

* Carbonate here implies calcite, calcium carbonate or other soluble or partially soluble carbonate minerals.

The mineralogy of a bentonite is best quantified by X-ray diffraction. Bentonites are variable in composition, both from source to source, but also within a source, as the bentonite is typically mined layer by layer within a deposit.

The bentonite supplier should have established quality assurance protocols, but some variability in bentonite mineralogy is unavoidable. Thus, the montmorillonite content may vary by 10 per cent or more. Other methods exist to evaluate montmorillonite content, including the industry-established methylene blue absorption method. However, such indirect methods should only be used as a guide to track potential changes in quality and not relied on as a true measure of montmorillonite content (Gates et al 2009, Likos et al 2010).

Calcite, aragonite, magnesite and other forms of calcium and magnesium carbonates are, in general, undesirable mineral impurities in bentonite. Despite having rather low solubility, their solubility is sufficient to elevate concentrations of Ca2+ and Mg2+ ions in solution, which can result in increases in the hydraulic conductivity of GCLs (Meer and Benson 2007).

Table E2 lists the most favourable bentonite properties for GCL applications.

E2.1.1.2 Bentonite form

Bentonite in GCLs can be supplied as a natural sodium bentonite, a sodium-activated bentonite (also referred to as activated bentonite, sodium-activated calcium bentonite or activated sodium bentonite) or as calcium bentonite (Egloffstein 2001). Natural sodium bentonites are arguably preferred for critical applications, as they typically contain essentially exchangeable Na^+, have the optimal mineralogy and chemistry, and require minimal processing to achieve a low hydraulic conductivity GCL.

The designation calcium bentonite traditionally has been used to describe bentonites containing less than 60 per cent exchangeable Na^+, with the remainder being Ca^{2+}, Mg^{2+}, K^+ or more typically, combinations of these. Bentonites sourced within Australia often have higher levels of exchangeable Mg^{2+} than Ca^{2+} but are still generally referred to as calcium bentonites.

Sodium activation, or beneficiation, must be done to increase the amount of exchangeable Na^+. This also serves to increase swelling, dispersion, hydration and gelling properties of the bentonite, which in its normal Ca^{2+} (or Mg^{2+}) form, would be suboptimal (Harvey and Lagaly 2006).

The typical distribution of cations in sodium-activated bentonite used for GCLs has been given by Egloffstein (2001) to be: 50–90 per cent Na^+, 5–25 per cent Ca^{2+}, 3–15 per cent Mg^{2+}, 0.1–0.5 per cent K^+. Obviously, actual distributions are dependent on bentonite source and processing.

In some bentonites, a portion of the Ca^{2+} and Mg^{2+} may be associated with a carbonate phase that is either inherent in the mineralogy or may form during beneficiation. Upon hydration, a part of these carbonates dissolves and releases Ca^{2+} and/or Mg^{2+}, which can displace Na^+ (Guyonnet et al. 2005). Thus swelling, dispersion and gelation of sodium-activated bentonites may be suboptimal, because significant levels of Ca^{2+} and Mg^{2+} will remain in the bentonite during hydration (Harvey and Lagaly 2006). In such cases, other additives, such as polymers or pH modifiers, may be added to improve the swelling and sealing capability of sodium-activated bentonites. However, the nature and suitability of these additives is difficult to check. If used, the manufacturer should provide their details and demonstrate their nature, suitability and long-term durability.

Calcium bentonite has also been used in GCLs but, since the hydraulic conductivity of calcium bentonite is typically more than one order of magnitude higher than that for sodium bentonite, they are not commonly used. Where they are used, GCLs with calcium bentonite typically have a much larger mass per unit area than GCLs with sodium bentonite, to help overcome the suboptimal performance.

E2.1.1.3 Particle size

In most bentonites used in GCLs, the dispersed montmorillonite particle size fraction of greatest importance is < 0.5 mm. This small particle size means that montmorillonites have specific surface areas as high as 850 m^2/g.

High specific surface area, strong water absorption and high swelling under confinement ultimately result in a material presenting a highly tortuous flow path for fluid. Confined swelling of well-dispersed bentonites is correlated with lower void ratios, which in turn result in lower hydraulic conductivity and diffusion.

A great deal of confusion exists regarding whether a powdered or granulated form of bentonite is best suited for GCL applications. Both forms are readily available in Australia and have different advantages and disadvantages (Vangpaisal and Bouazza 2004), and the form adopted by the manufacturer is a matter of preference. Both forms may or may not be beneficiated, may or may not have dispersion-enhancing additives and will undoubtedly have levels of non-swelling mineral impurities completely dependent on the source.

The powdered form generally has been pulverised so that a certain percentage passes a particular sieve size (for example, 50 per cent passing 75 mm), whereas the granulated form typically is five to 10 times larger. In GCLs, both forms of bentonite may be lost from the GCL during installation if improperly handled.

E2.1.2 Geotextiles in geosynthetic clay liners

Geotextiles are generally used as the carrier material beneath the bentonite and the cap (or cover) above it. The geotextiles can be nonwoven, woven, or composite nonwovens with a woven scrim.

Presently, most geotextiles are made from polypropylene resins with minor additions of additives such as high-temperature processing aids, ultraviolet light stabilisers and long-term durability additives (Koerner and Koerner 2010). Koerner and Koerner (2010) indicated that, when considering needle-punched, reinforced GCLs, at least one of the geotextiles must be of the needle-punched variety.

Nonwoven carrier geotextiles provide puncture protection to the bentonite layer of the GCL, allow in-plane drainage and filtration, and provide interlocking capabilities with internal fibre reinforcements and textured geomembrane interfaces (McCartney and Zornberg 2004).

Woven geotextiles are either of the slit-film or spunlaced variety, which have excellent strength and stiffness characteristics (they provide tensile resistance to the GCL), but must be of a sufficiently tight weave not to allow bentonite to squeeze through the openings and lead to lubrification of the interface between the GCL and the adjacent material.

Composite nonwovens with a woven scrim have the benefits of both the woven and nonwoven components and, when combined with thermal treatment, may provide enhanced performance for critical applications where the GCL may experience hydration at low confining stresses, where there is potential for internal erosion, or where there is potential for wet–dry cycles (Petrov and Rowe 1997, Lake and Rowe 2000, Rowe and Orsini 2003, Beddoe et al. 2010).

Thus, the properties of the geotextiles are an important consideration. In addition to opening size, the mass per unit area, tensile strength, tensile elongation and installation survivability properties are all important (Koerner and Koerner 2010). The fibres constituting the internal reinforcement are equally important, since shear stresses are transmitted to them as tensile forces. Therefore, when GCLs are subjected to long-term shear stresses, fibre durability is important, particularly with respect to sloping surfaces and quarry-type landfill liners

E2.1.3 ‘Geomembranes’ in geosynthetic clay liners

For the ‘geomembrane-supported’ GCL (non-reinforced GCLs), the geomembrane can be of any type, thickness or surface feature, according to Koerner and Koerner (2010). They indicate that the product can be installed in three ways:

- geomembrane up; bentonite down
- geomembrane down; bentonite up
- geomembrane down; bentonite up with an additional covering geomembrane above the bentonite.

It should be noted that the ‘geomembrane’ used to support the bentonite is typically much thinner than the geomembrane component of a composite liner and generally should not be relied on to provide the geomembrane component of a composite liner.

It should also be noted that some products are now being produced with a very thin film of plastic (‘geomembrane’) adhering to the carrier geotextile component of the GCL. This film provides some barrier to moisture, provided it remains intact during installation – however, the plastic layer can not be relied upon to provide a moisture barrier in addition to that provided by the bentonite in the GCL unless very considerable care is taken to protect this layer from damage during installation of the liner system.

E2.2 Material key properties

The engineering design of bottom, sideslope and capping landfill liners that include GCLs requires the assessment of water and gas flow, contaminant transport and stability. These in turn require consideration of hydraulic conductivity, gas permeability, chemical compatibility, diffusion, desiccation and possible panel separation and shear strength.

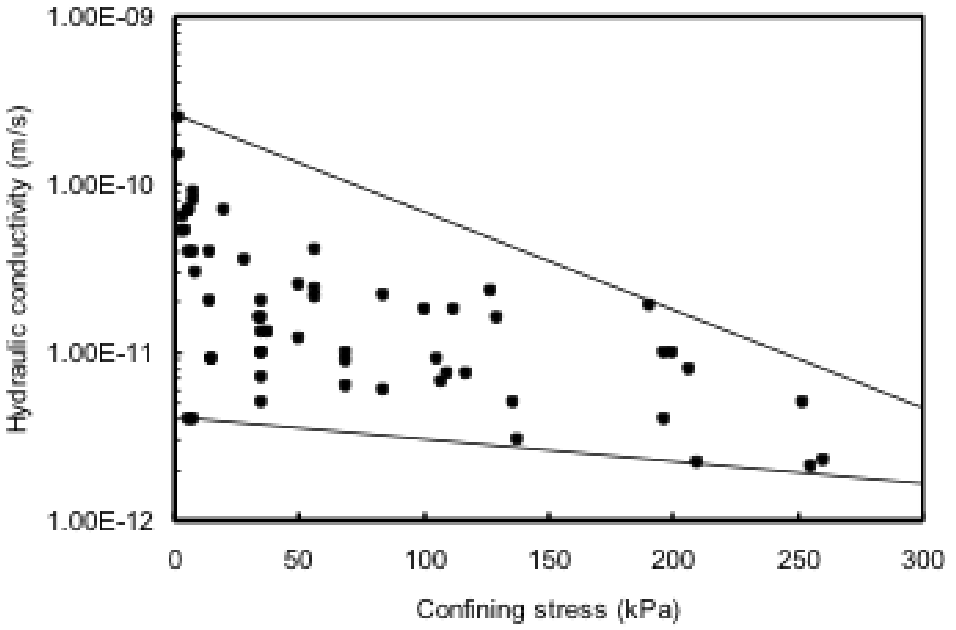

Figure E2: Variation of hydraulic conductivity to water of geotextile based GCLs versus confining stress (from Bouazza 2002)

The following section will touch on some key issues that need to be considered when selecting a geosynthetic clay liner.

E2.2.1 Hydraulic conductivity, leachate and chemical compatibility, diffusion

The hydraulic performance of GCLs depends on the hydraulic conductivity of the bentonite. In general, laboratory hydraulic conductivities to water of different types of sodium bentonite geotextile-supported GCLs vary approximately between 2 x 10^{-12} m/s and 2 x 10^{-10}m/s, depending on applied confining stresses and method of manufacture (Figure E2). One of the main problems encountered in the post-closure management of a landfill is the internal cap distress due to subsidence. The heterogeneous waste composition and ageing process (waste biodegradation) can lead to substantial differential settlement of the cover system, which in turn may lead to zones of tension cracking.

It has been shown that GCLs could withstand distortion and distress while maintaining their low hydraulic conductivity (Bouazza et al. 1996; LaGatta et al. 1997). GCLs often are used in basal and sideslope liners to contain liquids other than water; in this case, the evaluation of hydraulic conductivity of GCLs when acted upon by leachate solutions is of paramount importance. The full extent of reaction of the GCL with known or expected leachates may be predictable, but the long-term effects are generally unknown.

It is recommended that hydraulic conductivity to the actual permeant liquid be assessed via a ‘compatibility test’ where the specimen is permeated with the liquid to be contained or a liquid simulating the anticipated liquid.

The GCL features that influence its hydraulic conductivity with liquids other than water are: aggregate size, content of montmorillonite, thickness of adsorbed layer, prehydration, hydrating conditions, mass of bentonite per area, and void ratio of the mineral component (which may depend on the method of manufacture, with the lowest void ratio and best performance being reported for GCLs that are needle-punched with a scrim-reinforced carrier and thermally treated).

On the other hand, the main factor related to the permeant that influences the hydraulic conductivity is the ratio of monovalent and divalent (or more) concentration in the leachate and this is referred to as the molar ratio of monovalent to divalent (RMD value) cations.

The RMD is expressed as $(Mm/Md)^{0.05}$, where Mm and Md are, respectively, the molar concentration of monovalent (single-charge) and polyvalent (two or more charges) cations.

A particular RMD value can exist for a range of leachate ionic strengths, and importantly, divalent cations do not need to dominate the solution composition to control what happens on the exchange complex (as long as no other competing effects are present).

Diffusion is a chemical process involving contaminant migration from areas of higher concentration to areas of lower concentration, even when there is no flow of water. It will tend to control contaminant transport (diffusion will dominate over advection) in landfills with good CQC/CQA and where there is no significant damage to the basal/sideslope liner during installation or landfilling activities. Diffusion will occur for contaminants that can readily diffuse through a geomembrane (for example, VOCs).

In landfill cover system applications, a geosynthetic clay liner (GCL) used by itself may be exposed to inorganic cations such as calcium, magnesium and aluminium, which can alter the performance of the GCL's sodium bentonite component, especially if accompanied by drying and rewetting as a result of seasonal changes in temperature and rainfall.

For example, if divalent cations such as calcium or magnesium (Ca^{2+}, Mg^{2+}) or trivalent cations are present in the infiltrating water or the pore water of the nearby subgrade or cover soil, there can be an exchange of these cations for the monovalent sodium cation (Na^{+}) initially present on the bentonite of the GCL. This can cause irreversible damage to the bentonite, resulting in a functional failure of the GCL.

The low confining pressure typical of cover systems appears to enable exchange-driven internal clay fabric changes (which result in changes to void ratio and void size) to take place relatively unimpeded.

It is expected that, at high compressive pressures such as encountered in bottom liners of landfills, little or no detrimental effect would be observed (Daniel 2000).

Particular care should be taken in selecting soil covers and their thickness; in particular it is important to conduct a chemical analysis of the candidate soils prior to their selection. Compatibility testing should be performed on any cover soil used in conjunction with capping GCLs.

GCLs composed of natural sodium or sodium-activated bentonite should not be overlain by cover soils or overburden materials high in leachable, soluble or exchangeable calcium or magnesium. Exchange of Ca^{2+} for Na^{+} can take place rapidly and is exacerbated if accompanied by large shifts in the hydrology of the GCL. Furthermore, it is important to give attention to the hydration process of the GCL. A detailed review on cation exchange in geosynthetic clay liners can be found in Egloffstein (2000, 2001), Lin and Benson (2000), Bouazza et al. (2006, 2007).

E2.2.2 Desiccation and shrinkage

Bentonite typically used in GCLs contains a high proportion of montmorillonite, resulting in a low hydraulic conductivity of GCLs when hydrated. However, properties of bentonite that result in low hydraulic conductivity when hydrated also make it susceptible to dehydration and shrinkage upon drying, leading to desiccation cracking if proper construction procedures are not used.

GCLs are susceptible to shrinkage and desiccation cracking, particularly when below a geomembrane in a composite liner. Shrinkage and desiccation cracking can be caused by:

- thermal gradients generated by the waste above the GM–GCL composite liners
- thermal gradients generated by solar radiation on exposed GM–GCL composite liners
- thermal gradients generated by solar radiation on GCL liners in capping systems

Rowe (2005, 2009) indicated that landfill operation and the likely temperatures to be experienced at the liner need to be considered in landfill design in order to minimise the above effects. Furthermore, he indicated the following:

- The properties of the foundation layer underlying the GCL and the water retention curve of the GCL had a critical influence on the potential for desiccation. The unsaturated soil characteristics were important as well as the initial water content. Other things being equal, the higher the initial water content of the foundation soils (up to optimum water content), the better, provided that the liner is covered quickly. It is strongly recommended that composite liners involving GCLs (applies also for GCLs used by themselves in capping systems) be covered with the ballast layer as quickly as possible after placement. In cases where covering by the ballast layer can not be achieved quickly, the selection of the type of GCL can be quite critical (Thiel et al. 2006). The best field performance was reported for GCLs that are needle-punched with a scrim-reinforced carrier, are thermally treated and have a panel overlap not less than 300 mm.

- The higher the overburden stress at the time of GCL hydration, the less the risk of desiccation. Therefore it is recommended that the first few lifts of waste be placed over the composite liner as quickly as possible after the liner is placed, to minimise the potential for both short-term (for example, solar-induced) and long-term (waste temperature-induced) desiccation cracking.
- Increasing distance to the underlying watertable increased the risk of desiccation for aquifer depths up to about 5 m below the GCL, but relatively little change was predicted for increased depths beyond 5 m, due to the offsetting effects of reduced water content and temperature gradient.

E2.2.3 Gas Permeability

With major environmental concern regarding gas emission, control of landfill gas is becoming an important issue for the protection of public health and safety and for controlling greenhouse gas emissions. Recent studies have shown that the gas permeability (or permittivity) of GCLs may vary depending on moisture content (gravimetric and volumetric), manufacturing process and operational conditions (Bouazza and Vangpaisal 2003, 2004, 2007; Vangpaisal and Bouazza 2004; Bouazza et al. 2006).

E2.2.4 Slope stability, interface friction and internal shear

Designs using a GCL on sideslope liners and/or steep capping systems must consider both the interface friction against adjacent materials and the internal shear strength of the GCL.

The long-term integrity of a GCL can depend on there being adequate friction between the various components of the liner system; in particular, between the subgrade soil or geomembrane and the GCL, as well as between the GCL and any adjacent layers such as geocomposites or any other ancillary material (Bouazza et al. 2002).

Frictional characteristics between the GCL and the different lining components must be sufficiently high to transmit shear stresses generated during the lifetime of the facility and represent a critical aspect of the design of GCLs for side slopes in landfills and also steep covers.

Reinforced GCLs transmit shear stresses to internal fibre reinforcements as tensile forces. This makes the assessment of their internal shear strength of paramount importance. The reduction in long-term shear strength due to creep and ageing of reinforced GCLs can be addressed by performing long-term creep shear tests and developing strength reduction factors that are applied to short-term strength data (Marr and Christopher 2003).

Adequate friction is necessary to prevent slippage or sloughing on slopes of the installation.

In the case of installations with sloping sides, the GCL must be able to (not in any particular order):

- support its own weight on the side slopes
- withstand down-dragging during and after placement of the waste
- maintain a stable state when a geomembrane is placed on top of the GCL
- maintain a stable state when a GCL is placed on top of the subgrade soil
- maintain a stable configuration when other geosynthetic components such as geotextiles or geonets are placed on top of the GM-GCL composite liner.

Designing a stable slope with a GCL consists of the following steps (Gilbert and Wright 2010):

1. Define the geometry, loading conditions and consequences of a failure for the slope during construction, operation and after closure.
2. Select appropriate material properties for the GCL and all other materials in the slope. Consider rate of loading, deformations, normal stresses and fluid pressures in this selection.
3. Analyse and evaluate the stability.
4. Take measures to mitigate any concerns about stability of the slope.

It is important to stress the fact that published values of interface friction and internal shear strength should not be used in detailed design. Performance tests using site-specific material and mimicking field conditions should always be conducted.

In this respect, the interface shear test (ASTM 6243) is useful in evaluating the interface friction of GCLs with soils and/or geosynthetic components as well as their internal shear strength. However, one needs to be aware of the factors and conditions that could affect the results obtained from this test. These include hydration of bentonite, hydration liquid, consolidation procedure, normal stress, specimen size, shearing device, gripping/clamping systems, magnitude of shear displacement, shear displacement rate, properties of soil and geosynthetic materials forming interfaces on either side of the GCL and preparation conditions, and product type(s).

Improperly performed tests can give highly inaccurate results, so it is important to carefully consider testing procedures and to examine test data for inconsistencies.

E2.2.5 Equivalence of liner systems

The performance design trend imposes the quantitative evaluation of the equivalence of alternative liners and traditional liners. Nowadays, there is an increasing interest in the use of GCLs as a replacement for conventional compacted clay liners (CCLs). Because, in many jurisdictions, regulations prescribe acceptable barrier system configurations in terms of CCLs, this often raises the question whether a liner involving a GCL is equivalent to one involving a CCL (Rowe 2005, Bouazza 2002).

Rowe (1998) indicated that, when comparison between different products must be carried out, it is important to keep in mind that it is not possible to generalise about 'equivalency' of liner systems, since what is 'equivalent' depends on what is being compared and how it is being compared. Apart from their own features, the performances of liner systems are related to the contaminant amount, concentration and decay parameters, the aquifer characteristics and its distance from the bottom of the landfill, and the efficiency of capping and drainage systems. In this respect, to assess equivalence from an environmental perspective it is necessary to assess the equivalence in terms of contaminant impact on a receptor aquifer beneath a landfill by conducting a contaminant transport analysis.

Rowe (1998), Manassero et al. (2000) and Rowe et al. (2004) provided a framework to model the contaminant transport through geomembrane/ compacted clay liner (GM/CCL) and geomembrane/ geosynthetic clay liner (GM/GCL) composite liners. Furthermore, Rowe (2005) stressed the fact that, when selecting parameters for use in conjunction with a contaminant transport analysis, consideration should be given to:

- the potential for clay–leachate/GCL–leachate interaction and its effect on hydraulic conductivity
- the interaction with the adjacent GM and the effect on leakage
- diffusion and sorption
- the leachate head and corresponding gradient
- the provision of appropriate protection to the GM and GCL to minimise potential squeezing and local thinning of the GCL
- the potential for desiccation and shrinkage of the GCL.

E.3 Requirements for GCLS for basal and sideslope liners

The following parameters are considered minimum requirements for geosynthetic clay liners (GCLs) in landfill liners to maximise their service life.

It should be stressed that these requirements represent a minimum expectation for 'good practice'. A higher standard might be required in certain applications and the onus is on the engineer of record to establish if a higher standard or requirement is needed.

Note that GCLs must maintain a hydraulic conductivity less than or equal to the design value for the contaminating lifespan of the landfill (in other words, the period of time during which the escape of contaminant due to a failure of the engineered system would have an adverse impact on the environment (Rowe et al. 2004). This aspect must be taken into account in the design of the GCL liner and the liner system itself.

1. The geosynthetic clay liner shall be a reinforced, multi-layered system comprising two layers of geotextiles encapsulating a layer of dry bentonite. To minimise the potential problems, for applications where there is a risk of internal erosion (such as when the GCL rests on a permeable layer such as a gravel or geonet layer) or may be subjected to wetting–drying, a GCL with a scrim-reinforced carrier and thermal treatment with properties similar to or better than those for which there is test data in the literature is recommended, unless it can be clearly demonstrated by test results that an alternative GCL is suitable.

2. It is important to select or specify a bentonite that has been specially formulated to meet the specific, unique demands encountered by geosynthetic clay liners in landfills. As a minimum, the bentonite shall meet the specifications indicated below:

Property	Range or value
Montmorillonite content	> 70 wt%
Carbonate content*	< 1–2 wt%
Bentonite form	Natural Na-bentonite or >80 wt% Sodium as activated bentonite
Particle size	Powdered (e.g. 80% passing 75 micron sieve) or Granulated (e.g. < 1% passing 75 micron)
Cation exchange capacity	≥ 70 meq/100 g (or cmol/kg)
Free swell index	≥ 24 cm^3/2g

* Carbonate here implies calcite, calcium carbonate or other soluble or partially soluble carbonate minerals.

3. Other design requirements and technical specifications for the geosynthetic clay liner (for example, Atterberg limits, organic carbon content, mass area of bentonite, mineralogy, shear strength and hydraulic conductivity under expected field stresses to water and permeant with chemical composition similar to expected leachate).

4. Provide a statement (with justification) on the chemical compatibility of the GCL liner and the leachate. In particular, unless relevant testing has previously been conducted for very similar conditions (such as proposed GCL, stress level, leachate), the hydraulic conductivity tests supporting the design hydraulic conductivity should be conducted on samples hydrated to simulate expected field hydration and stresses and permeated with a simulated leachate that approximates that expected in the landfill until the ratio of the chemical composition in permeant influent and effluent is ≥ 0.9 (see Petrov and Rowe 1997; Rowe et al. 2004). Similar compatibility studies should be conducted for compacted clay liners.

5. Provide a statement (with justification) on diffusion coefficients, partitioning coefficients and any other parameter used in the design or analysis (for example, see Rowe et al. 2004).

6. Equivalency comparisons between CCL and GCL base liner systems should incorporate a contaminant transport impact assessment (for example, see Rowe and Brachman 2004);

7. The design of the liner needs to consider the various potential stresses imposed on the geosynthetic clay liner by the in-service configuration and conditions. It is necessary to include the calculations of the physical stresses due to:
   - o strains imposed at the anchor trench
   - o strains imposed over long, steep side slopes
   - o differential settlement of the subgrade and foundation soils, if any.

8. A statement on the effect of thermal gradients on the liner during installation and construction, and effect of temperature during operation (for example, the effect of waste temperatures). Describe how the waste temperature and the thermal gradients will be taken into account (for example, see Rowe 2005).

9. A statement on the effect of equipment traffic during installation. In particular the stresses resulting from application of the overlying layers. Describe how these stresses will be taken into account.

10. Specification for the geosynthetic clay liner protrusions and penetrations. Describe how the geosynthetic clay liner will be attached to penetrations and structures.

11. Demonstrate that there is adequate friction between the various components of the liner system to prevent slippage or sloughing on the slopes and there is adequate internal shear strength to prevent internal failure of the geosynthetic clay liner during construction and waste placement. In particular, the following must be assessed:
    - o the ability of the geosynthetic clay liner to support its own weight on the side slopes
    - o the ability of the geosynthetic clay liner to withstand down drag during and after waste placement
    - o the suitability of the anchorage configuration for the geosynthetic clay liner
    - o the ability to maintain a stable configuration when a geomembrane is placed on top of the geosynthetic clay liner
    - o the ability to maintain a stable configuration when other geosynthetic components such as geotextiles or geocomposites or soils are placed on top of the geosynthetic clay liner
    - o the ability to maintain a stable configuration when installed on top of the subgrade soil
    - o the ability to maintain a stable configuration during construction and waste placement.

12. A specification for liner strength and the calculations defining the minimum strength requirements:
    - o stresses resulting from settlement, compression or uplift
    - o installation stresses

- o operating stresses
- o thermal gradients
- o climatic conditions

13. Installation specifications should include details regarding:
    - o subgrade condition (including cracking and other irregularities) and suitability
    - o geosynthetic clay liner labelling
    - o methods of protecting the geosynthetic clay liner during shipping, storage and handling
    - o panel deployment layout plan, panel identification, method of deployment and placement , overlap orientation, overlap preparation, overlap methods
    - o procedures to be adopted to ensure hydration of the GCL
    - o procedures to be adopted to prevent premature hydration of the GCL
    - o procedures to be adopted to provide confinement to the GCL
    - o procedures to be adopted to prevent opening of the overlaps due to placement of overlaying layers or wet-dry cycle(s)
    - o procedures to be adopted to minimise the effect of trafficking by vehicles
    - o methods of placement in a trench
    - o procedures to deal with damages and defects;
    - o procedures to deal with inclement weather
    - o methods of dealing with or managing wrinkles (waves)
    - o methods of dealing with installation around protrusions and penetrations
    - o procedures to be adopted to prevent desiccation of geosynthetic clay liner and/or any underlying subgrade material
    - o procedures to be adopted to install a geomembrane on top of the GCL
14. Inspection activities, describe how the following will be taken into account:
    - o skill of the installation crew
    - o supervision of installation
    - o inspection and approval of the overlaps
    - o weather and temperature conditions during GCL deployment and overlapping
    - o wrinkles
    - o inspection of the surface of the GCL
    - o presence of damages and defects
    - o action on damages
    - o repair methods.
15. CQC/CQA plan.

E.4 Minimum requirements for GCL liners for landfill cover systems

The geosynthetic clay liner (GCL) in a final cover (either by itself or part of a composite liner) will be subjected to different stress and environmental conditions than experienced at the bottom or the sideslope of the landfill. In this respect, focus needs to be on its ability to resist desiccation cracking caused by environmental drying or cation exchange (this aspect tends to be exacerbated when the GCL is used by itself). Also important is its ability to deform with minimal impact on its hydraulic and gas integrity due to settlement or subsidence of the underlying waste.

The following parameters are considered minimum requirements for geosynthetic clay liner in landfill cover systems to maximise their service life. It should be stressed that these requirements represent a minimum expectation for 'good practice'. A higher standard might be required in certain applications and the onus is on the engineer of record to establish if a higher standard or requirement is needed.

Note that, in some cases, diffusion of vapours (such as VOCs) or gases can potentially occur from the underlying waste. In this case, this aspect needs to be considered in the design process.

1. The geosynthetic clay liner shall be a reinforced multi-layered system comprising two layers of geotextiles encapsulating a layer of dry bentonite. To minimise the potential problems, for applications where there is a risk of internal erosion (such as when the GCL rests on a permeable layer such as a gravel or geonet layer) or may be subjected to wetting-drying, a GCL with a scrim-reinforced carrier and thermal treatment with properties similar to or better than those for which there is test data in the literature is recommended unless it can be clearly demonstrated by test results that an alternative GCL is suitable.

2. It is important to select or specify a bentonite that has been specially formulated to meet the specific, unique demands encountered by geosynthetic clay liners in landfills. As a minimum, the bentonite shall meet the specifications indicated below :

Property	Range or value
Montmorillonite content	> 70 wt%
Carbonate content*	< 1–2 wt%
Bentonite form	Natural Na-bentonite or > 80 wt% sodium as activated bentonite
Particle size	Powdered (e.g. 80% passing 75 micron sieve) or Granulated (e.g. < 1% passing 75 micron)
Cation exchange capacity	≥ 70 meq/100 g (or cmol/kg)
Free swell index	≥ 24 cm^3/2g

* Carbonate here implies calcite, calcium carbonate or other soluble or partially soluble carbonate minerals.

3. Other design requirements and technical specifications for the geosynthetic clay liner (such as Atterberg limits, organic carbon content, mass area of bentonite, mineralogy, shear strength and hydraulic conductivity under expected field stresses).

4. Provide a statement (with justification) on the chemical compatibility of the GCL liner and any cover soil used in conjunction with capping GCLs. Ca2+ for Na+ exchange reactions can take place rapidly in cover-liner GCLs when exposed to liquids containing soluble Ca2+.

5. Provide a statement (with justification) on gas permeability, and any other parameter used in the design or analysis.

6. The design of the liner needs to consider the various potential stresses imposed on the geosynthetic clay liner by the in-service configuration and conditions. It is necessary to include the calculations of the physical stresses due to:
   - strains imposed over steep side slopes, if cover is slopped and consequently strains imposed at the anchor trench
   - differential settlement of the waste

7. Provide a statement (with justification) on the effect of settlement on the overlaps,

8. A statement on the effect of thermal gradients/cycles on the liner during installation and construction, and effect of temperature during operation (such as the effect of thermal cycles that could cause desiccation). Describe how thermal gradients/cycles will be taken into account.

9. A statement on the effect of equipment traffic during installation. In particular the stresses resulting from application of the overlying layers. Describe how these stresses will be taken into account.

10. Specification for the geosynthetic clay liner protrusions and penetrations. Describe how the geosynthetic clay liner will be attached to penetrations and structures. Describe how the effect of differential settlement and/or lateral movement of the materials around the protrusions/penetrations will be taken into account.

11. In the case of installations with sloping sides, it needs to be demonstrated that there is adequate friction between the various components of the liner system to prevent slippage or sloughing on the slopes of the installation and adequate internal shear strength to prevent internal failure of the geosynthetic clay liner. In particular, the following must be assessed:
    - the ability of the geosynthetic clay liner to support its own weight on the side slopes
    - the ability of the geosynthetic clay liner to withstand down drag during and after waste placement
    - the suitability of the anchorage configuration for the geosynthetic clay liner
    - the ability to maintain a stable configuration when a geomembrane is placed on top of the geosynthetic clay liner
    - the ability to maintain a stable configuration when other geosynthetic components such as geotextiles or geocomposites or soils are placed on top of the geosynthetic clay liner
    - the ability to maintain a stable configuration when installed on top of the subgrade soil.

12. A specification for liner strength and the calculations defining the minimum strength requirements:
    - stresses resulting from differential settlement
    - installation stresses
    - thermal gradients
    - climatic conditions.

13. Installation specifications should include details regarding:
    - subgrade condition (including cracking and other irregularities) and suitability
    - geosynthetic clay liner labelling
    - methods of protecting the geosynthetic clay liner during shipping, storage and handling

- panel deployment layout plan, panel identification, method of deployment and placement , overlap orientation, overlap preparation, overlap methods
- procedures to be adopted to ensure hydration of the GCL
- procedures to be adopted to provide confinement to the GCL
- procedures to be adopted to prevent premature hydration of the GCL
- procedures to be adopted to prevent potential desiccation of the GCL and/or any underlying material
- procedures to be adopted to prevent opening of the overlaps due to placement of overlaying layers
- procedures to be adopted to minimise the effect of trafficking by vehicles
- procedures to deal with damages and defects
- procedures to deal with inclement weather
- methods of dealing with or managing wrinkles (waves)
- methods of dealing with installation around protrusions and penetrations
- procedures to be adopted to install a geomembrane on top of the GCL.

14. Inspection activities, describe how the following will be taken into account:
    - skill of the installation crew
    - supervision of installation
    - inspection and approval of the overlaps
    - weather and temperature conditions during GCL deployment and overlapping
    - wrinkles
    - inspection of the surface of the GCL;Presence of damages and defects
    - action on damages
    - repair methods
15. CQC/CQA plan.

E.5 Minimum requirements for the installation of geosynthetic clay liners to be used in landfills

Engineering assumptions regarding geosynthetic clay liners (GCLs) performance rely on its robustness being maintained through the construction process. It is important to handle, store and install the material properly in order to ensure its longevity and to provide effective environmental protection.

Note that, as indicated earlier this document is neither a prescriptive document nor a set of specifications. It is aimed only at providing a set of minimum requirements and guidance notes in designing geosynthetic clay liners for landfill engineering purposes. The onus is on the engineer of record to ensure that design and installation of GCLs meet the EPA-required levels of environmental protection.

E5.1 Transportation, handling and storage

The GCLs shall be delivered to the site, handled and stored in such manner that no damage occurs to the GCLs. They shall be wrapped with weather and moisture-proof wrapping to prevent any contact with water prior to installation. In the event that it is suspected that the GCL may have come into contact with water, the CQA engineer should check the moisture content of the bentonite and make the decision on the course of actions to take.

The roll cores shall be sufficiently strong to ensure that they do not deflect by more than half their diameter during transit and handling.

The geosynthetic clay liner rolls should be stored in a location away from construction traffic but sufficiently close to the active work area to minimise handling. The storage area should be level, dry, well-drained and stable, and should protect the product from precipitation, chemicals, excessive heat, UV radiation, standing water, vandalism and animals.

GCL roll stacks shall be limited to the height at which installation personnel can safely manoeuvre the handling equipment; recommended maximum stack height is three rolls.

Best practice for handling GCLs is to use a spreader stinger bar (a bar protruding from the front end of a forklift or other equipment). The bar must be capable of supporting the full weight of the geosynthetic clay liner without significant bending. Under no circumstances may the GCL rolls be dragged, lifted from one end, lifted in the middle of the roll, lifted with the forks of a forklift or pushed to the ground from the delivery vehicle.

E5.2 Geosynthetic clay liner installation

In most cases, the lining task involves large areas, therefore it is important to proceed stage by stage in the geosynthetic clay liner installation process. It is suggested that this latter be composed of the following phases:

1. Installation planning and pre-installation conformance testing.
2. Construction and preparation of the subgrade.
3. Placement of the geosynthetic clay liner including transport, unrolling and placing, anchorage.
4. Overlapping of the geosynthetic clay liner panels, connection to structure penetration systems.

5. Placement of the overlying material.

E5.2.1 Planning and pre-installation conformance testing

The installation process must be preceded by a planning phase which should result in a detailed panel layout irrespective of the type of application. The layout should specify to scale the arrangement of the geosynthetic clay liner panels in the area to be lined, and the penetrations and connections.

Each roll of geosynthetic clay liner shall be labelled to provide the following identifying data:

- product name, grade and name of manufacturer
- date of manufacture, batch number
- roll number
- roll length
- roll weight
- roll width
- label with handling guidelines.

MQC documentation from the manufacturer of the GCL supplied must be submitted for approval by CQA Engineer. Submissions shall include:

- date of manufacture
- lot number, roll number, length and width
- bentonite manufacturer quality documentation for the particular lot of clay used in the production of the rolls delivered
- geotextile manufacturer quality control documentation for the particular lots of geotextiles used in the production of the rolls delivered
- cross-referencing list delineating the corresponding geotextile and bentonite lots for the materials used in the production of the rolls delivered
- QC program laboratory certified reports
- the manufacturer's approved QA stamp and the technician's signature.;

The geosynthetic clay liner should be tested for all critical properties by a third-party accredited independent laboratory before installation.

E5.2.2 Subgrade

The surface on which a geosynthetic clay liner will be deployed shall be firm and free of any sharp objects, stones, debris, standing water, sudden changes in grade (including indentations due to tyre tracks), or desiccation cracks. Under some circumstances the grain size distribution, dry density and moisture content of the subgrade may be specified to ensure appropriate subgrade stiffness/strength and moisture uptake by the GCL.

The geosynthetic clay liner shall not be installed until inspection of the subgrade has been undertaken and deemed suitable and in accordance with the specifications by the CQA engineer.

E5.2.3 Panel placement, overlaps

The GCLs shall be installed such that the panels are anchored at the crest of the slope and are continuous down side walls/slopes. The panels should also be continuous across the base or the cover. The arrangement of the GCL panels should be according to a predetermined layout plan to minimise the amount of end overlaps.

Overlap joints between panels shall be formed by overlapping the panels by a minimum of 300 mm and sealed by bentonite paste or powder/granules (sometimes referred to as accessory bentonite). The overlap zone shall be kept clean and shall not be contaminated with loose soil or other debris. There shall be no folds or wrinkles in the overlap zone and no traffic or walking shall occur on the completed overlap.

Bentonite used for overlapping shall comply with the same specifications as the bentonite used in the GCL delivered to the site (same rule applies for sealing penetrations and repairs). Research has demonstrated that adequate bentonite between overlapped panels is critical to obtaining good hydraulic performance at the overlap (Cooley and Daniel 1995, Daniel et al. 1997, Benson et al. 2004).

In the case of composite liners, particular care should be taken to avoid contaminating the upper surface of the GCL with bentonite powder. The presence of loose bentonite may affect welding of overlying geomembranes and may also influence interface friction.

If the slope design includes any transverse overlaps, intermediate anchorage of the panels on the slope will be needed. In this case, panels should be placed in a roofing tile fashion. The sealing of the panels shall be conducted in the same fashion as for parallel overlaps. Overlaps must be at least 1500 mm for any transverse overlaps (across the slope) and 300 mm for parallel overlap (downslope) to cater for possible movement. If settlement is likely to be significant such as in capping, the overlaps should be increased to allow for the predicted settlement.

The entire surface area of every roll shall be inspected by the CQA engineer (for example, during unrolling/installation) to ensure that there is no damage or other faults in the material (such as significant and obvious variability in thickness/mass per unit area, initial moisture content of the GCL). If damage is identified, it will need to be repaired according to the specifications put in place for the site.

Wrinkles are in general undesirable, as they increase the likelihood of poor intimate contact between the GCL and the geomembrane or subgrade material. In the event that wrinkles occur in the GCL or where wrinkles extend to the edge of the roll due to manufacturing tolerances, they will need to be removed prior to installation of any material cover.

Geosynthetic clay liners installed on slopes are required to be fixed in anchor trenches. This is done to secure the geosynthetic clay liner and prevent it from sloughing or slipping down the inside side slopes during construction or service. A normal minimum requirement is that the anchor trench must be at least one meter back from the top edge of the slope. The front edge of the trench is to be rounded to prevent the development of stress concentrations on the GCL or any other geosynthetics for that matter.

The geosynthetic clay liner should be laid on the inside wall and base of the trench only and the trench should be cleared of any debris, gravel or loose material before tte GCL is installed. The trench should be backfilled and compacted with low hydraulic conductivity soils.

GCLs shall not be installed in wet weather or windy conditions.

It is very important to ensure that the GCL is not left exposed to rain. In this respect, it is essential that covering and confinement activities be coordinated with GCL installation. If the deployed GCL panels have hydrated prematurely (for example, during rainfall) without confinement, then the GCL panels shall be replaced.

E5.2.3.1 Soil cover placement

Where a soil cover is placed directly on the GCL, the soil cover specification shall account for the compatibility of the GCL and the cover soil. The soil shall also be free of debris, roots, sharp objects and any other item which may under the overburden stress penetrate or tear the GCL.

Disturbance of the overlap area during placement must be avoided. It may be necessary to place the cover soil in this area manually. The cover should not be pushed or graded in a direction that may cause the overlap to move. The geosynthetic clay liner shall not be trafficked directly.

E5.2.3.2 Geomembrane cover placement

Where a geomembrane is placed directly on the GCL, it should be placed immediately following deployment and acceptance of the GCL.

E5.3 Repairs

If the GCL has been damaged during installation, it can be repaired by patching a new piece of GCL of the same material type and thickness extending 500 mm beyond the damaged area in each direction. The patched area must be augmented with bentonite powder or granules/paste as per normal jointing requirements.

E.6 Quality

E6.1 Manufacturing specifications and quality control

The quality of the geosynthetic clay liner (GCL) shall be in accordance with the requirements of the Geosynthetic Research Institute (GRI) – GCL3. The minimum specifications for quality GCL products are contained in GRI Test Method GCL3 Standard Specification for ‘Test Methods, Required Properties, and Testing Frequencies of Geosynthetic Clay Liners (GCLs)’. These specifications were developed by the Geosynthetic Research Institute (GRI), with the cooperation of geosynthetic clay liner manufacturers. The specifications set forth a set of minimum physical and mechanical properties that must be met, or exceeded by the geosynthetic clay liner being manufactured.

Note that, currently, there are no Australian manufacturing specifications. In this respect GRI GCL3 represents best practice. However, it should be stressed that the GRI requirements represent a minimum. Higher requirements may be necessary in certain applications and the onus is on the engineer of record to establish if higher requirements are necessary and to specify according to the particular engineering requirements.

Further note: always refer to the latest version of this specification).

In addition to the above, the following bentonite specifications shall be verified every 50 tonnes of the product:

Property	Range or value
Montmorillonite content	> 70 wt%
Carbonate content*	< 1–2 wt%
Bentonite form	Natural Na-bentonite or > 80 wt% sodium as activated bentonite
Particle size	Powdered (e.g. 80% passing 75 micron sieve) or Granulated (e.g. < 1% passing 75 micron)
Cation exchange capacity	≥ 70 meq/100 g (or cmol/kg)
Free swell index	≥ 24 cm^3/2g

* Carbonate here implies calcite, calcium carbonate or other soluble or partially soluble carbonate minerals.

A statement on the origin of the bentonite must be included, as well as certified copies of the quality control certificates issued by the bentonite supplier and reports on the tests conducted by the manufacturer to verify the quality of the bentonite used to manufacture the geosynthetic clay liner (GCL) rolls assigned to the project.

The geotextile components of the GCL must also have been through a QC programme. The manufacturer's geotextile QC program should be available for auditing.

E6.2 Construction quality control (CQC)

Installation of the geosynthetic clay liners must be undertaken by GCL installers with extensive installation experience and competence with the specified GCL. In the case of installation of multi-component liners composite, they shall provide sufficient evidence of installation experience and competence with other geosynthetics.

In either case, they must provide experience records prior to any installation.

E6.3 Third-party CQA consultant

Construction quality assurance (CQA) is defined as a planned system of activities that provide assurance that the geosynthetic clay liner was fabricated and installed as specified in the design.

It is an important factor in ensuring that design and installation of the GCL are done in accordance with the standards and specifications agreed with EPA. For this purpose, an independent, third-party CQA consultant having experience with geosynthetic clay liners and knowledgeable of geosynthetic clay liner characteristics must be appointed to verify that the works have been carried out to the agreed standards.

The duties of the third-party CQA consultant include inspections, verifications, audits and evaluation of materials and workmanship, provision of advice on installation, testing, repair and covering of the geosynthetic clay liner system, and issuing a final CQA report documenting the quality of the constructed facility.

E6.4 CQA plan

A CQA plan shall be submitted to EPA prior to the geosynthetic clay liner installation. The CQA plan needs to provide procedures for identifying non-conformance and for corrective action. The plan should cover the following:

- The nature of the non-conformance and its level of effect on the project.
- Determination whether the non-conformance is an isolated incident or a recurring problem.
- How amendments to procedures to prevent future occurrences of the non-conformance will be implemented.
- The nature of corrective action to be applied to rectify that specific non-conformance.
- The procedures and persons to be notified of the non-conformance and corrective measures.
- Procedures for reporting to the EPA major exceptions/variations to the approved technical specifications.

It should, at a minimum, include the following information for each geosynthetic clay liner product proposed:

1. Definitions to be used throughout the project to avoid confusion on acronyms and wording.
2. Descriptions of responsibilities, qualifications, and obligations for each party involved in the CQA plan.
3. The lines of communication and authority for the project. Identify and define the process for addressing request for information, design modifications or changes in the project specifications.
4. A formal process on handling deficiencies which defines responsibilities and the minimum documentation required to correct deficiencies.
5. A project meeting schedule.
6. The proposed level of supervision and quality control.
7. Verification process and review of the quality control certificates of the manufacturers of the GCL, the bentonite and the geotextile.
8. Verification process and review of the property values certified by the GCL manufacturer.

9. Verification process that the measurements of properties by the manufacturer are properly documented, test methods are acceptable, sampling procedure detailed and verification that the geosynthetic clay liner, the geotextile and the bentonite meet the project specifications.
10. Verification process and review of the quality control certificates of the geosynthetic clay liner rolls assigned to the project (note: this includes a need to agree with manufacturer on the frequency of the tests).
11. Details of the delivery, handling and storage of the geosynthetic clay liner on site prior to installation.
12. Verification process of the geosynthetic clay liner handling equipment and restraining methods used on the site.
13. Rejection criteria of the geosynthetic clay liner rolls.
14. Details of the installation staff's accreditations and verification of their experience.
15. Details of the conformance tests the CQA consultant will undertake on the geosynthetic clay liner rolls delivered to site. Any laboratory tests must be performed at an accredited, independent third-party laboratory.
16. Details of actions to take if geosynthetic clay liner fails conformance tests.
17. Approval procedure of the subgrade and anchor trench including details of testing.
18. Establishment of a field geosynthetic clay liner panel identification.
19. Details of actions to take to insure that field panels and overlap orientation are as indicated in the layout plan.
20. Measures to take to protect the liner if inclement weather occurs during installation.
21. Procedure for sampling and evaluation.
22. Procedures for inspecting overlaps preparation.
23. Details of actions to take in case of defects and or damages to the surface of the laid geosynthetic clay liner are identified and corrective measures.
24. Details of actions to take to minimise geosynthetic clay liner wrinkles and bridging.
25. Verification process of the geosynthetic clay liner installation around areas of protrusions and penetrations is made according to specifications.
26. Details of actions and procedure to take to protect and to confine the geosynthetic clay liners following installation.
27. Procedure for ensuring that the GCL does not exceed the manufactured moisture content.
28. CQA consultant daily recordkeeping. The daily log should contain the following:
    - weather and site conditions
    - records of the delivery handling and storage
    - quality of subgrade
    - description of any material received at the site, including quality control data provided by suppliers
    - location of daily construction activities and progress
    - conformance to panel layout design
    - recording of installation activities consisting of panel placement, roll numbers, overlap locations, repairs and testing results for all works
    - records (including photos) of the geosynthetic clay liner at the time that cover soil or geomembrane is placed over the geosynthetic clay liner
    - photographs of construction works and any items of specific interest. The captions of all photographs should contain the name of the project, the date on which the photograph was taken and the identity of the feature being photographed
    - type of equipment used in each work task (e.g. handling equipment)
    - testing conducted and test methods used
    - remedial action on GCL defects or overlap defects
    - placement of temporary protection to installed GCL
    - record of any material or workmanship that does not meet specified designs and corrective actions taken to remediate the problem
    - details of site visits
    - summaries of any meetings held and action taken
    - signature of CQA engineer.
29. Periodic acceptance reports summarising daily reports.

The contractor shall provide the CQA authority with the following listed test certificates and records prior to, during and at the completion of the works as each report and record is required:

- certification and test results of bentonite used in the production of the rolls from bentonite material supplier
- certification and test results of geotextiles, fibres used in the production of the rolls
- roll test data reports, for each roll of material
- accessory bentonite test reports

- completed as-built drawing, including roll numbers, panel layout, overlap locations and repair locations.

Any deviations from the approved CQA plan must be noted and explained and approved by EPA and the EPA-appointed auditor.

E6.5 Conformance testing

Table E3 provides guidance on the test properties and recommended minimum testing frequencies. Higher testing frequencies might be required in certain applications (if there is a need to identify the importance of the geosynthetic clay liner for the safety of the works, construction and stability included).

The onus is on the engineer of record to establish if higher requirements are more appropriate.

E6.6 CQA report

A CQA report must be prepared by the CQA consultant to demonstrate that all requirements of the project specifications and CQA plan have been complied with.

Table E3: Guidance on CQA testing for geosynthetic clay liners

Item	Property	Standards	Frequency
Conformance testing (upon shipment of GCL to the site)	Thickness (dry)	ASTM D1777	Each roll
	Mass per unit area of bentonite component of GCL	ASTM D5993	1 sample per 2,500 m^2
	Mass per unit area of GCL	ASTM D5993	1 sample per 500 m^2
	Montmorillonite content (X-ray diffraction method)		1 sample per 10,000m^2
	Cation exchange capacity of bentonite (methylene blue method)		1 sample per 500 m^2
	Mass/unit length of bentonite in overlaps (visual inspection and weighting)		1 sample per 40 m overlap
	Moisture content of bentonite	AS 1289.2.1.1	1 sample per roll or 500 m^2
	Swell index/free swell of clay	ASTM D5890	1 sample per roll or 500 m^2
	Water absorption	ASTM D5891	1 sample per roll or 500 m^2
	Peel strength (for needle-punched products only)	ASTM D6496	1 sample per roll or 500 m^2
	Tensile strength	ASTM D4595	As specified in CQA plan
	CBR of geotextile	AS 3706-4	As specified in CQA plan
	Puncture resistance of geotextile	AS 3706-5	As specified in CQA plan
	Index flux	ASTM 5887	1 sample per 10,000 m^2
Visual inspection of GCL	Colour, thickness, needle punching, presence of needles or broken needles, and sewing density or other faults in the material.		Every roll
Thickness of GCL (i.e. uniformity of bentonite distribution) and apparent variations in the as placed moisture distribution.	On-site		Each roll during placement. If thickness appears to be variable a check of the variability of the mass per unit area should be conducted

Note:

1 All conformance tests must be reviewed, accepted and reported by a CQA consultant before deployment of the geosynthetic clay liner

2 All testing must be performed on samples taken from the geosynthetic clay liner delivered to site under the CQA consultant supervision

3 All laboratory tests must be performed in a third party independent accredited laboratory

4 The required testing frequencies may be revised by the CQA consultant to conform with improvements in testing methods and/or in the state of the art practice and/or to account for the criticality of the application (i.e to account for the importance of the geosynthetic clay liner for the safety of works). Revisions must be approved by the relevant authorities before application

E.7 Bibliography

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E.8 Addendum A (standard test methods)

A list of commonly Australian Standards, ASTM standards and GRI test specifications used in geosynthetic clay liner (GCL) design is given below for guidance. This list is not exhaustive; onus is on the project engineer, CQA consultant, contractor and environmental authority to establish the list of standards needed for a given project.

E8.1 Australian Standards

- AS 1289.2.1.1: Methods of testing soils for engineering purposes – soil moisture content tests. Standards Australia.
- AS 3706–4: Determination of burst strength – California bearing ratio (CBR) – Plunger method. Standards Australia.
- AS 3706–5: Determination of puncture resistance-Drop cone method. Standards Australia.

E8.2 ASTM standards

- ASTM D5887. Test method for measurement of index flux through saturated geosynthetic clay liner specimens using flexible wall permeameter. ASTM, West Conshohocken, PA, USA.
- ASTM D5888. Practice for storage and handling of geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D5889. Practice for quality control of geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D5890. Test method for swell index of clay mineral component of geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D5891. Test method for fluid loss of clay component of geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.

- ASTM D5993. Test method for measuring the mass per unit area of geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D6072. Guide for obtaining samples of geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D6102. Guide for installation of geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D6141. Guide for screening the clay portion of a geosynthetic clay liner for chemical compatibility to liquids. ASTM, West Conshohocken, PA, USA.
- ASTM D6243. Method for determining the internal and interface shear resistance of geosynthetic clay liner by the direct shear method. ASTM, West Conshohocken, PA, USA.
- ASTM D6495. Guide for acceptance testing requirements for geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D6496. Test method for determining average bonding peel strength between the top and bottom layers of needle-punched geosynthetic clay liners. ASTM, West Conshohocken, PA, USA.
- ASTM D6766. Test method for evaluation of hydraulic properties of geosynthetic clay liners permeated with potentially incompatible liquids. ASTM, West Conshohocken, PA, USA.

E8.3 Geosynthetic Research Institute (GRI) test methods specifications

- GRI test method GCL3. Standard specification for test methods, required properties, and testing frequencies of geosynthetic clay liners (GCLs). Revision 1: 30 March 2009, Geosynthetic Research Institute, Folsom, PA, USA

APPENDIX F: Guidance on geotextile use as protection in landfills

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Executive summary

Geotextiles are frequently incorporated with other geosynthetics and soil components in barrier systems for landfills to protect geomembranes from the effect of stresses imposed by the overlying materials and as a separator/filter in the drainage layer. The purpose of the protective/cushion layer is to ensure satisfactory short and long-term hydraulic performance of the geomembrane liner.

This appendix provides details on minimum standards for geotextile cushion material, installation procedures and testing requirements. It is neither a prescriptive document nor a set of specifications. It is rather aimed at assisting engineers, specifiers, designers, regulators, facility owners and operators by providing a set of minimum requirements and guidance notes in designing geotextile cushions for landfill engineering purposes.

F.1 Introduction

Geotextiles consist of polymeric filament, fibres or yarns made mostly into woven or nonwoven textile sheets. The sheets are flexible and permeable and generally have the appearance of a fabric.

The most common types of filaments used in the manufacture of geotextiles include monofilament, multifilament, staple filament and slit-film. If fibres are twisted or spun together, they are known as a yarn.

Woven geotextiles are manufactured using traditional weaving methods and a variety of weave types: plain weave, basket weave, twill weave and satin weave. Nonwoven geotextiles are manufactured by laying down and orienting the filaments or fibres and then bonding filaments/fibres together by needle punching or by melt bonding.

Nonwoven geotextiles have different engineering properties than the woven geotextiles. The type of polymer will also influence the engineering properties of these products.

The primary functions of geotextiles used for landfill applications include separation, filtration, drainage, erosion control and protection. However, this appendix covers only the use of nonwoven geotextiles as a protection layer for geomembranes (in other words, placement of a geotextile to act as a stress relief layer); woven geotextiles are not included, since they are not commonly used as protection material.

This appendix provides details on minimum standards for geosynthetic protection material, installation procedures and testing requirements. It is aimed at assisting engineers, specifiers, designers, regulators, facility owners and operators in designing geotextile protection layers for landfill engineering purposes.

F.2 Background

Modern municipal solid waste (MSW) facilities are typically designed with a bottom barrier system intended to limit contaminant migration to levels that will result in negligible impact. The system includes a leachate collection system (LCS) and a composite liner involving an HDPE (high-density polyethylene) geomembrane (GM) over either a compacted clay liner (CCL) or a geosynthetic clay liner (GCL).

The LCS is intended to control the leachate head acting on the underlying liner, and collect and remove leachate. The leachate collection system typically incorporates a drainage blanket –comprising coarse gravel –which is separated from the geomembrane (GM) liner by a geotextile (GT) intended to protect the geomembrane from damage due to the local stresses imposed by the overlying drainage layer and waste. It is vital to protect the integrity of the geomembrane, a critical component of the containment facility, to ensure a satisfactory short and long-term hydraulic performance of the lining system. In this respect, the purpose of the protective layer is to:

- minimise the risk of geomembrane damage or puncture during construction and during the subsequent operation of the landfill
- minimise the strains in the geomembrane and hence the risk for future punctures forming due to environmental stress cracking.

To achieve the above, nonwoven needle-punched geotextiles have been widely used as a protection material. Such geotextiles can be made from different polymers (previously polyester, but now commonly polypropylene), different mass per unit area and different strengths (Koerner et al. 2010).

Two approaches, based on different design philosophies, are used to evaluate the performance of a proposed protection layer of a geomembrane liner in a municipal solid waste landfill. The first approach seeks to prevent short-term puncture of geomembranes; the second approach seeks to ensure the long-term performance of the geomembrane (Tognon et al. 2000).

The first design philosophy seeks to prevent local elongation of geomembranes past the yield point, thus allowing deformations whilst preventing puncture of the geomembrane. There is no upper limit given for the local strain – the aim is to provide short-term protection against puncture under the loads applied by the overlying waste. It is referred to as Level II protection in the classification proposed by Narejo (1995). Narejo defined three levels of protection against puncture for geomembranes under typical loading conditions:

- Level I is typically applied to liner systems for hazardous waste facilities. This level requires that the liner system be designed such that less than 0.25 per cent localised strain occurs in the geomembrane liner from the imposed loading.
- Level II (intermediate protection level) is for non-hazardous waste facilities. The 'intermediate protection level' lies between Level I protection and the yield of an HDPE geomembrane. The yield of HDPE geomembranes in the puncture mode is considered as failure of the level II protection. In other words, the liner system is allowed to have geomembrane strains greater than 0.25 per cent, but not resulting in yielding of an HDPE geomembrane liner.
- Level III protection is defined for non-critical applications. The limited loss of contained liquid through the geomembrane for such applications is considered neither harmful to the environment nor otherwise unsuitable. For such applications the yielding of the HDPE geomembrane liner may be allowed to occur, but it does not puncture.

Wilson-Fahmy et al. (1996), Narejo et al. (1996), Koerner et al. (1996) and, more recently, Koerner et al. (2010) provide a basis for protection layer design consistent with this philosophy.

The design method focuses on the selection of a nonwoven needle-punched geotextile protection layer with sufficient mass per unit area to provide an adequate global factor of safety against geomembrane yield. This approach is used in North America and governs in most of the cases the acceptability of the protection layer (for example, Richardson 1996; Reddy et al 1996; Reddy and Saichek 1998a, b; Richardson and Johnson 1998).

Along the same philosophy, Badu-Tweneboah et al. (1998) presented another approach for evaluating the effectiveness of geomembrane liner protection. The approach is based on the use of multi-axial tension tests (ASTM D5617) performed on geomembrane specimens after exposure to anticipated field conditions.

A criterion based on the geomembrane mode of failure in the multi-axial tension test is used to determine whether a certain level of mechanical damage is acceptable. This means that, for the damage to be acceptable, the tensile strain characteristics of the geomembrane must not be significantly affected. In either case, recent work by Gudina and Brachman (2006) and Brachman and Gudina (2008a, b) shows that geotextile protection layers that represent current North American practice are insufficient to limit the long-term tensile strains in the geomembrane.

The second design philosophy seeks to limit the development of local strains within the geomembrane. These are due to a combination of pressures from the overlying waste transmitted through the drainage layer, subgrade settlement and waste down-drag, over a long term. It is believed that protection against short-term puncture, although necessary, is not sufficient to ensure adequate long-term performance and avoid the likelihood of environmental stress cracking over time.

A 0.25 per cent local strain was set as the limiting value for local deformation (in other words, deformation due to drainage layer impingement) in several European countries. This value was proposed by the 'Quo Vadis working group' (Dixon and Von Maubeuge 1992; Gallagher et al. 1999) and was arrived at by taking the maximum total allowable strain to be six per cent, based on results from HDPE gas line pipe testing studies, and applying a factor of safety of two. This gives a total permissible strain of three per cent arising from the combined effects of differential settlement, waste down-drag, and drainage layer impingement.

Allowing for the strains (2.75 per cent) induced by installation and long-term settlement of the subgrade, the group set a 0.25 per cent local strain as the limiting value for local deformation (deformations caused by point loads from drainage aggregate). This is similar to level I protection proposed by Narejo (1995).

In order to assess the suitability and ability of a proposed protection layer to meet any performance criteria, a range of tests is available and it is usually linked to the design philosophy put in place. The tests may take the form of index, quasi-performance, performance or field tests.

Performance tests attempt to mimic site conditions as closely as possible through the use of site-specific materials and representative testing conditions or under operating conditions. The results of such tests are considered the most applicable to the selection of field protection layers.

The most common performance test is the cylinder test, which was formalised by the UK Environment Agency in 1998. The UK Environment Agency methodology (Environment Agency 1998) was developed to provide consistency in the undertaking and reporting of the cylinder test. The criteria employed to evaluate the performance of the geotextile are in terms of both damage and deformation of the geomembrane.

A full discussion of the UK EA methodology, including issues of local strain measurement and pass/fail criteria, is provided by Gallagher et al. (1999). The test has also been formalised as European Standard BS–EN 13719:2002.

In addition, several investigations utilising field and large-scale testing have been undertaken to assess the relative merits of various protection layers. These include field studies on the effects of construction and MSW loading (Reddy et al. 1996; Richardson 1996; Richardson and Johnson 1998; Reddy and Saichek 1998; Khay et al. 2006; Budkha et al. 2007). The results from these field studies give an indication of the short-term efficiency of the protection against damage during installation (there is no upper limit given for the local strain).

Large-scale laboratory tests aimed at evaluating the puncture protection for long-term performance of geomembranes have been conducted by various researchers (Zanzinger and Gartung 1998; Zanzinger 1999; Tognon et al. 2000, Dickinson and Brachman, 2008). Their results seem to indicate that a nonwoven needle-punched geotextile selected solely to prevent puncture is not capable of limiting the tensile geomembrane strains to allowable levels. There is no doubt that further research is needed to clarify the time-dependent effects on the local strains caused by the gravel particles. Selecting an adequate geotextile protection for geomembranes is a fundamental aspect of landfill barrier design if the robustness and integrity of these systems are to be ensured in the long term.

Environmental stress cracking can occur in HDPE materials and therefore the straining in a geomembrane must be restricted to an acceptable level, although to date the value for the limiting strain is not known with any accuracy (Jones et al. 2000). It is certainly difficult to draw a general recommendation that will ensure protection for any scenario. However, the use of performance tests combining mechanical and deformation criteria can help in selecting an adequate geosynthetic or soil protection layer.

F2.1 Types of geotextiles

As indicated above, the majority of geotextiles used as protection layers are polypropylene nonwoven needle-punched geotextiles. A high-density polyethylene material could be considered if a higher chemical resistance is specified.

F.3 Minimum requirements for geotextile protection layer

The following parameters are considered minimum requirements for geotextiles used as a protection material for geomembrane liners.

It should be stressed that these requirements represent a minimum expectation for ‘good practice’. A higher standard might be required in certain applications and the onus is on the engineer of record to establish whether a higher standard or requirement or a different material is needed.

1. The geotextile shall be 100 per cent polyester or polypropylene (with the exception of inhibitors and/or carbon black added for UV resistance) nonwoven needle-punched geotextile. It is important to select or specify a geotextile polymer that has been formulated to meet the specific, unique demands encountered by geotextiles protection material in landfill engineering. Geotextiles made from recycled materials shall be avoided as protection material.
2. Other design requirements and technical specifications for the geotextile (such as mass per unit area, tensile properties, tear resistance, puncture resistance and UV resistance).
3. A statement (with justification) on the chemical compatibility of the geotextile and the leachate. In particular, the ability of the geotextile to retain adequate strength and performance after exposure to leachate.
4. The design of the liner needs to consider the various potential stresses imposed on the geotextile by the in-service configuration and conditions. It is necessary to include the calculations of the physical stresses due to:
    - strains imposed at the anchor trench
    - strains imposed over long, steep side slopes
    - differential settlement of the subgrade and foundation soils, if any.
5. A statement on the effect of temperature during operation (for example, the effect of waste temperatures). Describe how the waste temperature will be taken into account.
6. A statement on the effect of equipment traffic during installation – in particular, discuss the stresses resulting from application of the overlying layers. Describe how these stresses will be taken into account.

7. A statement (with justification) on the effects of mineral precipitation on the geotextiles performance. In particular, discuss the ability of the geotextile to retain adequate strength and performance after exposure to the precipitates.
8. A statement (with justification) on the effects of microbial growth on the characteristics and the polymer of the geotextile. In particular, discuss the ability of the geotextile to retain adequate strength and performance after exposure to microbial growth.
9. A statement on the effect of exposure to ultraviolet (UV). Describe how UV exposure will be minimised.
10. Demonstration through conformance tests that the selected geotextile minimises local strains in the geomembrane to accepted levels for both short-term and long-term conditions.
11. Specification for the geotextile protection layer that will be placed between the geomembrane and the leachate collection system, including the method of placement.
12. Demonstration that there is adequate friction between the various components of the liner system to prevent slippage or sloughing on the slopes during construction and waste placement. In particular, the following must be assessed:
    - the ability of the geotextile to support its own weight on the side slopes
    - the ability of the geotextile to withstand down-drag during and after waste placement
    - the suitability of the anchorage configuration for the geotextile
    - the ability to maintain a stable configuration when the geotextile is placed on top of the geomembrane
    - the ability to maintain a stable configuration when soils and/or other geosynthetic components such as geocomposites are placed on top of the geotextile
    - the ability to maintain a stable configuration during construction and waste placement.
13. A specification for liner strength and the calculations defining the minimum strength requirements:
    - stresses resulting from settlement, compression or uplift
    - installation stresses
    - operating stresses
    - thermal stresses
    - climatic conditions.
14. Installation specifications should include details regarding:
    - subgrade condition and suitability
    - geotextile labelling
    - methods of protecting the geotextile during shipping, storage and handling
    - procedures to deal with inclement weather
    - panel deployment layout plan, panel identification, method of deployment and placement, overlap orientation, jointing methods
    - methods of placement in a trench
    - procedures to be adopted to minimise the effect of trafficking by vehicles
    - procedures to minimise wrinkles and bridging
    - procedures to deal with damages and defects
    - methods of placement of the leachate collection layer.
15. Inspection activities. Describe how the following will be taken into account:
    - skill of the installation crew
    - supervision of installation
    - inspection and approval of the jointing
    - weather and temperature conditions during geotextile deployment and jointing
    - inspection of the surface of the geotextile
    - presence of wrinkles
    - presence of damages and defects
    - action on damages
    - repair methods
    - control of panel uplift by wind.
16. CQC/CQA plan. minimum Requirements for the Installation of geotextile protection layers

F.4 Minimum requirements for the installation of geotextile protection layers

Engineering assumptions regarding geotextile performance rely on its robustness being maintained throughout the construction process. It is important to handle, store and install the material properly in order to ensure its longevity and to provide effective protection to the geomembrane.

Note: As indicated earlier, this document is neither a prescriptive document nor a set of specifications. It is aimed only at providing a set of minimum requirements and guidance notes in designing geotextile protection layers for landfill engineering purposes. The onus is on the engineer of record to ensure that design and installation of geotextiles meet the EPA Victoria required levels of environmental protection.

F4.1 Transportation, handling and storage

The geotextile rolls shall be delivered to the site, handled and stored in such manner that no damage occurs to the geotextile or its protective wrapping. The geotextile rolls shall be wrapped with weatherproof wrapping to protect material from ultraviolet degradation and moisture uptake. In the event that rolls are damaged, the CQA (construction quality assurance) engineer should assess the extent of the damage and consider possible rejection of the damaged rolls.

The geotextile rolls should be stored in a location away from construction traffic but sufficiently close to the active work area to minimise handling. The storage area should be level, dry, well-drained and stable, and should protect the product from precipitation, chemicals, excessive heat, ultraviolet (UV) radiation, standing water, vandalism and animals.

Geotextile roll stacks shall be limited to the height at which installation personnel can safely manoeuvre the handling equipment. The rolls should not be stacked on one another to the extent that deformation of the core occurs. Under no circumstances may the geotextile rolls be dragged, lifted with the forks of a forklift or pushed to the ground from the delivery vehicle.

F4.2 Geotextile installation

In most cases the lining task involves large areas, so it is important to proceed stage by stage in the geotextile installation process. It is suggested that the installation be conducted in the following stages:

17. Installation planning and pre-installation conformance testing.
18. Construction and preparation of the subgrade (i.e. geomembrane).
19. Placement of the geotextile, including transport, unrolling and placing, anchorage.
20. Jointing of the geotextile sheets.
21. Placement of the overlying material.

F4.2.1 Planning and pre-installation conformance testing

The installation process must be preceded by a planning phase, which should result in a detailed panel layout irrespective of the type of application. The layout should specify to scale the arrangement of the geotextile sheets in the area to be lined.

Each roll of geotextile shall be labelled to provide the following identifying data, and the label shall comply with AS3705–2003:

- product name, grade and name of manufacturer
- date of manufacture, batch number, polymer type
- roll number
- roll length
- roll weight
- roll width

Label information shall be affixed or attached to the roll at all times during deployment of the roll.

Manufacturer quality control (MQC) documentation from the manufacturer of the geotextile supplied must be submitted for approval by the CQA engineer. Submissions shall include:

- date of manufacture
- lot number, roll number, length and width
- polymer quality documentation used in the production of the rolls delivered.
- fibre quality documentation used in the production of the rolls delivered
- manufacturer quality control documentation for the particular lots of geotextiles used in the production of the rolls delivered
- QC program laboratory-certified reports
- the manufacturer's approved QA stamp and the technician's signature.

The geotextile should be tested for all critical properties by a third-party accredited independent laboratory before installation.

F4.2.2 Underlying surface

The geotextile shall be placed above the finished geomembrane. The contractor shall ensure that all CQA testing and recording has been fully completed on the geomembrane surface and all independent test results have been received prior to the installation of the geotextile protection material. The geomembrane surface upon which a geotextile will be deployed shall be free of any sharp objects, stones, debris, standing water, or other potentially damaging objects.

The geotextile shall not be installed until inspection of the geomembrane has been undertaken and deemed suitable and in accordance with the specifications by the CQA engineer.

F4.2.3 Placement and jointing

The geotextiles shall be installed such that the sheets are anchored at the crest of the slope and are rolled down side walls/slopes, so as to keep the geotextile free of wrinkles and folds. The sheets should also be continuous across the base or the cover. The arrangement of the geotextile sheets should be according to a predetermined layout plan.

The geotextile shall be deployed by hand or using vehicles on pneumatic tyres with low ground contact pressure to protect the underlying geomembrane. During placement, care must be taken not to entrap (either within or beneath the geotextile) stones, excessive dust or moisture that could damage the geomembrane or hamper subsequent seaming. Jointing between sheets shall be formed by overlapping by a minimum of 150 mm. The areas to be joined shall be clean and free of foreign matters.

Jointing of the sheets shall be conducted by stitching or by heat bonding using an approved hot-air device. The joints shall be continuous along the full join length. On slopes they should be constructed parallel to the slope gradient. In case heat bonding is used, the contractor shall ensure that the bonding method does not pose any risks of damage to the underlying geomembrane. In case of stitching, the thread type must be polymeric with chemical and UV light resultant properties equal or greater than that of the geotextile itself.

The geotextile protection material shall not have cross joints on slopes steeper than 1:5 (V:H).

The entire surface area of each and every roll shall be inspected by the CQA engineer (for example, during unrolling/installation) to ensure that there is no damage or other faults in the material (such as significant and obvious variability in thickness/mass per unit area, tears, holes or presence of broken needles). If damage is identified, it will need to be repaired according to the specifications put in place for the site.

Geotextiles installed on slopes must be fixed in anchor trenches. This is done to secure the geotextile and prevent it from sloughing or slipping down the inside side slopes during construction or service. A normal minimum requirement is that the anchor trench must be at least one meter back from the top edge of the slope. The front edge of the trench is to be rounded to prevent the development of stress concentrations on the geotextile, or any other geosynthetics for that matter.

The geotextile should be laid on the inside wall and base of the trench only, the trench should be cleared of any debris, gravel or loose material before the geotextile is installed. The trench should be backfilled and compacted with low hydraulic-conductivity soils.

If white-coloured geotextiles are used, precautions should be taken to prevent snowblindness of personnel.

It is very important to ensure that the geotextile is not left exposed to ultraviolet (UV) light. It is essential that covering activities be coordinated with geotextile installation. In this respect, all geotextile shall be covered as soon as practical after installation to reduce exposure time to UV radiation.

F4.2.3.1 Backfill placement

Where a drainage layer is placed directly on the geotextile, it should be done so that the geotextile is not shifted from its intended position and underlying materials are not exposed or damaged. Furthermore, deploying the overlying material should not mobilise excess tensile stress in the geotextile.

F4.3 Repairs

If the geotextile has been damaged (by tears, holes or otherwise) during installation, it can be repaired by patching a new piece of geotextile made from the same material. Any soil or other material that may have penetrated the damaged geotextile shall first be removed before any repair could be conducted.

On slopes, the patch shall be double-seamed into place with the seams 5 mm to 20 mm apart. Elsewhere a patch shall be spot-seamed in place with a minimum of 300 mm overlap in all directions.

F.5 Quality

F5.1 Manufacturing specifications and quality control

The quality of the geotextile shall be in accordance with the requirements of the Geosynthetic Research Institute (GRI) – GT12(b) or GT12 (a). The minimum specifications for quality geotextile products are contained in GRI Test Method GT12(b)/GT12(a), the standard specification for ‘Test methods and properties for nonwoven geotextiles used as protection (or cushioning) materials’.

These specifications were developed by the Geosynthetic Research Institute (GRI) with the cooperation of geotextile manufacturers. The specifications set forth a set of minimum physical and mechanical properties that must be met or exceeded by the geotextile being manufactured.

Note: Currently there are no Australian manufacturing specifications; in this respect GRI GT12(b)/GT12(a) represents best practice. However, it should be stressed that the GRI requirements represent a minimum. Higher requirements may be necessary in certain applications and the onus is on the engineer of record to establish whether higher requirements are necessary and to specify according to the particular engineering requirements. Always refer to the latest version of this specification.

A statement on the origin of the fibres and polymer must be included, as well as certified copies of the quality control certificates issued by the fibre suppliers and polymer manufacturers, as well as reports on the tests conducted by the manufacturer to verify the quality of the fibres and polymers used to manufacture the geotextile rolls assigned to the project. The geotextile must also have been through a quality control (QC) program including processes put in place to detect and remove broken needles.

The manufacturer's geotextile QC program should be available for auditing. The manufacturer should also provide a written certification that the geotextile conforms to the material requirements for the project.

F5.2 Construction quality control (CQC)

Installation of the geotextile must be undertaken by geotextile installers with extensive installation experience and competence with the specified geotextile. In the case of installation of multi-component liners composite, they shall provide sufficient evidence of installation experience and competence with other geosynthetics. In either case, they must provide experience records prior to any installation.

F5.3 Third-party CQA consultant

Construction quality assurance (CQA) is defined as a planned system of activities that provide assurance that the geotextile was fabricated and installed as specified in the design. It is an important factor in ensuring that design and installation of the geotextile are done in accordance with the standards and specifications agreed with EPA.

For this purpose, an independent third-party CQA consultant with experience with geotextile and knowledgeable of geotextile characteristics and other geosynthetics must be appointed to verify that the works have been carried out to the agreed standards. The duties of the third-party CQA consultant include inspections, verifications, audits and evaluation of materials and workmanship, provision of advice on installation, testing, repair and covering of the geotextile protection, and issuing a final CQA report documenting the quality of the constructed facility.

F5.4 CQA plan

A CQA plan shall be submitted to EPA prior to the geotextile installation. The CQA plan needs to provide procedures for identifying nonconformance and for corrective action. The plan should cover the following:

- the nature of the nonconformance and its level of effect on the project
- determination whether the nonconformance is an isolated incident or a recurring problem
- how amendments to procedures to prevent future occurrences of the nonconformance will be implemented
- the nature of corrective action to be applied to rectify that specific nonconformance
- the procedures and persons to be notified of the non-conformance and corrective measures
- procedures for reporting to EPA major exceptions or variations to the approved technical specifications.

It should at a minimum include the following information for each geotextile product proposed:

1. Definitions to be used throughout the project to avoid confusion on acronyms and wording.
2. Descriptions of responsibilities, qualifications and obligations for each party involved in the CQA plan.
3. The lines of communication and authority for the project. Identify and define the process for addressing request for information, design modifications or changes in the project specifications.
4. A formal process on handling deficiencies that defines responsibilities and the minimum documentation required to correct deficiencies.
5. A project meeting schedule.
6. The proposed level of supervision and quality control.
7. Verification process and review of the quality control certificates of the geotextile manufacturers, the fibre suppliers and the polymer manufacturers, with a list of characteristics of the material.
8. Verification process and review of the property values certified by the geotextile manufacturer.
9. Verification process that the measurements of properties by the manufacturer are properly documented, test methods are acceptable and sampling procedure detailed, and verification that the polymer, fibres and geotextile meet the project specifications.
10. Verification process and review of the quality control certificates of the geotextile rolls assigned to the project (note: need to agree with manufacturer on the frequency of the tests).
11. Details of the delivery, handling and storage of the geotextile on site prior to installation.
12. Verification process of the geotextile handling equipment and restraining methods used on the site.
13. Rejection criteria for the geotextile rolls.
14. Details of the installation staff's accreditations and verification of their experience.

15. Details of the conformance tests the CQA consultant will undertake on the geotextile rolls delivered to site. Any laboratory tests must be performed at an accredited, independent, third-party laboratory.
16. Details of actions to take if geotextile fails conformance tests.
17. Approval procedure of the underlying geomembrane and anchor trench, including details of testing.
18. Establishment of a field geotextile panel identification.
19. Details of installation and jointing techniques.
20. Details of actions to take to ensure that field panels and jointing orientation are as indicated in the layout plan.
21. Procedure for inspecting, testing and sampling joints, if appropriate.
22. Measures to take to protect the geotextile if inclement weather occurs during installation.
23. Procedure for sampling and evaluation.
24. Procedures for inspecting jointing preparation.
25. Details of actions to take in case defects and/or damage to the surface of the laid geotextile are identified, and corrective measures.
26. Details of actions to take to minimise geotextile wrinkles and bridging.
27. CQA consultant daily recordkeeping. The daily log should contain the following:
    - weather and site conditions
    - records of the delivery, handling and storage
    - quality of underlying geomembrane
    - description of any material received at the site, including quality control data provided by suppliers
    - location of daily construction activities and progress
    - conformance to panel layout design
    - recording of installation activities, consisting of panel placement, roll numbers, overlap locations, repairs and testing results for all works
    - records (including photos) of the geotextile at the time that cover soil is placed over the geotextile
    - photographs of construction works and any items of specific interest. The captions of all photographs should contain the name of the project, the date on which the photograph was taken and the identity of the feature being photographed
    - type of equipment used in each work task (e.g. handling equipment)
    - testing conducted and test methods used
    - remedial action on geotextile defects or jointing defects
    - placement of temporary protection to installed geotextile
    - record of any material or workmanship that does not meet specified designs and corrective actions taken to remediate the problem
    - details of site visits
    - summaries of any meetings held and action taken
    - signature of CQA engineer.
28. Periodic acceptance reports summarising daily reports.
29. The contractor shall provide the CQA authority the following listed test certificates and records prior to, during and at the completion of the works as each report and record is required:
    - certification and test results of geotextiles, fibres and polymer used in the production of the rolls
    - roll test data reports, for each roll of material
    - completed as-built drawing, including roll numbers, panel layout, overlap locations and repair locations.

Any deviations from the approved CQA plan must be noted and explained, and approved by EPA and the EPA-appointed auditor.

F5.5 Conformance testing

Table F1 provides guidance on the test properties and recommended minimum testing frequencies. Higher testing frequencies might be required in certain applications (need to identify the importance of the geotextile for the safety of the works, construction and stability included). The onus is on the engineer of record to establish whether higher requirements are more appropriate.

F5.6 CQA report

A CQA report must be prepared by the CQA consultant to demonstrate that all requirements of the project specifications and CQA plan have been complied with.

Table F1: Guidance on CQA testing for nonwoven geotextile protection material

Item	Property	Standards	Frequency
Conformance testing (upon shipment of geotextile to the site)	Thickness Mass per unit area	AS 2001–2.15 AS 2001–2.13	1 sample per 2,500 m^2 1 sample per 2,500 m^2
	Tensile strength Tear strength Burst strength Puncture resistance of geotextile	AS 3706–2 AS 3706–3 AS 3706–4 AS 3706–5	1 sample per 5000 m^2 1 sample per 5000 m^2 1 sample per 5000 m^2 1 sample per 5000 m^2
Destructive tests	Tensile tests for joints.	AS 3706–6	As required.
Visual inspection of geotextile	Colour, thickness, tears, holes, punctures, needle-punching, presence of needles or broken needles, and other faults in the material.		Each roll during placement.
Thickness of geotextile	On-site.		Each roll during placement. If thickness appears to be variable a check of the variability of the mass per unit area should be conducted.

Note:

All conformance tests must be reviewed, accepted and reported by a CQA consultant before deployment of the geotextile cushion material.

All testing must be performed on samples taken from the geotextile delivered to site under the CQA consultant's supervision.

All laboratory tests must be performed in an accredited, independent, third-party laboratory.

The required testing frequencies may be revised by the CQA consultant to conform with improvements in testing methods and/or in the state-of-the-art practice and/or to account for the criticality of the application (i.e to account for the importance of the geotextile for the safety of works). Revisions must be approved by the relevant authorities before application.

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F.7 Addendum A (standard test methods)

A list of commonly Australian Standards, ISO and GRI test specifications used in geotextile cushion design is given below for guidance. This list is not exhaustive; onus is on the project engineer, CQA consultant, contractor and environmental authority to establish the list of standards needed for a given project.

F7.1 Australian Standards

- AS 2001–2.13: *Determination of mass per unit area and mass per unit length of fabrics.* Standards Australia.
- AS 2001–2.15: *Determination of thickness of textile fabrics.* Standards Australia
- AS 3705: *Geotextiles – Identification, marking and general data.* Standards Australia.
- AS 3706–1: *General requirements, sampling, conditioning, basic physical properties and statistical analysis.* Standards Australia
- AS 3706–2: *Determination of tensile properties-Wide strip method burst strength.* Standards Australia.
- AS 3706–3*: Determination of tearing strength-trapezoidal method.* Standards Australia.
- AS 3706–4: *Determination of burst strength – California bearing ratio (CBR) – Plunger method.* Standards Australia.
- AS 3706–5*: Determination of puncture resistance – Drop cone method.* Standards Australia.
- AS 3706–6: *Determination of seam strength*. Standards Australia.

F7.2 International Organization for Standardization (ISO)

- BS EN 13719:2002, *Geotextile and geotextile-related products. Determination of the long term protection efficiency of geotextiles in contact with geosynthetic barriers,* ISBN: 0 580 40575–3.

F7.3 Geosynthetic Research Institute (GRI) test methods specifications

- GRI Test Method GT12 (b). ISO version. *Standard specification for test methods and properties for nonwoven geotextiles used as protection (or cushioning) materials.* Revision 1: 8 February 2008, Geosynthetic Research Institute, Folsom, Pa., USA.
- GRI Test Method GT12 (b). ASTM version. *Standard specification for test methods and properties for nonwoven geotextiles used as protection (or cushioning) materials.* Original: 18 February 2002, Geosynthetic Research Institute, Folsom, PA, USA.