ANZECC

GUIDELINES FOR THE ASSESSMENT OF ON-SITE CONTAINMENT OF CONTAMINATED SOIL

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AUSTRALIAN AND NEW ZEALAND
ENVIRONMENT AND CONSERVATION COUNCIL

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LIST OF ABBREVIATIONS

ANZECC - Australia and New Zealand Environment and Conservation Council
BC - British Columbia (Canada)
BTEX - Benzene, toluene, ethylbenzene and xylene
CL - clay, low plasticity
CH - clay, high to medium plasticity
CQA - construction quality assurance
GC - clayey gravel
GCL - geosynthetic clay liner
GM - silty gravel
GP - poorly graded (one size, uniform) gravel
GW - well graded gravel

Ksat - coefficient of hydraulic conductivity
MEK - methyl ethyl ketone
mg/kg - milligrams per kilogram
MH silt, high plasticity

ML - silt, low plasticity

MWLP - meteoric water leachate procedure

NEHF - National Environmental Health Forum
OC - organochlorine (pesticides)

OL - organic soils, high plasticity
PAH - polycyclic aromatic hydrocarbons
PCB - polychlorinated biphenyl
PCP - pentachlorophenol
SC - clayey sand
SM - silty sand
SP - poorly graded (uniform) sand
SPLP - synthetic precipitation leachate procedurre
SW - well graded sand
TCLP - toxicity characteristic leachate procedure
UDL - unsaturated drainage layer
USEPA - United States Environmental Protection Agency

GLOSSARY OF TERMS

Adsorption - to retain by chemical interaction at the surface of a solid. (Contrast with absorption - to physically retain within a porous matrix.)

Aquifer - a saturated geologic unit which is sufficiently permeable to transmit significant quantities of water under normal hydraulic gradients.

Attenuation - the effect of reducing contaminant concentration through a combination of physical and chemical interactions, including sorption and dispersion.

Bentonite - a type of clay mineral with a high capacity for retaining positively charged chemical species. Typically found in "expansive" or "reactive" clays.

Bioaccumulation - the property of being stored in biological tissue, rather than being progressively metabolised or excreted.

Capillary break cover - a combination of fine grained soil layer over a coarser soil layer, used for temporary containment of precipitation above a waste storage cell.

Carcinogenic - cancer causing.

Composite liner - describes two liners in intimate contact with each other (eg, a geomembrane placed on top of a clay liner)

Diffusion - spreading of contaminants in response to very short range concentration gradients, rather than by movement of the water in which they are dissolved or mixed.

Double liner - describes two liners separated by a permeable drainage layer (eg, a geosynthetic clay liner above a geodrain, above a clay liner).

Geosynthetic clay barrier - a man-made barrier typically comprising a layer of bentonite sandwiched between two layers of geotextile.

Geotextile - a permeable man-made fabric commonly made of polypropylene or other inert polymers.

Hydraulic conductivity - a coefficient used to describe the ease with which water can move through a saturated porous medium (commonly expressed in metres per second or metres per day). Loosely referred to as "permeability".

In-gradient containment - a method of limiting contaminant migration by actively controlling hydraulic gradients near the waste cell so that flow of groundwater or leachate is inwards towards the centre of the cell.

Monofill - a cell or repository used for the disposal or storage of a single type of waste (eg contaminated soil).

Monolayer cover - a fine grained soil layer used for temporary storage of precipitation above a waste storage cell.

Organoleptic - having the property of being readily detected by taste or odour at very low concentrations (eg, hydrogen sulphide).

Phytotoxic - toxic to plants.

GLOSSARY OF TERMS (Continued)

Resistive barrier - a layer which controls contaminant movement through its low physical permeability.

Reactive barrier - a layer which controls contaminant movement by chemically reacting with the contaminant species (causing neutralisation, precipitation, etc).

Sesquioxide - descriptive of a group of iron or aluminium compounds, common in highly weathered clay soils, with a relatively high capacity for retention of negatively charged chemical species.

1. INTRODUCTION

These guidelines have been prepared to assist governments, industry, developers and consultants considering on-site containment options for sites affected by contaminated soils. The guidelines are intended to complement existing environmental policy documents on the general issue of waste management. They differ to existing waste guideline documents in several particulars:

- They are concerned with a single type of waste: contaminated soil. The guidelines are not applicable to process wastes, effluents, municipal rubbish, demolition debris, etc.

- The guidelines are only applicable in cases where the contaminated soil originates from the same site at which the waste is to be disposed. The guidelines are not intended for landfills receiving wastes from other sites.

The guidelines describe general environmental protection objectives and approaches to contaminated soil containment to support those objectives. However the information presented in these guidelines is not intended to take the place of detailed; site specific design for actual waste containment facilities. The general aims of the approaches described in these guidelines for on-site containment are:

- to protect environmental quality and amenity and to protect public health
- to promote appropriate and consistent environmental exposure standards
- to minimise the amount of waste being disposed of unnecessarily in public landfills.

In preparing these guidelines, it has been necessary to review a wide body of technical information and numerous environmental legislation and policy documents. The principal sources of information considered were:

- Australian and overseas documents concerning waste classification systems
- Australian and overseas documents concerning the degree and nature of hazards posed by different types of contaminated soil
- Australian and overseas documents concerning the location, design, construction, operation and closure of waste disposal facilities
- recent technical literature on engineering aspects of containment systems, including the properties and environmental performance of various geotextiles.

References to sources of more detailed information are provided throughout the body of these guidelines, and listed in a bibliography at the end of this document.

2. LEGISLATIVE CONTEXT

Section 2 Summary

In Australia, regulations governing the approval of on-site containment for the remediation of contaminated soil is generally controlled by individual State environmental protection authorities. To date, regulations for on-site soil containment have not been prescriptive, although the design and siting of such facilities must be demonstrated to comply with environmental objectives described in States' policy documents.

In Australia, waste classification and development of waste management policies are usually carried out by the state environmental regulatory body. This same body is generally the authority responsible for licensing of waste transport, approval of waste disposal facilities and for the review and approval of specific landfill proposals.

State environmental regulatory bodies also act as the lead agencies in reviewing and/or approving contaminated land management proposals (sometimes in consultation with the state health authority). In most states, different sections of the state environmental agency deal with waste disposal and contaminated land management, which has sometimes complicated the process for administering projects involving the disposal of contaminated soil.

Local government authorities and state planning authorities typically participate in regulation of wastes (including contaminated soil) through their role in defining land use zones. In most states, local municipalities also operate some landfill disposal facilities.

In contrast to the well-established regulatory framework for regulation of landfills and other waste disposal facilities, the regulation of remedial works effected for the purpose of managing contaminated sites is not dealt with by a formal assessment procedure in all states. Some states, such as Queensland, have implemented a process whereby the use of burial or containment as a remedial option must be formally justified before gaining Department of Environment approval. In other states, such as Western Australia, a formal environmental impact assessment may be required for remedial works. However, in many jurisdictions the review, assessment and approval of remedial works are carried out on an *ad hoc*, case-by-case basis (particularly in the case of smaller scale site clean-ups).

Appendix A of these guidelines presents an overview of the regulatory and administrative arrangements currently in place in Australia for managing contaminated soils, with particular reference to management options which involve on-site containment of the soils. Details of relevant states legislation and policy documents are also provided in Appendix A.

3. SITE SELECTION

Section 3 Summary

Site characteristics and surroundings exert a major influence on the potential long-term environmental impact of on-site waste containment facilities. For this reason, careful site investigation is at least as important, if not more important, than the selection and design of engineered components of a containment system. Assessments of sites nominated for use as on-site containment facilities must address:

- *Set backs, exclusion zones and buffer zones to protect and accommodate surrounding land uses and environmental values*
- *Topography and surface characteristics*
- *Subsurface conditions*

3.1 General Principles

The decision to employ on-site containment as the remedial method of choice on any given site involves a decision process which differs fundamentally from the decision process used for selecting new landfill sites. The obvious difference between the two decision processes is that in the case of on-site containment of contaminated soils, the site under consideration is already, by definition, affected by contamination. This will in some circumstances result in a decision to retain contaminated soil on site at a location which would not normally be considered as highly suitable for landfilling. For example, in cases where excavation of the soil at a site located in a residential neighbourhood will result in serious health risks to surrounding land occupiers, it may be necessary to consider containment options. In other cases, there may be no landfill available to accommodate the quantity of material requiring remediation, without seriously compromising the management of other waste streams. Thus, the decision process for choosing on-site containment involves optimising some risk factors which would typically not exist at a "greenfields" site being considered for development as a landfill.

In determining suitability of a site for on-site containment of contaminated soil the following principles should be considered.

Principle 1. *In considering whether to employ on-site containment as a means of managing contaminated soil the primary objective of the decision making process must be to protect the health and safety of human and environmental receptors.*

Both short term and long term impacts of alternative management options must be considered. Short term risks include exposure of workers and neighbours during remedial activities. Short term risks to the environment include the effects of accidental or deliberate transfer of contaminants between environmental compartments. The degree of uncertainty associated with any given management strategy or remedial process should be taken into account when comparing alternative approaches.

The Australia and New Zealand Environment and Conservation Council have recommended a hierarchy of remedial approaches for managing contaminated soils. In the ANZECC hierarchy, on-site containment is generally regarded as a less desirable remedial solution than options involving treatment of the contaminated soil. The preference for options involving treatment does not mean that treatment options are necessarily "safer" than are containment options. The preference for treatment options arises from two general principles of resource management:

Principle 2. *Remedial options should minimise the need for on-going management and regulatory scrutiny of the site.*

Principle 3. *Remedial options should minimise constraints on reasonable and usual use of the land.*

In seeking to adopt the ANZECC hierarchy of site remediation approaches, many municipalities and waste authorities have been faced with the difficulty of deciding whether the soil wastes can justifiably be allocated an increasing proportion of valuable land fill space. It is important to recognise and address this potential tension between local (site) impacts and more global (community) impacts early in the decision-making process when reviewing possible remedial options.

Principle 4. *The preferred remedial strategy should support the best use of available waste treatment and disposal facilities (and other public resources) while providing an agreed, appropriate level of safety and environmental protection.*

The four principles listed above should be included in any assessment of a proposal for on-site containment of contaminated soil. Other factors influencing the choice of on-site containment as a remedial approach include the time required to implement the remedial measures, the cost to implement and operate the remedial system, and the acceptance by other stakeholders of the remedial strategy (public perception). Public perception issues in particular are diverse and difficult to deal with except on a case-by-case basis. They may include aesthetic concerns, concerns surrounding liability of future site occupiers, perceived risks to local amenity, health or to the environment, concerns for impact on property values at the site or surrounding the site, cultural responses to "polluted" land, etc.

3.2 Assessing Site Suitability for On-site Containment

However sophisticated the engineered components of an on-site containment system, they must be regarded as a secondary system, which supplements the natural containment of contaminants afforded by site topography and subsurface conditions. In the long term, and in the case of unexpected failures in management systems or physical controls, the site characteristics will determine the likelihood of an adverse impact on safety or the environment. Therefore, a detailed appraisal of site conditions is at least as important, if not more important, than the design of engineered containment system components. Hydrogeological and geotechnical assessment is required for any site proposed for containment of contaminated soil. Often this is performed as part of the contamination assessment and remedial design.

3.2.1 Setbacks and Surrounding Land Uses

Set backs, buffer distances and exclusion zones between the containment structure and existing natural or built features may serve three purposes:

- The set back protects the containment structure from mechanical damage or other disturbance by outside agents, for example encroachment of flood waters from a nearby watercourse.

- The buffer zone provides a volume of soil which may serve to attenuate, disperse or temporarily store contaminants accidentally released from the containment facility.

- An exclusion zone serves to prevent coexistence of two land uses which are considered fundamentally incompatible, or which would require excessive engineering and management effort to ensure mutually compatible and safe conditions at a site.

Set backs

It is a matter of common sense that containment structures should not be built in areas susceptible to flooding, landslip, or excessive erosion, particularly if other more suitable disposal sites are available. The actual sensitivity of containment facilities to disturbance by flooding, ground movements or erosion will depend upon the physical and chemical attributes of the waste contained in the system, and the engineering characteristics of the containment system. Certain synthetic liners, for example, are better able to accommodate differential settlements or other ground movements which would cause liners to stretch (refer Section 6). However, the tolerance of commonly available membranes, modified earthen seals and flexible pavements would not usually be sufficient to justify the installation of a containment structure in an area with a high likelihood of wave erosion, landslip, or other disturbance resulting in loss of mechanical support or large scale differential settlements.[1]

Various states have stipulated minimum set backs from a landfill to the 1 in 100 year flood level. Typically the minimum set back is in the order of 100m. For specific containment proposals, the waste soil contaminant characteristics (especially water solubility) should be considered when selecting an appropriate set back from flooding or other high water levels. The susceptibility of the containment system to the mechanical forces imposed by flooding would also have to be taken into account.

Buffer zones

In establishing a waste repository, it is necessary to consider the proximity of the repository to surrounding receptors. "Receptors" may include environmental media used for ecosystem support (soil, air, water), structures, people or other biota. In some cases, intangible components of the environment (such as a culturally significant "sense of place" or "neighbourhood") might also be considered potential receptors. The function of the buffer zone is to protect these potential receptors by absorbing, dispersing, arresting, or screening contaminants in such a way that receptors are not exposed to contaminants above an agreed tolerable exposure level.

The size of the buffer zone must necessarily be linked to its capacity to contain or otherwise attenuate any contaminants of concern. There are many factors which determine the capacity of a volume of soil to contain or attenuate contaminants. They include: soil porosity, clay content, exchange capacity, organic matter content, moisture content at the time that contaminants are introduced, particle size distribution, mineralogy, contaminant physico-chemical characteristics, etc. [Refer additional discussion in Section 3.2.3.]

The size of the buffer zone must also reflect the proposed site monitoring and maintenance systems, and the feasible engineering actions that could be undertaken to respond to loss of containment. For example, the distance from the containment structure to the receptor must, as a minimum, be greater than the greatest likely travel distance of a contaminant of concern over an interval corresponding to the time between monitoring events. In certain cases the size of the buffer zone may depend upon the geographic relationship (eg up-wind or down-wind, up- or down- hydraulic gradient) between the repository (contaminant source) and the potential receptor.

Various states have established generic guidelines on buffer distances (horizontal or vertical) separating landfills from specified natural or built features, such as surface water bodies, seasonal high watertable

[1] There are nonetheless cases of substantial landfill structures being engineered on difficult sites - for example, the Toyon Canyon municipal landfill, which serves the city of Los Angeles is a 36 hectare landfill, with an average waste depth of 88m. It has been built in a seismically active area, and has cover slopes of 1 vertical in 2 horizontal.

levels, residential dwellings, etc. However, a rigorous site specific assessment would involve at least a semi-quantitative analysis of the likely rates and magnitude of contaminant migration in the event of loss of containment, and an assessment of the possible consequences if the contaminant release results in exposure of a given receptor. In the first instance, these assessments should be carried out assuming that both the containment systems and the monitoring systems are ineffective (worst case scenario). A more realistic assessment may then be carried out by conducting a probabilistic analysis of the engineered components of containment system, including estimating the likelihood of various modes of containment failure, assessing the likelihood that monitoring systems will detect a loss of containment, and assessing the feasibility of remedial response in the event of loss of containment

The ultimate choice of buffer distance will depend upon the risk management strategy adopted by the regulatory authority, and by other stakeholders involved in the approvals process.

Exclusion Zones

Virtually all jurisdictions have defined a set of land uses which they consider to be fundamentally incompatible with the establishment of a contaminated waste landfill. Land uses which are considered to warrant special consideration and a high level of protection are treated as exclusion zones within which landfilling activities are prohibited. Many, but not all, exclusion zones are considered incompatible with waste disposal or containment operations because the act of constructing the containment facility could in itself result in unacceptable impact on the protected land use. Typical examples would include areas of special cultural significance, nature reserves, scenic areas, etc.

Water catchment areas and areas underlain by high quality water resources are often treated as exclusion zones because the attainment of the level of certainty required of engineered systems and monitoring systems would be virtually impossible to demonstrate in practice.

In the case of existing contaminated sites discovered in such sensitive areas, it is unlikely that approvals would be granted for the construction of a containment facility except as a temporary management measure.

3.2.2 Topography

Site topography influences at least four aspects of containment system design and performance:

- local slope characteristics may determine the susceptibility of the area to instability
- local relief may influence the choice of containment structure design (for example, below ground or above ground) and degree of engineered containment that must be provided
- local relief will influence the choice of materials used in constructing barrier layers and will determine the relative ease with which barrier layers and other containment system components may be constructed and installed
- position in the landscape may affect the level of engineering effort required to exclude water from the containment structure.

To date, regulatory authorities have generally not been prescriptive concerning siting of containment facilities on sloping terrain, although the draft *Interim Criteria for Major Landfill Depots in South Australia* recommended that "major landfills" should not be sited in areas with ground slopes nominally greater than 10% (1 vertical in 10 horizontal). From a practical perspective it is possible to engineer containment structures, especially those for soil monofills, on substantially steeper slopes. Site specific assessment of slope stability factors must be carried out to determine the maximum safe slope on which a soil monofill may be founded.

Whether located on flat terrain or on sloping ground, the stability of a large waste mass contained within a repository could constitute a risk under certain conditions. However the opportunities for improving the waste mass stability through appropriate waste placement techniques are much greater for soil monofill repositories than would be the case for municipal waste landfills or other containment structures used for mixed waste streams.

On a smaller scale, the slope of the surface and sides of the containment structure will influence the design and maintenance requirements of the repository. Steeper slopes may be necessary to limit the lateral extent of the repository, and are desirable to extent that they help prevent ponding of rainfall or other water impinging on the repository cover layer. However, there are several disadvantages to very steep slopes including increased erosion potential, difficulties in achieving satisfactory compaction of clay capping layers, risk of soil creep or poor adhesion between consecutive layers of synthetic barrier materials, difficulties in maintaining surface vegetation on very steep slopes.

In some jurisdictions (eg, Province of Quebec, Canada) the maximum elevation of contaminated soils contained in the waste repository may not exceed the surface level of the surrounding natural ground.

This effectively means that the finished surface level of the waste repository will be at, or slightly above, the natural surface level of the surrounding ground. This is not generally the case in Australia (ie, mounded repositories are permitted), although there is usually a requirement to take into account local landscapes and to seek to have the final contours of the repository configured so as to blend in sympathetically with the natural topography. From an engineering perspective, it is usual to require a minimum slope of 2% on surface capping and drainage layers, and to allow a maximum side slope of about 1 vertical in 3 horizontal, or other slopes as determined from a site specific stability analysis.

3.2.3 Subsurface Conditions

Subsurface conditions have the potential to influence at least four key aspects of the design and operation of containment systems. These include:

- they determine the level of mechanical support available for the repository structure
- they define a set of environmental receptors (soil and groundwater)
- they determine the nature, rate and magnitude contaminant migration from the repository, in the event of loss of containment
- they influence the contaminant attenuation capacity of any buffer zones.

Mechanical Support of Repository

For substantial soil waste repositories, as for any major engineered structure, the site assessment must include a geotechnical evaluation of the engineering suitability of subsurface conditions for support of the proposed structure. A geotechnical appraisal would typically address issues including the bearing capacity of the subsurface soil or rock, estimates of total and differential settlements, lateral earth pressures, uplift forces due to groundwater (if present), slope angles which may be safety maintained without additional ground support. In certain environments, such as in areas of carbonate sands or limestone, it may be necessary to consider the possibility of loss of mechanical support if loss of containment were to allow migration of acidic leachate, with consequent dissolution of the soil or rock mass. In some situations, small scale loads, such as point loads imposed on liners by rough rocky substrates may also need to be considered.

As a general rule, sites characterised by soft or loose or compressible soils are considered less suitable for the mechanical support of waste repositories than are sites underlain by stiff or very stiff soils or weathered rock.

Although it is possible to construct repositories entirely above ground, it is often cheaper or simpler to satisfy mechanical support requirements by constructing below ground repositories, or above ground repositories which make use of existing relief to provide lateral support (eg, by filling in a natural gully).

Environmental receptors

In considering the suitability of a site for use as an on-site waste soil repository, a key consideration is the potential for loss of containment to have a harmful impact on nearby receptors. Generally, groundwater is viewed as the most sensitive subsurface environmental receptor, although in special cases subsurface soils or rock could suffer harm as a result of loss of containment. (For example, there are cases in which the leakage of acidic wastes has given rise to serious erosion of limestone, with the resulting possibility of damage to nearby building footings supported on the limestone.)

Most Australian states have recommended minimum vertical separation distances between seasonal high groundwater levels and the base of a landfill or waste repository. In a number of states, the minimum separation distance has been linked to water quality and/or aquifer yield characteristics. This amounts to a graded scale of protection of existing or potential beneficial uses. That is, water judged to have high potential as a large scale drinking water supply is protected to a more stringent standard than water which is saline and useful for fewer beneficial uses.

This approach to site selection must be adopted with caution, as it can overlook the role of a groundwater as a transporter of contaminants. That is, while a low yielding, saline water layer may not be considered valuable as an environmental receptor, it may nonetheless serve as an effective conduit for contaminants to other locations, thereby exposing more sensitive receptors (eg, aquatic biota) to the transported contaminants. In some jurisdictions, this issue has been addressed by applying ANZECC water quality criteria for surface waters (ecosystem support) as the default groundwater protection level in areas where water is not suitable for drinking. This is a simple, but perhaps overly conservative method of evaluating the level of containment required to protect environmental receptors. [Refer further discussion in following section headed "Contaminant transport".]

It is generally agreed in Australia that waste containment repositories should not be built in a way that would allow seasonal high water tables to contact the base or sides of the repository. Typical minimum separation distances between the base of the repository and the highest seasonal water table level are in the order of 2m to 5m for a lined waste containment cells. Unlined waste cells would need to be further still from the seasonal high water level, in order to make allowance for a soil buffer zone which would serve to attenuate any contaminants migrating from the waste mass. Contaminated sites with very shallow depths to a seasonal water table would therefore be unlikely to be considered suitable for remedial options involving below ground containment of wastes.[2] Such sites are judged to carry an unacceptably high risk of exposing an environmental receptor (groundwater) to contaminants, in the event of loss of containment. An above ground containment may still be considered possible if appropriate environmental protection measures have been included.

Contaminant transport

Assessment of the suitability of subsurface conditions at a site for establishment of an on-site containment facility requires careful consideration of contaminant transport characteristics of the subsurface soil or rock layers. In most cases, the site assessment involves an evaluation of the potential for transport of contaminants in water, either in solution, as a separate immiscible phase entrained with water, or in association with colloidal particles. In some cases vapour phase transport of contaminants must also be considered (eg some forms of mercury, benzene, MEK, etc). For sites proposed for the construction of soil monofills, it would not normally be necessary to consider subsurface permeability to liquids other than water, as the soil repositories would typically only be used for soils containing levels of liquid contaminants (such as oils or solvents) at a concentration considerably below the residual saturation content of the soil.

The permeability of subsurface materials to water is normally described in terms of the coefficient of hydraulic conductivity, or the Darcy coefficient of permeability, k_{sat}. Subsurface materials with high k_{sat} values are considered less suitable than those with low k_{sat} values. In the event of loss of containment, more permeable soils or rocks will allow more rapid migration of contaminants (particularly in the case of water soluble or highly volatile contaminants). In assessing the potential for contaminant transport through subsurface materials it is particularly important not to overlook the presence of highly permeable layers such as sandy lenses or fractured rock layers, which may make a disproportionate contribution to contaminant transport (relative to the thickness of the layer).

Regulatory bodies occasionally stipulate maximum recommended in-situ k_{sat} values for subsurface soils or rock surrounding waste repositories, sometimes including the requirement that the layer having the specified k_{sat} value be demonstrated to have some minimum thickness. For example, a typical requirement would be that soils surrounding the repository have a maximum hydraulic conductivity of $1x10^{-7}$ m/s, and that this condition should extend to a level no less than 5m below the base of the repository.

[2] In some circumstances, there may be few alternatives to on-site waste containment despite the presence of a relatively shallow water table (eg, where there are no facilities for treating or disposing of the waste, or where the act of disturbing the contaminated soil is judged to be a greater threat to public safety or the environment than the alternative of leaving the material on site). In such cases, the containment system must be designed to minimise the risk of contact between the soil waste and the groundwater. Vertical barriers and/ or active hydraulic control of groundwater flow directions may be used for this purpose (refer Section 6.7).

The test conditions under which soil or rock permeability testing are carried out must be clearly specified, as the representativeness of the test result is very sensitive to test methods, and can vary by one or more orders of magnitude depending upon the method of testing adopted.

Contaminant Attenuation

Sites characterised by cohesive (clayey) soils are commonly regarded as more suitable for siting of on-site containment facilities than are sites underlain by granular (sandy or gravelly) soil or by rock. The preference for cohesive soils relates in part to ease of construction considerations, and to the potential for contaminant transport through subsurface media. It also relates to the ability of subsurface materials to physically filter or to chemically interact with and retain contaminants.

For many positively charged inorganics, especially metallic contaminants, cohesive soils offer decided advantages over sandy soils because of the ability of clay minerals to chemically bond to the contaminant species. This is also the case for certain negatively charged inorganics, such as phosphate, and certain types of clay (those with a high sesquioxide content).

In most cases, chemical retention of organic contaminants is more dependent upon the organic matter content of the soil, rather than on soil clay content. Pore size distribution, soil particle surface area and initial saturated porosity of soils exert a strong influence on the quantity of organic contaminant (especially non-polar organic content) that will be retained at residual saturation in an undisturbed soil mass (Initially wet soils will tend to retain less chemical than initially dry ones.) In general clayey soils and fine sands are able to retain a larger mass of organic contaminant per volume of soil than are coarse sands or sand/gravel mixtures.

Although it is generally true that clayey soils offer greater ability to sorb or temporarily retain contaminants than do granular soils, the magnitude of the difference in attenuation capacity will depend very much upon contaminant chemistry and soil mineralogy. For example, the level of retention of certain negatively charged inorganic contaminants such as nitrate or chloride is relatively low in both sands and clays, although the rate of transport will naturally be much faster in sandy soils.

Subsurface conditions comprising predominantly rock materials are considered to offer little capacity for contaminant attenuation. This is related to the low surface area per mass of material, the low surface charge of the rock material (relative to a clay mineral), and to the (usually) low organic content of the rock mass. In some cases rock masses may have sufficient porosity or vesicularity to retain relatively large quantities of organic contaminants. This characteristic of rock materials makes them particularly difficult to manage in cases where they become contaminated and begin to act as secondary sources of contamination.

As a general rule of thumb, the order of preference for subsurface conditions relating to the capacity of soils or rock to retain or attenuate contaminants is as follows:

Highest attenuation capacity

↓	Medium to high plasticity clays and silts (CH, OH)
↓	Medium plasticity clays with high sesquioxide content (CL/CH)
↓	Low plasticity clays and inorganic silts (CL, MH)
↓	Highly organic sands or silts or silty/clayey sands (OL, SC, SM)
↓	Sands and low plasticity inorganic silts (SW, SP, SM, ML)
↓	Sand/gravel mixtures (GC, GM, GW, GP)
↓	Fractured, relatively unweathered rock

Lowest attenuation capacity

(Letters in parentheses refer to soil designations in accordance with the Australian Standard for Geotechnical Site Investigations, AS 1726 - 1993).

4. ENVIRONMENTAL BEHAVIOUR OF CONTAMINANTS

Section 4 Summary

Effective containment of soil affected by chemical contaminants requires an understanding of the environmental behaviour of the contaminants. The key contaminant attributes which influence the environmental fate of contaminants are:

- *Physical characteristics (particle size, viscosity, etc)*
- *Water solubility*
- *Volatility*
- *Chemical persistance*
- *Affinity for organic matter (including fats)*

The issue of waste characteristics is central to the design of an appropriate containment system. Two important considerations in the construction of on-site soil waste monofills are "What is the maximum level of contamination permissible in soils placed in the monofill?", "What environmental behaviours do the contaminants in the waste soil exhibit?" In preparing this guideline document, it has been assumed that the system allowing on-site containment of some soil wastes should not extend to soils which present levels of risk normally associated with "hazardous" or "intractable" process wastes. Neither should the levels of liquid contaminants in the soils be so high that they cannot be held at residual saturation in the soil pore space. Soils affected by radioactive or biomedical contamination were also excluded from the on-site containment system.

An overview of existing waste classification systems currently applied to contaminated soil proposed for landfill disposal is presented in Appendix B. Tables A1 and A2 (in Appendix A) present a summary comparison of various Australian and North American soil waste classification criteria.

It is not within the scope of this document to reconcile the soil waste classification systems currently in use in each state. However, for the purpose of designing on-site containment systems, it is helpful to have a systematic framework which relates containment requirements to waste characteristics (potential hazards and environmental behaviours) of broad classes of chemical contaminants.

Preliminary assessment of contaminated soil containment requirements, is facilitated by describing the soil waste in terms of a simple classification system comprising ten main classes of contaminants. Table 1 presents a summary of the contaminant groupings. The groupings have been delineated on the basis of physical and chemical contaminant characteristics which affect the environmental behaviour of the contaminants. To some degree, the waste groupings are also characterised by type of hazard (for example, many Group 3 contaminants are carcinogenic; many Group 9 and Group 10 contaminants have a high potential for bioaccumulation). Additional description of the contaminant groupings is presented in Appendix C. These groupings can be used to provide an indication of the waste characteristics and hence the form of containment that may be suitable for isolating and confining the waste.

The groupings suggested for the purpose of identifying required containment system components do not generally rely on laboratory estimates of "environmental leachability". Leachability testing may be required to provide a basis for assessment of potential environmental impacts.

In the case of inorganic contaminants, there is little option but to make some use of leaching tests, as a means of estimating the environmental behaviour of the contaminant (and the resulting containment requirements). This is because usual laboratory analytical methods for many inorganic contaminants do not provide sufficient information on the form of the chemical to allow solubilities to be predicted. For example, lead sulphate (PbSO4), is about forty times more soluble than lead carbonate (PbCO3), but about two hundred times less soluble than lead chloride ($PbCl_2$). Lead oxide (Pb_3O_4) is essentially insoluble in water. Determinations of total lead content of a contaminated soil sample do not specify which species of lead is present in the soil.

Although most existing waste classification systems make use of the Toxicity Characteristic Leachate Procedure, other procedures may be more relevant and appropriate when assessing dedicated soil waste monofills. For example, USEPA method SW846-1312, the "synthetic precipitation leaching procedure" uses an unbuffered dilute mixed inorganic acid extractant (sulphuric and nitric acid solution at approximately pH 5) to mimic the effect of rainfall percolating through waste soil. The method technique is essentially identical to the TCLP test, but does not used an organic acid. The use of an organic acid would be more appropriate in cases where co-disposal of soil waste and municipal rubbish is proposed.

TABLE 1
CONTAMINANT GROUPS - LINKAGE TO HAZARDS AND EXPOSURE ROUTES

CONTAMINANT GROUP	Description	Examples	HUMAN HEALTH	Toxic/Carcinogenic by Inhalation of Vapour	Toxic/Carcinogenic by Ingestion of soil	Toxic/Carcinogenic by Ingestion of Water	Toxic/Carcinogenic Irritant by Dermal Contact	ENVIRONMENTAL	Toxic to Plants or Soil Invertebrates	Impairs Microbial Function	Toxic to Terrestrial Vertebrates	Toxic to Aquatic Biota	Bioaccumulation	Other/Comment
1	High solubility inorganics	Ammonia, copper sulphate		**	***	***	**		**	**	**	***	**	Bioaccumulation is of concern only for selected inorganics.
2	Low solubility inorganics	Metallic lead		*	***	**	*		*	*	***	*	**	
3	Halogenated organics (volatile)	Trichloroethane, chloroform, chlorobenzene		***	**	***	**		***	***	**	***	*	
4	Halogenated organics (non-volatile, moderately to highly soluble	p-chlorophenol, pentachlorophenol		**	**	**	**		***	**	**	***	*	
5	Halogenated organics (non-volatile), low solubility	PCB, DDT		*	***	**	***		***	**	**	**	***	
6	Highly soluble, volatile non-halogenated organics	Benzene, MEK		***	**	***	*		**	**	**	**	*	
7	Moderately soluble, volatile non-halogenated organics	Hexane, toluene, xylene		***	**	**	*		**	**	**	***	*	Organoleptics may affect environmental amenity.
8	Highly soluble, non-volatile non-halogenated organics	Phenol		**	**	**	**		**	**	**	***	*	
9	Moderately soluble, non-volatile non-halogenated organics	Naphthalene, dinitrotoluene		**	**	**	**		**	**	**	**	***	
10	Low solubility, non-volatile non-halogenated organics	Benzo(a)pyrene		**	***	**	**		**	**	***	**	***	

*** Main driver ** Secondary exposure * Low risk exposure

TABLE 1 NOTES
(page1 of 1)

1. Inorganic contaminants can be classified as "high solubility" or "low solubility" on the basis of the result of a standard leaching test (MWLP or SPLP, USEPA SW-846 method 1312; TCLP may also be used, but is less relevant to soil monofills). The default classification in cases where no leachate testing has been performed is Class 1.

2. "Highly soluble" organics are defined as those compounds with an aqueous solubility at 20°C equal to or greater than 1000 mg/L. "Moderately soluble" organics are defined as those having an aqueous solubility greater than 10 mg/L but less than 1000 mg/L at 20°C. "Low solubility" organics are those having an aqueous solubility equal to or less than 10 mg/L at 20°C.

3. "Volatile" organics are defined as those compounds exhibiting at vapour pressure equal to or greater than 5mm mercury at 20°C.

5. CONTAINMENT OBJECTIVES

Section 5 Summary

The minimum functional components of a contaminated soil containment facility must be determined on a case-by-case basis. The design of any given soil containment facility must take into account:

- *Waste characteristics (hazardous properties, environmental behaviour, contaminant concentration)*
- *Potential exposure pathways (based upon a site investigation)*
- *Potential receptors (based upon a site investigation)*

5.1 General

The containment technologies selected for an on-site disposal facility depend upon a number of factors (ease and cost of implementation, level of on-going management required, etc.). The principal factor to be considered in selecting a containment technology is the containment objective. The containment objective must relate to the type and degree of hazard potentially associated with the waste type. For example, if the waste is a volatile chemical with the potential to cause cancer when inhaled, a key containment objective is to control the release of soil gas to atmosphere. It may equally be necessary to control the subsurface migration of soil gases.

Implementation of risk control by means of containment typically requires the identification of

- Exposure pathways
- Hazardous properties of the waste
- Potential receptors

5.2 Link Between Waste Group and Hazard Exposure

Section 4 outlined a framework for describing soil contaminants by allocating them to one of ten main groupings, defined on the basis of environmental behaviours. The environmental behaviour of a contaminant (especially its volatility, water solubility and affinity for fats or other organic matter) will determine which exposure pathways are potentially of concern. These exposure pathways will in turn dictate the containment requirements applicable to the waste on a particular site.

To some extent, the contaminants within each of the groupings shown in Table 1 also share certain hazard characteristics. For example, virtually all of the Group 3 contaminants listed in Table 1 are suspected or confirmed carcinogens (by inhalation). Table 1 also provides an overview of the hazards associated with each of the contaminant groupings with an indication of major risk drivers, secondary drivers and low risk exposures. As an example, Group 6 contaminants, such as benzene, are predominantly toxic or carcinogenic by an inhalation exposure route. Because they are also highly water soluble, they may also be harmful if ingested in drinking water, or through indirect inhalation of water vapour during showering, etc. The relative contribution of dermal exposure to overall risk presented by benzene contaminated soil is low to negligible in most circumstances.

Table 1 is divided into two main receptor classes: human receptors and environmental receptors. Under "environmental receptors" there are three examples of receptors directly affected by soil contamination, and two examples of receptors which are indirectly affected by soil contamination. The "direct" environmental receptors are

- plants or animals which may be harmed through contact with or uptake of contaminated soil
- microbiological systems which may be disrupted or impaired in the presence of soil contaminants
- terrestrial vertebrates (such as birds or grazing animals) which may be harmed through ingestion of soil.

The "indirect" receptors include

- aquatic biota which may be harmed by contaminants leached out of the contaminated soil and transferred to surface waters
- animals at higher trophic levels in a food chain which may be harmed by the ingestion of plants or animals which have bioaccumulated, and possibly bioconcentrated, soil contaminants.

5.3 Link Between Containment Function and Hazard Exposure

The linkage between containment system functional components and hazard exposures is readily apparent. Volatile contaminants which are harmful when inhaled may require a containment system incorporating the capacity to collect gases and to direct them to an appropriate treatment or discharge point. Repositories proposed to hold contaminants which are toxic by ingestion of water or by contact with water, or which otherwise have the potential for environmental harm when present in water (eg aesthetic impacts such as foaming or discolouration) must incorporate provisions for excluding rainfall, surface water and groundwater from the contained waste soil mass. The repository would normally also incorporate functional elements for controlling the movement of leachate. Contaminants which are principally of concern only when ingested by humans may only require containment which provides for elimination or control of dust which may settle and be ingested, and for physical separation between human receptors and the soil waste. An example of containment satisfying this functional requirement is the placement of a surface pavement over the contaminated soil. Table 2 presents a matrix showing the minimum functional requirements of a containment system for different hazard exposure routes.

TABLE 2
MINIMUM CONTAINMENT FUNCTIONS
FOR SPECIFIED HAZARDS / EXPOSURE ROUTES

Hazard / exposure route	Gas migration control	Water exclusion (rainfall and runoff)	Physical separation by covering	Isolation using bottom linings	Isolation using vertical barriers	Detect, collect, and recover leachate
HUMAN HEALTH						
Toxic/Carcinogenic by Inhalation of Vapour	X					
Toxic/Carcinogenic by Inhalation of dust			X			
Toxic/Carcinogenic by Ingestion of soil			X			
Toxic/Carcinogenic by Ingestion of Water		X	X	O	O	X
Toxic/Carcinogenic/ Irritant by Dermal Contact			X			
ENVIRONMENTAL						
Toxic to Plants or Soil Invertebrates (uptake / contact / inhalation)	(X)	X	X		X	
Impairs Microbial Function (contact)	(X)	X	X	O	O	
Toxic to Terrestrial Vertebrates (ingestion)		X	X			
Toxic to Aquatic Biota (contact / ingestion)		X	X	O	O	X
Bioaccumulation (ingestion/contact)		X	X	O	O	X

X = Required containment system component
O = Recommended component (may be achieved by using one or more of the options marked "O").
(X) = May be required for some contaminants

6. CONTAINMENT TECHNOLOGIES

Section 6 Summary

A range of technical options is available to satisfy the functional requirements involved in providing secure containment of contaminated soils. Increasing the complexity of a containment system does not necessarily result in a higher level of protection. The choice of a preferred design may be heavily influenced by site specific constraints on construction methods. Flaws arising during construction can have an overriding influence on the effectiveness and reliability of a containment system.

6.1 Function of Containment System Components

Containment systems generally comprise several components each performing its own function, but generally interacting with other components. It is convenient to describe these components under the following six categories of purpose:

- physical separation by simply covering
- water exclusion
- isolation using bottom linings
- leachate detection, collection and removal
- isolation using vertical barriers
- gas collection and extraction (may be required in some cases).

Figure 1 illustrates some of the basic functions of soil containment systems. Appendix D provides a discussion on various natural and synthetic materials used in the construction of containment systems.

<u>*Physical separation*</u> of contaminated soil from humans and animals in many cases is all that needs to be achieved. A layer of uncontaminated soil, a pavement or a building floor may provide sufficient protection to potential receptors.

<u>*Water exclusion*</u> is often the most important objective of containment works, either for the purpose of eliminating leachate generation, or for the purpose of reducing it to a level that makes it economically viable to collect, to remove and to treat it. Water exclusion may be achieved by combinations of surface drainage to prevent ponding, placement of soils to store water for subsequent removal by evapotranspiration, subsoil drainage and the installation of barrier layers to retard vertical percolation. The most common form of water exclusion is covering or capping over a contaminated area. <u>*Oxygen exclusion*</u> may be a second function, or even a prime function, for barrier layers, for example in the containment of acid sulphate soils or of sulphide bearing mine wastes.

Isolation using linings may be used to retard flows of liquid or dissolved contaminants and/or gases or dissolved gases from contaminated soil. The linings comprise layers of compacted clay and/or synthetic sheet. *Composite liners* employ two liners in direct contact, with each tending to seal any defects in the other. *Double liners* employ two liners separated by a drainage layer which enables the detection and removal of any leakage from the upper liner. The drainage layer sometimes is used for flushing, or for producing inward gradient conditions for the upper liner.

Leachate detection, collection and removal is usually provided in lined containments. Build up of accumulated leachate is prevented, and leachate depths (pressure heads) above the liner are kept small, so as to reduce the flow of leachate through the liner.

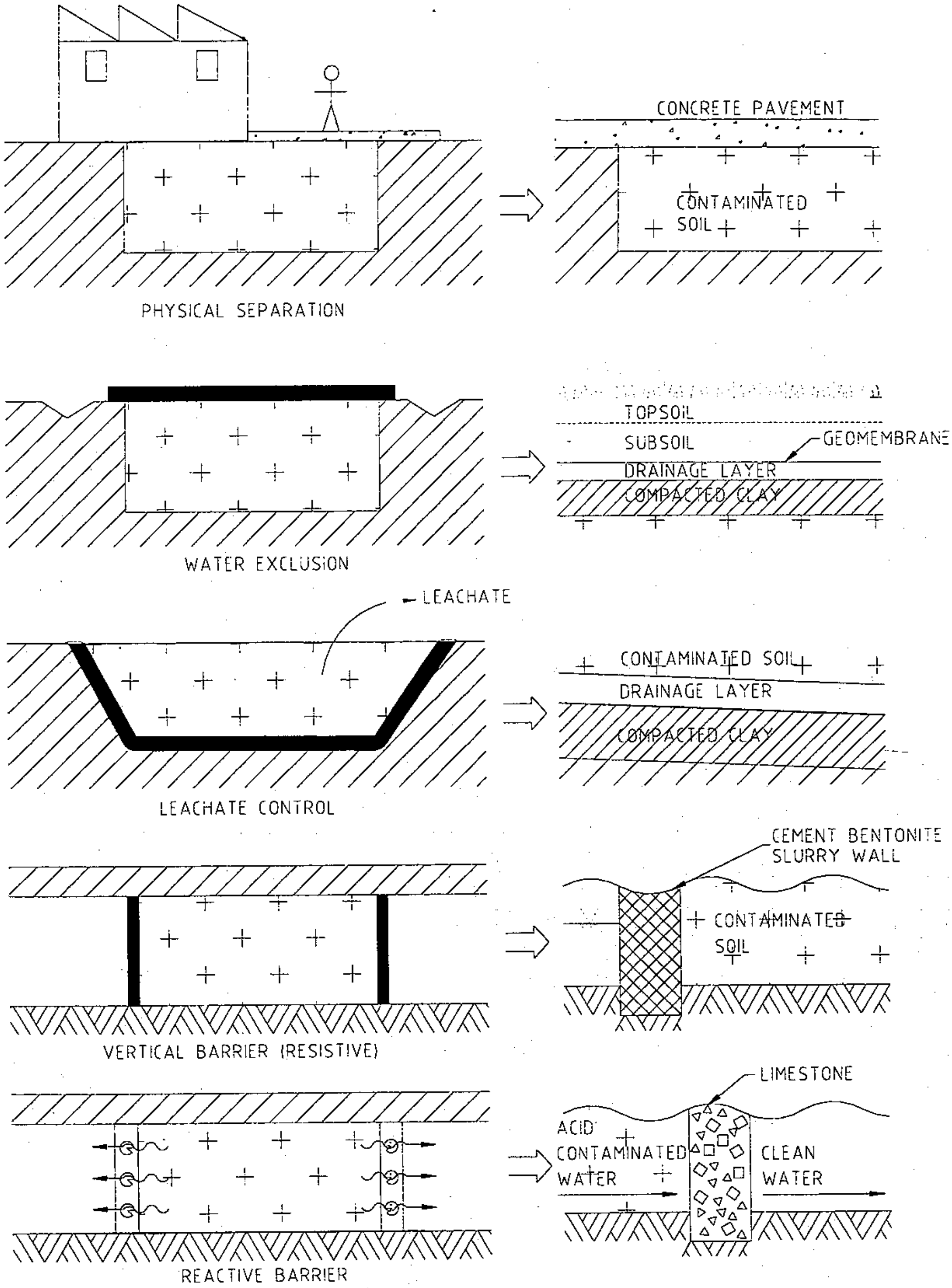
Isolation using vertical barriers may be effective where the site overlies soils of low permeability at relatively shallow depths. Vertical cut-offs can be keyed into the low permeability base to isolate the contaminated soil mass. Alternatively cut-offs can be installed to make inward gradient containment practicable, ie pumping of water from inside the containment ensures that only inward flow of groundwater occurs. In this case the cut-off reduces the quantity of water that must be pumped. Barriers can also be sited up-gradient to divert groundwater that might otherwise flow through a body of contaminated soil. Such barriers may be keyed into a low permeability formation below the aquifer, or be sited only to intercept the upper portion of the aquifer if that will adequately divert flow.

Reactive barriers react with or adsorb contaminants from outward seeping leachate. They are placed down gradient from a contaminant source to treat water as it passes through the wall (or a "gate" in the wall).

Gas extraction if needed can be provided via a permeable *gas collection blanket*, installed below a gas barrier (usually the barrier installed to serve as a water exclusion barrier), and/or *horizontal wells* (trenches with permeable backfill and collector pipes), and/or *vertical wells* (bored holes provided with collector pipes in permeable backfill).

FIGURE 1

CONTAINMENT SYSTEM COMPONENTS



Other components commonly included in containment systems are provided not for the direct purpose of effecting containment, but rather to support and protect other system components. For example:

Plant growth medium. Topsoil is needed to maintain healthy vegetation. A topsoil thickness of 0.10m to 0.15m is commonly specified. Thicker layers would function satisfactorily but cost more. Uncompacted soil is required below the topsoil layer to provide root support and to provide additional water storage. A minimum thickness of 0.2m is considered to be adequate for grass cover, and 0.7m for (appropriate) trees and shrubs.

Mechanical protection of geosynthetics. If a geosynthetic barrier is used, with no drainage layer, the thickness of loose (uncompacted) subsoil beneath the topsoil layer should be increased to 0.5m minimum, to ensure that a total cover of 0.6m is provided above the geosynthetic layer. This is the minimum depth of soil considered necessary to protect the geosynthetic barrier layer from damage from vehicular traffic and other post-construction surface loads.

Protection from biological disturbance. A compacted clay layer may be provided above any shallow drainage or barrier layers as a means of controlling biological disturbance. Even tree roots have been found to be deflected by a compacted clay surface. The compacted clay layer might also offer some protection from burrowing animals.

The remainder of Section 6 describes in more detail several key components of soil containment systems including separation layers, water exclusion and drainage layers (also known as capping or cover layers), lining and leachate management systems, vertical barriers for control of groundwater or leachate, and reactive barriers for control of contaminant migration. The section concludes with a brief discussion of quality assurance in construction of containment systems. More detailed technical discussion or background information on a number of these topics is provided in appendices to this report. References to this additional information are presented in the relevant sections below.

6.2 Physical Separation by Covering

If all contaminants are effectively immobile (e.g. Group 2 and possibly Groups 5 and 10 contaminants in Section 4 of this guideline) and only physical separation is required, it may be sufficient to provide a thickness of soil that is unlikely to be penetrated by likely future users of the site.[3] A minimum soil cover thickness of about 0.5m is commonly adopted, but thicker layers may be required where there is

[3] In some jurisdictions regulators may be willing to dispense with even the need for a covering layer, providing soils are mixed to attain an average condition of "minimal contamination" throughout the accessible soil mass. However, this "disperse and dilute" approach is not universally accepted.

high risk of penetration or little opportunity for effective institutional management controls[4], such as in residential situations where gardening activities are expected. The soil separation layer may be underlain by a layer of "marker mesh" to serve as a visual signal that a potentially hazardous material exists below the mesh layer. Thinner soil cover or no soil cover is often considered acceptable where cover is provided by a permanent concrete floor slab, or a permanent concrete or asphalt surfaced pavement.

6.3 Water Exclusion

Water exclusion is an important function in the design of many soil containment facilities. The exclusion of water helps to prevent mobilisation of contaminants and can be achieved in part through use of covering or capping layers over the contaminated soil. This section presents an overview of a number components of water exclusion systems, including:

- surface drainage
- water retention and evapotranspiration
- subsoil drainage
- barrier layers.

Additional information on some of these system components is presented in Appendix D. Figure 2 illustrates the water exclusion processes which may be incorporated in a soil containment system.

A substantial portion of the discussion in this section and in the supporting appendices centres on barrier layers, which play an important role in water exclusion systems. Most of the barrier layers installed to date could be classed as *low permeability barriers*. However there is growing interest in the potential for use of *capillary break covers* and *monolayer covers,* which do not rely on low water permeability. These alternatives are described in this section.

In this guideline document the term "barrier layer" has been used to describe a near surface layer constructed over contaminated soil which is either undisturbed or placed in a purpose-built repository. "Liners" are discussed separately to "barrier layers" (refer Section 6.4 for a discussion of liners).

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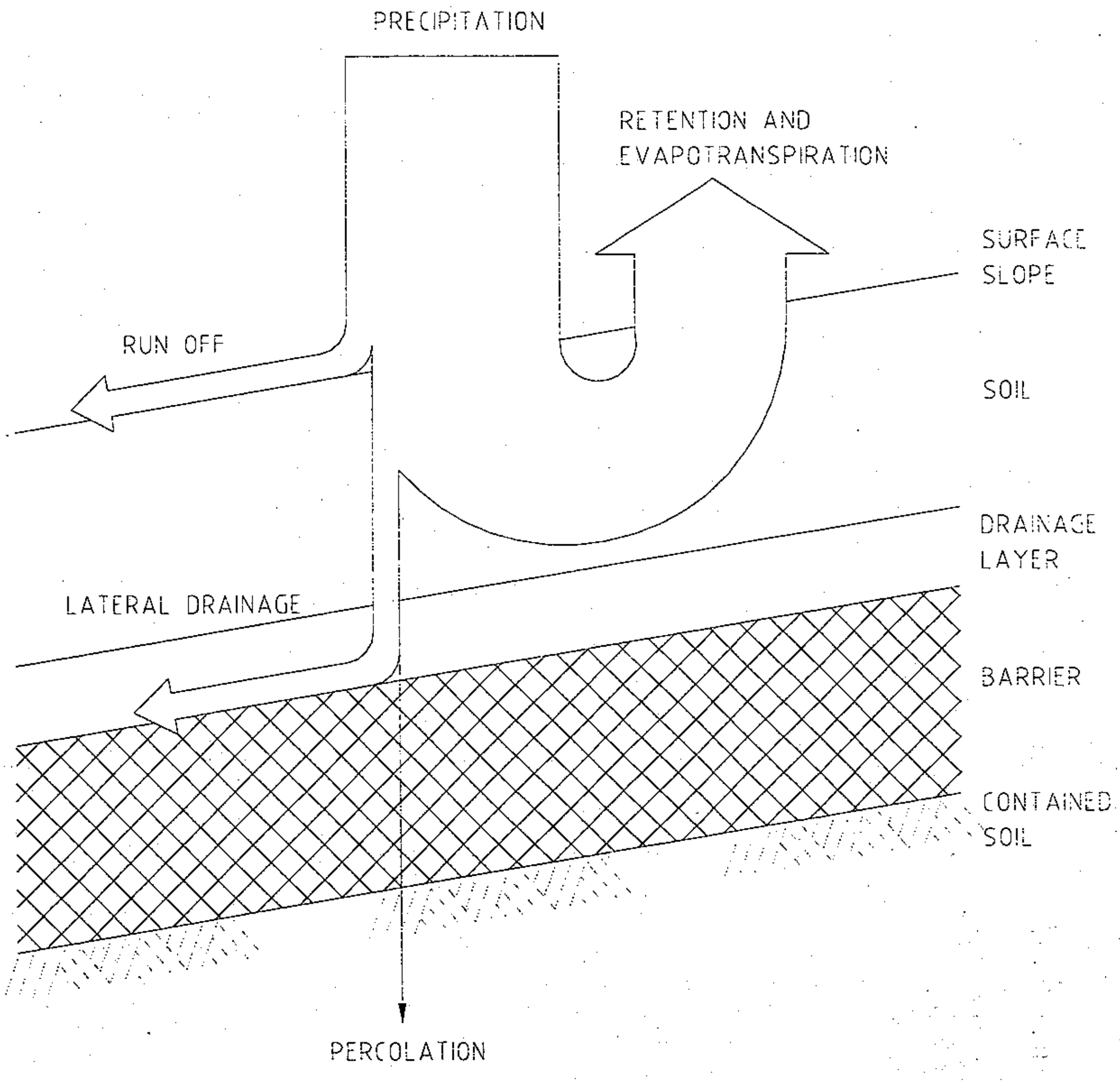
[4] Although the use of *caveats* on individual residential titles is sometimes suggested as an institutional control to prevent inappropriate uses of land with subsurface contamination, it is doubtful whether such controls would prove truly effective in the long run.

FIGURE 2

WATER EXCLUSION PROCESSES



6.3.1 Surface Drainage

Good surface drainage is an essential feature of water exclusion systems. The effect of good drainage is not so much to increase run-off (which changes little with increases in slope for a vegetated surface) but to eliminate ponding which will result in infiltration. Minimum surface slopes ranging from 1% to 5% may be specified for soil containment cells, depending on the intended final use of the land, the quality of surface finish, the likelihood of later rutting and the amount of localised settlement of the soil fill that should be allowed for. Surface water collector drains should be lined along the invert and should slope sufficiently to ensure drainage despite any settlements of fill that might occur.

6.3.2 Water Retention and Evapotranspiration

Layers of uncontaminated soil will usually be installed over the containment cell to serve a variety of purposes including landscaping, support of vegetation, physical separation and protection of underlying layers from surface wheel loads, excavations, penetration (eg, by pickets, tree roots, animals). A less obvious but usually very important function of the surficial soil layers is the storage of water which otherwise would percolate downwards into the contained soils. In warm climates, much of the stored water will in time be removed by evaporation and transpiration. If the system is well designed, the water percolating to lower layers will be greatly reduced, and sufficient water will be stored to keep surface vegetation healthy.

Infiltration modelling can be used to assess the balance between infiltration and evapotranspiration. Computer programs are available and are routinely used (see Appendix F for a brief discussion of common water balance models). These models enable the water storage function of the cover soils to be analysed and optimised.

6.3.3 Sub-Soil Drainage

Once water reaches the top of a barrier layer it will be divided between:

a) stored free water
b) lateral drainage, downslope over the barrier surface
c) water percolation through the barrier.

The installation of an efficient drainage layer above the barrier will promote lateral drainage, thus reducing the head of stored water and minimising percolation through the barrier. The effectiveness of the drainage layer will depend on the materials used, layer thickness, barrier surface slope and distance between water sheds and collector drains (drainage path length). Modelling can be performed to adjust these parameters in order to optimise drainage slopes. Slopes of less than 2% are unlikely to be acceptable (5% if there is a likelihood of differential settlement). Drainage path lengths in the range 25m to 100m are common.

Drainage is commonly provided by geonets or geodrains, sand, thick geotextiles or by the cover soils i.e. no supplementary drainage is provided. The efficiencies of these options differ greatly. (Refer Table 3 for additional detail.)

TABLE 3
EFFECT OF DRAINAGE
INSTALLED ABOVE A LOW PERMEABILITY BARRIER

Percolation as a percentage of precipitation percolating through a low permeability barrier (Long Term Average)				
	With a geonet drainage layer	With a sand drainage layer	With a geotextile drainage layer	With no drainage layer
Compacted Clay Barrier	1.0	10.8	10.5	15.6
Well Constructed Geomembrane Barrier	0.0	1.1	2.7	5.0
Poorly Constructed Geomembrane Barrier	1.4	17.9	17.4	19.8

Notes: *The data presented in Table 5 are drawn from a recent computer simulation completed by Golder Associates for a site in Queensland (Golder Associates Pty Ltd, 1997). Mandeville and Tomlin (1997) report even more striking differences, e.g. approximately 94 and 23 kilolitres of percolation per month per hectare, through a geomembrane barrier on 4% and 25% slopes, using a sand drainage layer, compared with 0.17 and 0.017 kilolitres per month per hectare respectively using a geocomposite drain. In both cases the striking improvement in water exclusion is achieved due to the reduction in average head of ponded water above the barrier - in Mandeville and Tomlin's analyses, from 540mm to 0.4mm*

If a subsoil drainage layer is provided, its presence will effectively diminish the capacity of the soils above to store water. To counteract this effect a layer of compacted clayey soil can be installed above the drainage layer. A layer thickness of 0.15m is suitable, providing this is enough to ensure that no lower layers are damaged during construction of the compacted layer. If lower layers may be damaged, the thickness of the clay layer may need to be increased to at least 0.3m and compaction should be modest and be performed only at the surface of the clayey soil. Compaction trials can be conducted to confirm that no damage will be done.

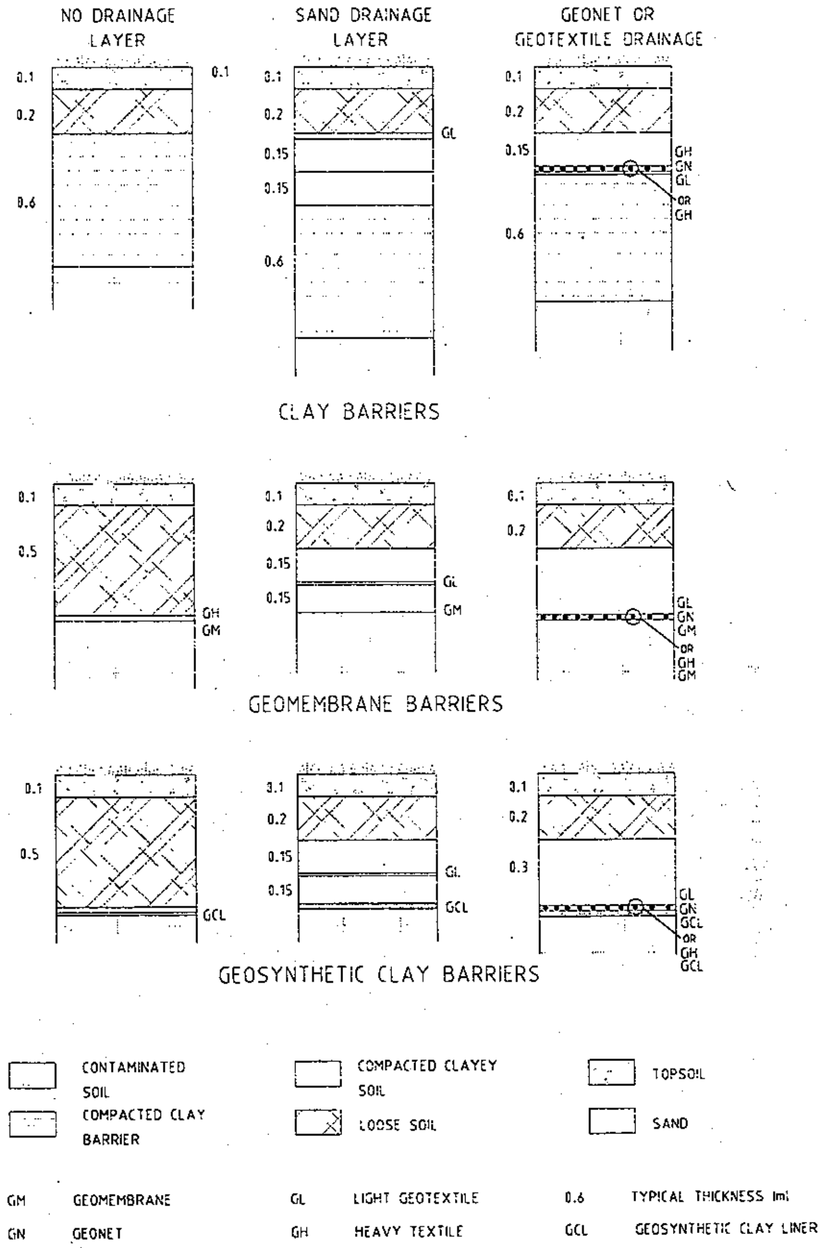
Subsoil drains for side slopes need to be carefully chosen. There sometimes is an additional need for drainage on slopes to safeguard against seepage forces which may destabilise the cover soils. On slopes steeper than about 25%, the installation of a sand drainage layer is difficult. A geodrain is preferred in such cases. Geodrains used over geomembranes on slopes must also be carefully selected to ensure adequate friction between geodrain and geomembrane. Even using a textured (rough) geomembrane, the friction angle for some geodrains is as low as 11 degrees (19%), i.e. the geodrain could slip on a 1 in 5 (V:H) slope. Other geodrains however provide much higher friction angles, up to 25 degrees (47%), which is nearly twice the friction needed on a 25% slope.

6.3.4 Low Permeability Barriers

Low permeability barriers in current use include compacted clay barriers, geomembrane barriers, and geosynthetic clay liners (GCLs), either used alone or paired to provide composite barriers. Figure 3 illustrates a number of possible configurations of cover systems incorporating low permeability barriers.

FIGURE 3

EXAMPLES OF LOW PERMEABILITY BARRIER COVER SYSTEMS



There are advantages and disadvantages with all of the common liner/barrier materials available. Table 4 summarises the advantages and disadvantages for compacted clay liners, geomembranes and geosynthetic clay liners. This table is based on a similar table by Daniel (1995).

TABLE 4
ADVANTAGES AND DISADVANTAGES OF ALTERNATIVE BARRIER MATERIALS
(Based on Daniel, 1995)

MATERIAL	ADVANTAGES	DISADVANTAGES
COMPACTED CLAY BARRIERS	1. Long history of use. 2. Regulatory approval is virtually assured. 3. Large thickness ensures that layer will not be breached by puncturing. 4. Large thickness provides physical separation between waste and surface environment. 5. Cost is low <u>if material is locally available.</u>	1. Difficult and slow to construct 2. Soil can desiccate and crack. 3. Closing of cracks is likely to be slow compared with storm duration. 4. Low resistance to cracking from differential settlement. 5. It is difficult to compact soil above poorly compacted fill. 6. Suitable soils are not always locally available and may not be available at needed times. 7. Difficult to repair if damaged. 8. Slow construction <u>Note</u>: 2 and 4 may be over-rated in the literature
GEOMEMBRANE BARRIERS	1. Rapid installation. 2. Virtually impermeable to water if properly installed. 3. Not vulnerable to desiccation. 4. Can withstand differential settlement. 5. Not dependant on availability of local soils, and usually available at short notice. 6. Low weight reduces settlement. 7. Easy to repair. Plant roots probably will not penetrate.	1. Potential friction problems at interfaces with other materials but textured versions are less restricting. 2. Geomembranes can be punctured during or after installation, and careful consideration must be given to protective measures.
GCL BARRIERS	1. Rapid installation. 2. Very low hydraulic conductivity to water if properly installed. 3. Can withstand large differential settlement. 4. Self-healing characteristics. 5. Not dependent on availability of local soils, and usually available at short notice. 6. Low weight reduces settlement. 7. Very easy to repair. <u>Note</u> : 4 has been challenged in some recent literature.	1. Low shear strength of hydrated bentonite, but needle punched versions have adequate shear strength in usual situations. 2. GCLs can be punctured during or after installation. 3. Potential strength problems at interfaces with other materials. 4. Erosion via dispersion may occur of bentonite from GCLs below a water drainage layer - not proven. 5. It may be that a GCL can bulge into an overlying drainage layer. Careful selection is needed and maybe the addition of a suitable geotextile. 6. Needle-punched GCLs require protective cover equal to at least twice the width of loaded areas, eg tyres. Non-needle punched GCLs require more. 7. It is suspected that plants may be able to penetrate into the GCL. 8. GCLs must be protected from severe desiccation GCLs may function poorly, in some chemical environments: waste specific and site-specific consideration is needed.

Compacted Clay Low Permeability Barriers

Compacted clay barriers offer the advantage that they provide both a resistance to water flow and the ability to limit diffusive migration of some contaminants. However they are susceptible to damage as a result of desiccation and may be damaged if underlying waste soil layers undergo differential settlement and cause the clay barrier to crack.

The availability of a sufficient quantity of suitable clay and the availability of suitable construction plant and experienced operators/supervisors are important factors to be considered when considering the suitability of a compacted clay barrier. Table 5 summarises minimum selection and placement criteria for clays used in compacted clay barriers.

TABLE 5
MINIMUM CRITERIA:SELECTION AND PLACEMENT OF CLAY USED IN COMPACTED CLAY BARRIERS

Parameter	Criterion
Plasticity index	10% - 30%
% < 75 micron	≥ 30%
% < 2 micron	≥ 15%
Compaction moisture content	Optimum to optimum +6%
Compaction density	≥ 94% Standard dry density

If the quality of available soil or the quality of construction is such that the barrier cannot attain a field permeability of 1x 10^{-9} m/s or less, there is very little advantage in providing the clay barrier, as it will provide little reduction in water infiltration (Refer data presented in Table 6).

TABLE 6
EFFECT OF CLAY BARRIER PERMEABILITY ON INFILTRATION OF PRECIPITATION

Coefficient of Permeability of Barrier Layer m/s	Percolation as Percentage of Precipitation (long term average)	
	With no Subsoil Drainage	With 0.15m thick Sand Drainage Layer
No Barrier	22.2	-
1 E-8	16.7	8.4
3 E-9	9.7	3.4
1 E-9	3.7	1.4

Notes: *Results in Table 8 are based upon a recent study computer simulation (Golder Associates 1997) of percolation through a compacted clay barrier 0.6m thick Such results are typical and underlie the common requirement for a coefficient of permeability not exceeding 1 E-9m/s. Permeabilities much below 1 E-9 m/s are difficult to produce in the field.*

To a minor degree, providing a thicker liner can reduce the amount of water that will penetrate a compacted clay layer. However recent research suggests that merely providing a large thickness of clay will not compensate for poor construction technique - in fact, it has been suggested that there is little benefit in providing a clay barrier thickness in excess of 0.9m. (Refer Appendix E for additional discussion).

Geomembrane Barriers

Geomembrane barriers offer the advantage of predictable physical characteristics, and extremely low permeability (assuming good quality installation). They offer some resistance to diffusive migration of most contaminants. Because of the thinness of the membrane, they occupy little space in a containment cell. However, they are relatively weak structural elements and must be not be subjected to excessive tensile stresses. Certain types of geomembrane may become brittle upon exposure to UV radiation. Although relatively easy to install, by comparison with compacted clay liners, many geomembranes are susceptible to puncture damage. Consideration must be given to the frictional properties of the geomembrane, so that a potential slippage plane is not created at the interface of the membrane layer and layers above or below it.

Geosynthetic Clay Barriers

One of the chief advantages of geosynthetic clay barriers is their ease of installation. This makes the use of geosynthetic clay barriers particularly attractive in areas where there is an absence of skilled, experienced operators. Because of the thinness of the clay layer in these barriers, they may not offer the same resistance to diffusive migration of contaminants as do thicker compacted clay liners. They may also show alteration of flow properties as a result of chemical exposure more readily than would clay liners. Care must be exercised when placing a geosynthetic clay barrier in contact with a synthetic drainage layer, as there is some potential for the bentonite from the GCL to clog the interstices of the drainage layer. Geosynthetic clay barriers must be protected from excessive surface loads (such as wheel loads from vehicular traffic) by placing a sufficient thickness of cover soil over the GCL.

More detailed discussion of various types of natural and synthetic low permeability barriers is presented in Appendix D.

6.3.5 Capillary Break Covers and Monolayer Covers

Capillary Break Covers

Capillary break covers are currently being explored as an alternative to low permeability (resistive) barriers, particularly for application in semi-arid and arid locations. To date application is experimental, but sophisticated computer design programs have been developed and laboratory and field testing is well advanced. Field studies so far have shown that capillary break and monolayer covers suit arid and semi-arid regions. In wetter regions the greater thicknesses needed are likely to make such covers uneconomic.

The principle exploited in design has been described as "wicking". At its simplest the cover comprises a relatively thick layer, perhaps 0.8m, of fine silty soil. Beneath this is a layer of poorly graded (uniform, or "one sized") coarse sand or fine gravel, say 0.2m thick. Design is aimed at providing sufficient thickness of upper finer soil to enable year round storage of infiltrating water, allowing for progressive removal by evapotranspiration.

Water percolation down through the coarse capillary barrier layer will be insignificant until so much water is present in the upper layer that it is nearly saturated and "suction" (negative pore water pressure) in the fine layer is reduced to the "water entry value" for the coarse layer. If this occurs water will flood down until suction becomes high enough to arrest the flow. This is termed "breakthrough". Design is aimed at preventing, or limiting the occurrence of, breakthrough.

The simplest design approach is to ensure that the fine layer can store the infiltration from precipitation until it can be removed by evapotranspiration. A more complex capillary barrier design includes the provision of a sloping fine-coarse interface to promote lateral flow of water in the fine layer. In appropriate soils this will occur relatively readily, even under unsaturated conditions. Lateral drainage can cause an increase in moisture content in the downhill direction, near the toe of the containment cell, which may result in breakthrough. Collector drains are provided at intervals to prevent this.

A more sophisticated model includes an unsaturated drainage layer (UDL). The UDL could be a layer of fine sand located between the silty soil and the capillary break layer. When suction in the silty layer is low water will percolate negligibly into the fine sand layer and it will act as a capillary break. As water accumulates and suction rises a point will be reached when breakthrough occurs into the fine sand layer. Then the fine sand layer, being more conductive than the silt layer, will promote lateral flow and act as an underdrain. At the same time the gravel layer will continue to act as a capillary break, and as before will continue to do so until suction in the sand layer falls to the gravel's water entry value. This is less likely to occur because of the improved removal of water via the UDL.

Monolayer Covers

A related cover option that is currently under investigation and being trialled in the field is the monolayer cover. This is simply a layer of fine soil so thick that it wholly contains the zone of significant seasonal moisture change. It is well known that seasonal moisture changes are negligible below some depth that depends on weather patterns and soil types. This depth generally ranges from 1.5 to 3.0m.

The preferred soil for a monolayer cover would be a fine grained soil, probably a silty soil, with large water storage capacity and relatively low saturated conductivity. Such properties reduce the required thickness of the monolayer. Because of the relatively great depth of soil required for this type of cover, the soil used for the monolayer needs to be available at a low cost if it is to constitute a cost effective option, by comparison with other types of water barrier.

The cover can be made to work better by placing finer soil with lower saturated conductivity at the surface, in order to increase run-off. However in some environments run-off must be avoided or controlled, for example in arid areas where vegetation may be sparse and erosion needs to be guarded against. For such situations total infiltration into the monolayer may need to be induced.

The fine soil layer used in a capillary break or monolayer cover must not crack on drying. Cracks will effectively short circuit the storage layer. This places further limitations on the choice of soil. Soils should be clayey silts, clayey sands or sandy clays of low plasticity. The availability of suitable soils will often be a serious limitation.

The operating principle for these covers is not conducive to the reliable support of dense vegetation. This may be of concern aesthetically. It also means that removal of water by transpiration cannot be relied upon, so that layer thicknesses must be large enough to accommodate and temporarily store all infiltrating water. Placement of cobbles or similar rock facing may be required for the purpose of erosion control (normally provided by vegetation in conventional cover systems).

Further information on the use of capillary break and monolayer covers for water exclusion is provided by Schwarbrick (1997), Benson and Khire (1991), Barres and Bonin (1994), and Morris and Storment (1997).

6.4 Isolation Using Linings

6.4.1 Purpose of Lining

It may be decided to place contaminated soil in a purpose-built on-site repository. In this case it will be necessary to decided how to prepare the base of the repository. It some instances it may be determined from hydrogeological investigation and modelling that the native soils have sufficiently low permeability or attenuating capacity that lining of the base is not required. However in many instances lining is required to further retard contaminant migration. Lining may be needed for one or more of the following purposes:

- to reduce the transport of soluble or miscible contaminants via water infiltrating through the contaminated soil

- to prevent ground water flowing into and through the contaminated soil

- to reduce diffusion of contaminants from the contaminated soil

- to restrict gas emissions.

The first of these is the most common purpose. Liners commonly do not retard diffusion much better than the foundation soils - at least at sites likely to be suitable for repositories. If significant gas emissions are expected then additional measures (such as active gas extraction or passive venting) may be required.

6.4.2 Constraints Imposed by Lining

The decision to provide a low permeability liner imposes certain constraints. Primarily these relate to the potential for accumulation of contaminated water (leachate) above the liner. The potential for accumulation of leachate may impose the need to provide a leachate collection system, comprising a leachate drainage layer and usually some means for ensuring that the drainage layer remains freely draining - unattended for decades. The shape of the repository will be constrained by the need to drain leachate towards collection points. If leachate collection is used, then pumping will be required to remove the collected leachate. Leachate will need to be treated and disposed of. A low permeability cover, of high quality, will need to be provided over the repository to limit the quantity of leachate that must be catered for.

The latter point raises an important question. If a cover of high quality is provided to minimise long term infiltration, is it necessary to provide a high quality liner as well - plus a leachate collection and removal system - plus ongoing pumping and leachate treatment?

Much of our current thinking about repository design derives from planning of municipal solid waste and similar landfills. A liner is almost automatically prescribed for municipal landfills because the putrescible refuse may arrive wet, or become wet during placement prior to capping (usually a delay of several months). However, there is no similar imperative for the provision of a liner in a contaminated soil repository, provided it is completed quickly. As stated in Section 4, these guidelines do not relate to the management of soils with levels of liquid contaminants so high that they cannot be held at residual saturation in the soil pore space. Further, it is not expected that soils will become saturated through long exposure to precipitation.

In the case of dedicated soil containment facilities (in contrast to mixed waste landfills), it may be preferable to invest resources on soil treatment, or on a more refined cover system, instead of on a lining and leachate management system. If infiltration is sufficiently reduced, natural processes should in most cases be able to cope with the small remaining contaminant fluxes. Another advantage of relying more on the cover, and eliminating or simplifying the liner, is reduced uncertainty in design. Covers need to shed relatively pure water. Liners often work in complex environments prone to chemical precipitation and/or biomass build up that can totally clog leachate drainage elements, compromising the function of the liner. Further, covers are accessible, liners are not. In shor, there are some very good reasons for carefully analysing any proposal that relies on a lining system for the primary containment of contaminants.

6.4.3 Liner System Components

Figure 4 illustrates some examples of possible configurations for single and double liner systems. *Single Liner* systems generally contain the following components:

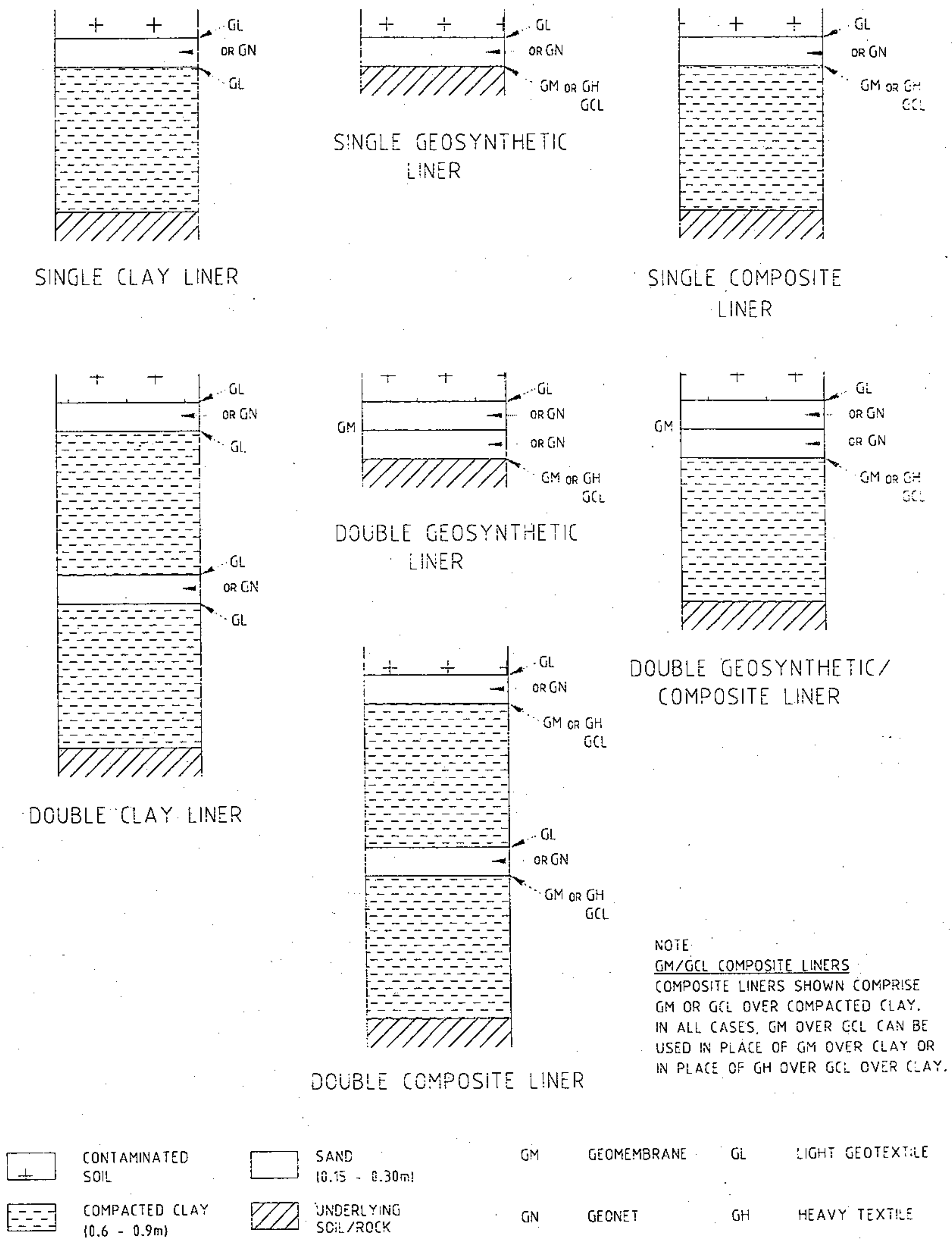
- barrier layer
- leachate collection layer
- leachate sump(s) and pump-out equipment.

Double liner systems are sometimes required. Their components from bottom to top are:

- secondary barrier layer (secondary liner)
- leachate collection layer (secondary leachate collection and removal systems)
- primary barrier layer (primary liner)
- leak detection layer (primary leachate collection and removal system)
- leachate sumps and pump-out equipment.

FIGURE 4

EXAMPLES OF SINGLE AND DOUBLE LINER SYSTEMS



Barrier Layers

The barrier layers used for lining are essentially the same as those used in cover systems. The same materials are used and construction techniques are similar. Discussion of the relative merits of these materials and of barriers made from them, and comments on barrier design were given in Section 6.3.4. The early discussion related specifically to barriers used in cover systems. All the discussion on low permeability barriers presented in Section 6.3.4 applies equally to barriers used for lining, except for a few differences noted below:

- **Compacted clay liners** are relatively less susceptible to the construction difficulties that may affect compacted clay when used as part of a low permeability capping system. This is because the support provide by the soil subgrade at the base of a containment cell is generally better and less likely to suffer differential settlements than would be the case for the waste material upon which the capping layer is built. Disturbance by plant roots is also less likely to be a concern for lining layers than for clay layers used in capping systems.

- **Geomembranes**, used as a single low permeability barrier in a lining application, are less likely to perform satisfactorily than would be the case in a capping application. This is because there is a relatively greater likelihood of water accumulating above the liner than above a geomembrane in a capping layer. With a persistent head of leachate above the membrane liner, there would be little impediment to flow of leachate through any defects that may exist in the geomembrane liner.

- **Geosynthetic clay barriers** may be somewhat more susceptible to chemical alteration when used as liners, due to the presence of contaminant species in leachate. This factor is relatively unimportant when using geosynthetic clay barriers in capping systems. In critical applications, it may be necessary to carry out field or laboratory testing to verify the compatibility of the GCL with leachate from the waste to be contained. The potential for loss of stability due to low frictional resistance in the bentonite layer of the GCL may also limit the usefulness of GCLs for lining of large containment cells.

Barrier layers installed below a waste mass are potentially exposed to more complex chemical environments than are barriers used to exclude rainfall and surface runoff. Comments on chemical compatibility of barrier materials are found in Appendix D.

Liners are often installed as *composite liners*, comprising (for example) a geomembrane installed over and in intimate contact with a compacted clay liner or a geosynthetic clay liner. Composite liners effectively incorporate a "back-up system" to prevent flow of leachate or diffusion of contamination. It is not common to use a single geomembrane in a liner application without some type of "backup" such as a compacted clay liner. There is also some reluctance to using geosynthetic clays as single noncomposite liners, due to the relatively limited attenuation capacity of the thin bentonite layer. Geomembranes or GCLs may be used as the single uppermost liner layer in a double liner system. However, the secondary (lower) liner layer in such a system would typically be a composite liner.

Additional comments on and comparisons between available geomembrane materials are provided in Appendix D.

6.5 Leachate Detection and Collection

Leachate collection layers are used to reduce hydraulic gradient (pressure head) on liners thus further reducing rate of seepage and to avoid accumulation of leachate within a lined repository. Soil leachate collection systems may not always be necessary for containment of contaminated soil since repositories are constructed over relatively short periods and rainfall accumulation may not be an issue. Further, the contaminated soils may be of low permeability and there is very little risk of leachate generation if the repository is well capped. There are a number of examples in Australia where waste repositories have been constructed with base liners and high quality capping layers but without leachate collection systems.

Sub-soil drainage layers for use in cover systems were discussed in Section 6.3.3. That discussion applies equally to most leachate collection layers used in liner systems, but some elaboration is needed.

Depending on the soil to be contained, there may be a risk of chemical precipitation and/or biological clogging. This is a mounting problem in municipal landfills, in some of which earlier designed leachate collection systems have become non-functional. Much recent literature is devoted to this subject. For municipal landfills, current designs commonly call for leachate collection layers comprising one-size coarse gravels (25 to 40mm) with no geotextile between the collection layer and the refuse. Collector pipes are provided with commensurably large openings and tend to be at least 200mm in diameter to facilitate cleaning out.

Most contaminated soil monofills will not produce similar problems, but the possibility must be considered in design. If clogging is very unlikely to occur, then collection layers similar to sub-soil drainage layers would be suitable. If clogging may occur, precautions may need to be taken to prevent or accommodate the build-up.

6.6 Gas Collection and Removal

Gas collection systems are a common component of municipal landfill containment systems, where they serve to control methane gas generated through the anaerobic decomposition of organic wastes. They would only rarely be incorporated in soil waste containment systems, as there is very little likelihood of *in-situ* generation of any substantial amount of gas from chemically contaminated soils (assuming usual low levels of degradable organic matter).

In some circumstances, a gas collection system may be incorporated in a soil containment system to enable the control of volatile contaminants such as benzene and other components of petrol- or solvent-contaminated soil. Normally gas collection and removal systems of this type would be a feature of soils contained *in-situ* rather than those which are excavated and replaced in a purpose-built repository, since much of the volatile contaminant would be lost during the handling of soils placed in a repository.

A typical *in-situ* containment system incorporating gas collection would include vertical contaminant barriers (such as a slurry wall or vertical geomembrane) installed to a natural low permeability barrier (such as a clay layer). These two low permeability barriers would serve to contain the contaminated soil mass. A network of horizontal slotted pipes could be installed in a high-permeability gas drainage blanket above the waste mass to intercept and direct volatile contaminants. The drainage blanket would be overlain by a low permeability gas barrier. Depending upon the quantity, concentration, toxicity and other physico-chemical characteristics of the volatile contaminants (density, flashpoint, odour threshold, etc), the gas collected may be passively vented to atmosphere, actively pumped to a treatment plant, or flared. Special care must be taken when selecting pumps and fittings to ensure that potential corrosion hazards or explosive risks are mimimised.

In-situ gas collection systems may form part of a soil treatment system. For example, vapour extraction systems used to treat petroleum contaminated soils act in a triple capacity. They induce desorption of contaminants from the soil particle, they promote microbial degradation of organics by introducing oxygen to the subsurface environment, and they may be used to actively control and direct the flow of volatile contaminants. These types of combined gas collection / soil treatment systems are only likely to be effective in granular (clayey or gravelly) soils.

6.7 Vertical Barriers

Applications for vertical barriers for containments were outlined in Section 6.1. In brief, these include :

- confinement of contaminants
- reducing inflow to make in-gradient containment practicable
- directing groundwater flow.

6.7.1 Resistive Barriers

Vertical barriers are typically used as resistive barriers to contain volumes of contaminated soil in-situ, and may be the containment method of choice where the contaminated soils do not lend themselves to excavation and handling. This might be the case in very soft ground, or in cases where the contaminated soils cannot be easily handled without creating a negative environmental impact, such as strong odours. Figure 5 shows examples of vertical cut-off applications. Commonly used vertical barriers include :

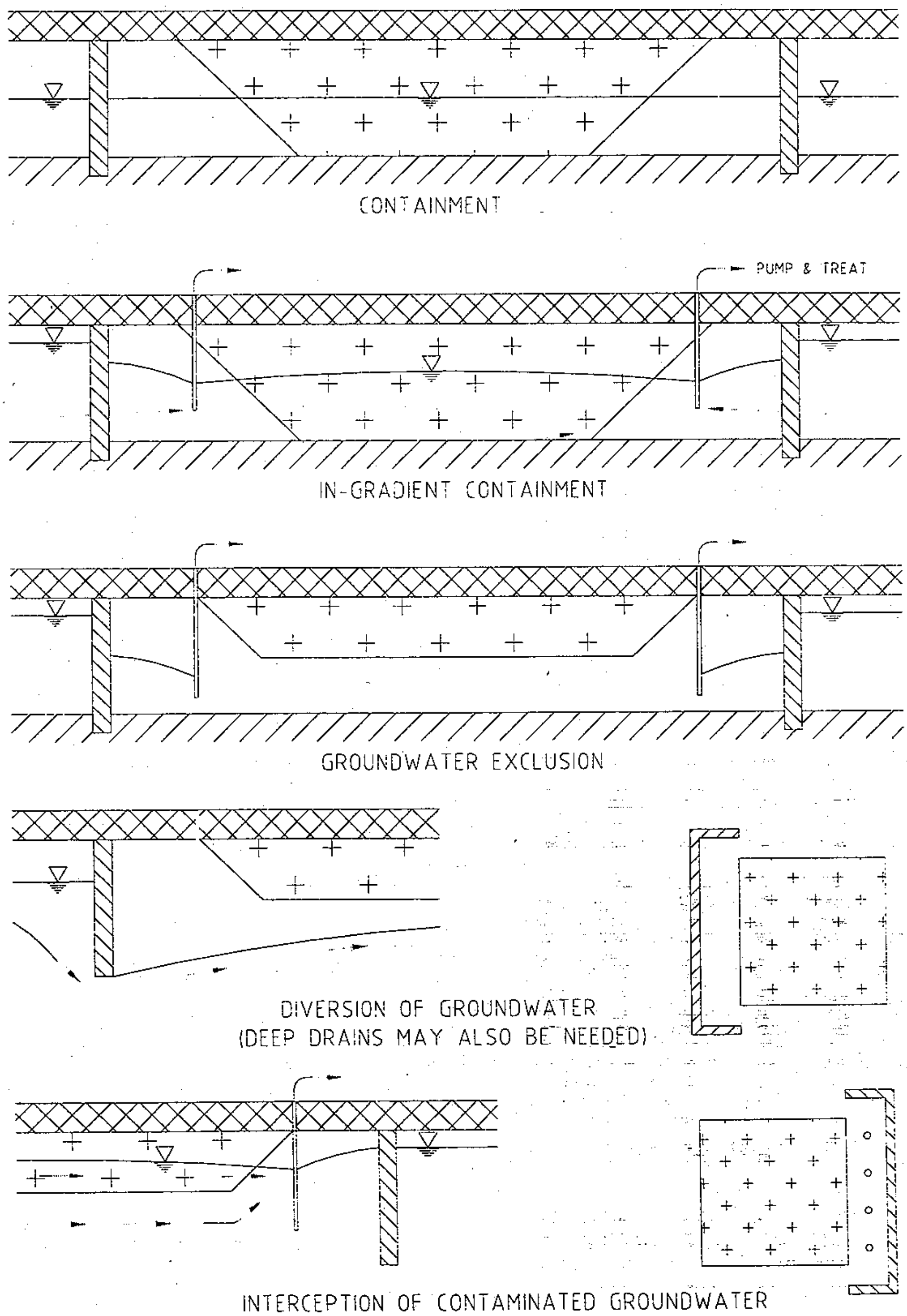
- slurry walls
- geomembrane walls
- sheet pile walls
- grouted cut-offs.

The chief difference between these types of barriers relates to the method of barrier construction. The different construction techniques will determine the suitability of a given method for a particular set of subsurface conditions. For example, installation of sheet piling would not generally be attempted in very stiff or rocky soil; grouting is conventionally used mainly in granular soils (sands or gravels). The types of vertical barrier also differ in their compatibility with corrosive subsurface environments.

An important consideration in the selection and use of vertical barriers for contaminant containment is the degree of construction control that is possible in order to verify the "as built" configuration of the barrier. In critical applications such as those involving highly toxic contaminants, or even some organoleptic contaminants, the preferred vertical containment system will be one which can be inspected or tested to ensure that there are no flaws which may allow outward migration of contaminants or inward migration of water. It some cases, the issue of construction control may be an overriding consideration. In such cases it may be decided that a purpose-built repository involving liners is preferable to a system using vertical barriers to contain in-situ contaminated soils, as lined repositories tend to be more compatible with rigorous quality assurance testing.

FIGURE 5

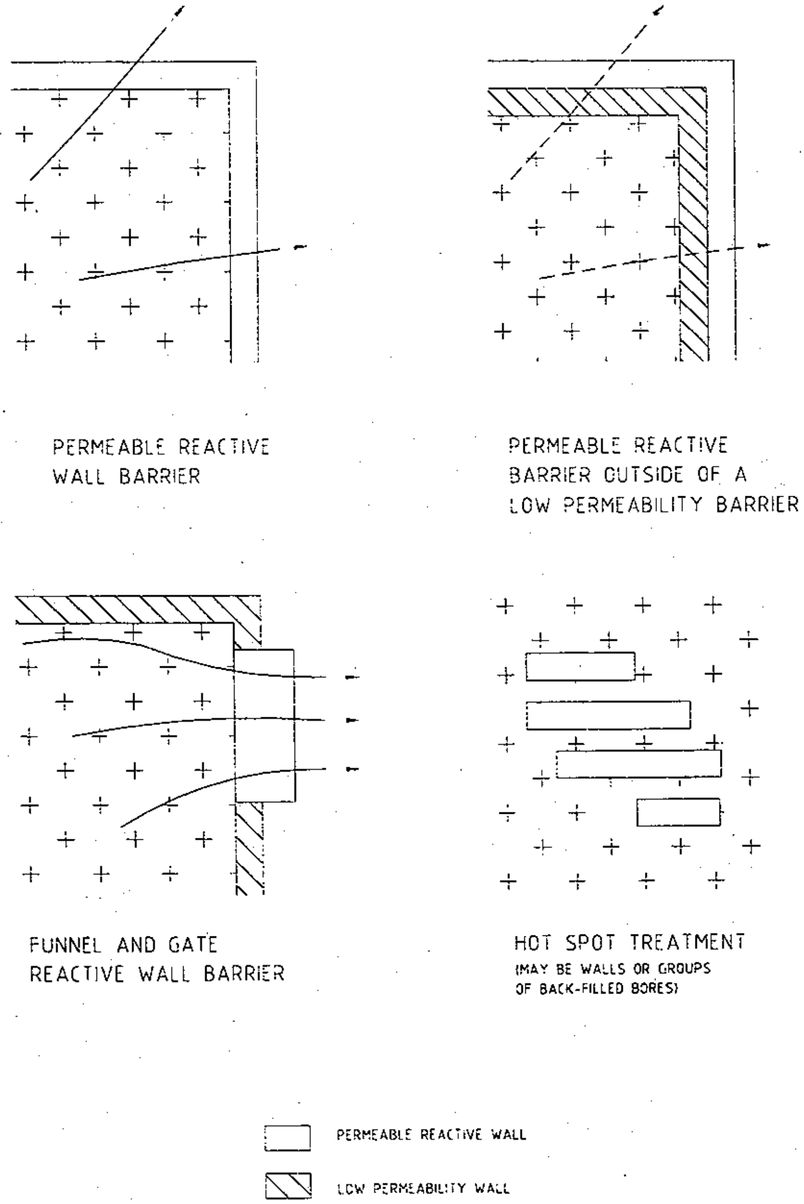
EXAMPLES OF VERTICAL CUT OFF APPLICATIONS



6.7.2 Reactive Barriers

Ideally, vertical (resistive) barriers and liner barriers would totally seal a containment. In reality they do not. However reactive barriers can be constructed to remove certain contaminants from the water that does escape the resistive barrier and/or the water that is affected by diffusion of contaminants through the resistive barrier. The reactive barrier contains selected or modified soil or rock, with or without other agents, which can react with or sorb the target contaminants. Various configurations of the complementary resistive and reactive barriers are possible. Some possible configurations are illustrated in Figure 6. Much of the technology required is relatively new and much is still under development.

FIGURE 6
EXAMPLES OF REACTIVE WALL APPLCATIONS



Reactive Materials

Ordinary bentonite and bentonite-like clays (smectite, illites) function even in resistive (low permeability) barriers as reactants. Polyvalent cations and a wide range of organic compounds can be strongly adsorbed and anion diffusion can be retarded as a result of sorption by reactive clay surfaces. Wagner, (1994), describes the conflicting roles of clays in clay liners. They serve to remove contaminants but in the process they may become more permeable, compromising their resistive function. Wagner's resolution involves constructing a layer of clay specially chosen for its reactive capabilities, overlying or underlying a layer of clay chosen to provide a stable sealing layer.

Suitable clays can be modified to increase their reactivity and adsorbtivity. Lundy, McLeod and Bouazza, (1997), describe the use of "pillared clays". These are smectite clays into which quaternary ammonium ions (NR_4^+) have been introduced. These large ions prop the smectite sheets apart, increasing the surface area available for adsorption. Other pillaring agents confer other properties. A wide range of pillared clays are being developed for use in catalysis, and their use in reactive barriers is under trial.

Other reactive barrier materials include limestone, currently used in mining, to remove acids and to promote the fixation of metals. Reactive barriers containing zero valent iron (pure metallic iron) are becoming the preferred in North America for treating groundwater containing chlorinated solvents (Duran, Grounds and Bogan, 1997). Precipitation agents and reduction agents are also being trialled.

Reactive Barrier Configuration

Reactive barriers can be arranged in various ways:

- continuous barriers
- "funnel and gate" barriers
- isolated "hot-spot" treatments
- vertical walls
- bottom and side-slope barriers.

Continuous reactive barriers may be located inside or outside of a complementary resistive barrier. Funnel and gate arrangements employ vertical resistive barriers located to divert contaminants fluxes towards one or more panels of reactive barrier. Details are provided by Lundi, McLeod and Bouazza, (1997) and Wagner, (1994). Additional description of vertical barrier characteristics and construction methods is provided in Appendix E.

6.8 Construction Quality Assurance

Construction quality assurance is an important requirement for construction of lining and capping systems. Where reliance on very low permeability is required, it is critical to demonstrate that design specifications have actually been met. This is particularly important for clay compaction and geomembrane installation since small defects may have a major impact on performance.

It is important to understand that CQA is not an optional extra that may improve the quality of a barrier installation. Quality assurance must be regarded as an integral component of construction - no less important than the purchase of clay, membrane or GCL. Without an appropriate level of quality control and assurance, expenditure on clay, membrane or GCL, and labour or equipment for installation of barriers, could be a total waste of money.

There are well documented procedures for CQA testing of clay compaction and geomembrane installation. Descriptions of these are included in Parker et al (1993). Suppliers and manufacturers of geosynthetic products can provide model CQA plans that may be readily adapted to specific projects.

7. SELECTION OF AN APPROPRIATE CONTAINMENT SYSTEM

Section 7 Summary

The selection and design of an on-site soil containment system involves an optimisation process which balances a need for reliable containment against other stakeholder needs. Sometimes it is appropriate to adopt a less secure engineering technique, but to incorporate alternative environmental control measures to limit either the likelihood or the consequence of a loss of containment from the lower security containment cell.

A general approach to the design of landfill containment systems was described in Parker et al (1993). The approach emphasised the iterative nature of the design process, and the importance of defining clear environmental objectives against which to test a proposed design. Choosing the most appropriate containment system for remediation of contaminated soils also requires a site specific focus.

The general components of a containment system are dictated mainly by waste characteristics, which will generate certain minimum containment requirements. To some degree, these minimum requirements may be modified to take into account site specific conditions. (For example, it is possible that a regulatory agency may agree to approve a repository without a leachate barrier for containment of soluble wastes if the site conditions are such that groundwater is very deep and there are no nearby surface water receptors). However, the precautionary principle generally would dictate that the minimum functional requirements identified in Table 4 should serve as the basis for containment system design.

The *preferred means* of achieving the minimum functional requirements will, however, depend upon site specific conditions (including physical conditions ownership and management arrangements, intended post-remediation site use, adjoining land uses, etc) since it is only in the context of these specific conditions that it is possible to define the likely consequence of loss of containment. For example, the consequences of a loss of containment from a waste repository located in a densely inhabited residential area may differ substantially to an identical repository on a physically similar site in a remote area.

Any loss of containment which has potentially severe consequences should be analysed to identify possible failure modes (causes of loss of containment). The likelihood of each failure mode can then be assessed for the various containment options being considered. For example, an asphalt pavement, a shallow layer of uncompacted soil, and a concrete floor could each serve the functional objective of separating human receptors from soil which would be harmful if ingested. One way that loss of containment could occur is by erosion of the surface cover. The soil cover clearly has a higher potential to be affected by erosion than do the engineered pavements, although site conditions including slope, rainfall, etc will determine the actual degree of risk for loss of containment by that failure mode at that the particular site.

For the same site, loss of containment could result from children digging through the separation layer while at play. It is obvious that on a residential site there is a higher likelihood of this failure mode occurring with uncompacted soil capping, than with a concrete pavement. Therefore, on a residential site, the concrete cap satisfies certain containment requirements better than does a shallow thickness of uncompacted soil.[5]

Unfortunately, the concrete cap may not meet certain other minimum requirements or expectations of stakeholders. It may then be necessary to select an alternative option for achieving the same containment function, possibly incorporating some controls to improve the reliability of that option (ie, reducing the likelihood of a particular failure mode). In the case described, a decision might be made to adopt soil cover in place of the less "failure -prone" concrete. However the thickness of the soil layer might be increased and a layer of marker mesh placed to reduce the likelihood of the failure mode described as "loss of containment due to surface penetration by children at play".

This optimisation process for selection of an appropriate containment system is illustrated diagrammatically in Figure 7. This optimisation approach may be carried out qualitatively, semi-quantitatively or quantitatively, depending upon the sensitivity of the site and the consequences of release of contaminants.

[5] (On a physically similar site used for commercial purposes, it may be that there is not much difference in the likelihood that children will cause loss of containment (because there are no children playing on the site).

FIGURE 7

SELECTION OF APPROPRIATE CONTAINMENT SYSTEM

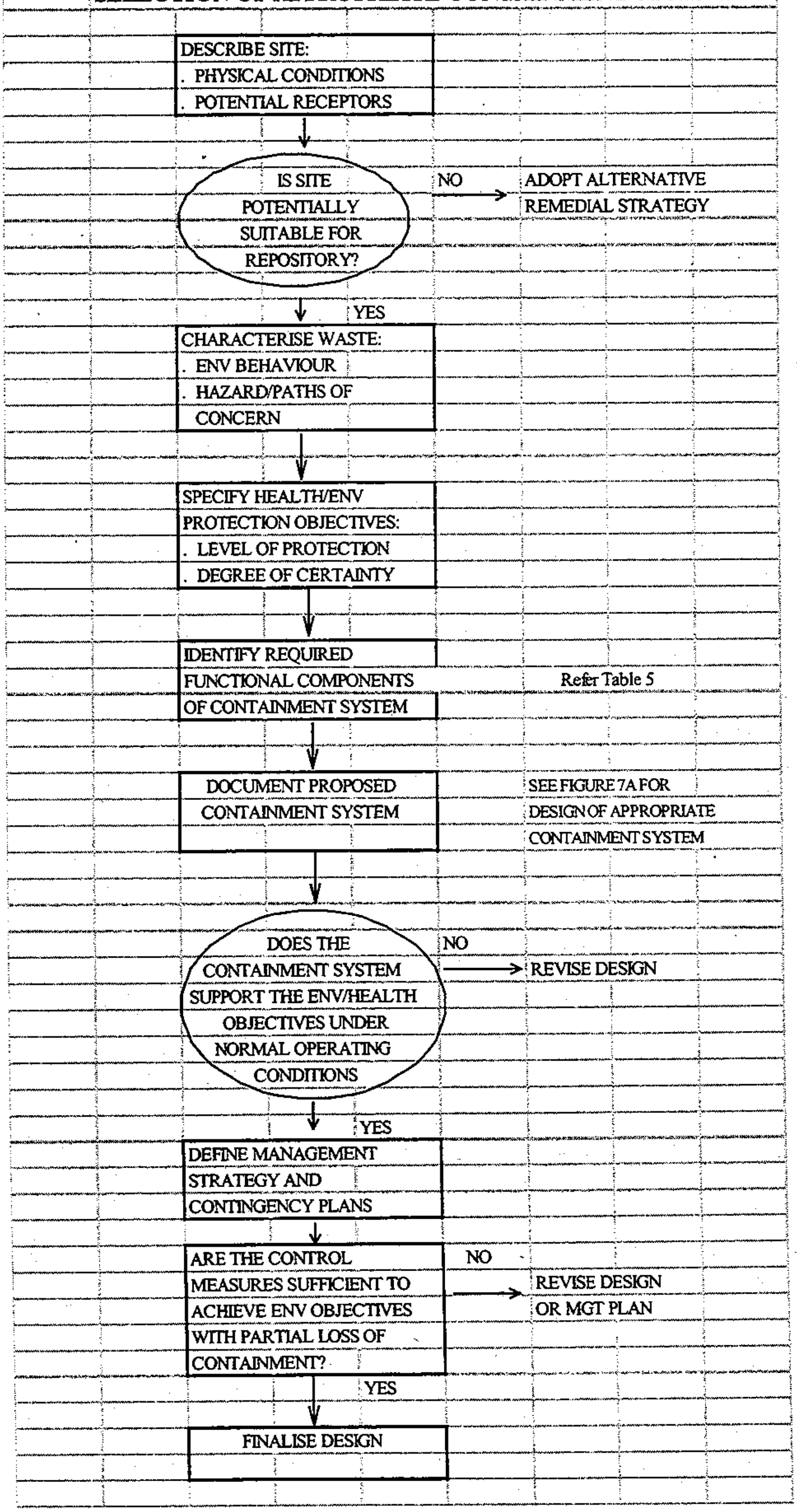
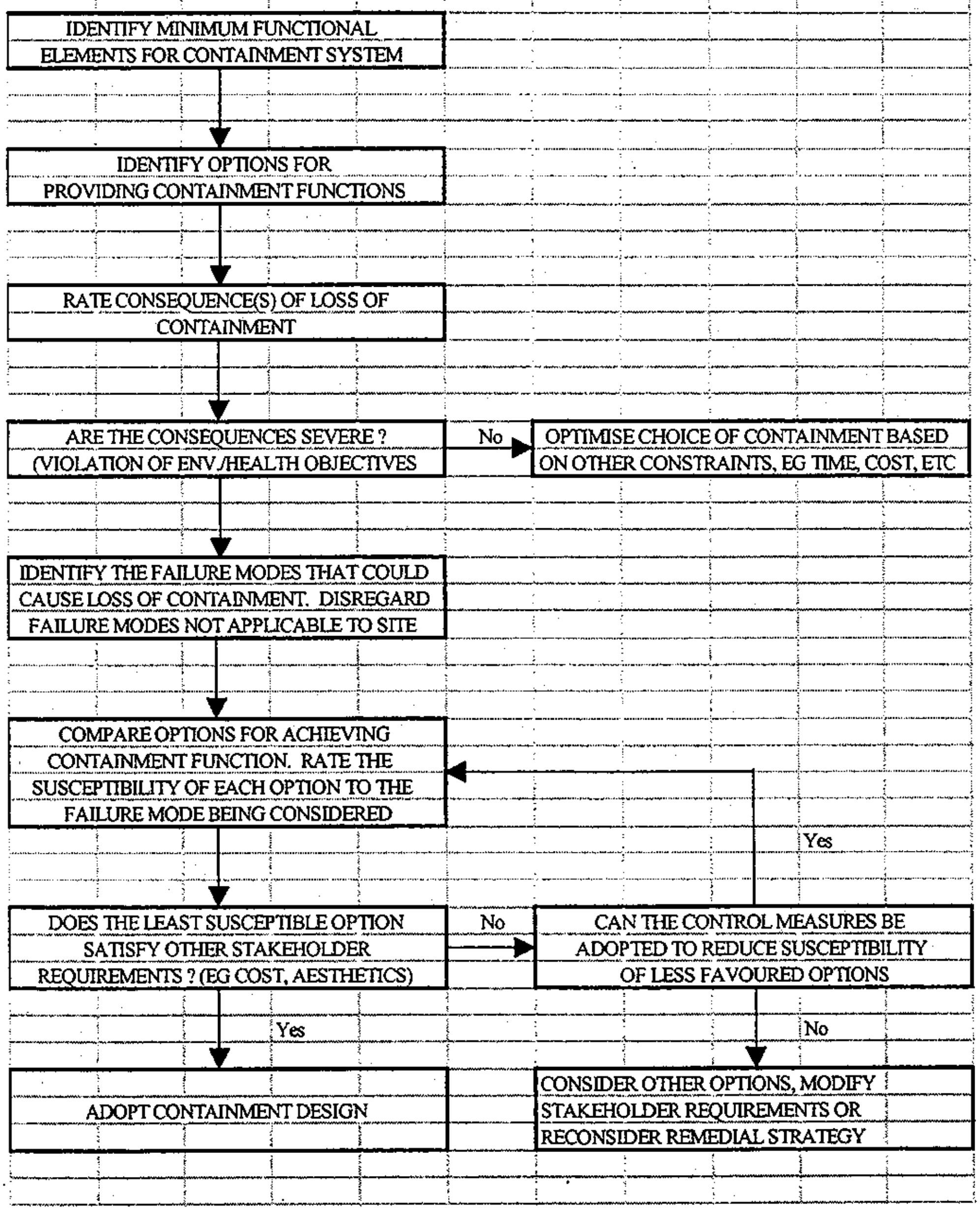


FIGURE 7A
CONTAINMENT SYSTEM DESIGN



8. OPERATIONAL CONSIDERATIONS

Section 8 Summary

Soil waste containment structures are engineered features typically having a design life span ranging from at least fifty years up to several hundred years. Attainment of these design service life spans requires ongoing maintenance and monitoring, in addition to initial careful installation of containment system components. Post-closure uses of sites where on-site containment systems have been installed must accommodate ongoing management requirements of the containment system. As well, a risk based assessment of the compatibility of the two land uses, allowing for partial or total loss of containment is recommended, prior to approving any particular post-closure land use.

The efficacy of any containment system depends appropriate site selection, sound design, careful installation and effective post-installation management practices. The level of post-installation management required must be a key consideration when choosing between containment options.

In the case of soil mono-fills developed for the purpose of contaminated site clean up, it is often necessary to consider how land tenure arrangements may influence post-remediation site management. For example, will the land (and the containment facility) be under government control, under the control of a body corporate, or privately controlled by a company or individual? The management demands of the containment system must be realistically matched to the capability of the likely future controller(s) of the site. Irrespective of the sophistication or simplicity of the management requirements of the facility, they must be documented. Copies of the management plan must be lodged with the site controller and with any regulatory bodies responsible for the enforcement of the plan.

As with any environmental management plan, repository operating plans should clearly identify:

- environmental objectives
- control systems supporting each objective
- maintenance requirements for each control system
- routine monitoring requirements for each control system
- range of acceptable values for monitored parameters
- action levels which trigger intervention in response to monitoring observation
- contingency responses in the event that failure of control systems is identified outside routine monitoring (emergency response)
- a documentation protocol to record maintenance activities, monitoring results, non-conformances, and actions taken to rectify any non-conformance
- a reporting procedure to ensure effective communication of information.

One of the benefits of preparing a post-remediation management plan before construction of the repository, is that it serves to highlight any gaps in the facility risk management strategy. For example, if there are no feasible emergency responses to mitigate serious damage to the environment in the event of accidental loss of containment, the overall site selection and facility design must be reconsidered.

8.1 Post-closure repository management

Typically, post-installation management of a waste containment facility requires consideration of up to five sources of potential impact. They are:

- settlement, slippage or other mass movement of the repository, or of repository components
- failure of drainage systems
- release of leachate through liners (with or without demonstrable impact on groundwater or surface water quality)
- release of gas, dust or odour
- damage to surface infrastructure.

Settlement and Other Movement

Excessive settlement or slippage of soils within or surrounding a large repository may ultimately threaten the stability and integrity of containment structures. Localised settlements may also reduce the effectiveness of drainage systems or gas control networks. For substantial repositories, it would be usual to use precision levelling techniques to periodically check for soil movement. Routine visual inspections by an experienced observer may also help to identify evidence of potentially damaging soil movement. Typical symptoms of settlement or slippage could include cracking or unevenness in surface pavements, localised ponding of rain or runoff water, obvious creep of surface vegetation and topsoil, wet patches indicating localised seepage faces, etc.

Failure of drainage systems

Section 6 described the need for careful design of drainage systems to ensure that water is effectively excluded from the repository, and to minimise ponding of liquids above any low permeability barriers within the repository. Surface drainage systems require periodic maintenance to keep them free of debris and obstructions, and to ensure that ground settlement does not compromise the minimum fall required for gravity flow of water. In repositories incorporating subsurface low permeability barriers, it is advisable to make provision for detection of liquid levels above the barrier. If drainage systems intended to control the head of liquid above the barrier have failed, the first symptom will be an increase in the liquid level above the barrier. This provides an earlier warning of potential loss of containment than does a system relying solely on monitoring leachate below the barrier.

Release of leachate

For repository facilities at which pollution of groundwater or surface waters is a potential concern, it is usual to require two forms of routine monitoring. Monitoring of leachate quality and quantity is carried out within the containment cell. Facility management plans must make provision for ongoing testing of leachate levels, analysis of leachate, and management of leachate in the event that it must be removed from the containment cell. (Typically, management plans require removal of leachate if the head of liquid above a low permeability barrier exceeds about 300mm.)

Monitoring of groundwater (and possibly surface waters) is also routinely carried out as a means of verifying satisfactory control of contaminants in the repository. Monitoring in itself is not a means of controlling contaminants (although this suggestion is sometimes made in proposal for waste repositories). The reliability of groundwater monitoring even as a site management tool (and not a contaminant control method) will be highly influenced by surface conditions and by contaminant characteristics. Fractured rock, lensed alluvial soils and other soils characterised by preferential flow paths may reduce the reliability of a groundwater monitoring network. Similarly, contaminants which react with subsurface materials, or which migrate in a phase separate to water may be difficult to monitor accurately.

Design of a monitoring network for use on a remediated site requires considerable care and skill to ensure that monitoring results can be interpreted unambiguously. Careful thought must also be given when defining monitoring outcomes which will trigger a corrective intervention. Ideally, the monitoring response protocol will already have been defined during the repository design phase, so that there is a clear and logical connection relating possible containment failure modes, estimated groundwater responses, and possible environmental consequences.

As with any groundwater monitoring network, it is necessary to establish background or reference monitoring bores as well as bores intended to intercept any contaminant plumes. Naturally, any bores installed must be constructed in a way that prevents accidental transfer of contaminants to otherwise clean water-bearing zones.

Release of gas or odours

Routine monitoring for volatile contaminants less common for contaminated soil monofills than for putrescible landfills, although the techniques for gas interception and detection would be similar. Generally, gaseous releases from contaminated soil would be of serious concern only in cases where infrastructure (buildings, water pipes, service conduits, etc) is built over, or in very close proximity, to the waste repository.

In designing a gas monitoring and control network, it is important to remember that gas may migrate in different directions and at different rates to water. When defining a gas monitoring response plan, it is advisable to make use of modelling techniques to identify potential "worst case" scenarios which would result in excessive contaminant concentrations at a specified receptor site. Modelling will help in the identification of appropriate sampling locations and sampling times (for example, with respect to climatic conditions), and will assist in selecting appropriate action levels.

Damage to surface infrastructure

The most basic maintenance and monitoring at a soil waste repository site relates to the surface infrastructure. Typical maintenance requirements include mowing of grass covers, ensuring that capping layers are not damaged by growth of large shrubs or trees, ensuring the integrity of surface covers provided for the purpose of erosion control (whether vegetative, earth materials or engineered pavements), maintenance of perimeter fencing or signage, enforcement of any institutional or planning controls on the site (prohibition of vegetable gardens, construction of swimming pools, etc).

Results of routine monitoring of surface conditions, should as a minimum be documented in a written record. Periodically, it is recommended to supplement the written inspection notes with a photographic record. Inspections should be carried out in accordance with a planned schedule, to enable easier comparison between monitoring events.

8.2 Design Life of Soil Containment Facilities

The design life of soil containment facilities will, at best, be limited by the durability of the materials and engineered systems which make up the containment system. A study of the serviceable life of engineered landfill components carried out on behalf of the Government of Ontario (Canada) in 1993 concluded that the likely service life of a number of major engineered components of landfills typically had an uncertainty in the order of $\pm$50% to $\pm$100%. (That is, the best case estimated life span was in the order of 1.5 to 2 times the worst case estimate.) Table 9 summarises the conclusions of this study. The results presented in Table 9 assume appropriate design and construction techniques. Naturally, in cases where construction is faulty or use is made of flawed or unsuitable materials, the life of the containment system will be substantially less. In extreme cases, a badly designed or constructed containment system may never provide secure containment.

TABLE 9.
ESTIMATED SERVICE LIFE OF CONTAINMENT SYSTEM COMPONENTS

Component	Best Case Estimate (years)	Worst Case Estimate (years)
Primary leachate collection system	At least 50	At least 30
Geonet primary leachate collection system	30	Up to 30
Compacted clay liner	At least 500	Hundreds
Geomembrane liners in contact with raw leachate	At least 75	At least 30
Geomembrane liners in secondary system	150	At least 50
Secondary leachate collection system	At least 500	At least 100
Passive hydraulic control system (no pumping)	At least 500	At least 100

Note: Information in Table 9 is based upon "Evaluation of Service Life of the Engineered Components of Landfills: IWA Landfill Search", (Government of Ontario, Canada, 1993). *Both the best case and worst case estimates assume that the component has been appropriately designed for the application, fabricated to meet acceptable specifications and correctly installed.*

8.3 Post-closure Land Use

All soil containment systems require some level of maintenance and monitoring. The extent to which a site used for on-site containment of contaminated soils may be suitable for other land uses depends in part upon whether the other land uses can be carried out in a manner which is compatible with repository maintenance and monitoring requirements. In granting approval for post-closure uses of sites used for disposal of contaminated soil, careful consideration must be given to ensuring the continuation of environmental management controls (for both routine and emergency response conditions). Other considerations for post-closure land use include the necessity of protecting the integrity of the containment structure and the need to maintain an acceptable level of risk in the event of an accidental loss of containment.

These considerations effectively mean that a wider range of post-closure land uses is likely to be possible on sites where the nature of the contamination is relatively benign (typically low contaminant concentration, low water solubility, low water volatility, low toxicity and/or bioaccumulation potential). For example, at a site requiring only physical separation by capping, the capping layer might be provided by a concrete floor pavement or an asphaltic road pavement. If the contaminated soil is placed in a manner that does not affect engineering integrity of the superstructure, these two uses of the site are compatible, providing that the building or the roadway do not limit any necessary maintenance or monitoring of the soil repository.

The precautionary principle dictates that certain post-closure uses - those which would result in a high likelihood of exposure of sensitive receptors in the event of loss of containment - should be avoided. Examples of post-closure uses which are, in principle, incompatible with soil-waste containment storage include single residential dwellings, production of some edible crops or fish (aquaculture), provision of habitat for sensitive flora or fauna.

Changing land use, or even land tenure arrangements, can affect many aspects of the operation and management of a containment structure. The effectiveness of institutional controls is particularly sensitive to changes in land tenure and land management arrangements. Engineering controls such as liners, drains, and capping layers can be seriously comprised or rendered ineffective by uninformed modifications of site surface or subsurface conditions. One approach to systematically considering the suitability of possible post-closure land uses is to make use of the process described in Figure 7A to consider the possible consequences of loss of containment under the proposed new land use arrangements. Particular care should be taken to consider scenarios during construction of the new land use (eg, installation of below ground services) as well as the finished land use scenario.

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APPENDIX A

REGULATORY CONTEXT

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REGULATORY CONTEXT

Following is a brief discussion of regulating issues relating to containment of contaminated soils in each state and territory of Australia..

Australian Capital Territory

The ACT Department of Urban Services is the statutory entity accountable for management of wastes. In general (and in the absence of any specific contaminated land legislation), issues relating to management of contaminated soil are assessed on a case by case basis by Environment ACT. Disposal of wastes (including contaminated soils) to established landfill sites is administered by the Waste Management Unit of the Department of Urban Services. The Waste Management Unit has adopted the use of NSW waste classification and management guidelines for solid wastes.

There is currently no formal process for assessing or approving the establishment of contaminated soil containment units on sites subject to remedial actions. Neither is there provision for formal licensing or registration of such containment facilities. In the event that containment were to be adopted as a remedial strategy for redevelopment of a contaminated site, it is likely that the local planning authority would seek the opinion of Environment ACT as to the suitability of the proposed containment facility in the context of the overall redevelopment plan.

New South Wales

The New South Wales Environment Protection Authority ("NSW EPA") is responsible for approving landfill disposal of solid wastes, including contaminated soils, under the *Waste Minimisation and Management Act* (1995) and *Regulation* (1996). Under the *Contaminated Land Management Act 1997*, NSW EPA would have a specific role in assessing proposals for on site containment of contaminated soils, in addition to their traditional involvement in licensing off-site soil disposal. The assessment/approval role would apply to both statutory and voluntary site clean-ups.

Approvals for landfilling of solid wastes follows a defined planning process which requires formal evaluation of environmental impacts in the case of a site whose chief function is as a landfill. A similar, though possibly less formal, process is likely to apply in cases where soil wastes are contained on sites whose main use is other than waste disposal. (For example, a waste storage area incorporated in an urban commercial redevelopment site.) Soil waste characteristics and solid waste landfill design and operational requirements have been addressed in detailed guideline documents prepared by NSW EPA.

Relevant legislation and guidelines:

- *Managing Land Contamination: Planning Guidelines State Environmental Planning Policy55 - Remediation of Land (1998)*
- *Waste Minimisation and Management Act* (1995)
- *Protection of the Environment Operations Act (1997) and Protection of the Environment Operations (Waste) Regulation* (1996)
- *Contaminated Land Management Bill* (1997)
- *Environmental Guidelines: Assessment, Classification and Management of Liquid and Non-liquid Wastes* (1999)
- *Guidelines: Solid Waste Landfills* (1996)
- *EIS Practice Guideline, DUAP* (1996)

Northern Territory

The body responsible for waste management is the Department of Lands, Planning and Environment. The *Waste Management and Pollution Control Bill* (1996) provides a legal basis for the "prescribing of the procedures...for the appropriate management of wastes and contaminants...and the management of polluted land". At the time of drafting this guideline, no formal guidelines or policies had been issued in the Northern Territory to address the process for gaining approvals to dispose of contaminated soil in on-site containment facilities.

Relevant legislation and guidelines:
- *Waste Management and Pollution Control Strategy (1995)*
- *Waste Management and Pollution Control Bill (1996)*

Queensland

The Department of Environment (Hazardous Wastes and Contaminated Sites Section, Waste Management Branch) has overall responsibility for regulating landfill disposal of solid wastes. Landfill containment of contaminated soils is generally not approved for soils affected by biodegradable hydrocarbons (in such cases, bioremediation is considered the preferred option). For other types of contaminants, on-site containment of contaminated soils is encouraged, providing certain waste characteristic criteria are satisfied. Not all containment designs require liners. Where appropriate to the waste type and site conditions, other options (such as capping or separation layers only) may be approved.

A DoE licence is required to construct and operate a landfill which receives contaminated soil from off-site. In the case of sites not functioning chiefly as landfills, but where containment cells are constructed as part of a site clean-up, no DoE licence is required. However, revisions to the *Contaminated Land Act 1991* have been proposed to ensure that such containment facilities are registered, and that their approved site management plans are implemented.

Contaminated soils are specifically listed under Schedule 8 of the *Queensland Environmental Protection (Interim) Regulation (regulated wastes)*. However, no special solid waste criteria have been developed for soil wastes (or other environmental media), separate to other wastes arising from industrial processes.

Currently, design of significant containment facilities is approved by DoE on a case-by-case basis, as part of the licence approval procedure. However, the *Draft Environmental Protection (Waste Management) Policy* and related regulations have foreshadowed some broad design and operational performance requirements (including post-closure care and maintenance) for various landfill types. Details of smaller on-site containment facilities would be approved as part of a site management plan under the *Contaminated Land Act*.

Relevant legislation and guidelines:
- *Contaminated Land Act (1991)*
- *Environmental Protection Act (1994)*
- *Draft Environmental Protection (Waste Management) Policy*
- *Queensland Environmental Protection (Interim) Regulation (regulated wastes)*

South Australia

The South Australian Environment Protection Authority (Department of Environment, Heritage and Aboriginal Affairs) is accountable for regulation of solid wastes. There is currently no formal process for applying for permission to use on-site containment as a remedial option, although SA EPA have indicated that in the case of high level contaminated wastes, their preferred management approach would involve treatment, then disposal as a "listed waste".

In cases where a very large amount of soil is proposed to be placed in an on-site containment cell, SA EPA may require that the facility be licensed. Irrespective of the size of the containment facility, SA EPA expect to be notified of the condition of the site, so that the information can be included in the state contaminated sites register.

There are no formal approvals processes associated with the construction and operation of on-site soil containment facilities (ie, on sites whose chief use is not as a landfill), however SA EPA expect to be notified and kept informed of any such activities.

SA EPA have issued a set of waste classification criteria specifically targeting soils to be disposed of to (off-site) landfills. These criteria would presumably also be relevant to on-site containment facilities. A consultation draft describing interim criteria for siting, design and operation of "major landfill depots" was released in October 1997.

Relevant legislation and guidelines:

- *Environment Protection Act* (1993)
- *Interim Criteria for Major Landfill Depots in South Australia* (1997)
- *Disposal Criteria for Contaminated Soil (Technical Bulletin No 5* - Nov 1997)

Tasmania

The regulatory authority accountable for management of wastes, including contaminated soils, is the Department of Environment and Land Management. The Department endorses the ANZECC hierarchy of contaminated soil management approaches (ie, treat soil where possible, rather than dispose in landfill), however they are prepared to consider on-site containment options. Assessment of remedial approaches involving on-site soil containment is carried out on a site by site basis. There are no formal approvals, licensing or registration procedures in place for on-site containment facilities. However, the Department is regularly consulted by planning authorities on post-closure or post-redevelopment uses of former contaminated land. The Department indicated that it would generally be unwilling to support post-closure use of containment sites for land uses involving residential development (other than associated passive open space) or for support of structures.

Tasmania has developed a well documented Code of Practice for landfill sites.. Many of the environmental controls identified in the code of practice are relevant to the design and operation of on-site waste soil containment facilities constructed for the purpose of site remediation. It is possible that some of the administrative arrangements for gaining approvals to construct and operate a landfill could be applied to an on-site containment facility. For example, under *the Environmental Management and Pollution Control Act 1994* certain landfills (those receiving more than 100 tonnes/annum of solid waste) are subject to a formal environmental impact assessment procedure.

Relevant legislation and guidelines:

- *Environment Protection (Waste Disposal) Regulations (1974)*
- *Land Use Planning and Approvals Act (1993)*
- *Environmental Management and Pollution Control Act (1994)*
- *Tasmanian Solid Waste Management Policy (1994)*
- *Tasmanian Hazardous Waste Management Policy (1994)*
- *Tasmanian Landfill Code of Practice* (Draft - 1996)

Victoria

The Environment Protection Authority is the government body accountable for regulating waste management and management of contaminated land. There is currently no statutory process by which EPA need to participate in the selection of on-site containment as a remedial option. There is some ambiguity concerning whether EPA may require prior approval for construction of waste containment structures solely intended to accommodate soils from the same site. Potentially, the construction and operation of such a facility may require a Works Approval. Containment facilities accepting contaminated soil from other sites do require formal EPA approval (usually in the form of a Works Approval, then an operating licence).

The EPA Bulletin "*Classification of Wastes*" delineates five main categories of solid waste, three of which are relevant to contaminated soil. There are no generic guideline documents on the design, siting or operation of landfills other than the *State Environment Protection Policy for Municipal Landfills*, which chiefly focuses on environmental outcomes, rather than on design criteria.

Relevant legislation and guidelines:

- *Environment Protection Act*
- *State Environment Protection Policy (Siting and Management of Landfill Receiving Municipal Wastes)*
- EPA Information Bulletin 448 - *Classification of Wastes* (1995)

Western Australia

The Department of Environmental Protection is the statutory body responsible for regulation of wastes and waste disposal facilities. DEP are also accountable for contaminated land regulation. In July 1997, the Environmental Protection Authority released an interim policy entitled, "*A Site Remediation Hierarchy for Contaminated Sites*" (Interim Policy No 17). This document is one in series of publications on policies, guidelines and criteria for environmental impact assessment in Western Australia. In the interim policy document, the EPA states that the use of on-site "cap and contain" remedial options will only be considered in cases where treatment of the contaminated material has been shown not to be practicable.

The Department has developed a set of solid waste classification criteria applicable to soils, as well as to other solid waste streams (domestic waste, industrial process wastes, etc). A key feature of the waste classification system is the use of TCLP test results, and comparison of those results with drinking water criteria. Depending upon the concentration of TCLP-leachable contaminants (and to a lesser extent, the total contaminant concentration), wastes may be accepted by one or more of the five recognised classes of landfill.

Landfills are classified on the basis of level of management control, site characteristics, and type of containment provided. DEP have made specific recommendations concerning siting requirements and engineering features of containment facilities destined to receive "low-hazard wastes". Presumably any similar standards of design would be applied to any requests for approval to construct an on-site soil containment facility.

Relevant legislation and guidelines:

- *Environmental Protection Act, 1986 - 1993*
- *Health Act (1911) (Currently under revision)*
- *Metropolitan Water Supply, Sewerage and Drainage Act (1909)*
- *Country Areas Water Supply Act (1947)*
- *Industrial Waste Management in Western Australia - A Situation Report (August 1992)*
- *Criteria for Landfill Management (1993)*
- *Waste Acceptance Criteria for Landfills in Western Australia (1995)*
- *Proposed Site Selection and Waste Acceptance Criteria for Low-Hazard Waste* (unpublished report)
- *A Site Remediation Hierarchy for Contaminated Sites*, Interim Policy No 17 (July 1997)

TABLE A1
COMPARISON OF CONTAMINATED SOIL CLASSIFICATION SYSTEMS -
TOTAL CONTAMINANT CONCENTRATIONS

Soil Contaminant [1]	NSW SCC2 [2]	NSW SCC3 [3,4]	Vic "Low Level" [5,6,7]	WA Class IVA [8]	SA "Low Level" [10]	US EPA "Bright Line" [11]	BC "Groundwater Protection" [12]	BC Commercial/ Industrial" [3]	NEHF Commercial/ Industrial [14]
Antimony	-	-	-	-	-	310	-	40	-
Arsenic	500	2,000	300	3,000	750	400	15 (60)	300 (150)	500
Barium	-	-	-	-	-	10,000	-	2,000	-
Beryllium	100	400	-	-	150	100	-	8	100
Boron	-	-	-	-	-	-	-	-	-
Cadmium	100	400	50	500	60	390	3 (2.5)	100 (700)	100
Chromium (VI)	-	-	-	-	750	-	-	-	500
Chromium (total)	1,900	7,600	2,500	2,500	-	3,900	60 (60)	500 (800)	-
Cobalt	-	-	500	5,000	1,000	-	-	300	-
Copper	-	-	1,000	10,000	7,500	-	350,000 (30,000)	50,000 (250)	5,000
Cyanide ("amenable" or WAD)	300	1,200	-	-	-	10,000	-	100	-
Cyanide (total or SAD)	5,900	23,600	500	5,000	3,500	-	-	500	2,500
Fluoride	10,000	40,000	4,500	45,000	-	-	-	2,000	-
Lead	1,500	6,000	3,000	30,000	5,000	4,000	4,000 (40,000)	1,000 (2,000)	1,500
Mercury	50	200	20	200	110	70	-	10	75
Molybdenum	1,000	4,000	400	4,000	-	-	-	40	-
Nickel	1,050	4,200	1,000	10,000	3,000	10,000	-	500	3,000
Selenium	50	200	100	1,000	-	3,900	-	10	-
Vanadium	-	-	-	-	-	5,500	-	-	-
Zinc	-	-	5,000	50,000	50,000	10,000	7,500 (550)	30,000 (600)	35,000
Tin	-	-	500	5,000	-	-	-	300	-

TABLE A1 Continued
COMPARISON OF CONTAMINATED SOIL CLASSIFICATION SYSTEMS - TOTAL CONTAMINANT CONCENTRATIONS

Soil Contaminant [1]	NSW SCC2 [2]	NSW SCC3 [3,4]	Vic "Low Level" [5, 6, 7]	WA Class IVA [8]	Qld Industrial Refuse (Unlined)[9]	Qld Industrial Refuse (Lined)[9]	SA "Low Level" [10]	US EPA "Bright Line" [11]	British Columbia "Groundwater Protection" [12]	British Columbia "Commercial/ Industrial" [13]	NEHF "Commercial/ Industrial"[14]
Aldrin					-	-			-	-	-
Dieldrin	<50	<50	-	-	-	-	-	40	-	-	-
Aldrin + dieldrin	<50	<50	-	-	-	-	50	-	-	-	50
Chlordane	<50	<50	-	-	-	-	50	500	-	-	250
DDT	<50	<50	-	-	-	-	50	2,000	-	-	1,000
DDE	<50	<50	-	-	-	-	-	2,000	-	-	-
DDD	<50	<50	-	-	-	-	-	3,000	-	-	-
Heptachlor	<50	<50	-	-	-	-	50	100	-	-	-
Total OCs	<50	<50	10	100	5	10	50	-	-	-	50
Benzene	18	72	-	-	10	20	-	500	0.04 (8)	4,000 (150)	-
Toluene	518	2,073	-	-	300	600	-	520	2.5 (300)	20,000 (30)	-
Ethylbenzene	1,080	4,320	-	-	500	1,000	-	260	7 (1,000)	10,000 (50)	-
Xylenes	1,800	7,200	-	-	250	500	-	320	20 (-)	200,000 (50)	-
BTEX (total)	-	-	70	700	500	1,000	-	-	-	-	-
Total PAHs	200	800	200	2,000	500	1,000	200	-	-	-	-
Benzo(a)pyrene	10	23	-	-	-	-	5	90	- (-)	15 (10)	100
Total PCBs	<50	<50	-	50	-	-	50	1,000	-	15 (50)	5
C6 - C9 petroleum hydrocarbons	650	2,600	1,000	10,000	500	1,000	1,000	-	-	-	50
>C9 petroleum hydrocarbons	10,000	40,000	10,000	100,000	25,000	110,000	10,000	-	-	-	-
Phenols + cresols	518	2,073	10	100	250	500	50,000	10,000	-	5	-
PCP					5	20		6.5 (0.05)	-	3,000 (50)	42,500

TABLE A1 NOTES
(page 1 of 2)

1. All values are expressed as mg/kg on a dry weight soil basis. Unless otherwise indicated, concentrations are for "total" contaminant concentrations.

2. Reference: "*Environmental Guidelines: Assessment, Classification and Management of Non-liquid Wastes*", NSW EPA, July 1997. The SCC2 value is a total contaminant concentration which may not be exceeded in wastes classified as "solid wastes" unless the waste is treated by an approved method to reduce contaminant mobility. This value must be used together with TCLP test results under the NSW waste classification system.

3. Reference: "*Environmental Guidelines: Assessment, Classification and Management of Liquid and Non-liquid Wastes*", NSW EPA, 1999. The SCC3 value is a total contaminant concentration which may not be exceeded in wastes classified as "industrial wastes" unless the waste is treated by an approved method to reduce contaminant mobility. This value must be used together with TCLP test results under the NSW waste classification system. Wastes which exceed the SCC3 value and are not immobilised must be classified as "hazardous wastes".

4. The NSW waste classification system is used by Environment ACT in regulating wastes in the ACT.

5. Reference: "*EPA Information Bulletin 448 - Classification of Wastes*", Victoria EPA, May 1995. The values in the table represent the maximum total contaminant concentrations allowed in soils disposed as "low level contaminated soil". TLCP test results must also be considered when classifying soil waste under the Victorian system. If total concentrations exceed the values in Table A1 or if the leachable contaminant concentrations exceed the values in Table A2, the soil must be classed as "Prescribed Waste".

6. The Victoria EPA soil waste classification system is also used by Environment Tasmania .

7. Criteria for Western Australian waste class IV are identical with the Victoria EPA low level soil criteria. Reference:

8. Reference: "*Proposed Site Selection Criteria and Waste Acceptance Criteria for Low-Hazard Waste in Western Australia*", Western Australia Department of Environmental Protection, 1996. The values shown in the table represent the maximum total concentration allowed in Western Australian wastes classified as "low hazard" wastes. In making this classification, results of TCLP tests must also be taken into account (refer Table A2). If either the total Class IVA or the leachable Class IVA criteria are exceeded, the waste must be treated or classified as a Class V (hazardous) waste.

9. Reference: "*Liquid Industrial Waste Policy and Management Plans*", Brisbane City Council, 1994. Under the Queensland waste classification system, no upper bound is set for total concentrations of many inorganic contaminants in solid industrial refuse, providing leachability criteria are met.

TABLE A1 NOTES
(page 2 of 2)

10. Reference: *EPA Technical Bulletin No 5, "Disposal Criteria for Contaminated Soil"*, SA EPA, November 1997. The values presented in this table represent the maximum concentration of contaminant accepted in soils classified as "low level contaminated soils". The results of TCLP testing must also be considered when classifying soils as "low level" (refer Table A2). If either the values shown in this table or the leachable concentrations shown in Table A2 are exceeded, the waste must be treated or classified as "high level contaminated soil". There are no high level soil waste disposal facilities in South Australia.

11. Reference: United States Federal Register, Part II, Environmental Protection Agency, 40 CFR Part 260, "*Requirements for Management of Hazardous Contaminated Media, Proposed Rule*", 29 April 1996. The soil "bright line" value is the concentration in soil wastes below which soils are no longer subject to regulation as "hazardous waste". See text for further discussion of the "Bright Line" concept.

12. Reference: British Columbia (Canada) *Waste Management Act, Contaminated Sites Regulation, BC Reg 375/96*, 16 December 1996 (effective 1 April 1997). The values presented in this column represent the concentration of contaminant in soil that should not be exceeded if beneficial uses of groundwater (for human consumption) or of surface water (for ecosystem support) are to be protected. Values in parentheses represent environmental criteria; other values were derived on the basis of a human health-based risk assessment. These values are included in Table 1 for comparison with "worst case" situations where no containment is provided and where groundwater or surface waters are potential receptors of stored soil waste.

13. Reference: British Columbia (Canada) *Waste Management Act, Contaminated Sites Regulation, BC Reg 375/96*, 16 December 1996 (effective 1 April 1997). These values are not intended to be applied to soil wastes. They represent Canadian soil quality criteria for land used for commercial or industrial purposes. Values in parentheses represent the lowest "environmental" criterion for this land use category (for example, phytotoxicity, ingestion of soil by animals, damage to microbial processes, etc) excluding the criteria derived for the purpose of protecting water quality. (Refer previous column.) Other values in the table were derived from human health-based risk assessments and typically relate to unintentional ingestion of soil.

14. Reference: National Environmental Health Forum Monograph, Soil Series No 1, *Health-Based Soil Investigation Levels*, 1996. These values are not intended to be applied to soil wastes. They represent proposed Australian soil quality criteria for land used for commercial or industrial purposes. The values shown in the table do not take into account environmental impacts of soil contaminants.

15. A dash "-" means no criteria were provided in the reference document.

TABLE A2
COMPARISON OF CONTAMINATED SOIL CLASSIFICATION SYSTEMS - LEACHABLE CONTAMINANT CONCENTRATIONS

Soil Contaminant [1]	NSW TCLP2 [2]	NSW TCLP3 [3, 4]	Vic "Low Level" [5, 6, 7]	WA Class IV	WA Class IVA [7]	Qld Industrial Refuse (Unlined) [8]	Qld Industrial Refuse (Lined) [8]	SA "Low Level" [9]	US EPA "Bright Line" Groundwater [10]
Antimony	-	-	-	-	-	0.5	5	-	0.1
Arsenic	5	20	5	5	7	0.5	5	5	0.05
Barium	-	-	-	-	-	10	100	-	30
Beryllium	1	4	-	-	-	-	-	1	0.02
Cadmium	1	4	0.5	0.5	2	0.05	0.5	0.5	0.2
Chromium (VI)	5	20	-	-	-	-	-	5	-
Chromium (total)	5	20	5	5	50	0.5	5	-	2
Cobalt	-	-	-	-	-	0.5	5	-	-
Copper	-	-	10	100	2,000	10	100	10	10
Cyanide ("amenable" or WAD)	3.5	14	10	-	70	-	-	10	-
Cyanide (total or SAD)	16	64	10	10	70	1	5	10	-
Fluoride	150	600	150	150	1,500	15	150	-	-
Lead	5	20	5	5	10	0.5	5	5	-
Mercury	0.2	0.8	0.1	0.1	1	0.01	0.1	0.1	0.1
Molybdenum	5	20	-	-	50	0.1	1	-	2
Nickel	2	8	-	-	20	0.5	5	2	7
Selenium	1	4	1	1	10	0.1	1	-	2
Vanadium	-	-	-	-	-	0.5	5	-	3
Zinc	-	-	50	500	-	50	500	250	100

TABLE A2 Continued
COMPARISON OF CONTAMINATED SOIL CLASSIFICATION SYSTEMS - LEACHABLE CONTAMINANT CONCENTRATIONS

Soil Contaminant [1]	NSW TCLP2 [2]	NSW TCLP3 [3,4]	Vic "Low Level" [5,6]	WA Class IV	WA Class IVA [7]	Qld Industrial Refuse (Unlined) [8]	Qld Industrial Refuse (Lined) [8]	SA "Low Level" [9]	US EPA "Bright Line" Groundwater [10]
Aldrin	-	-	-	0.1	-	0.001	0.01	-	0.005
Dieldrin	-	-	-	0.1	-	0.001	0.01	-	0.005
Aldrin + dieldrin	-	-	-	0.1	-	-	-	0.1	-
Chlordane	-	-	-	0.6	-	0.006	0.06	0.6	0.02
DDT	-	-	-	-	-	0.003	0.03	1.3	0.2
DDE	-	-	-	-	-	-	-	-	0.3
DDD	-	-	-	-	-	-	-	-	0.4
DDT + DDE + DDD	-	-	-	0.3	-	-	-	-	-
Heptachlor	-	-	-	0.3	-	0.003	0.03	0.3	0.02
Benzene	0.5	2	-	1	-	0.1	1	1	3
Toluene	14.4	57.6	-	-	-	3	30	14.4	70
Ethylbenzene	30	120	-	-	-	5	50	30	40
Xylenes	50	200	-	-	-	2	20	50	700
BTEX (total)	-	-	-	-	-	5	50	-	-
Total PAHs	NA	NA	-	-	-	0.1	1	-	-
Benzo(a)pyrene	0.04	0.16	-	0.001	-	0.002	0.02	0.001	0.01
Total PCBs	NA	NA	-	-	-	-	-	-	0.01
C6 - C9 petroleum hydrocarbons	NA	NA	-	-	-	25	50	-	-
>C9 petroleum hydrocarbons	NA	NA	-	-	-			-	-
Phenols & cresols	14.4	57.6	-	200	-	7	70	14.4	220
PCP	-	-	-	1	-	0.1	1	-	1.7

TABLE A2 NOTES
(page 1 of 2)

1. All values are expressed as mg/L. Except for the US EPA "Bright Line" groundwater values, the liquid referred to is the leachate from soil extractions performed using the Toxicity Characteristic Leachate Procedure (TCLP).

2. Reference: *"Environmental Guidelines: Assessment, Classification and Management of Non-liquid Wastes"*, NSW EPA, July 1997. The TCLP2 value is a leachable contaminant concentration which may not be exceeded in wastes classified as "solid wastes" The TCLP value must be used together with the total contaminant concentrations (SCC2) listed in Table A1.

3. Reference: *"Environmental Guidelines: Assessment, Classification and Management of Non-liquid Wastes"*, NSW EPA, July 1997. The TCLP3 value is a leachable contaminant concentration which may not be exceeded in wastes classified as "industrial wastes. This value must be used together with total contaminant concentration (SCC3) values listed in Table A1. Wastes which exceed the TCLP3 value must be classified as "hazardous wastes".

4. The NSW waste classification system is used by Environment ACT in regulating wastes in the ACT.

5. Reference: "*EPA Information Bulletin 448 - Classification of Wastes*", Victoria EPA, May 1995. The values in the table represent the maximum leachable contaminant concentrations allowed in soils disposed as "low level contaminated soil". Total contaminant concentrations must also be considered when classifying soil waste under the Victorian system. If leachable concentrations exceed the values in Table A2, the soil must be classed as "Prescribed Waste".

6. The Victoria EPA soil waste classification system is also used by Environment Tasmania .

7. Reference: "*Proposed Site Selection Criteria and Waste Acceptance Criteria for Low-Hazard Waste in Western Australia*", Western Australia Department of Environmental Protection, 1996. The values shown in the table represent the maximum leachable concentration allowed in Western Australian wastes classified as "low hazard" wastes. In making this classification, total contaminant concentrations must also be taken into account (refer Table A1). If either the total Class IVA or the leachable Class IVA criteria are exceeded, the waste must be treated or classified as a Class V (hazardous) waste.

8.Reference: "*Liquid Industrial Waste Policy and Management Plans*", Brisbane City Council, 1994.

TABLE A2 NOTES
(page2 of 2)

9. Reference: *EPA Technical Bulletin No 5, "Disposal Criteria for Contaminated Soil"*, SA EPA, November 1997. The values presented in this table represent the maximum concentration of contaminant accepted in soils classified as "low level contaminated soils". Total contaminant concentrations must also be considered when classifying soils as "low level" (refer Table 2). If either the values shown in this table or the total concentrations shown in Table 1 are exceeded, the waste must be treated or classified as "high level contaminated soil". There are no high level soil waste disposal facilities in South Australia.

10. Reference: United States Federal Register, Part II, Environmental Protection Agency, 40 CFR Part 260, "*Requirements for Management of Hazardous Contaminated Media, Proposed Rule*", 29 April 1996. The groundwater "bright line" value is the concentration in contaminated groundwater wastes below which the water is no longer subject to regulation as "hazardous waste". Health based risk modelling carried when deriving the Bright Line values assumed no attenuation of contaminants (ie direct ingestion of water). No environmental receptors were considered. See text for further discussion of the "Bright Line" concept.

11. A dash "-" means no criteria were provided in the reference document.

APPENDIX B

OVERVIEW OF EXISTING WASTE CLASSIFICATION SYSTEMS

APPENDIX B
OVERVIEW OF EXISTING WASTE CLASSIFICATION STATUS

Numerous systems exist in Australia and overseas for the assessment and classification of soils to be used for various land uses ("soil resource quality assessments"). Relatively fewer systems have been developed specifically for the classification of soils proposed to be disposed of in landfills ("soil waste classification"). In most cases soil waste classification systems have been developed as an extension of the soil resource quality assessments. This has in some instances had the effect of causing soil wastes to be regulated more stringently than are comparable process wastes or other waste streams containing potentially hazardous contaminants.

The US EPA have concluded that the application of stringent waste management criteria (designed to discourage the unnecessary generation of process wastes) to other types of waste, such as contaminated soils, has had a negative overall impact. Specifically, the US EPA considers that over zealous regulation of contaminated environmental media has mitigated against the clean up of some contaminated sites. In order to address this issue, the US EPA has recently released a set of waste criteria specifically targeting environmental media (soil and groundwater). (See reference 30). Under the proposed US EPA environmental media rules, a distinction is made between highly contaminated soil wastes (those exceeding the so-called "Bright Line"), which must be managed under existing hazardous waste approvals systems, and less heavily contaminated soils which may be disposed to landfill or otherwise managed in accordance with requirements imposed by local or state regulatory authorities.

The essential concept of the Bright Line approach is that it provides a legal basis for local or state regulators to impose waste management conditions appropriate to contaminated media at a specific site, and allows the regulators the discretion to recognise certain contaminated soils as a category of waste which does not necessarily require handling as "hazardous waste".

The Bright Line cut-off is based upon total contaminant concentrations in soil, and does not consider leachable contaminant concentrations. The concentrations selected for the soil Bright Line values were derived by considering a level of human health risk (due to ingestion or inhalation of contaminants) of 1×10^{-3} for carcinogenic contaminants and a hazard index of 10 for non-carcinogenic contaminants. The risk assessment assumes that human receptors are in direct contact with the soil waste (ie, the waste is not contained in a repository). Ecosystem impacts are not specifically taken into account. An arbitrary maximum concentration of 10,000 mg/kg was set for any contaminant which did not generate health risk based criteria at a lesser concentration.

Canadian regulators have developed a number of different sets of soil quality standards. These generally refer to soil quality for protection of specified beneficial uses, and as such are not directly applicable to the issue of soil waste disposal in a monofill. However, some of the Canadian soil guidelines do make recommendations for concentrations of contaminants in soil which should not be exceeded in order to protect the quality of underlying groundwater or of nearby surface waters. These criteria have some applicability to waste disposal, in that they represent the worst case condition in which there is a complete failure of all waste containment systems. The soil "groundwater protection" values must be taken as general guidance values only, since they naturally rely on a (very conservative) modelled estimate of contaminant discharge, which would need to be adjusted for individual site conditions.

In Australia, the most comprehensive soil waste classification system is that recently enacted in New South Wales (Reference 23). The New South Wales soil waste classification system is unique in Australia in that it is not derived from a classification system designed to categorise soils according to their suitability for various land uses. In fact, the New South Wales system is largely based upon the US EPA system designed for process wastes (and not the more recent "environmental media" rules). The New South Wales system provides for four different classes of soil waste - "Inert", "Solid", "Industrial", and "Hazardous". Allocation of soils to a waste category requires determination of total contaminant concentrations and (generally) the determination of leachable contaminant concentrations using the Toxicity Characteristic Leachate Procedure (or other approved elutriation test). Under the NSW waste classification system the elements aluminium, barium, boron, cobalt, copper, iron, manganese, vanadium and zinc need not be tested for.

In Queensland, soil wastes proposed for disposal in approved landfills are assessed on the basis of the total concentration of contaminant and leachable contaminant concentrations. In the case of certain inorganic contaminants, including metals, only a leachable contaminant criterion is applied. Different maximum allowable concentration limits apply, depending upon whether the soil is destined for a lined landfill or an unlined landfill. Leachability is assessed using the Toxicity Characteristic Leachate Procedure

APPENDIX C

CONTAMINANTS GROUPED BY ENVIRONMENTAL BEHAVIOUR

APPENDIX C

CONTAMINANTS GROUPED BY ENVIRONMENTAL BEHAVIOUR

GROUP 1

Group 1 soil contaminants include a wide range of inorganic chemicals which have a relatively high water solubility at ambient temperatures. Examples would typically include nitrate, sulphate, some forms of lead, copper, zinc, etc. Contaminants in this group are typically non-carcinogenic, although there are some exceptions (for example arsenic). At the concentrations proposed to be allowed in on-site soil monofills, the Group 1 contaminants would typically not result in acute toxic effects on human health. However they could give rise to human health effects through repeated or continuous long term exposure in the absence of appropriate controls (ie, containment).

Certain contaminants in this group are unusual in that they are relatively harmless to humans, but can have serious environmental impacts, either through their chronic toxic effects on biota (including micro-organisms), or their ability to cause sub-lethal avoidance or yield reduction responses. Copper is a good example of chemicals in the sub-category of "environmentally harmful" inorganics. The key exposure routes for Group 1 contaminants are ingestion of soil, contact with soil (for plants and soil organisms), and ingestion of or contact with groundwater or surface waters.

GROUP 2

Group 2 contaminants include the inorganic chemicals in Group 1. However in Group 2, the contaminants show relatively low water solubility. Therefore, the exposure routes of water ingestion or contact with groundwater or surface waters is of much less importance. To some extent, the exposure route of contact with soils (for plants and soil organisms) is also less important, since the environmentally harmful impact of these inorganic contaminants typically relies on some uptake of the contaminant in a water soluble or an "exchangeable" form. The key exposure routes of concern for Group 2 contaminants are usually ingestion of soil or inhalation of soil dusts.

GROUP 3

Group 3 contaminants are volatile, halogenated organics such as chloroform, trichloroethylene, or vinyl chloride. Many of the Group 3 contaminants are confirmed animal carcinogens and hepatotoxins (liver toxins). These contaminants typically exhibit high water solubility. The Group 3 contaminants are relatively less persistent in the environment than some other halogenated contaminants. In the environment (and in biological systems) they tend to undergo progressive dehalogenation. Group 3 contaminants do not typically bioaccumulate or biomagnify to any important extent. The key exposure routes of concern for Group 3 contaminants are inhalation of soil vapours, contact with soil (for soil organisms), ingestion of groundwater, and contact with groundwater or surface water (for aquatic biota).

GROUP 4

Group 4 contaminants are relatively non-volatile, but moderately to highly water soluble halogenated organics. They include some herbicides (chlorophenoxy compounds such as 2,4-D), insecticides such as Lindane, and a range of chlorophenols. As their uses suggest, these contaminants present particular hazards for the environment, although their acute mammalian toxicity is not particularly great. The Group 4 contaminants are generally more persistent in the environment than are Group 3 contaminants. However, in common with the Group 3 contaminants they do not show any great tendency to bioaccumulate. The key exposure routes for Group 4 contaminants are those affecting environmental receptors, namely contact with soil and contact with groundwater or surface waters.

GROUP 5

Group 5 contaminants are non-volatile, low solubility halogenated organics, such as the cyclodiene pesticides, other pesticides including DDT and its metabolites, and polychlorinated biphenyls (PCBs). This group of contaminants is of particular concern due to the persistence of the chemical contaminants, the tendency of contaminants to bioaccumulate in fatty tissues and the well documented bioconcentration of contaminants which may occur in the environment. The uses of these types of chemicals as insecticides is indicative of the potential for this group of contaminant to have harmful effects on biota. Many contaminants in this group are considered to be carcinogenic or potentially carcinogenic. The concentration of contaminants in wastes proposed for on-site containment would not typically result in acute mammalian toxicity. The main exposure routes for Group 5 contaminants are soil contact (especially for invertebrate species and higher animals in the food chain, but also skin contact with human receptors), and soil ingestion.

GROUP 6

Group 6 contaminants are highly volatile, highly water soluble, non-halogenated organics. Some of the most widely used industrial solvents such as methyl ethyl ketone, formaldehyde and acetone would fall into this group. The most commonly encountered Group 6 contaminant on contaminated sites is benzene. Once released into the environment, these contaminants are very difficult to recover although they biodegrade to some extent and will be retarded in the soil by sorption on soil organic matter. Group 6 contaminants are toxic by inhalation. Some Group 6 contaminants, including benzene, are carcinogenic. The main exposure paths of concern for Group 6 contaminants are inhalation of soil vapours and ingestion of groundwater or surface waters containing dissolved contaminant.

GROUP 7

Group 7 contaminants are moderately soluble, volatile non-halogenated organics. They typically include aromatic petroleum hydrocarbons such as toluene, xylene, and ethylbenzene, together with some other low molecular weight petroleum hydrocarbons. The C_6 - C_9 petroleum hydrocarbons have been categorised as Group 7 contaminants, although they fall on the low end of what would normally be considered "soluble organics". Low molecular weight aliphatic petroleum hydrocarbons may show higher than predicted mobility in the environment in part due to increased aqueous solubility in the presence of salts, and in part due to co-dissolution effects in the presence of monocyclic aromatics. Many of the Group 7 contaminants are organoleptic. That is, they have a low odour or taste threshold which may cause tainting of water supplies and of the flesh of fish and shell fish at low concentrations. The main exposure routes of concern for Group 7 contaminants are inhalation of soil vapours and contact with groundwater or surface waters (for aquatic organisms).

GROUP 8

Group 8 contaminants are highly soluble, non-volatile, non-halogenated organics, such as phenol or similar substituted monoaromatics. When present in chemically available forms, these contaminants are readily absorbed through the skin. However, when present in soils at concentrations below the soil residual saturation limit, the chief hazard presented by Group 8 contaminants relates to the impact of these substances on water quality and well-being of aquatic organisms. This group of contaminants does not bioaccumulate to any appreciable extent. Chemically available forms of these contaminants are susceptible to microbial degradation in soils.

GROUP 9

Group 9 contaminants are moderately soluble, non-volatile, non-halogenated organics, typically with one or two aromatic rings. Examples include dinitrotoluene (from explosives), di-n-butylphthalate (from plastics manufacture) or naphthalene. These contaminants are more mobile in the environment than are the larger polycyclic aromatics. For the most part, Group 9 contaminants are considered only slightly to moderately toxic by ingestion. There is little reported evidence of carcinogenicity or mutagenic effects. The main exposure of concern in soils containing Group 9 contaminants is the potential for bioaccumulation and bioconcentration in animal populations, as some Group 9 contaminants have been reported to cause harmful reproductive effects.

GROUP 10

Group 10 contaminants are very low solubility, non-volatile, non-halogenated organics. They include many polycyclic aromatic hydrocarbons (PAHs), some phthalate esters, and high molecular weight aliphatic petroleum hydrocarbons (C_{10} - C_{40}). Group 10 contaminants typically show high affinity for fatty tissue, and tend to bioaccumulate and to bioconcentrate. Many Group 10 contaminants have been reported to be associated with carcinogenic or tumorigenic effects. Group 10 contaminants are very persistent in the environment. The chief exposure paths of concern for Group 10 contaminants are soil ingestion and (for animal receptors) contact with soil.

APPENDIX D

CONSTRUCTION MATERIALS

APPENDIX D
CONSTRUCTION MATERIALS

D1. INTRODUCTION

The materials used for construction of containment cells fall into the following main classes:

Natural Materials

- Topsoil
- Subsoil
- Clayey soil
- Bentonite
- Sand
- Gravel

Geosynthetic Materials

- Geomembranes
- Geotextiles
- Geonets
- Geogrids
- Geopipes
- Geosynthetic clay liners
- Geodrain

Each of these materials is briefly discussed in the following sections. The selection of construction materials depends on a range of factors including compatibility with waste to be contained, the level of security required, availability and cost. These issues are discussed in later sections.

D2. NATURAL MATERIALS

Topsoil and subsoil can be used to separate human and animal receptors from the contained soil, for landscaping and vegetation support, and to reduce infiltration into the contained soil via water storage and evapotranspiration.

Clayey soil is the traditional material for construction of containment barriers, both for bottom and side-slope lining and for inclusion in cover systems. The clayey soil must be properly sourced, be pre-cured within the required moisture content range (relatively high), be thoroughly compacted in layers and then be protected from desiccation and distortion.

Bentonite is a general term for a class of naturally occurring, highly swelling, smectite clays, usually rich in sodium montmorillonite. These clays can swell to 15 times their dry volume in pure water and to many times their dry volume in most ground waters. They can be mixed at the rate of 3 to 10% with sand or fine soil to produce an homogeneous, deformable barrier of very low permeability. Bentonite combined with other materials, typically geotextiles, is available in sheet form. These materials referred to as geosynthetic clay liners (GCL) are gaining acceptance for containment use, particularly as covering or capping over waste materials.

Sand is widely used for drainage blankets, but these days preference is growing for geosynthetic drains of equal or lower cost.

Gravel is needed for water and gas drainage functions, in drainage trenches, in vertical wells, etc. Coarse gravel may be necessary where chemical and/or biological clogging is anticipated.

D3. GEOSYNTHETIC MATERIALS

D3.1 Applications Using Geosynthetic Materials

Geomembranes are synthetic flexible sheets of very low permeability, typically made from polymers and usually between 0.75 and 2.50mm thick. They are used in various applications which require a low permeability barrier to limit the movement of liquids or gases. High density polyethylene, HDPE, is probably the most widely used geomembrane material. Its popularity stems from its wide ranging chemical stability and biological resistance, price, and the availability of reliable field seaming and seam testing procedures. Descriptions of other common geomembrane materials are provided in Section D3.2.

Geotextiles are permeable fabrics produced by weaving or randomly knitting polymer fibres. Relatively inert polypropylene and polyester are the most commonly used polymers. Geotextiles are used in containments for a variety of purposes including:

- as permeable separators of materials that would otherwise intermingle (soil from gravel for example)
- as protective cushioning layers (above and/or below a geomembrane for example)
- for in-plane transmission of fluids (as a gas drainage layer for example).

Geonets are purpose-designed drainage sheets. They comprise extruded grids designed to provide very high in-plane transmissivity when installed between other geosynthetics, e.g. between two geomembranes, or between a geomembrane and a geotextile. They are usually made of polyethylene, and sometimes of polypropylene or polyester.

Geopipes commonly are pipes made of plasticiser-free PVC, but in aggressive environments, particularly where access is difficult, pipes made of HDPE (more expensive) may be required. The pipes can be smooth-walled or corrugated and are often perforated. Geopipes are used in drainage applications.

Geocomposites are special purpose products made by joining geosynthetics one to another or by joining geosynthetics and natural materials. Two classes of geocomposite are particularly important in the present context:

- *Geosynthetic clay liners (GCLs)* most commonly comprise a layer of bentonite sandwiched between two layers of geotextile. The geotextiles may be linked by sewing through the assembled geocomposite, or by needle punching, which drags fibres from one geotextile through the other, knitting the two together. In its dry state the GCL may typically be about 6mm thick. When hydrated it may be 4 to 12mm thick depending on overburden load. The main types of GCL are described in Section D3.3. Geosynthetic clay liners are most commonly used as bottom or side liners to limit the movement of contaminants. They are less likely to be used in capping systems.

- *Geodrain* sheets may comprise a geonet bonded to a geotextile on one or both sides. Other drain sheets comprise co-extruded fibre mats and geotextile, and still others comprise a vacuum formed drainage core bonded to a geotextile on one or both sides. Such sheets can be used in place of separate geonet and geotextile sheets, which simplifies construction. Another class of geodrain is the strip, core or edge drain, which comprises a narrow (150 to 450mm) but thick (15 to 30mm) drainage core completely sheathed with a geotextile "stocking". Edge drains are designed to have high flow capacities and are installed to receive and remove flows from drainage sheets or drainage blankets.

D3.2 Properties of Geomembrane Materials

Descriptions of various geomembrane materials available are provided below.

D3.2.1 High Density Polyethylene (HDPE)

HDPE, High density polyethylene (HDPE) is a semi-crystalline polymer. Its crystallinity confers high chemical resistance to most aggressive agents (as for all these materials, suppliers can provide data sheets). Carbon black is blended with the polymer to provide resistance to ultraviolet light.

Very reliable methods have been developed for seaming adjoining sheets in the field. The hot wedge automatic welder, in particular, if properly used, produces very reliable dual fusion track welds. These feature two parallel lines of fusion welding with an unwelded strip between them about 10mm wide. Large lengths of seam can be efficiently tested by pumping air into the non-welded channel, sealing, then observing the retention or loss of air pressure.

Disadvantages of HDPE include its high coefficient of thermal expansion, which can make it necessary (in hot environments) to carry out field fabrication at dawn and dusk or at night. When the sheet is hot, large ripples can form which interfere with seaming. It is also necessary to ensure a calculated amount of slack exists before covering HDPE, or anchoring its extremities, if temperature is above the likely future minimum.

HDPE sheet is stiff, which makes fabrication, and installing in peripheral anchor trenches, difficult. Its stiffness also reduces available friction since the sheet deforms less readily to mesh in with underlying surface textures. Low friction, however, is countered reasonably well by the availability of roughly textured sheet, textured one side on both. Textured sheets will adhere to most materials likely to be found on slopes in the range of steepness usually encountered.

An important consideration is the susceptibility to environmental stress cracking. This is a tendency of the semi-crystalline material to crack under sustained (even low) tension, particularly in some alkaline or organic environments. Market-leading products, these days, are made from resins that have been developed to improve resistance to environmental stress cracking. Even so, HDPE proposed for use over materials likely to produce a harsh chemical environment may need to be tested to confirm resistance to stress cracking in that environment - standard tests are available (they take a few weeks). "Cheap" products are available that definitely should be tested. An alternative precaution is to severely limit the tensile stresses likely to develop in a HDPE sheet. Some designers require tensile stresses to be limited to as little as 10% of the yield strength of the membrane (yield strength typically is about 150N/m for each mm of sheet thickness).

Despite these problems HDPE is now widely used for cover barriers. Commonly available thicknesses range from 0.75 to 2.5mm. The thinner sheet is more difficult to weld and defects are therefore more likely; thicker sheet costs proportionally more. For cover barriers thicknesses of 0.75 or 1.00mm are common: thicker membranes are usually chosen for bottom liners. A thinner sheet can be used in a cover barrier because a defect in the cover generally presents less serious problems that would a similar defect in a bottom liner.[6]

[6] The difference can be likened to that between a hole in the roof, and a hole in the floor, of a water tank. There is little head driving leakage through a hole in the roof (or a cover barrier) and it only rains on occasions. There may be a substantial head, all or most of the time, above the floor of a tank (or bottom liner) and leakage could be much more serious.

D3.2.2 Low Density Polyethylenes

VLDPE, LLDPE and VFPE, very low density, linear low density and very flexible polyethylene geomembranes are generally similar to HDPE, but have been formulated to be less crystalline to counter some of HDPE's disadvantages. These membranes are somewhat less stiff; some have lower coefficients of expansion; they have excellent multi-axial elongation properties; they are extremely deformable between yield and break (e.g. 600% post-yield elongation), and are much less prone to environmental stress cracking.

Their chemical resistance and durability tend however to be lower than that of HDPE. When this is not of concern, VLDPE, LLDPE and VFPE provide attractive alternatives to HDPE.

D3.2.3 Polyvinyl Chloride (PVC)

PVC, polyvinyl chloride (PVC) is usually encountered as a brittle solid, but by adding a large quantity of plasticisers (30 to 35% by weight) PVC can be transformed into a soft pliable solid that is suitable for the manufacture of geomembranes. However, reliance on potentially mobile plasticisers makes PVC susceptible to hardening by a wide range of organic chemicals and by ultraviolet light.

Field seaming of PVC is commonly carried out using solvent based adhesives, but thermal fusion using hot air and hot wedge methods is increasingly being used and in good hands is to be preferred. Because of its flexibility PVC membrane can be folded, allowing sheets, say, $2000m^2$ to be factory seamed and delivered to site "accordion style". Factory seaming is carried out using hot air or high frequency welding. In this way 90% or more of all seams can be factory welded under ideal conditions. However this gain, when comparing with alternative membranes, is more apparent than real. PVC sheet is usually manufactured in strips about 2m wide. HDPE membrane is normally supplied in 4.5 to 6.7m wide rolls, each containing about $2000m^2$ of unwelded geomembrane (1.0mm sheet).

PVC geomembrane is competitively priced and it is commonly used. It is a very flexible and amenable geomembrane in situations where the risk of hardening is absent. Many contaminated soil containments would be expected to meet this requirement.

D3.2.4 Flexible Polypropylene

FPP, flexible polypropylene (FPP) geomembranes have been developed relatively recently. Unreinforced sheets are very flexible and have excellent multi-axial elongation properties. They conform well to underlying surface textures, which increases their friction angles. Scrim reinforced sheets (polypropylene calendered over woven polyester fabric) possess high tensile strength, which may be required in certain applications (although not usually in the context of a soil monofill). Chemical and ultraviolet radiation resistance is good. Thermal welding in the field is claimed to be easier than for HDPE.

D3.2.5 Other Geomembrane Materials

CSPE, Hypalon, chlorosulphonated polyethylene is a modified polyethylene that is soft and pliable. CSPE geomembranes are always scrim reinforced. They have good chemical and ultraviolet light resistance and have been used for floating covers. They are less likely to be chosen these days for use as buried layers. They cure with time. When fresh they can be seamed by solvent bonding or by thermal welding. However when they cure (one year), solvent bonding and thermal welding become impossible. Solvent based adhesives must then be used - with difficulty and with unreliable results.

EPDM, ethylene propylene diene monomer (EPDM) is one of the earlier developed geomembranes. It is an elastomer similar to butyl rubber and therefore cannot be thermally welded. The sheet is prefabricated into large sheets with vulcanised seams, and joined in the field using semi-vulcanised tape. EPDM is very flexible, has good resistance to many chemicals and to ultraviolet light, but is not resistant to aliphatic hydrocarbons or to chlorinated solvents. It has a soft surface which provides high interface friction.

EIA, XR-5, ethylene interpolymer alloy (EIA) is an alloy of PVC and an ethylene interpolymer. It has the flexibility of PVC but contains no potentially mobile plasticisers. It is scrim reinforced, is manufactured in strips about 2m wide and is factory prefabricated similarly to PVC. It can be thermal welded in the field. EIA is extremely resistant to most organic and inorganic chemicals. Overall it has excellent properties for use in cover barriers. It is however expensive and most likely would be chosen only when its special properties are indispensable.

D3.3 Composite Product: Geosynthetic Clay Liners

There is a range of liner products incorporating both natural and man-made components. This class of liner is known as a geosynthetic clay liner (GCL). GCLs can be grouped into two categories as follows:

Adhesive Bonded GCL's. GCL's differ primarily in the way the layers of geosynthetic and bentonite are bonded to each other. The earliest GCLs were bonded to the geotextiles, or in some cases to only one geotextile by adding adhesive to the bentonite. The structure of these GCL's limits their usefulness. There is a risk of excessive hydration before an adequate weight of covering materials is in place - the weakened GCL may need to be removed and discarded. Other difficulties encountered with adhesive bonded GCLs include problems with surface loads squeezing the bentonite from place to place, and low shear strength within the bentonite layer. The problem of low shear strength is generally exacerbated by the relatively light weight cover used, particularly on slopes (e.g. using geonet and minimal cover soils). The low confining pressures allow relatively large swelling and consequent lowering of strength in the bentonite layer. These attributes can limit the use of these GCLs to use on surfaces with small slopes.

The problems described have been partially reduced by sewing through the whole structure in parallel lines, commonly 50mm to 100mm apart. The sewing limits swelling, reduces squeezing and limits it to one direction, and adds shear strength by linking the geotextiles and, under light cover, by reducing swelling.

One early form of GCL, which is still available, is different in that a layer of adhesive bonded bentonite is attached directly to an HDPE membrane. Such materials, arguably, could be classes as composite liners. Their use is similarly limited by the risk of premature swelling, risk of squeezing and risk of low shear strength.

Unsewn geotextile versions are being phased out, but the HDPE and sewn geotextile versions remain available. They are very cost effective in applications where their limitations are of no importance.

Needle-punched GCL's. Needle-punched GCLs are more commonly used: often with a geomembrane forming a composite barrier. For use as single component barriers, high quality GCL's are currently more expensive than the geomembranes they might replace and the added expenditure would need to be justified.

Woven and non-woven geotextiles of various weights are used. Strength and ability to retain bentonite, and cost, vary accordingly. Woven fabrics provide higher strength but tolerate low extension. Non-woven fabrics retain bentonite better than woven fabrics.

Single and double needle punching are used, the latter providing higher internal shear strength. In some needle-punched non-woven GCL's the punched-through fibres are fused (heat calendered) to improve pull-out resistance. The fused surface is stiffer and retains bentonite better, both of which may be important in design.

APPENDIX E

DESIGN AND CONSTRUCTION OF RESISTIVE BARRIERS

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E1. COMPACTED CLAY BARRIERS

E1.1 Barrier Design: Minimum Thickness

The thickness of a compacted clay barrier (and more importantly the number of layers or lifts forming the barrier) will also affect the large scale permeability achieved in the field. Benson and Daniel, 1994a and 1994b, (see also Fuleihan and Wissa, 1995) made an in-depth study of this subject. They analysed stochastic models of flow through defects in successive compacted clay lifts, and also analysed a large body of case histories in which large scale permeability tests were carried out. Their conclusions included the following:

- *Decreasing hydraulic conductivity with increasing thickness was observed for poorly built liners and well-built liners. Little reduction in hydraulic conductivity is achieved, however, when the thickness is increased beyond 0.60 - 0.90m (four to six lifts).*

- *If at least four lifts are used, the degree of bonding between lifts, i.e. the degree to which zones of high horizontal hydraulic conductivity at lift interfaces are eliminated, is far more important that the number of lifts. Stated in practical terms, the overall hydraulic conductivity of a well-built liner composed of four lifts will be far lower than the hydraulic conductivity of a poorly built liner containing many more lifts. Adding more lifts beyond a minimum of four to six lifts(0.60 - 0.90m) will not ameliorate the problems left from poor construction (poor bonding between lifts or high mean hydraulic conductivity within a lift).*

- *A reasonable minimum thickness for low-hydraulic conductivity, compacted soil liners is 0.60 - 0.90m (four to six lifts).*

E1.2 Selection and Placement of Clay Used in Low Permeability Barriers

Suitable clayey soils are likely to have a plasticity index between 10% and 30%, be well graded, have more than 30% (by mass) finer than 75 microns, more than 15% clay sized (smaller than 2 microns) and less than 50% gravel sized (Benson, 1991). They should be tested (using flexible wall permeameters) to establish the range of combinations of moisture content and dry density needed to ensure the required low permeability. A typical outcome was reported by Parker and Goad, (1992). The required range of moisture contents was Optimum Moisture Content to Optimum plus 6%, and dry densities needed to be at least 94% of that produced by Standard compaction for the soil at the same moisture content.

Construction practicality and strength considerations are likely to limit the upper bound of acceptable moisture content.

E1.3 Construction Requirements for Compacted Clay Barriers.

Obtaining the required low permeability in the field is the next step. This is usually achieved using sheepsfoot or pad foot rollers. One problem to be overcome is that the needed soil conditioning and compaction procedures run counter to most earthworks operators experience : (high density is not the goal). Compared with normal earthworks (ie compaction for structural reasons) the clay may appear wet, have low strength and upper layer may appear to be poorly compacted. Site specific procedures may be required to handle clay at moisture contents appropriate for barrier construction.

Compaction must remove secondary structure. It is not sufficient that clay clods internally have the required low permeability. Voidy structures between clods must be eliminated. Benson and Boutwell (1992) reported test results from large scale field permeability tests that were as much as 100 times the results from small scale laboratory tests.

Parker, Bateman and Williams (1993) and Trautwein and Williams (1994) discuss the need to perform large scale field tests on finished and/or test pad barriers. These field scale tests may take weeks or months. The records show that permeability can be produced in the field as low as that measured in the laboratory, but only with careful construction procedures under strict quality control.

E2. GEOSYNTHETIC CLAY BARRIERS

2.1 Properties of Geosynthetic Clay Barriers (GCLs).

An important advantage in employing a GCL for cover or capping layers is relative ease of installation. These barriers are very much easier to install than a compacted clay barrier, and also easier to install than a geomembrane. Care is still needed but installation techniques are less specialised. In remote areas this may make GCLs particularly cost effective. GCLs require less stringent surface preparation than do geomembranes, particularly compared with HDPE. Thermal expansion is not a problem because sheets are joined simply by overlapping 0.15 to 0.30m. (Sheet widths are 4.0 to 5.3m.) Woven sheets become sealed one to the other by exuded bentonite. Some non-woven products are provided with a strip of bentonite factory-applied along one edge of the sheet. Others require rolling on, in the field, of a strip of bentonite paste. Patches and modifications likewise can be made later without the need to employ specialists. However, covering before hydration occurs is essential.

The GCLs sealing action is due to the very low permeability of hydrated bentonite. Its coefficient of permeability is commonly in the order of 1 E-11m/s, which is about 100 times lower than that of a well constructed clay liner. Its thickness, correspondingly, is about 100th that of a clay liner so that it offers much the same impedance to flow of water.

The same may not be true for impedance to the movement of some contaminants. Diffusion through a GCL appears to be faster for some substances, than through a compacted clay liner. Diffusion coefficients are generally much lower for bentonite than for soils used in constructing compacted clay barriers, but the small thickness of the bentonite layer affects the rate and magnitude of diffusive transport. (The same can be true of geomembranes.) Moreover, some substances (such as alcohols and organic acids) can affect the hydration of the bentonite and either increase (or decrease) water flow as well. In the presence of chemicals there is a potential for poor containment performance that must be assessed on a product-specific and site-specific basis.

A popular perceived advantage of GCLs is their capacity for self-repair. Because the bentonite is not fully hydrated it has potential to expand to repair small defects. Some recent studies however foster some caution about self repair. Substantial damage by plant roots, and strong desiccation may result in irreversible damage Melchoir, 1997, for example reported severe penetration by plant roots and poor recovery, partly because the sodium bentonite had, as a result of ion exchange, become (less expansive) calcium bentonite.

Another uncertainty with GCLs arises where they are overlain by a drainage layer, particularly by a geodrain. Bulging of the geonet into the apertures of a geodrain (rib spacing may be 10mm) can reduce its transmissivity, by as much as an order of magnitude. A further problem is the risk of exudation of bentonite. This might further jeopardise the geodrain by clogging the remaining spaces, and/or could deplete the GCL of bentonite. A GCL must be carefully selected if it is to interface with a geodrain. A heat calendered surface is expected to perform better in respect to both bulging and exudation. GCLs incorporating a thick geotextile should also be better. Other GCLs may require a relatively thick geotextile to be installed between the GCL and the geodrain - depending on the nature of the geotextile already incorporated.

A further design matter to be addressed is the thickness of cover required to protect the GCL from squeezing aside of the hydrated bentonite under surface loads. Some recent laboratory tests were reported by Koerner and Narejo(1995) and other tests were reported by Jajjar and Bashar(1996) and Battista and Fox(1996). The aim of the testing was to discover how much cover is needed to prevent squeezing of bentonite with surface load taken up to bearing capacity failure within the overlying soils. The testing suggests that cover thickness should be at least 1.5 times the width of the loaded area (for example the width of a vehicular tyre) and preferably 2 times the width of the loaded area. These findings are in general agreement with US Army Corps of Engineers' requirement for a minimum cover of 0.45m (US Army, 1995). It was recommended in Section 6.4.2 that at least 0.3m of cover should be provided over geosynthetics during construction (using low pressure equipment apply loads well below bearing capacity). In the same Section a final minimum cover of 0.6m was recommended over geosynthetics. These are empirical values and are commonly specified as minima (larger minima are sometimes required). The limited experimental evidence available makes them seem realistic.

E3. VERTICAL BARRIERS

E3.1 Slurry Walls

Slurry walls are subsurface walls constructed by slurry techniques. An excavation is made to the required depth using an excavator or "clamshell" which is a purpose-built cable suspended grab designed to produce a relatively narrow trench - 0.6m to 1.2m. Depths as large as 25m are routinely reached. The trench is maintained full of clay-water slurry to support the walls. As water begins to seep out, a filter cake of clay develops to seal the walls. This retains the slurry and enables it to fully support the walls.

The slurry must either be displaced by permanent backfill as excavation advances, or the slurry itself must be capable of hardening into a stable material.

If the trench is to be backfilled, it can either be continuously excavated and backfilled, or be excavated and backfilled in panels. If the former, backfilling will trail some distance behind excavation. The distance will be kept as small as is practicable. If excavation is in panels, alternate panels each a few metres long will be excavated to full depth, then be backfilled and cured. Infill panels will then be excavated and backfilled to complete the cut-off. This is the same procedure as is used to construct diaphragm walls.

If the wall is backfilled, the backfill may be a soil-bentonite mixture, a soil-cement-bentonite mixture, or a soil-cement mixture. Sometimes a low strength concrete mixture is used. In special circumstances high resistance non-corroding cut-offs may be constructed - e.g. using sulphate resisting cement concrete, fly-ash concrete or an asphaltic mixture.

If the slurry used for support is intended to harden it most likely will be a cement-bentonite-water mixture (typically about 6% bentonite w/w, 18% ordinary Portland cement and 76% water).

The coefficient of permeability of a soil-bentonite wall is typically 1 E-9m/s, and that of a cement-bentonite wall about 1 E-8m/s.

The main advantages of slurry cut-off walls were described by Daniel and Koerner (1995) as follows:

- the depth of the trench may be checked to confirm penetration to the desired depth, and excavated materials may be examined to confirm penetration into a particular stratum;

- the backfill can be checked prior to placement to make sure that its properties are as desired and specified;

- the wall is relatively thick (compared to a sheet pile wall or a geomembrane wall);

- there are no joints between panels or construction segments with the most common type of slurry trench cut-off wall construction.

E3.2 Geomembrane Walls

Geomembrane walls are gaining in popularity. They comprise a continuous geomembrane, usually HDPE, installed vertically. The geomembrane may consist of geomembrane panels (1 to 5m wide) joined by preformed edge interlocks, and sealed with an expanding neoprene packer. Alternatively it may be a continuous sheet with welded seams where needed. Common sheet thicknesses are 1.0mm to 2.5mm. A geomembrane can be used to improve slurry walls that otherwise may not have as low a permeability as is required: this may be the case for a cement-bentonite slurry wall for example. Geomembrane walls can also be installed alone, to shallow depths in soft ground, by means of specially designed insertion plates and a vibrator.

E3.3 Sheet Pile Walls

Sheet pile walls comprise interlocking steel or thick geosynthetic sheets about 0.5m wide. For geosynthetics the web thickness is 3mm or more. Steel sheet piles are installed by driving or vibrating into the ground. Geosynthetic sheet piles are installed using driving plates.

Sheet pile walls, historically, have suffered from leakage due to necessary looseness of interlocks and to variable degrees of damage during driving. A recent innovation is the fitting of an expanding neoprene cord within the interlocks to improve sealing - it expands on hydration.

Advantages of sheet pile walls include ease of construction (no excavation is necessary), availability of experienced contractors for installing them, freedom from maintenance, and reasonable cost. Disadvantages include potential for corrosion (of steel in some environments), difficulty of driving in rocky ground, and tendency to leak, particularly when driving is difficult. These disadvantages limit the usefulness of sheet piles for many waste containment projects.

E3.4 Grout Curtains

High pressure grouting can be used to construct vertical barriers. Grouting spears are driven or drilled into place, and grout is pumped out near the head of the spear in stages during withdrawal. The grout is mixed in an agitator and is pumped at the required pressure around a circulation line. The spears are connected to the circulation line by control fittings which provide for regulation of pressure and injection rate.

Ordinary Portland cement grout is widely used (water to cement ratio 0.6 to 1.0), with or without clays, sands or flyash. Ordinary Portland cement however cannot be injected into soils finer than coarse sand. Microfine cement can be used to grout fine sand, but is relatively very expensive. Silicate based grouts can penetrate finer soils. Two components are mixed and chemicals are added to control viscosity and setting time. The grout fills the soil voids with a tough calcium silicate gel of very low permeability. Various organic compounds have also been used for grouting. These usually comprise a monomer, hardener and catalyst which require premixing or injection via a mixing nozzle. Many are now out of favour because of environmental and health considerations, relating either to the components or to the solvents used. Some water based acrylic compounds (with health and safety documentation) are however being introduced. These can also permeate fine soil structure, but they tend to be very expensive.

As a guide, the following table illustrates the limits of usefulness of various kinds of grout -

Type of Grout	Limit of Usefulness (Note 1)
Ordinary Portland Cement	Fissured rock, fissures > 0.5mm
Microfine Cement	Sand, k = 1 E-5m/s
Cement-Bentonite, Bentonite-Water	Gravel and sand, k = 1 E-4m/s
Organic Chemicals	
• dense	k = 1 E-5m/s
• diluted	k = 1 E-7m/s

Note 1 : These are illustrative relative values: many factors affect actual limits, particularly the degree of non-uniformity of void sizes in the soil.

It is judged, from the relatively few references to it in current literature, that grouting is not widely practised for containment of contamination. It would appear technically suitable: but compared with readily applied alternatives many forms of grouting are costly; and widely experienced contractors and operators must be found; and it is an inescapable fact that there is no way of really knowing that the grout has fully penetrated all the intended volume. Nevertheless the potential usefulness of grouting should not be overlooked. The process has a long history of successful application in civil engineering for cutting off and diverting groundwater. There is a wealth of practical experience, albeit the preserve of specialists, and well executed grouting should be able to serve similar functions for the containment of contamination.

APPENDIX F

WATER BALANCE MODELLING

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WATER BALANCE MODELLING

Most infiltration modelling is currently performed using the computer program HELP - Hydrological Evaluation of Landfill Performance - Schroeder et al, 1994. The HELP model was developed by the US Army Corps of Engineers and its development was sponsored and reviewed by the US Environmental Protection Agency (EPA). The input parameters required are: precipitation, daily; temperature, daily; solar radiation, daily; evapotranspiration characteristics; seasonal average wind velocities; and landfill and cap geometry.

The model calculates runoff, infiltration, evapotranspiration and water storage for the numerous layers present, on a daily basis over the period of analysis - commonly 10 years.

The HELP model provides a sophisticated fusion of numerous, long established hydrological and agronomic empirical relationships. Various relationships link rainfall, solar radiation, air temperature, plant growth, evapotranspiration, surface runoff, snowfall and melt, unsaturated permeability, water flow, moisture content and water storage. The model includes recent embellishments to these established relationships, and some new relationships, for example dealing with the factors that determine rates of leakage through geosynthetic membrane liners.

The HELP model is not rigorous. Two problems that have been given some attention in recent times deal with the underestimation of runoff during brief storms of high intensity, and the inability of the model to account accurately for water flow in response to soil water suction gradients - empirical relationships are relied upon above a nominated evaporative zone depth and capillary rise from below the evaporative zone depth is not possible in the model.

More rigorous, but less versatile models have been developed, of the type discussed in the previous section dealing with capillary barriers and monolayer covers. SoilCover, UNSATID, RMA42 and UNSAT-H are such models. SoilCover is typical. It is a one dimensional finite element package that models transient conditions. It predicts the exchange of water and energy between the atmosphere and a soil. The theory is based directly on well known Darcy's and Fick's Laws which describe the flow of liquid water and water vapour, and Fourier's Law which is used to describe conductive heat flow in the soil profile below the soil/atmosphere boundary. SoilCover predicts the evaporative flux from a saturated or an unsaturated soil surface on the basis of daily atmospheric conditions, vegetation cover, and soil properties and conditions. A freezing and thawing formulation is also incorporated.

Soil parameters used are: soil porosity and specific gravity; soil water characteristic curve (soil moisture v. suction); unsaturated conductivity data; thermal conductivity and specific heat versus water content; and some freezing data.

In practice the designer must choose between simpler, easier to use, less accurate, yet conservative models (e.g. HELP) and more accurate, more complex models (e.g. SoilCover) requiring extensive input and formidable computing time.

However, one other, and very important, difference is the ability of HELP to estimate water flows diverted by subsurface lateral drainage layers. Programs such as SoilCover are strictly one-dimensional. They can allow for, but cannot predict, the magnitude of lateral drainage - yet the effectiveness of most cover systems is critically dependent on the efficiency of lateral drainage.

It is concluded that the HELP model is the most appropriate model to use for the design of resistive barrier (i.e. conventional) cover systems. It may over-estimate infiltration, but indications are that over-estimation is probably not serious for a humid climate. Importantly it can be used to assess the relative effectiveness of alternative provisions for lateral drainage. In general it is also expected to display the relative merits of alternative systems. Whilst the estimation of infiltration may not be accurate in absolute terms, the model is regarded as valuable for measuring the relative merits of alternative cover systems. These will range from nearly useless to nearly perfect. It is considered to be of more importance to assess where each of a wide range of systems is on this scale, than to know the exact performance of one or two chosen systems. HELP is practical in this regard, and the model does appear to provide reasonable approximations to actual performance for other than arid areas.

Of equal importance, HELP can provide comparisons between systems with different means of providing lateral drainage. It is believed to be the only model that can do this. The HELP model, despite the need for further refinement, appears to be the most appropriate tool currently available for the hydrological appraisal of conventional barrier cover designs. Accordingly, it is at present almost universally used.

Further information can be found in papers by Fleenor and King (1995), Lange *et al* (1997), Khire *et al* (1997) and Schwarbrick and Koupai (1997).