INDEPENDENT EXPERT GROUP REVIEW OF THE TULLAMARINE LANDFILL MANAGEMENT AND CAP DESIGN

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EXECUTIVE SUMMARY

This report summarizes the review of the closure design and post-closure management for the Tullamarine Landfill (the Landfill) conducted by Edward Kavazanjian, Jr., Ph.D., P.E. , Consulting Engineer, and Richard Thiel, P.E. , President of Thiel Engineering, referred to herein as the Independent Expert Group (IEG). As required by the Terms of Reference prepared by the State of Victoria, Australia, Environmental Protection Authority (EPA), the IEG conducted a critical review of the objectives and proposals for closure and post-closure management of the Landfill against contemporary international best practice standards for similar landfills. The review included review of documents provided by the EPA, the landfill owner, and members of the local community, a site visit, participation in a public meeting at which testimony was given by the landfill owner and members of the community, and independent analyses of cap performance by the IEG.

Review of the proposed final cover designs for the Tullamarine Landfill indicates that the caps as constructed for Mound 3 and as designed for Mounds 1 and 2 meet international best practice standards for hazardous waste final cover (cap) design, construction, and management with four exceptions: absence of a biotic barrier, absence of a free-draining drainage layer, absence of a blanket gas collection layer beneath the entire area covered by the caps, and lack of a comprehensive post-closure Operations, Maintenance, and Monitoring Plan for the site. Absence of a biotic barrier in the Tullamarine cap mandates that appropriate institutional controls be put in place to mitigate the potential for inadvertent intrusion through the cap. These controls should include restricting access to the site and restricting and controlling activities on top of the cap. These controls should be memorialized in a Post-Closure Operations, Maintenance, and Monitoring plan and in deed restrictions.

The saturated hydraulic conductivity of the drainage layers for the Tullamarine caps are from two to three orders of magnitude lower than the value representative of international best practice. Analyses conducted to evaluate the infiltration performance of the Tullamarine caps show that cap performance would have been enhanced by a higher saturated hydraulic conductivity for the drainage layers and could also be enhanced by placement of an additional 30 cm of vegetative soil on the caps. However, the calculated infiltration through the cap as designed (for Mounds 1 and 2) or as constructed (for Mound 3) is very small, on the order of 1.6 mm per century for Mounds 1 and 2 and 2.9 mm per century for Mound 3. This level of infiltration poses no threat to human health or the environment. Due to the cost and risks associated with potential cap enhancements and the high level of environmental protection provided by the caps as built or design, the IEG does not recommend implementation of any of the potential cap enhancements.

The infiltration through the cap depends to a large extent on the size and frequency of defects (holes) in the geomembrane, which in turn depends to a large extent upon Construction Quality Assurance (CQA). Review of the CQA program for the Tullamarine Landfill as implemented for Mound 3 and as described in the design documents for Mounds 1 and 2 indicates it is exemplary and meets all international best practice standards for independent third party monitoring, testing, and reporting. Therefore, the size and frequency of defects in the geomembrane for the infiltration analysis was assumed based upon field data for geomembranes constructed with good CQA. We recommend that a dipole electric leak location survey be performed on the constructed caps to attempt to detect defects in the geomembrane. Based upon the assumption that a reasonable level of sensitivity is achievable, this test can be used as a basis to preclude the existence of any potential large rips or tears in the geomembrane (the primary threat to the integrity and effectiveness of the caps) and possibly may be able to detect small defects. Considering the modest cost of such a survey, we believe the increased confidence in cap integrity and performance provided by the survey justifies it performance.

Independent analyses were also conducted by the IEG to evaluate the impact of the absence of a blanket gas collection layer beneath the entire cap with respect to gas migration control. The IEG analysis was based on a very conservative assumption of a landfill gas generation rate equal to one-half of a typical gas generation rate for municipal solid waste. This analysis indicated a gas pressure buildup below the cap of less than 1% of standard atmospheric pressure, a value within a standard accepted range for landfill cover gas control. This level of gas pressure would not be expected to result in significant pressure-driven gas migration. However, due to the uncertainties associated with the gas generation model, the post closure plan should include gas migration monitoring and contingency measures for additional gas control.

We recommend that a single, comprehensive Post Closure Operations, Monitoring, and Maintenance (OM&M) Plan be developed for the site, consistent with international best practice standards. The Post-Closure OM&M Plan should be reviewed at five year intervals and updated, as needed, by the responsible party for the site.

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1.0 INTRODUCTION

This report summarizes the review of the management and cap (final cover) design for the Tullamarine Landfill, a hazardous waste landfill in Victoria, Australia. This review was conducted by Edward Kavazanjian, Jr., Ph.D., P.E. , Consulting Engineer, and Richard Thiel, P.E. , President of Thiel Engineering, referred to herein as the Independent Expert Group (IEG). The review was conducted in accordance with the Terms of Reference prepared by the State of Victoria, Australia, Environmental Protection Authority (EPA). In accordance with the Terms of Reference, the IEG conducted a critical review of the objectives and proposals for management of the Tullamarine Landfill against contemporary international best practice standards for similar landfills, reviewed the cap design and its ability to meet performance objectives, benchmarked against national and international best practice for landfills containing hazardous waste, and considered enhancements that could be made to the cap design, or other elements contributing to effective management of the landfill, to identify if and where significant improvements could be achieved.

This report and attachments thereto describe the review process and the analyses conducted in support of the review and summarizes of the findings and recommendations of the IEG.

2.0 REVIEW PROCESS

The IEG review included review of documents provided by the EPA, the landfill owner, and members of the local community, a site visit and participation in a public meeting at which one testimony was given by the landfill owner and members of the community by one member of the IEG, and independent analyses of cap performance by the IEG.

Documents reviewed by the IEG included the Principles of the 1970 Environmental Protection Act of the State of Victoria, closure and post-closure operations and monitoring plans for the landfill, reports documenting performance monitoring of the landfill, documentation of the design and construction of the landfill cap, minutes of community meetings and attachments thereto, and miscellaneous correspondence with the EPA from various stakeholders.

3.0 LANDFILL MANAGEMENT

3.1 Overview

As required by the Terms of Reference, the IEG conducted a critical review of the objectives and proposals for closure and post-closure management of the Tullamarine Landfill against contemporary international best practice standards for similar landfills. The review considered community concerns and expectations with reference to the history, current status and possible future use of the landfill as reflected in the community meeting attended by one member of the IEG, in meeting minutes and attachments to the minutes from earlier community meetings, and in miscellaneous correspondence between members of the community and EPA.

3.2 Closure Design and Construction

3.2.1 Best Practice Standards

The primary community concern regarding closure design and construction appeared to be the adequacy of the cap (or final cover) for the landfill. The stated goal of at least one community member was that the landfill cap be not merely an adequate cap but the best possible cap. Several different cap cross sections (including both whole sale revisions of and enhancements to the current cap design) have been proposed by representatives of the community. Concern was also expressed over the potential for lateral gas migration, as reflected by detection of vinyl chloride in ground water beneath the car park for the airport adjacent to the landfill.

As opposed to bottom liner systems for hazardous waste landfills, and as opposed to final cover systems for municipal solid waste landfills, in general, there is not a standard prescriptive design for the final cover of hazardous waste landfills. In fact, in some jurisdictions regulations explicitly state that final cover design is a site-specific consideration and no standard design exists (e.g. US “Subtitle C” regulations for design and operation of hazardous waste landfills). The cap cross section shown in Figure 3.1 is often assumed to represent best practice for design of a final cover at a hazardous waste or low level radioactive waste site (NRC, 2007). A similar design is recommended in guidance provided by the USEPA (1989). Features of this cap include, from bottom to top:

- a prepared foundation layer;
- a composite infiltration barrier layer composed of a low permeability soil layer overlain by a flexible geomembrane barrier layer;
- a cover drainage layer;

- a cover protection layer sometimes referred to as a biotic barrier; and
- an erosion control layer, typically in the form of a vegetated cover layer.

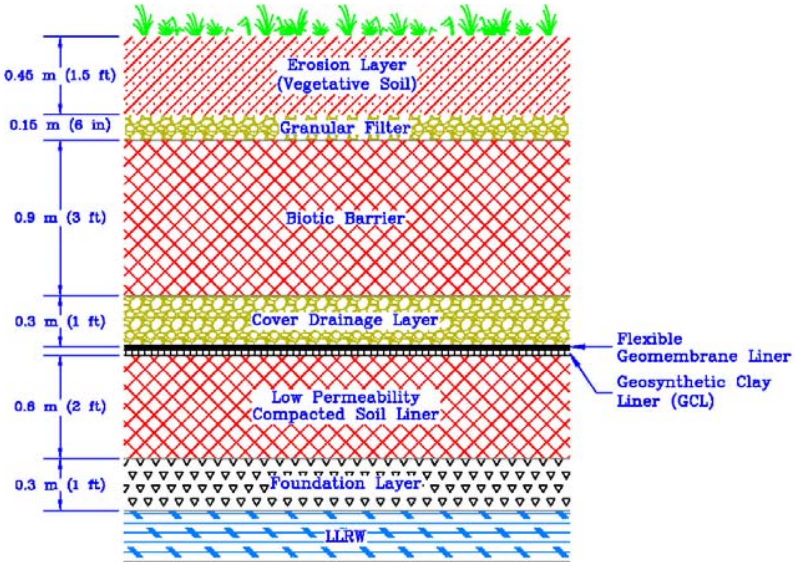

Figure 3.1 Recommended cover cross section for a hazardous waste or low level radioactive waste landfill (NRC, 2007)

While the cross section in Figure 3.1 represents a standard design for final covers at hazardous waste sites, a wide variety of alternative designs have been employed in recent practice and, in fact, alternatives to this standard design, developed on a site-specific basis, have been appearing with increasing frequency. In some cases, the alternative consists merely of a site-specific modification to the standard cross section shown in Figure 3.1. Typical modifications include omission of the biotic barrier layer if institutional controls minimize the potential for inadvertent intrusion through the cap, substitution of a geosynthetic clay liner for the low permeability soil layer, various types of geosynthetic or granular drainage layers, and addition of a gas collection layer beneath the geomembrane if there is concern over the potential for generation of gases in the waste. In other cases, a cap with a completely different infiltration control mechanism may be employed. For instance, evapotranspirative final covers consisting of a single relatively thick layer of vegetated cover soils with appropriate hydraulic properties and no geomembrane or cover layer have been approved and constructed at several hazardous waste sites in the United States, including the Rocky Mountain National Arsenal (Zornberg and McCartney, 2005) and the Operating Industries, Inc. Landfill (Zornberg et al. 2003) Superfund sites.

One best practice feature for cap design not shown in Figure 3.1 is the use of a protective, or cushion geotextile on top of the geomembrane. Infiltration through a composite barrier layer such as the one shown in Figure 3.1 is a function of the number of defects (holes) in the geomembrane barrier. A geomembrane barrier with no holes would effectively eliminate infiltration through the cap and would not require the underlying low permeability soil layer (as this soil layer is a redundant barrier designed to minimize any leakage through defects in the geomembrane). The primary source of defects in geomembrane barriers is punctures that develop during construction from workers and equipment operating on top of the geomembrane in order to place the overlying soil layers. Experience has shown that a cushion geotextile can significantly reduce the number of punctures in a geomembrane due to placement of overlying materials. Other measures that can reduce the number of defects in a geomembrane, and hence minimize infiltration, include a rigorous Construction Quality Assurance (CQA) program during placement of the geomembrane and overlying materials and an electrical leak location (ELL) survey of the geomembrane after placement of the overlying soil layer(s).

As alluded to above, an important component of final cover design and construction is the CQA program. The objective of the CQA program is to monitor and document that the cap has been constructed in accordance with the design intent and in a manner designed to minimize flaws and defects in the cap. International best practice is that this CQA program be implemented by an independent third party (i.e. someone not beholden to the Contractor or the Owner) and include conformance testing of the materials used in cap construction, continuous observation and monitoring of cap construction, and field and laboratory testing of the as-built cap components.

3.2.2 Tullamarine Cap

Comparison of the Tullamarine cap design and construction with the best practice standards described above shows both substantial compliance with best practice standards as well as some deviation from these standards. In general, the cap cross section at Tullamarine complies with the standard cross section shown in Figure 3.1. Exceptions of the cap at Tullamarine from the cross section shown in Figure 3.1 include:

- placement of a blanket gas collection layer under only a portion of the cap (rather than under the entire cap); and
- omission of a biotic barrier above the geomembrane barrier layer.

In addition to the exceptions noted above, the saturated hydraulic conductivity of the drainage layer in the standard cross section shown in Figure 3.1 is from two to three orders of magnitude greater than the design value for the cap on Mounds 1 and 2 and the as-built value for the cap on Mound 3.

Inclusion of the gas collection system is a necessary enhancement to the standard cap design due to the recognized potential for gas generation from the waste at the site. However, because the gas collection layer was not a complete blanket collection layer beneath the entire cap, analyses were constructed to evaluate the efficacy of the limited extent of the gas collection layer at Tullamarine. These analyses are described in a subsequent section of this report.

As noted above, omission of the biotic barrier from the cap mandates that adequate institutional controls be put in place to mitigate the potential for inadvertent intrusion through the cap and into the waste. Institutional control may include restricting access to the site or on top of the cap and restricting and controlling all activities on top of the cap. Perhaps the greatest threats of inadvertent intrusion are presented by transfer of ownership or maintenance responsibility for the site to a third party who is not sensitive to the potential for intrusion through the cap and construction activities associated with post-closure development on top of the cap. Both the EPA and the landfill owner state that that there are no plans for post-closure development on top of the cap at this time and that they anticipate that the owner of the site, Transpac Waste Industries, will maintain ownership and responsible charge of the site for the foreseeable future. As discussed subsequently, these considerations should be memorialized in a Post-Closure Operations, Maintenance, and Monitoring plan and deed restrictions. Furthermore, any changes in site ownership or post-closure use must be subject to review and approval by EPA.

The function of the drainage layer on top of the geomembrane is to minimize the build-up of hydraulic head on top of the geomembrane, and thereby minimize infiltration through defects in the geomembrane, by providing a free-draining lateral drainage mechanism for infiltration that comes through the overlying soil layer(s). The drainage layer materials provided over the Tullamarine mounds are not what would be considered “high permeability,” “free draining” granular soils. The lower saturated hydraulic conductivity of the drainage layers in the

Tullamarine caps could potentially result in an increase in infiltration through the cap due to a buildup of hydraulic head in the drainage layer (and thus on top of the geomembrane), depending on the ability of the overlying vegetative cover layer to limit the flow into the drainage layer through evapotranspirative action. Therefore, analyses were conducted to evaluate the potential build-up of hydraulic head on the geomembrane and the impact of such build-up on infiltration through the cap. These analyses are summarized later in this report and are described in more detail in Attachment 1.

Our review of the CQA program for the Tullamarine Landfill as implemented for Mound 3 and as described in the design documents for Mounds 1 and 2 indicates it is exemplary and meets all international best practice standards for independent third party monitoring, testing, and reporting.

3.3 Post-Closure Site Management

3.3.1 Best Practice Standard

Best practice for post-closure site management generally involves preparation of a comprehensive Post Closure Operations, Monitoring, and Maintenance (OM&M) Plan. Such a plan generally includes a detailed description of the following:

- identification of responsible parties for operation, maintenance, and monitoring of the site, including contact information (address, phone number, email);
- periodic inspections of the cap and monitoring systems, including inspection procedures and reporting requirements;
- procedures for investigating and remediating any deficiencies observed during cap inspections, e.g. excessive erosion or settlement, unhealthy vegetation, or ponding of water on the cap after a storm, and documentation and reporting requirements for any remedial action;
- other regular operations and maintenance activities at the site, including a operation of any mechanical equipment and monitoring systems, a schedule of maintenance activities, and record keeping and reporting requirements;
- site monitoring systems and procedures, including a schedule of monitoring and reporting activities and reporting requirements;
- trigger levels for monitoring parameters at which investigation and/or remedial action is required and the procedures to be followed once a trigger level is reached;
- procedures to be followed in the event of an extreme event (e.g. wildfire, flood, windstorm, airplane crash), including inspection and reporting;

- approved contractors for monitoring, repairs, and remedial actions;
- a cost estimate for 30 years (this is the standard minimum time-frame used in the United States) of post-closure operations, maintenance, and monitoring, including provisions for an foreseeable remedial action; and
- a financial assurance mechanism to provide for the estimate 30-year cost of post-closure operations, maintenance, and monitoring.

The Post-Closure OM&M Plan should be continuously updated, as needed, by the responsible party for the site. All updates to the OM&M Plan should be reviewed and approved by the governing regulatory body (EPA Victoria). Furthermore, a comprehensive review of the OM&M Plan should be conducted at 5-year intervals. While current practice is to not consider the financial aspects of the OM&M Plan in the periodic review, there is a growing recognition that for many sites, including most hazardous waste sites, OM&M will extend well beyond the initial 30-year post-closure period. Therefore, consideration should be given to reviewing the 30-year OM&M cost estimate and financial assurance provisions as part of each 5-year review.

3.3.2 Tullamarine Cap

No comprehensive OM&M Plan is currently available for the Tullamarine site. Separate monitoring plans for several of the existing monitoring systems are either available or in preparation. Discussions with EPA indicate that a Post-Closure Operations and Maintenance Plan including consideration of financial responsibility is being prepared for the site. We recommend that a single, comprehensive OM&M Plan be prepared for the site consistent with the best practices described above.

4.0 CAP PERFORMANCE ANALYSES

4.1 Overview

Independent analyses were conducted by the IEG to evaluate the performance of the Mounds 1 and 2 cap as designed and the Mound 3 cap as constructed with respect to infiltration control and gas migration control. Performance analyses were also employed to evaluate potential enhancements to the as-designed and as-constructed caps. These analyses included evapotranspirative infiltration analyses to evaluate the potential for build-up of hydraulic head on top of the geomembrane barrier layer, analyses of the leakage through the composite geomembrane-low permeability soil barrier layer due to a build-up of hydraulic head on top of the cap, and analysis of gas pressures and venting beneath the composite barrier layer.

The evapotranspirative analysis of the potential for hydraulic head build-up on top of the geomembrane was based upon properties of the overlying soil as documented in the Construction Quality Assurance reports for Mound 3 and as called for in the specifications for Mounds 1 and 2. Climate records from Weather Station No. 86282 at the Tullamarine International Airport adjacent to the site were employed in the analysis. The evapotranspirative analysis employed the computer programs HELP (Schroeder at al., 1994) and UNSAT-H (Fayer, 2000).

Analyses of the leakage through the composite barrier layer were based upon the Giroud equation for leakage through defects in the geomembrane component of a composite barrier layer, the hydraulic head calculated in the evapotranspirative infiltration analysis, an assumed frequency and size of defects in the geomembrane based upon typical values from the literature, and the saturated hydraulic conductivity of the low permeability soil component of the composite barrier layer. For the analyses of the as-constructed cap for Mound 3, the saturated hydraulic conductivity of the low permeability soil component of the composite barrier layer was based upon the results of Construction Quality Assurance (CQA) testing. For the analyses of the as-designed cap for Mounds 1 and 2, the design value of the saturated hydraulic conductivity of the low permeability soil layer was employed.

Analyses of gas pressure buildup beneath the cap were based upon the following assumptions: 1) the gas generation rate was 50% of the typical generation rate for municipal solid waste (MSW) landfills containing putrescible (organic degradable) waste, 2) the spacing of geosynthetic strip drains installed beneath the cap for gas collection purposes was 40 m, and 3) a gas permeability for the waste immediately beneath the cap was based upon typical values from the literature.

4.2 Water Infiltration Analyses

The infiltration analyses of the cap were conducted by modeling the water balance in the vegetated soil layer overlying the geomembrane and then predicting the net flux of water through defects in the geomembrane and the underlying soil layer and into the underlying waste. Table 4.1 presents the as-designed soil profile assumed for the cap on Mounds 1 and 2 and the as-constructed profile for the Mound 3 cap employed in the infiltration analyses.

TABLE 4.1 - Cover Profiles

Mounds 1 & 2 (from top to bottom)

Layer	Thickness (mm)	Permeability (cm/s)
Topsoil	150	$3.7\text{x}10^{-4}$
Subsoil (Upper)	300	$2\text{x}10^{-5}$
Subsoil (Lower)	300	$1\text{x}10^{-4}$
Geotextile	> 3.0 (min mass 350 g/m^2)	NA
Geomembrane	≥ 1	NA
Select Compacted Clay	200	$1\text{x}10^{-8}$
Compacted Clay	300	$1\text{x}10^{-6}$

Mound 3 (from top to bottom)

Layer	Thickness (mm)	Permeability (cm/s)
Uncompacted Topsoil	150	$3.7\text{x}10^{-4}$
Compacted Subsoil	600	$1\text{x}10^{-4}$
Geotextile	min mass 270 g/m^2	NA
Geomembrane	≥ 1	NA
Select Compacted Clay	200	$1\text{x}10^{-8}$
Compacted Clay	300	$1\text{x}10^{-6}$

Notes:

1. The permeability of the “Select Compacted Clay” below the geomembrane is specified to be a maximum value of 1E-07 cm/s. For our base-case analyses, we assumed it to be a lower value of 1E-08 cm/s. This is based on the results of the CQA report for Mound 3 where all 5 tests on the hydraulic conductivity of this clay layer were reported as less than 1E-09 cm/s. We conservatively increased this by a factor of 10 to account for the laboratory confining pressure used during the test and a safety factor.
2. For the Mound 3 cap, the “Compacted Subsoil” was specified to have a lateral permeability > 2.5E-05 cm/s. For our base-case analyses, we assumed the higher (as-built) value of 1e-04 cm/s, which was based on the CQA report for Mound 3.

Infiltration analyses were also conducted to assess the sensitivity of the final cap analyses to the properties of various cover components and to evaluate potential enhancements to cap hydraulic performance. The sensitivity variables that were evaluated in the infiltration analyses included:

- Drainage layer properties
- Hydraulic conductivity and thickness of low permeability (i.e., clay) layer
- Composition and thickness of overlying cover soils (i.e., topsoil/subsoil layers)

The net flux into the waste through the as-designed cap for Mounds 1 and 2 and the as-built cap for Mound 3 was compared to the net flux through a standard US Environmental Protection Agency “Subtitle C” cap which was taken as representative of the international best practice standard.

A two-step approach was used in the analysis as follows: (1) the water balance of the soil and drainage layers above the geomembrane was modeled to determine the average head buildup within the cover profile, and (2) percolation, or, leakage rates through the composite geomembrane-low permeability soil barrier layer and into the waste were calculated based on the well-known semi-empirical “Giroud” equation. For the analysis of the average head buildup with each cover profile, the computer programs HELP and UNSAT-H were employed in an iterative manner to develop consistent input parameters based upon the evapotranspiration model in UNSAT-H and the algorithm used in HELP to evaluate the buildup of hydraulic head in a drainage layer (these are considered to be the relative strengths of these two programs). The final HELP parameters were employed in an analysis that assumed ten consecutive “average” years with respect to the climate to predict the average head buildup in the drainage layer on top of the geomembrane.

Figure 4.1 shows the difference among the various cover configurations evaluated in the infiltration analyses with respect to the average annual head in the drainage layer. Infiltration through the cap and into the waste may be assumed to be proportional to the average head in the drainage layer.

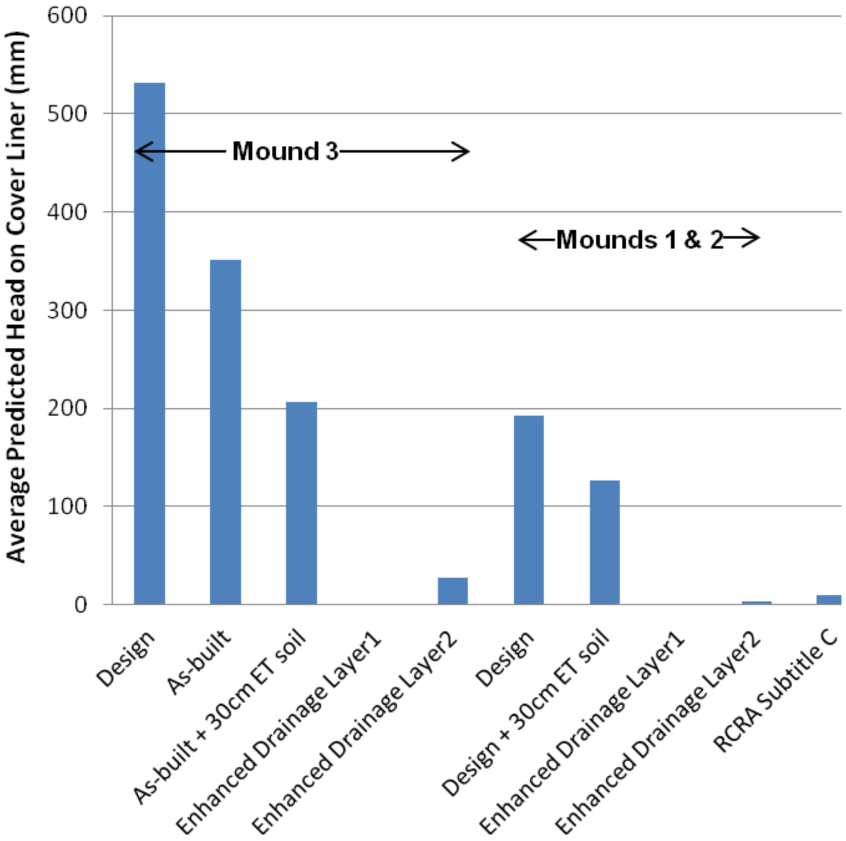

Figure 4.1 – Average head predictions

The analysis of the leakage through the composite geomembrane-low permeability soil layer required assumptions of the size and frequency of defects in the geomembrane. The leakage evaluation assumed six 1 cm^2 holes per hectare of geomembrane cover. This assumption represents a conservative assumption for a geomembrane protected by a cushion geotextile and based on experience with electric leak location surveys on projects with good quality assurance controls and is consistent with our review of the construction documents (Mound 3 Audit) and observations made during the site visit by Dr. Kavazanjian in December 2010. We kept the number and size of holes the same for all of our computations so that relative comparisons could be made among the different cover configurations presented in Table 4.2. While a different defect frequency and/or size may change the calculated infiltration into the waste, the relative value of infiltration among the various caps considered in the analysis should remain approximately the same. Furthermore, the primary threat to cap integrity are large rips or tears in the geomembrane, a possibility we assume is precluded by the use of good CQA practices. As discussed (and recommended) subsequently, this assumption can be substantiated by an electrical leak detection survey of the caps.

Additional details regarding the approach and assumptions used for the infiltration modeling are presented in Attachment 1. Results of the infiltration analyses are summarized in Table 4.2.

The results of the analyses presented in Table 4.2 indicate the following:

- The difference between constructing 20 cm and 100 cm of select clay below the geomembrane is relatively insignificant.
- The calculations for the existing cover systems suggest that, on average, they will allow 1.6 mm per century of water infiltration in Mounds 1 and 2 and 2.9 mm per century of water infiltration in Mound 3.
- The calculated average infiltration values for the existing cover systems, while small, are 3 to 6 times greater than the performance calculated for the recommended RCRA Subtitle C cap design as described by the USEPA.
- The calculated average infiltration is reduced by approximately 40% with the addition of 30 cm of loamy topsoil to the existing covers to enhance water storage and evapotranspiration.
- Water infiltration could have been reduced to de-minimis levels if a more highly transmissive drainage layer been installed over the top of the geomembrane.

TABLE 4.2 - Average Annual Percolation Predictions Through Final Cover Sections (mm/yr)

Clay Layer Thickness, Permeability	Mound 3					Mounds 1&2				RCRA Subtitle C "Guidance" Cover [3]
	Design	As-built	As-built + 30 cm ET soil	Enhanced Drainage Layer[1]	Enhanced Drainage Layer[2]	Design	Design + 30 cm ET soil	Enhanced Drainage Layer[1]	Enhanced Drainage Layer[2]	
20 cm, 10^{-6} cm/s	1.349	0.869	0.507	0.000	0.076	0.474	0.315	0.000	0.011	0.005
20 cm, 10^{-7} cm/s	0.246	0.158	0.092	0.000	0.014	0.086	0.057	0.000	0.002	
20 cm, 10^{-8} cm/s	0.045	**0.029**	0.017	0.000	0.003	**0.016**	0.010	0.000	0.000	
100 cm, 10^{-6} cm/s	1.136	0.770	0.469	0.000	0.075	0.441	0.300	0.000	0.011	

Notes:

[1] Drainage Layer consists of geocomposite with transmissivity, T = $2x10^{-3}m^2/s$.

[2] Drainage Layer consists of 30 cm of $1.0x10^{-2}$ cm/s sand.

[3] RCRA Subtitle C cover includes a 60cm compacted clay layer with permeability less than $1.0x10^{-7}$cm/s, overlain by geomembrane, overlain by 30 cm thick drainage layer with k=0.01 cm/s.

[4] Percolation calculations assume six 1 cm^2 holes per hectare in the geomembrane, and 'good' contact with the underlying clay.

4.3 Gas Control Analysis

It is commonly observed that installation of a low-permeability cover system over old landfills that lack bottom liner systems can exacerbate lateral gas migration problems because the free-surface venting of gases from the top of the landfill is eliminated. To address this issue it is common to construct a gas-collection-and-extraction layer directly beneath the final cover system and, if needed, introduce an active (i.e. suction-based) gas collection system. The current design of the Tullamarine cover systems includes a dendritic network of strip-drains and collector pipes leading to one central vent at the crest of the landfill mounds for passive gas collection and venting or flaring.

The IEG was asked to provide an opinion regarding the adequacy of the constructed gas venting system to prevent lateral gas migration. To provide a basis for this opinion, the IEG performed an analysis to estimate the gas pressures that might build up below the new final covers based on a very conservative assumption of a landfill gas generation rate equal to one-half of a typical gas generation rate for municipal solid waste (MSW). In reality, the gas generation rate at the Tullamarine landfill is likely less than 10% of the typical gas generation rate for MSW because of the lack of a substantial quantity of putrescible waste at Tullamarine.

The calculations used to estimate that gas pressures were based on the method developed by Thiel (1998). The assumptions, input parameters, and results are shown on the spreadsheet output presented in Attachment 2. The analyses were based on the assumption that a typical spacing between gas vent strips on the Tullamarine caps is 40 m (based on the design drawings for Mounds 1 and 2), that the liquid hydraulic conductivity of the waste near the surface is approximately 2×10^{-3} cm/s (a typical value for MSW). The results indicate a gas pressure buildup below the cap of less than 1 kPa. This level of gas pressure would represent less than 1% of standard atmospheric pressure and is within a standard-accepted range for landfill cover gas control. Furthermore, this level of gas pressure would not be expected to result in significant advective (pressure-driven) gas migration. However, if monitoring indicates that lateral gas migration is occurring at the site, additional gas control could be provided, as necessary, by the application of suction on the cover vent and/or installation of vertical extraction wells around the perimeter of the cap.

5.0 SUMMARY AND CONCLUSIONS

5.1 Summary

Review of the proposed final cover (cap) designs for the Tullamarine Landfill and of international practice for closure of hazardous waste sites indicates that the caps as constructed for Mound 3 and as designed for Mounds 1 and 2 of the Tullamarine Landfill meet international best practice standards for hazardous waste cap design, construction, and management with four exceptions: absence of a biotic barrier, absence of a free-draining drainage layer, absence of a blanket gas collection layer beneath the entire area covered by the caps, and lack of a comprehensive post-closure Operations, Maintenance, and Monitoring Plan for the site. Institutional controls compensate for the absence of a biotic barrier to mitigate the potential for inadvertent intrusion through the cap. Numerical modeling was conducted to evaluate the impact of the absence of a free-draining drainage layer and of a blanket gas collection layer beneath the entire area covered by the cap on cap performance. Numerical modeling of the gas collection system was also conducted.

Numerical modeling of cap performance resulted in an estimated infiltration through the as-built or as-designed caps over the first 100 years of post closure care to be in the range of 1.6 to 2.9 mm per century (0.016 to 0.029 mm per year) over the 39 hectare cap. This is an annual infiltration rate of 0.4 to 0.7 microns of liquid per hectare, less liquid than would be applied to a dinner plate with a single pull of the trigger of a spray bottle. While the anticipated infiltration of surface water through the caps and into the waste is very small and poses no threat to human health or the environment, a free draining drainage layer would have reduced the estimated infiltration through the caps to even lower *de-minimus* levels. The analysis also suggests that placement of an additional 30 cm of vegetative cover soil on the caps would reduce the anticipated infiltration by approximately 40 percent.

Numerical modeling of the gas management system based upon very conservative assumptions regarding the gas generation rate indicates that the passive gas collection system, composed of a gas collection blanket of limited extent and dendritic geosynthetic strip drain collectors, should be adequate to minimize the build-up of gas pressure beneath the cap and thereby control lateral gas migration. Expected gas-pressure buildup below the existing constructed caps is estimated to be less than 1% of standard atmospheric pressure, and therefore gas migration is not expected to be of concern. However, post-closure monitoring of subsurface gas concentrations to monitor the effectiveness of the gas control system is required, as the impact of capping on gas generation is somewhat unpredictable. The post-closure management plan should include contingency plans for enhancing the gas collection system by installing an active collection system (i.e. placing a vacuum on the gas collection layer) and/or installing vertical gas extraction wells around the perimeter of the landfill in the event that monitoring indicates that lateral gas migration is occurring.

Construction quality assurance (CQA) is essential to establishing that a cap has been constructed in a manner such that it will perform as intended by the design. Review of the CQA report for Mound 3 and of the CQA plan for Mounds 1 and 2 construction shows that CQA for construction of the caps for the Tullamarine Landfill meet international best practice standards. An electrical leak location survey would help validate assumptions made regarding the frequency and size of cap defects (a key factor in estimating infiltration) which were based upon field data from caps constructed with good CQA, thereby enhancing confidence in the leakage estimates and cap performance.

Continued environmental monitoring and operation and maintenance of the environmental control systems at the site are essential components of post-closure care. No comprehensive post-closure operations, maintenance, and monitoring (OM&M) plan was available for review. However, some individual monitoring plans exist and we understand that other plans for post-closure OM&M are in preparation. International best practice for a comprehensive post-closure OM&M plan includes a description of monitoring systems, monitoring parameters, and monitoring schedules, provisions for inspection of the cap and gas management and monitoring systems on a regular basis and after extreme events that could impact their integrity, standard procedures for maintenance and repair, documentation and reporting requirements for these activities, a 30-year post-closure care cost estimate, provision of financial assurance for the post-closure care costs, and periodic review and revision of the post-closure plan.

5.2 Conclusions and Recommendations

- The as-constructed cover for Mound 3 and the as-designed cover for Mounds 1 and 2 for the Tullamarine Landfill provide a very high level of environmental protection. (The quality of construction for Mounds 1 and 2 is inferred to be similar to that reviewed for Mound 3).

- Numerical modeling of cap performance resulted in an estimated infiltration through the as-built or as-designed caps over the first 100 years of post closure care to be in the range of 1.6 to 2.9 mm per century (0.016 to 0.029 mm per year) over the 39 hectare cap. This is an extremely small level of infiltration and poses no threat to human health or the environment.

- Performance modeling of the gas collection system suggests that it is adequate to control the low level of gas generation expected at the site. However, post-closure monitoring of subsurface gas concentrations and contingency provisions for active gas collection and/or installation of supplemental vertical gas collection wells are recommended due to the uncertainties associated with the modeling.

- Although in hindsight it is clear that certain design and construction measures could have been taken to further improve the infiltration performance of the Tullamarine final cover systems, we do not recommend physical changes to improve the constructed cover systems. The caps provide a very high level of infiltration control and the risk of construction damage associated with additional construction on top of the already constructed covers and the cost of such construction outweighs the benefit. Taking into consideration the results of the infiltration analyses that indicate that the existing caps provide a high level of environmental protection, this conclusion is in the spirit of the Principles of the Environment Protection Act (1970).

- We recommend that a dipole electric leak location survey be performed on the constructed caps to attempt to detect defects in the geomembrane in accordance with ASTM Test Method D7007. It cannot be known ahead of time what level of sensitivity (i.e. size of hole) this type of survey will have for the constructed caps, as that will have to be determined during calibration of the test on site. However, based upon our assumption that a reasonable level of sensitivity is achievable, this test can be used as a basis to preclude the existence of any potential large rips or tears in the geomembrane (the primary threat to the integrity and effectiveness of the caps). The survey may possibly even be able to detect small defects in the geomembrane. Any defects that are detected by the survey can easily be repaired by carefully digging up the cover soils at those locations, performing repairs on the geomembrane in accordance with standard procedures, and replacing the cover soils. Considering the modest cost of such a survey, we believe the increased confidence in cap integrity and performance provided by the survey justifies it performance.

- Development of a comprehensive, integrated post-closure Operations, Maintenance, and Monitoring Plan with financial assurance and periodic reviews is recommended for compliance with international best practice standards.

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ATTACHMENT 1

FINAL COVER LEAKAGE EVALUATION - MOUNDS 1, 2 & 3

TULLAMARINE HAZARDOUS WASTE LANDFILL

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1.0 INTRODUCTION

The team of Richard Thiel (Thiel Engineering) and Edward Kavazanjian (Consulting Geotechnical Engineer) were selected by the EPA Victoria to review the Tullamarine Cap Design. Among the tasks assigned to our review team were the following, which define the scope of results reported in this attachment:

- Model the expected performance of the Tullamarine landfill cap (Mounds 1, 2, and 3) with regard to water infiltration
- Compare the predicted performance with international best practice standards

The hydraulic performance analyses of the cap presented herein were conducted by modeling the water balance in the vegetated soil layer overlying the geomembrane and then predicting the net flux of water through defects in the geomembrane and the underlying soil layer and into the underlying waste. The net flux into the waste through the as-designed cap for Mounds 1 and 2 and the as-built cap for Mound 3 was compared to the net flux through a standard US Environmental Protection Agency “Subtitle C” cap which was taken as representative of the international best practice standard. In the course of this final cover performance evaluation, the review team identified the characteristics of the soils above and below the geomembrane cover as key aspects of the cap configuration that warranted attention. Therefore, the hydraulic performance analyses of the cap in this study included modeling the effect of enhancing the properties of the underlying soil layers on the net flux of water into the waste. The final cover profiles (as-designed cap for Mounds 1 and 2 and as-built for Mound 3) that were employed in the performance analyses described herein are presented in Table 1.

As noted above, final cover performance modeling included an assessment of the sensitivity of the net flux into the waste to the properties of various cover system components to provide a relative numerical assessment of existing and alternative final cap profiles and thereby provide a means for quantitatively assessing the potential for enhancing cap performance. The sensitivity variables that were evaluated as part of this study included:

a) the hydraulic conductivity of the drainage layer above the geomembrane;
b) the hydraulic conductivity and thickness of low permeability (i.e., clay) soil layer beneath the geomembrane; and
c) the composition and thickness of cover soils overlying the drainage layer (i.e., topsoil/subsoil layers).

2.0 APPROACH

A two-step approach was used to calculate the net flux of water through the cap and into the waste. The two-step approach used in the analysis was as follows: (1) the water balance of the soil and drainage layers above the geomembrane was modeled using the computer programs HELP (Schroeder at al., 1994) and UNSAT-H (Fayer, 2000) to determine the average hydraulic head buildup on top of the geomembrane component of the geomembrane-low permeability soil composite barrier layer, and (2) percolation, or leakage, through the geomembrane-low permeability soil composite barrier layer was calculated based on the well-known semi-empirical "Giroud" equation for leakage through defects (holes) in a composite barrier layer and a size and frequency of defects if the geomembrane assumed on the basis of typical values for geomembrane caps constructed with good Quality Assurance procedures.

2.1 Water Balance Modeling

To obtain predictions of the average hydraulic head on top of the geomembrane, the water balance of the various cover profiles was modeled using a combination of the HELP and UNSAT-H computer models. HELP is a 'quasi 2-dimensional' simplistic water balance model (Schroeder et al. 1994) and UNSAT-H is a more rigorous 1-dimensional finite difference model that employs Richards' equation for evapotranspirative unsaturated flow (Fayer 2000). Both models are commonly used for design of landfill cover systems in the United States and other countries.

The HELP and UNSAT-H models were set up using the same or equivalent climate, soil, and vegetation input to the greatest extent possible (considering the different algorithms employed in each model). Initially, a particular cover configuration was analyzed using the HELP model. The daily lateral drainage from the HELP output was then used to create a 'specified flux' lower boundary condition in UNSAT-H (such that the flow into the drainage layer on top of the geomembrane in the UNSAT-H model would be the same as it was in the drainage layer for the HELP model). The 1-D UNSAT-H model (including only the soil layers above the drainage layer) was then run with the specified flux lower boundary condition to evaluate the head build-up in the drainage layer. The results of the UNSAT-H simulations provide more rigorous estimates of evapotranspiration (ET) than the HELP model. Therefore, the HELP model was re-run adjusting input parameters such as 1) Evaporative zone depth, 2) Leaf Area Index, and 3) surface runoff curve number until the evapotranspiration and runoff predictions from HELP matched those of UNSAT-H. This process was repeated until the results of the two models converged. Once the results from the HELP and UNSAT-H models converged, an average precipitation year (2000) was repeated for ten consecutive years using the HELP model in order to reach steady state conditions. The resulting average annual head predictions from the 10th year of this HELP run were used for the leakage calculations.

The water balance analysis described above was repeated for each cover configuration presented in Table 2. The results of the water balance analysis were then input to the leakage calculations described in the next section. Climate parameters input to the water balance analyses were based upon climate records from Tullamarine International Airport adjacent to the site. Input parameters for the water balance analyses are described in Section 3 of this report. Results of the water balance analyses are described in Section 4 of this report.

2.2 Leakage Calculations

The average annual head on the liner from year 10 (steady state) of the ten-year HELP simulations were used to calculate leakage through the composite liner system based on the Giroud equation for leakage through defects in composite liner systems (Giroud et al. 1997). Consistent with our review of the CQA data for Mound 3 and the CQA program for Mounds 1 and 2, CQA for geomembrane installation and placement of the overlying soil was assumed to be "good".

The leakage evaluation assumed six 1 cm^2 holes per hectare of geomembrane cover. This assumption represents a conservative assumption for a geomembrane protected by a cushion geotextile and based on experience with electric leak location surveys on projects with good quality assurance controls and is consistent with our review of the construction documents (Mound 3 Audit) and observations made during the site visit by Dr. Kavazanjian in December 2010. We note that the previous Golder (2001) infiltration analysis assumed 6 smaller holes on the order of 0.1 cm^2 in area (one-tenth the size assumed herein) per hectare and zero larger holes. We note that the predicted leakage depends directly on the size and frequency of holes (defects) in the geomembrane. The leakage rate varies linearly with the number of holes, assuming they are all the same size. We kept the number and size of holes the same for all of our computations so that relative comparisons could be made among the different cover configurations presented in Table 2. As discussed in the accompanying main report, we recommend that an electric leak location survey be performed on the completed caps to preclude the existence of any 'very large' holes that could potentially exist as a result of construction activities and, possibly, depending on the sensitivity of the survey, validate our assumptions regarding the frequency of large holes in the geomembrane.

Only the top 20 cm of the low permeability soil layer was considered in the leakage calculations. As described by Giroud et al. (1997), a higher permeability layer underlying a lower permeability layer will have no effect on advective water flow. Thus the lower 30 cm of $1x10^{-6}$ cm/s low permeability soil in the Mounds 1, 2 and 3 caps was not considered in the leakage calculations. Results of the leakage analyses are described in Section 4 of this report.

3.0 WATER BALANCE MODEL INPUT

3.1 Climate

Climate data input to the water balance analyses were based upon climate records from Weather Station No. 86282 at Tullamarine International Airport adjacent to the site. To initialize the water balance model, an average precipitation year (2000) was repeated ten times. Inspection of model outputs for years 9 and 10 indicate that this was sufficient to reach steady state conditions in each model. For HELP simulations, daily values of measured precipitation, temperature, and solar radiation were input into the model. For UNSAT-H, daily values of precipitation and potential evapotranspiration (PET) are required as input. As PET values were not available from the weather station data, the daily PET values were calculated as 90% of measured pan evaporation data at the site. Figure 1 shows the monthly precipitation and simulated PET values used in the water balance analyses.

3.2 Soil Properties

The hydraulic parameters for the soil layers in the various cross sections considered in the analysis were based either on measured or design values where available and on default parameters from the HELP model for representative soil types where necessary (i.e. where they were not available from measurements of soil used in construction or from design documents). For the upper subsoil layer, unsaturated flow hydraulic properties were based on the estimated soil-water characteristic curves (SWCCs) reported by Golder (2010). To obtain the unsaturated flow input parameters for UNSAT-H, these SWCCs were fit with a van Genuchten equation fitter (van Genuchten 1980) such that porosity, field capacity and wilting point were consistent with the respective values for this soil layer in the HELP model. A pore-interaction term of -1 was conservatively assumed for all soil layers. Figure 2 shows the SWCC curves used in the water balance analyses.

The saturated hydraulic conductivity of the various soil layers were based on design values for Mounds 1 and 2 since QA data from construction of these layers is not yet available. For Mound 3, the as-built condition was simulated using saturated hydraulic conductivity testing data from construction adjusted for field conditions. In adjusting the saturated hydraulic conductivity for field conditions, the average measured values from laboratory CQA tests were increased by an order of magnitude to account for higher confining pressure in the laboratory tests compared to the filed condition and the fact that the hydraulic permeability from large-scale field tests (e.g. sealed double ring infiltrometer tests) are typically several times greater than the values measured on small-scale laboratory specimens.

In the analyses of potential enhancements to the cap, the supplemental cover soil was assumed to have the same properties as the upper subsoil layer in Mounds 1 & 2. For purposes of relative comparison, the topsoil and subsoil layer properties in the benchmark RCRA Subtitle C cover were assumed to be equal to those from the other covers evaluated.

3.3 Vegetation Properties

The vegetation data was primarily based on Golder's previous model input, which included a growing season from Julian day 60 to Julian day 365 each year, maximum leaf area index of 2.0, and evaporative zone/root depth of 40cm, which experience has shown to be conservative. In UNSAT-H, the percent bare area was assumed to be 50%, based on recommendations in McGuire et al. (2009).

3.4 Profiles

The final cover profiles simulated in the analyses are shown in Tables 1 and 2. In general, the cover configurations for Mounds 1 & 2 and Mound 3 each included four different combinations of low permeability soil layer thickness and saturated hydraulic conductivity (including the as-built or as-designed combination, as appropriate). Furthermore, each configuration was evaluated for two enhanced drainage layer scenarios and for the case of 30 cm of supplemental cover soil placed on top of the as-built or as-designed covers. The enhanced drainage layers considered in the analyses consisted of 1) a geocomposite with a transmissivity equal to 2×10^{-3} m^2/s, and 2) the recommended RCRA Subtitle C drainage layer of 30 cm of 1×10^{-2} cm/s soil (EPA, 1989). The final cover on Mound 3 was evaluated for both the as-built and as-designed conditions, with the as-built analyses taking into account the fact that the saturated hydraulic conductivity of the low permeability soil as constructed was less than the design value. In addition, the performance of the RCRA Subtitle C cover recommended by the USEPA (1989) subject to the Tullamarine climate conditions was modeled as the best-practice alternative for comparison to the Mounds 1 and 2 and Mound 3 caps described above.

4.0 RESULTS

The average annual head showed a strong dependence on the properties of the drainage layer. The thickness of the evapotranspirative cover soil layer also had an impact on average annual head values. Figure 3 shows the average annual head calculated for the various cover configurations considered in the water balance analyses.

Differences in the average annual head translate directly to differences in average annual leakage, or percolation, through the cover and into the waste. Average annual percolation predictions for the various cover configurations considered in the analyses described above are shown in Table 2. The following observations can be made based upon these results:

- The difference between constructing 20 cm and 100 cm of select low permeability soil below the geomembrane is relatively insignificant.
- The calculations for the existing cover systems suggest that, on average, they will allow 1.6 mm per century of water infiltration in Mounds 1 and 2 and 2.9 mm per century of water infiltration in Mound 3. These are extremely small values that present no threat to human health or the environment.
- The calculated average infiltration values for the existing cover systems, while small, are 3 to 6 times greater than the performance calculated for the RCRA Subtitle C cap design recommended by the USEPA (1989).
- The calculated average infiltration is reduced by approximately 40% with the addition of 30 cm of loamy topsoil on top of the existing covers to enhance water storage and evapotranspiration.
- Water infiltration could have been reduced to *diminimis* levels (values representative of the RCRA Subtitle C cap design recommended by USEPA (1989)) if a more highly transmissive drainage layer been installed over the top of the geomembrane.

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TABLE 1
Cover Profiles

Mounds 1 & 2 (from top to bottom)

Layer	Thickness (mm)	Permeability (cm/s)
Topsoil	150	$3.7\text{x}10^{-4}$
Subsoil (Upper)	300	$2\text{x}10^{-5}$
Subsoil (Lower)	300	$1\text{x}10^{-4}$
Geotextile	> 3.0 (min mass 350 g/m^{2})	NA
Geomembrane	≥ 1	NA
Select Compacted Clay	200	$1\text{x}10^{-8}$
Compacted Clay	300	$1\text{x}10^{-6}$

Mound 3 (from top to bottom)

Layer	Thickness (mm)	Permeability (cm/s)
Uncompacted Topsoil	150	$3.7\text{x}10^{-4}$
Compacted Subsoil	600	$1\text{x}10^{-4}$
Geotextile	min mass 270 g/m^{2}	NA
Geomembrane	≥ 1	NA
Select Compacted Clay	200	$1\text{x}10^{-8}$
Compacted Clay	300	$1\text{x}10^{-6}$

Notes:

1. The permeability of the “Select Compacted Clay” below the geomembrane is specified to be a maximum value of 1E-07 cm/s. For our base-case analyses we assumed it to be a lower value of 1E-08 cm/s. This is based on the results of the CQA report for Mound 3 where all 5 tests on the hydraulic conductivity of this clay layer were reported as less than 1E-09 cm/s. We conservatively increased this by a factor of 10 to account for the laboratory confining pressure used during the test and a safety factor.
2. For the Mound 3 cap, the “Compacted Subsoil” was specified to have a lateral permeability ≥ 2.5E-05 cm/s. For our base-case analyses, we assumed the higher (as-built) value of 1e-04 cm/s, which was based on the CQA report for Mound 3.

TABLE 2
Average Annual Percolation Predictions Through Final Cover Sections (mm/yr)

Clay Layer Thickness, Permeability	Mound 3					Mounds 1&2				RCRA Subtitle C "Guidance" Cover [3]
	As-Designed	As-built	As-built + 30cm ET soil	Enhanced Drainage Layer[1]	Enhanced Drainage Layer[2]	As-Designed	Design + 30cm ET soil	Enhanced Drainage Layer[1]	Enhanced Drainage Layer[2]	
20 cm, 10^{-6} cm/s	1.349	0.869	0.507	0.000	0.076	0.474	0.315	0.000	0.011	0.005
20 cm, 10^{-7} cm/s	0.246	0.158	0.092	0.000	0.014	0.086	0.057	0.000	0.002	
20 cm, 10^{-8} cm/s	0.045	**0.029**	0.017	0.000	0.003	**0.016**	0.010	0.000	0.000	
100 cm, 10^{-6} cm/s	1.136	0.770	0.469	0.000	0.075	0.441	0.300	0.000	0.011	

Notes:

[1] Drainage Layer consists of geocomposite with transmissivity, $T = 2x10^{-3} m^2/s$.

[2] Drainage Layer consists of 30 cm of $1.0x10^{-2}$ cm/s sand.

[3] RCRA Subtitle C cover includes a 60cm compacted clay layer with permeability less than $1.0x10^{-7}$cm/s, overlain by geomembrane, overlain by 30 cm thick drainage layer with k=0.01 cm/s.

[4] Percolation calculations assume six 1 cm^2 holes per hectare in the geomembrane, and 'good' contact with the underlying clay.

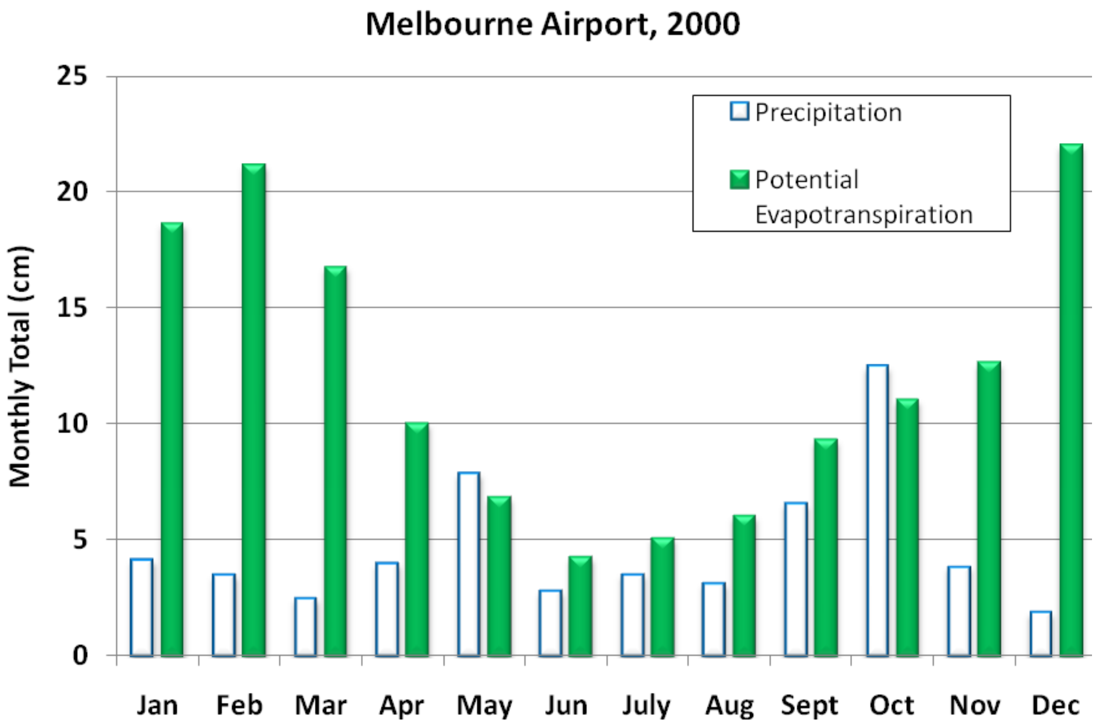

Figure 1 – Simulated Monthly Precipitation vs PET Totals

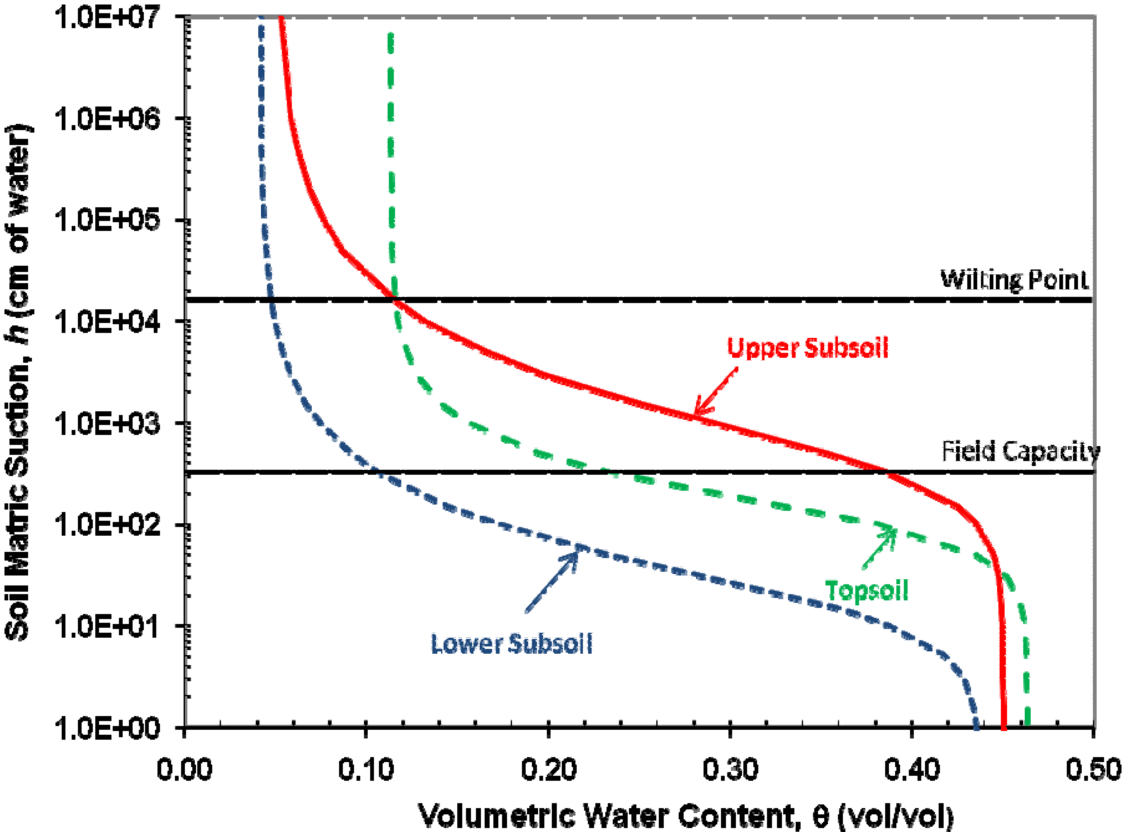

Figure 2 – Soil Water Characteristic Curves of Simulated Soils

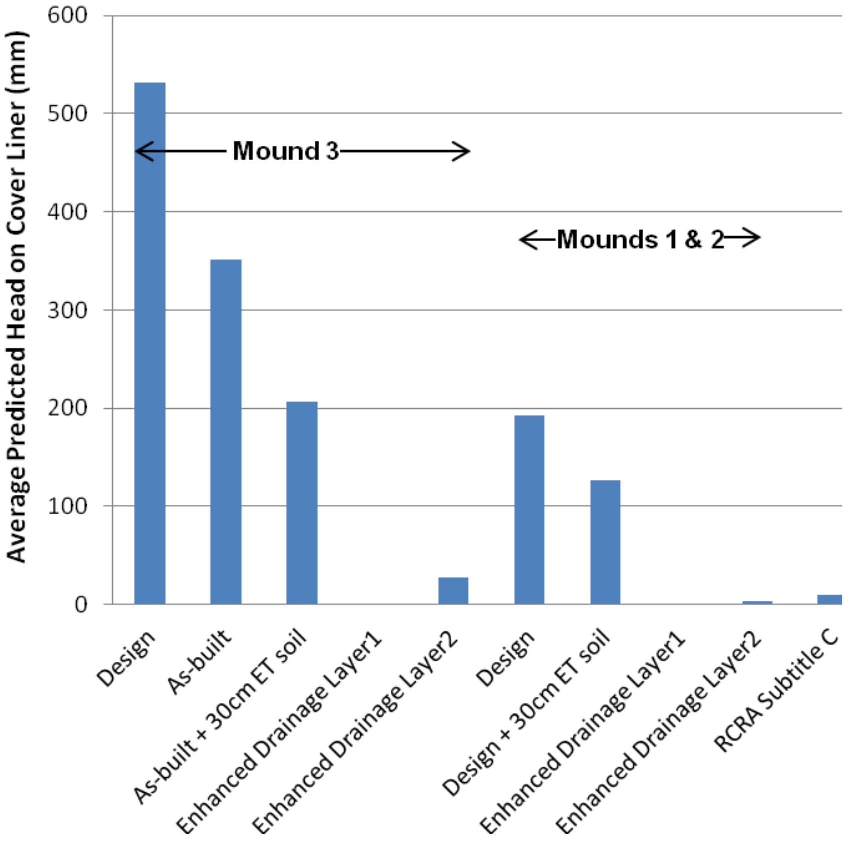

Figure 3 – Average Head Predictions

Notes: Enhanced Drainage Layer 1 consists of a geocomposite with transmissivity, T = 2.0 x$10^{-3}$$m^2$/s, Enhanced Drainage Layer 2 consists of 30 cm of 1.0x10^{-2} cm/s sand

ATTACHMENT 2

GAS PRESSURE AND VENTING EVALUATION

TULLAMARINE HAZARDOUS WASTE LANDFILL

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GAS PRESSURE AND VENTING EVALUATION

The calculations used to estimate that gas pressures were based on the method developed by Thiel (1998). The assumptions, input parameters, and results are shown on the attached spreadsheet output. The analyses were based on the assumption that a typical spacing between gas vent strips on the Tullamarine caps is 40 m (based on the design drawings for Mounds 1 and 2), that the liquid hydraulic conductivity of the waste near the surface is approximately $2x10^{-3}$ cm/s (a typical value for MSW). The analyses were also based on a very conservative assumption of a landfill gas generation rate equal to one-half of a typical gas generation rate for municipal solid waste (MSW). In reality, the gas generation rate at the Tullamarine landfill is likely less than 10% of the typical gas generation rate for MSW because of the lack of a substantial quantity of putrescible waste at Tullamarine.

The results indicate a gas pressure buildup below the cap of less than 1 kPa. This level of gas pressure would represent less than 1% of standard atmospheric pressure and is within a standard-accepted range for landfill cover gas control. Furthermore, this level of gas pressure would not be expected to result in significant advective (pressure-driven) gas migration. However, if monitoring indicates that lateral gas migration is occurring at the site, additional gas control could be provided, as necessary, by the application of suction on the cover vent and/or installation of vertical extraction wells around the perimeter of the cap.

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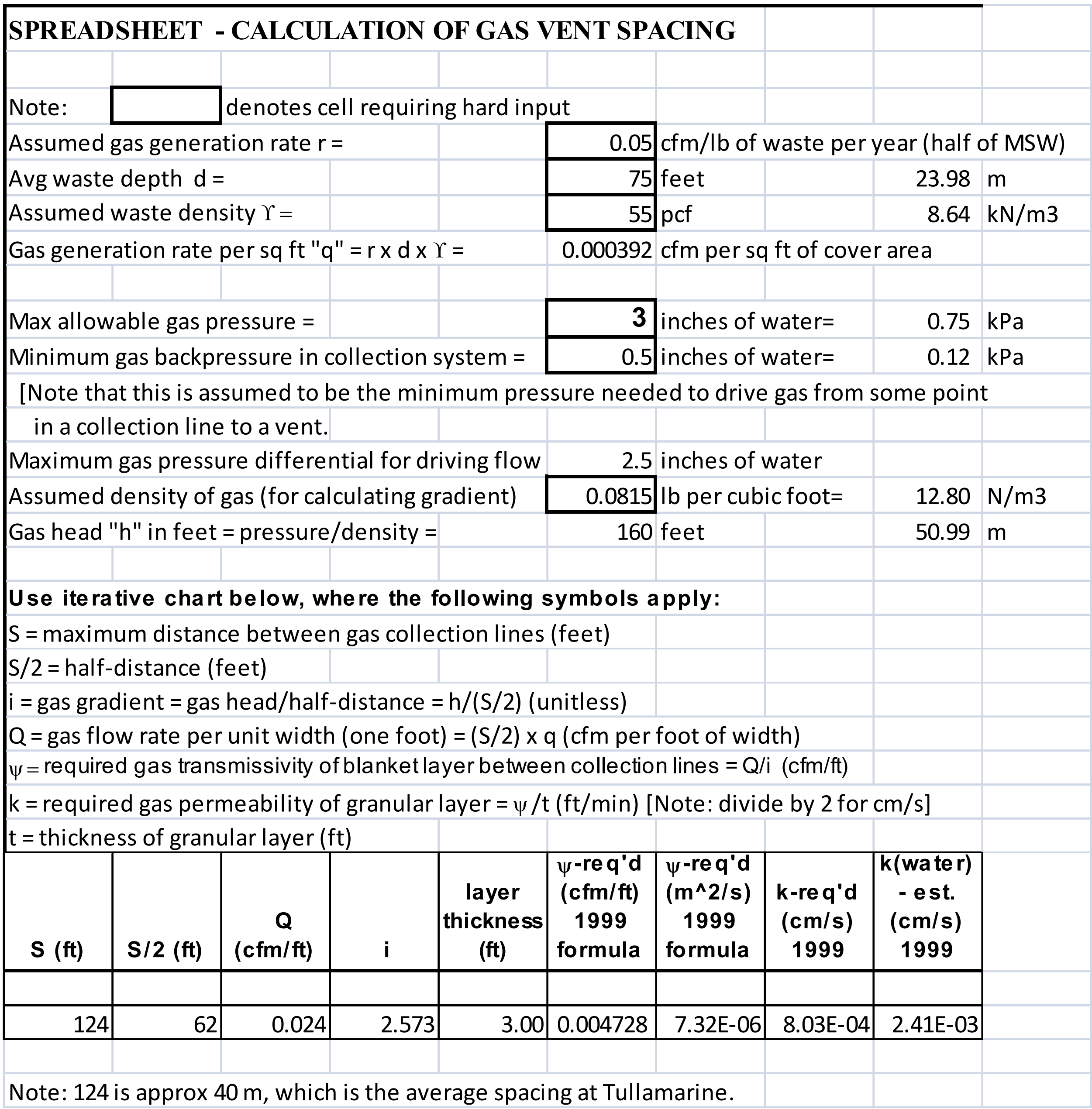

SPREADSHEET - CALCULATION OF GAS VENT SPACING

Note: ☐ denotes cell requiring hard input

Assumed gas generation rate r =	0.05	cfm/lb of waste per year (half of MSW)		
Avg waste depth d =	75	feet	23.98	m
Assumed waste density ϒ =	55	pcf	8.64	kN/m3
Gas generation rate per sq ft "q" = r x d x ϒ =	0.000392	cfm per sq ft of cover area		
Max allowable gas pressure =	3	inches of water=	0.75	kPa
Minimum gas backpressure in collection system =	0.5	inches of water=	0.12	kPa

[Note that this is assumed to be the minimum pressure needed to drive gas from some point in a collection line to a vent.

Maximum gas pressure differential for driving flow	2.5	inches of water		
Assumed density of gas (for calculating gradient)	0.0815	lb per cubic foot=	12.80	N/m3
Gas head "h" in feet = pressure/density =	160	feet	50.99	m

Use iterative chart below, where the following symbols apply:

S = maximum distance between gas collection lines (feet)
S/2 = half-distance (feet)
i = gas gradient = gas head/half-distance = h/(S/2) (unitless)
Q = gas flow rate per unit width (one foot) = (S/2) x q (cfm per foot of width)
ψ = required gas transmissivity of blanket layer between collection lines = Q/i (cfm/ft)
k = required gas permeability of granular layer = ψ /t (ft/min) [Note: divide by 2 for cm/s]
t = thickness of granular layer (ft)

S (ft)	S/2 (ft)	Q (cfm/ft)	i	layer thickness (ft)	ψ-req'd (cfm/ft) 1999 formula	ψ-req'd (m^2/s) 1999 formula	k-req'd (cm/s) 1999	k(water) - est. (cm/s) 1999
124	62	0.024	2.573	3.00	0.004728	7.32E-06	8.03E-04	2.41E-03

Note: 124 is approx 40 m, which is the average spacing at Tullamarine.