

Predicted temperatures and service lives of secondary geomembrane landfill liners

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ABSTRACT: The heat flow through double composite landfill liner systems is modelled for different liner configurations and different modes of landfill operation. The estimated temperature is used to estimate the likely service life (SL) of the secondary geomembrane (SGM) and to compare this with the SL of the primary geomembrane (PGM). The results show that the temperature in SGM is high enough to impact on its SL, and this should be considered in the design of landfill liners. The SL of the SGM was a minimum for an all-geosynthetic system, ranging between 310 years if the PGM temperature is at or below 30°C and 50 years when the PGM is at 50°C. This SL could be improved to between 390 years at 30°C and 75 years at 50°C by the use of a primary composite liner involving a GM and either a GCL and a 1 m thick foundation layer or a 1 m thick CCL. These predictions assume that the temperature of the primary liner remains constant over the period of time being considered. Consideration of a temperature–time history will give longer estimates of service life for a given peak liner temperature. Nevertheless, this study suggests that the temperature of the secondary liner requires consideration in the design of MSW landfills to ensure that the SL of the system is likely to exceed the contaminating lifespan for a particular design.

KEYWORDS: Geosynthetics, Geomembranes, Secondary liners, Temperature, Service life, Thermal conductivity

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1. INTRODUCTION

To provide protection of groundwater from contamination, modern municipal solid waste (MSW) landfill facilities are expected to have a barrier system that will protect the environment for the contaminating lifespan of landfill (expected to be hundreds of years; Rowe *et al.* 2004). Meeting this requirement requires consideration of the factors that can affect leakage through composite liners (Rowe 2005; El-Zein and Rowe 2008; Saidi *et al.* 2008) and the long-term performance of the geomembrane, such as wrinkles and tensile strains in the geomembrane (e.g. Take *et al.* 2007; Thusyanthan *et al.* 2007; Brachman and Gudina 2008a, 2008b; Fowmes *et al.* 2008). An additional important factor influencing the long-term performance of geomembrane liners is the liner temperature (Rowe 2005).

Both the biodegradation of organic waste and the hydration of ash can generate heat, which is transmitted to

the primary liner. For example, temperatures of 30–40°C have been observed at the base of MSW landfills with an operating leachate collection system (Rowe 2005; see also 'Dry cell' reported by Koerner and Koerner 2006 and Koerner *et al.* 2008 in Figure 1). Higher temperatures have been observed at the base of landfills without a leachate collection system, or where the collection system has failed. For example, at the Tokyo Port landfill (Japan) the maximum basal temperature reached 50°C, and after 20 years is still above 40°C (Figure 1). By increasing the availability of moisture, such as when landfill is operated as a bioreactor, the temperature in the body of the landfill and on the liner may increase. Thus the moisture-augmented 'wet cell' at a landfill in Pennsylvania generated temperatures higher than 50°C after about 5 years' operation (Figure 1). In contrast, the maximum liner temperature in a normal 'dry cell' at the same landfill reached 30–35°C (Koerner *et al.* 2008). Likewise, Yesiller and

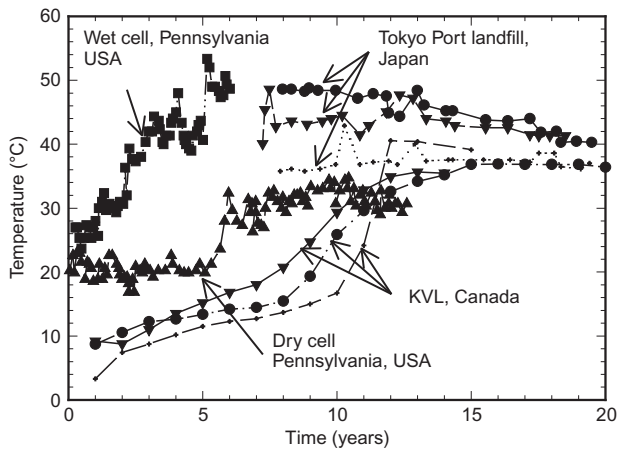


Figure 1. Observed temperatures at the base of landfills (compiled from data reported by Yoshida and Rowe 2003, Rowe 2005 and Koerner *et al.* 2008)

Hanson's (2003) limited monitoring of temperature at another US landfill confirms that leachate recirculation increases the landfill, and hence liner, temperature.

Elevated temperature accelerates ageing of a GM (Hsuan and Koerner 1998; Rowe 1998; Sangam and Rowe 2002; Rowe and Rimal 2008a, 2008b; Rowe *et al.* 2008). High temperature at the GM in a composite liner system also gives rise to thermal gradients from the GM to depth in the surrounding soil. This thermal gradient induces moisture to move away from the upper part of the liner, and may result in desiccation of the clay component (Holzlöhner 1990; Gottheil and Brauns 1994; Döll 1997; Heibrock 1997; Philip *et al.* 2002; Zhou and Rowe 2003; Southen and Rowe 2004; Rowe 2005; Southen and Rowe 2005a, 2005b).

To predict the service life (SL) of liner components, it is necessary to have an estimate of the liner's temperature. Numerical analyses have been performed to model heat transfer in the body of a landfill and in the landfill liner (Yoshida *et al.* 1997; Yoshida and Rowe 2003; Hanson *et al.* 2005). Yoshida and co-workers (Yoshida *et al.* 1997; Yoshida and Rowe 2003) modelled heat transport due to conduction and water flow in a landfill, and predicted the temperature at the base of the landfill. This model simulated heat generation due to aerobic and anaerobic degradation processes. The likely temperature was examined for different heat generation scenarios, and for different cover and liner drainage conditions. Rowe (2005), Koerner and Koerner (2006) and Koerner *et al.* (2008) have reported the observed temperatures at the top of the primary liner in landfills. These approaches provided the temperature needed to predict the SL of the PGM and the upper thermal boundary conditions for modelling of potential desiccation of underlying clay liners (Döll 1997; Heibrock 1997; Philip *et al.* 2002; Zhou and Rowe 2003; Rowe 2005).

Previous studies have focused on single-liner systems, and predictions have been made of the SL of the PGM (Rowe 2005). However, to date, no one has examined the likely temperature of the secondary geomembrane (SGM) in a double-lined landfill, or the implications of this for

the potential SL of the SGM. Thus the objective of this paper is to examine theoretically the likely temperature of the SGM in a double composite liner for a number of different configurations of the landfill barrier system and different modes of operation of landfill. These results will then be used to assess the likely SL of the SGM and compare this with the corresponding prediction of the SL of the PGM.

2. THEORY

For a heterogeneous material, heat transport in three dimensions is given by

$$\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + \dot{q} = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where λ_x , λ_y and λ_z are the thermal conductivity in the x , y and z directions; \dot{q} is the volume energy addition; ρ is material density; c is specific heat (the product ρc is called the heat capacity); T is temperature; and t is time.

Owing to the large areal extent of landfill liner compared with its thickness, a one-dimensional model is generally sufficient for modelling heat flow. Assuming one-dimensional conditions, and assuming that no energy is added or taken out of the system, Equation 1 reduces to

$$\lambda \frac{\partial^2 T}{\partial x^2} = \rho c \frac{\partial T}{\partial t} \quad (2)$$

Rearranging the terms then gives

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c} \frac{\partial^2 T}{\partial x^2} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (3)$$

where α is called the thermal diffusivity. We seek a solution to Equation 3 subject to a specified temperature boundary condition at the PGM and a specified constant temperature at an underlying aquifer (assumed to be flowing fast enough to prevent the build-up of heat in the groundwater).

3. PARAMETERS

The thermal conductivity, thermal diffusivity and/or heat capacity are required for simulating heat conduction (knowing any two of these parameters, one can calculate the third). For soil liners and drainage layers the thermal properties can be estimated directly from published data. Since little has been published regarding the thermal properties of geosynthetics, they were calculated based on the properties of their components.

3.1. Thermal conductivity

3.1.1. Thermal conductivity of soil

The thermal conductivity of soil depends on the soil structure, the number and nature of contacts between soil particles, and the volumetric fraction of the water, gas and solid phases (Farouki 1986): it therefore depends on the dry density, porosity and volumetric moisture content (or degree of saturation) of the soil. For dry soil, the higher the porosity (or the lower the density), the lower the thermal conductivity. For wet soil, the relationship be-

tween thermal conductivity and porosity is more complex. For example, in the saturated case, higher porosity corresponds to lower thermal conductivity only when the thermal conductivity of the soil particles is greater than that of the water (Farouki 1986). For a given unsaturated soil, an increase in moisture content results in an increase in thermal conductivity (Salomone and Kovacs 1984; Salomone *et al.* 1984; Salomone and Marlow 1989; Becker *et al.* 1992). In addition to the aforementioned factors, mineral composition, grain-size distribution and particle shape may affect thermal conductivity.

Published data for soils of known composition and/or classification were collected, grouped according to soil type, and plotted against the degree of saturation (Figures 2 to 5). It should be noted that only some of the data were directly reported with the degree of saturation. For the data reported with moisture content, degree of saturation was calculated based on the reported or typical values of void ratio, to allow all data to be collected onto the one plot.

Despite the increasing trend observed between thermal conductivity and degree of saturation (Figures 2–5), the data are considerably scattered. The variability of data raises the question of the extent to which the uncertainty regarding thermal properties would affect the predicted temperature at the SGM. To answer this question a series of sensitivity analyses were performed, as discussed later. For the sensitivity analyses the upper and lower bounds of thermal conductivity were chosen to be the upper and lower limits of the 95% prediction intervals shown in Figures 2 to 5.

3.1.2. Thermal conductivity of geosynthetics

Because of the paucity of measured data, the thermal conductivities of the geosynthetics typically used in a landfill barrier system were calculated based on the properties of their constituents. Since a high-density polyethylene (HDPE) GM used in landfill liners is predominately (~97%) HDPE, the thermal conductivity was taken to be within the range of the values reported for HDPE (i.e. 0.46 to 0.51 W/m°C; Dean 1999). Since a geotextile and a geonet are porous, the relationship between their thermal conductivity and that of the constitu-

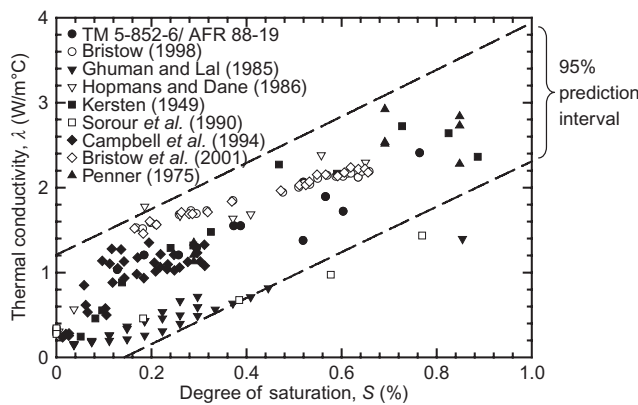


Figure 2. Thermal conductivity against degree of saturation for sand

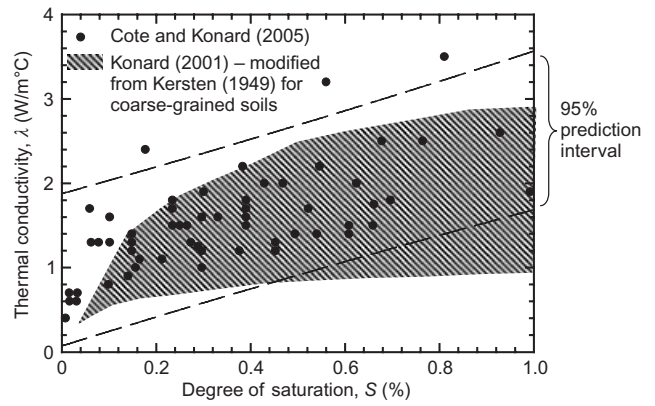


Figure 3. Thermal conductivity against degree of saturation for gravel

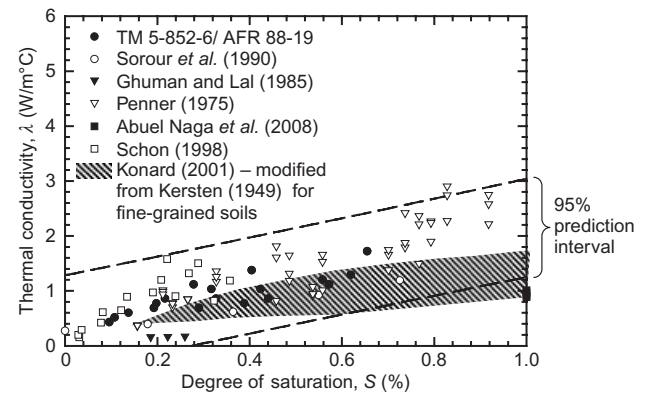


Figure 4. Thermal conductivity against degree of saturation for clay

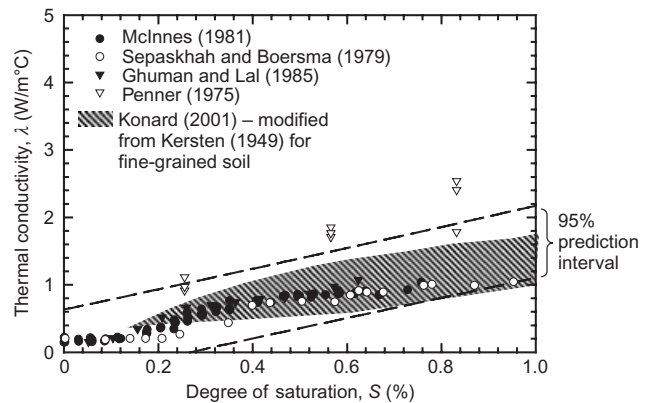


Figure 5. Thermal conductivity against degree of saturation for silt

ents (water, air and polymer) is complex, and depends on the arrangement of the constituents as well as on their thermal conductivity and volumetric fraction. Two extremes can be assumed for particle arrangement: parallel and series arrangements. The thermal conductivity of the real case will typically fall between these two bounds (called Wiener bounds; Birch and Clark 1940). For the sensitivity analyses, the Wiener bounds were used as the maximum and minimum limits for the thermal conductivity for geotextiles and geonets. For GCLs, the thermal

conductivity was calculated based on the values for a layer of bentonite and two layers of geotextile.

3.2. Heat capacity

The heat capacity of a porous material can be obtained using the weighted sum of those of its constituents, according to

$$\rho c = \sum_i \rho_i c_i x_i \quad (4)$$

where ρ_i , c_i and x_i are the density, specific heat and volumetric fraction of the i th constituent, respectively. For soil, Equation 4 can be rewritten in terms of n (porosity) and S (degree of saturation) as

$$\rho c = (1 - n)\rho_s c_s + nS\rho_w c_w + n(1 - S)\rho_a c_a \quad (5)$$

where the subscripts s, w and a denote solid particles, water and air. A similar approach was adopted for geotextiles and geonets.

3.3. Thermal diffusivity

Thermal diffusivity (α) is given by

$$\alpha = \frac{\lambda}{\rho c} \quad (6)$$

In this study, the maximum and minimum values of thermal conductivity and heat capacity were obtained as described above, and the thermal diffusivity was then calculated using Equation 6. Table 1 shows the range of thermal diffusivity values used for this analysis.

4. MODELLING

The governing differential equation was solved using the finite layer technique (POLLUTE v7; Rowe and Booker 2005) for specified top liner and aquifer temperatures. As a base case, analyses were performed for a 30°C difference in temperature between PGM (upper boundary) and aquifer (lower boundary), corresponding, for example, to a liner temperature of 40°C and an aquifer temperature of 10°C. However, since the temperature profile is a linear function of the temperature difference, the results for other combinations of thermal boundary conditions can easily be calculated from these results. Thus if the liner temperature were 30°C and the aquifer 10°C, giving a 20°C difference, the increase in liner temperature would be two thirds of that calculated for a difference of 30°C.

The temperature profile was calculated for the different

likely configurations of landfill barrier systems shown in Figure 6. The liners shown in Figure 6a involve only geosynthetic materials, whereas those in the other cases considered comprise both soil and geosynthetics. The thickness of the various barrier system components considered is given in Table 2. Geotextile protection layers above the GM and filter layers above the gravel were neglected, since trial analyses showed that they had a negligible effect (less than 0.1°C) on the predicted SGM temperatures. Analyses were conducted to examine the effect of material properties and liner configurations on the temperature level of the SGM liner. It was assumed that there was no active effort to move air in the leak detection system (LDS), and hence no cooling of the SGM due to air exchange in the LDS.

5. TEMPERATURE RESULTS

To examine the sensitivity of the SGM temperature to thermal properties, analyses were performed for both the upper limit (denoted by maximum α) and lower limit (denoted by minimum α) of the thermal diffusivities, as given in Table 1. Figure 7 shows the calculated temperature profile for an 'all geosynthetic' barrier system (Figure 6a), and Figure 8 focuses on the temperature in its geosynthetic components. Depth zero is the top of the PGM. It can be seen that thermal diffusivity does not significantly influence the final temperature profile, although it does affect the time it takes for the temperature to reach steady state. This is because the thermal conductivity of the components of the barrier system does not differ sufficiently to have a significant effect on the temperature profile. The time required to come to thermal equilibrium is quite short. Even for minimum thermal diffusivity the system took less than 2 years to come to thermal equilibrium. The temperature of the SGM was almost as high as that of the PGM (a rise of 29.7–29.8°C for the SGM as compared with 30°C for the PGM). In this case any difference in SL of the PGM and SGM will be due to the difference in exposure to leachate, as discussed in the next section.

For the barrier system composed of both soil and geosynthetics (Figure 6b), the results obtained for the maximum and minimum thermal diffusivities were not significantly different (Figure 9) at steady state. However, for the minimum diffusivity, it took much longer to reach thermal equilibrium (3.6 years) than for the maximum diffusivity (0.8 years). The predicted SGM temperatures

Table 1. Thermal diffusivities used for liner materials (m²/s)

	Saturated	Dry
Geomembrane	2×10^{-7} to 3×10^{-7}	
Clay	4×10^{-7} to 15×10^{-7}	1×10^{-7} to 8×10^{-7}
Clayey silt to silty clay (used for FL and AL)	3×10^{-7} to 15×10^{-7}	0.7×10^{-7} to 8×10^{-7}
Gravel	5×10^{-7} to 17×10^{-7}	2.5×10^{-7} to 10×10^{-7}
Geotextile	2×10^{-7}	1×10^{-7}
Geonet	1.75×10^{-7}	0.5×10^{-7} to 3×10^{-7}

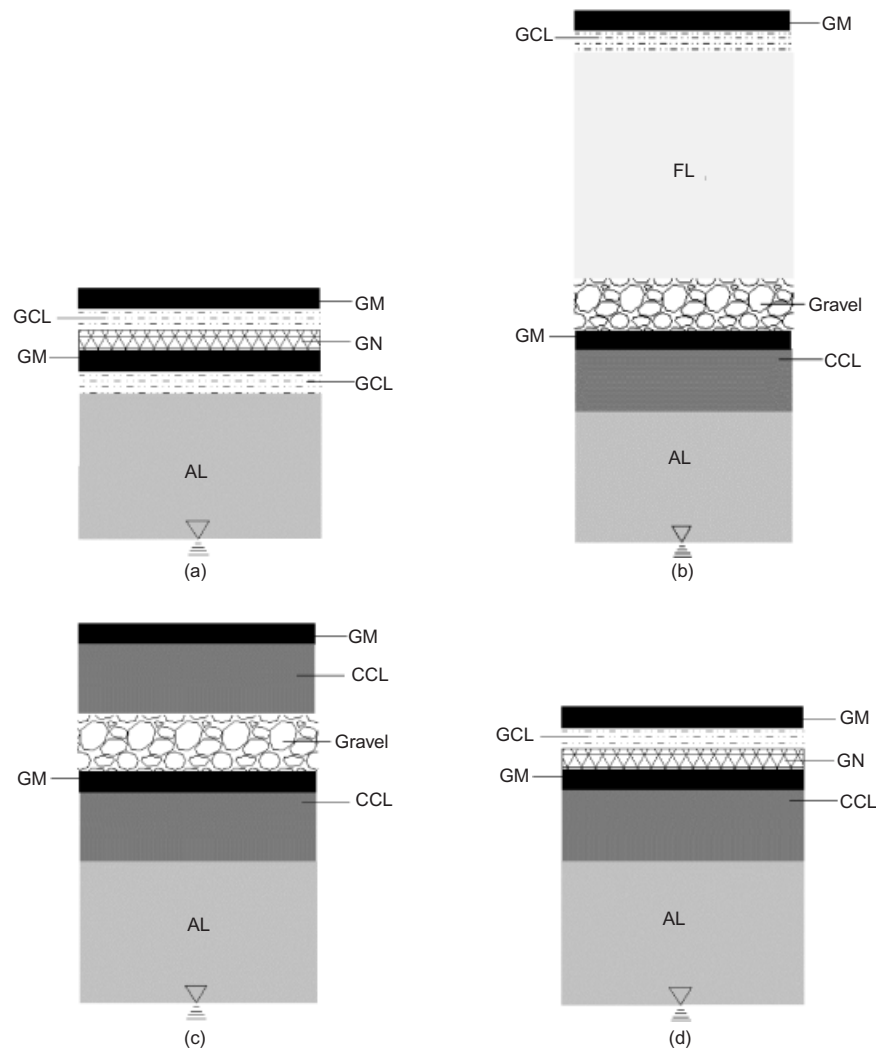


Figure 6. Configurations of barrier systems studied: GM, geomembrane; GN, geonet; GCL, geosynthetic clay liner; CCL, compacted clay liner; FL, foundation layer; AL, attenuation layer. Layer thicknesses are given in Table 2

are compared in Figure 10 and Table 3 for the systems shown in Figures 6a and 6b. The temperature in an ‘all geosynthetic’ barrier system was 1–10°C higher than in a barrier system involving both soil and geosynthetics. Thus the geometry of the barrier system and the thickness of the liners affect the final temperature of the SGM. Moreover, Figure 10 confirms that, for the range of thermal

diffusivities examined, the final temperature of the SGM was not particularly sensitive to thermal diffusivity, varying by a maximum of 2.6°C for the system shown in Figure 6b.

Table 2. Thickness of barrier components

Figure 6a	Figure 6b	Figure 6c	Figure 6d
GM: 2 mm GCL: 10 mm	GM: 2 mm GCL: 10 mm FL: 1 m	GM: 2 mm CCL: 1 m ^a	GM: 2 mm GCL: 10 mm
GN: 5 mm GM: 2 mm GCL: 10 mm AL: 3 m	GR: 0.3 m GM: 2 mm CCL: 1 m AL: 3 m ^a	GR: 0.3 m GM: 2 mm CCL: 1 m AL: 3 m	GN: 5 mm GM: 2 mm CCL: 1 m AL: 3 m

GM = geomembrane, GCL = geosynthetic clay liner, GN = geonet, AL = attenuation layer, FL = foundation layer, GR = gravel, CCL = compacted clay liner.

^aBase case: for other cases see the text

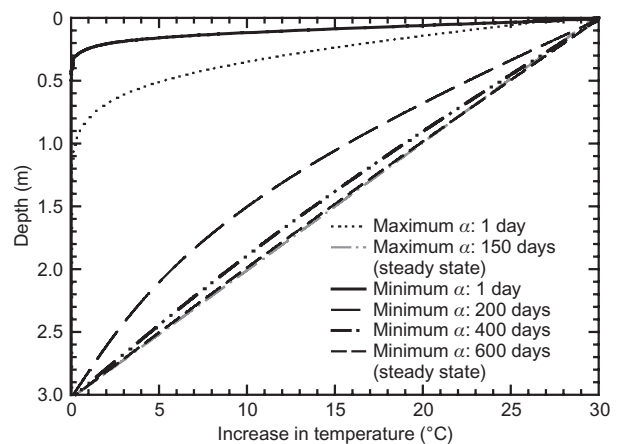


Figure 7. Temperature profile for barrier system shown in Figure 6a and upper and lower limits of thermal diffusivity (depth = 0 is top of PGM and depth=0.017–0.019 m is SGM)

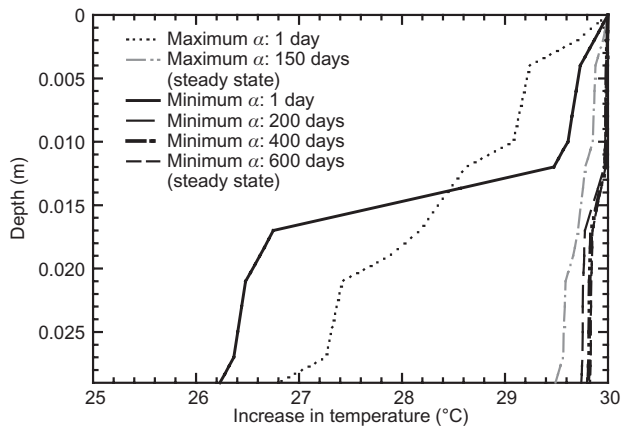


Figure 8. Temperature profile within geosynthetic components of Figure 7 (depth = 0.017–0.019 m is SGM)

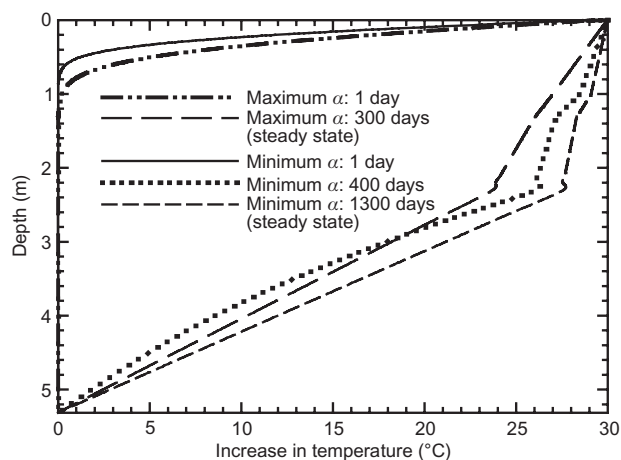


Figure 9. Temperature profile for barrier system shown in Figure 6b and upper and lower limits of thermal diffusivity (depth = 1.312–1.315 m is SGM)

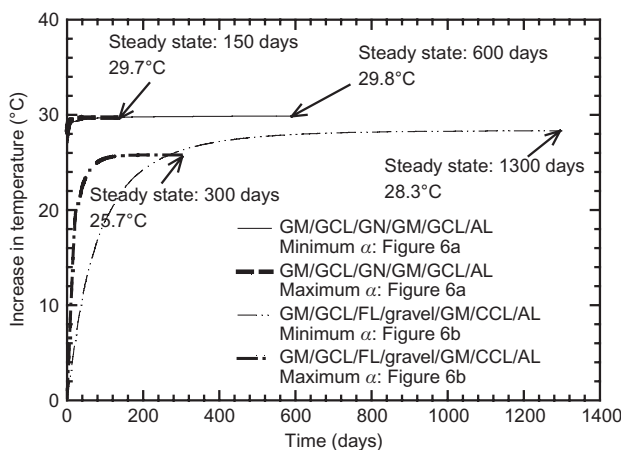


Figure 10. Temperature against time on secondary geomembrane for barrier systems shown in Figures 6a and 6b

To aid in understanding of the factors affecting the temperature of the SGM, three different landfill liners, two of similar thickness (Figures 6b and 6c) and one thinner (Figure 6d), were examined. Heat transfer was simulated for the average thermal diffusivity. As shown in

Figure 11, a decrease in primary liner thickness resulted in a higher temperature on the secondary liner.

The distance from thermal boundaries (e.g. thickness of the primary liner) is an important factor influencing the secondary liner temperature. To illustrate this effect, the case shown schematically in Figure 6c was examined for different thicknesses of primary compacted clay liner. As shown in Figure 12, an increase in the thickness of the primary CCL from 0.5 m to 3 m decreases the SGM temperature from 27.7°C to 22.6°C.

In addition to the thickness of the primary liner, the thickness of the attenuation layer (i.e. the depth to the aquifer) may affect the temperature profile. To illustrate this, the system shown schematically in Figure 6b was examined for different attenuation layer thicknesses. As shown in Figure 13, the deeper the aquifer, the higher the temperature in landfill liner because of its greater remoteness from the cooling provided by flow in the aquifer.

The moisture content of the attenuation layer can also affect the secondary liner temperature because of the effect this has on thermal diffusivity. The two extreme cases of a dry and a saturated attenuation layer are examined in Figure 14 for the barrier systems shown in

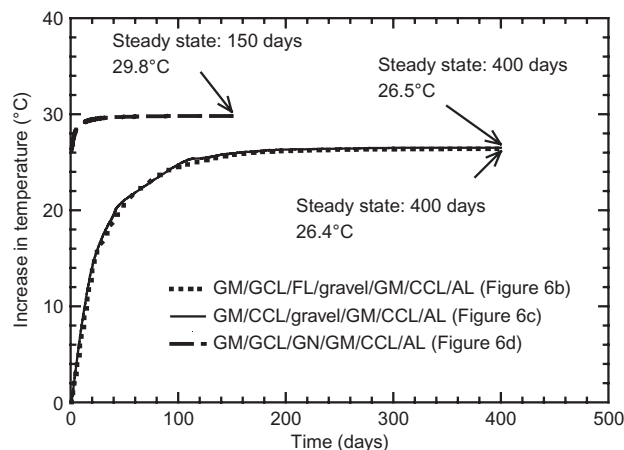


Figure 11. Temperature in secondary geomembrane for different barrier systems (for average thermal diffusivities)

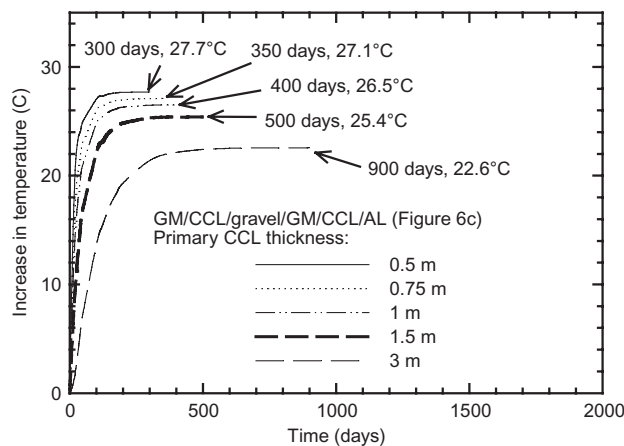


Figure 12. Effect of thickness of primary liner on temperature of secondary geomembrane (average thermal diffusivities)

Table 3. Summary of primary and secondary liner temperatures and estimated GM service lives, based on average thermal diffusivity, methodology for estimating service life as described by Rowe (2005) and OIT depletion data from Rowe and Rimal (2008a, 2008b)

Barrier system (see Figure 6 and Table 2)	PGM temp. (°C)	SGM temp. (°C)	Unadj. SGM SL (years)	Unadj. SGM SL minus PGM SL (years)	Mean SGM SL (years)	Mean SGM SL minus PGM SL (years)
6a: GM/GCL/GN/GM/GCL/AL = 3 m	30	29.9	365	95	310	40
	40	39.8	140	35	125	20
	50	49.8	60	15	50	5
6b1: GM/GCL/FL = 1 m/GR /GM/CCL = 1 m/AL = 1 m	30	24.9	605	335	515	245
	40	32.3	290	185	250	145
	50	39.7	145	100	125	80
6b2: GM/GCL/FL = 1 m/GR/GM/CCL = 1 m/AL = 3 m	30	27.6	460	190	390	120
	40	36.4	195	90	170	65
	50	45.2	85	40	75	30
6b3: GM/GCL/FL = 1 m/GR/GM/CCL = 1 m/AL = 10 m	30	29.1	395	125	340	70
	40	38.7	155	50	135	30
	50	48.3	65	20	60	15
6c1: GM/CCL = 0.5 m/GR/GM/CCL = 1 m/AL = 3 m	30	28.5	420	150	360	90
	40	37.7	170	65	150	45
	50	46.9	75	30	65	20
6c2: GM/CCL = 0.75 m/GR/GM/CCL = 1 m/AL = 3 m	30	28.1	440	170	370	100
	40	37.1	180	75	160	55
	50	46.1	80	35	70	25
6c3: GM/CCL = 1 m/GR/GM/CCL = 1 m/AL = 3 m	30	27.6	460	190	390	120
	40	36.5	195	90	165	60
	50	45.3	85	40	75	30
6c4: GM/CCL = 1.5 m/GR/GM/CCL = 1 m/AL = 3 m	30	26.9	495	225	420	150
	40	35.4	215	110	185	80
	50	43.9	100	55	85	40
6c5: GM/CCL = 3 m/GR/GM/CCL = 1 m/AL = 3 m	30	25.1	595	325	505	235
	40	32.6	280	175	240	135
	50	40.1	140	95	120	75

Numbers for PGM and mean SGM SL represent the mean of the unadjusted and adjusted predictions as described by Rowe (2005). Unadjusted SL is also given for SGM. Service lives all rounded to nearest 5 years. Note (mean) service life of primary GM is estimated to be 270 years at 30°C, 105 years at 40°C and 45 years at 50°C.

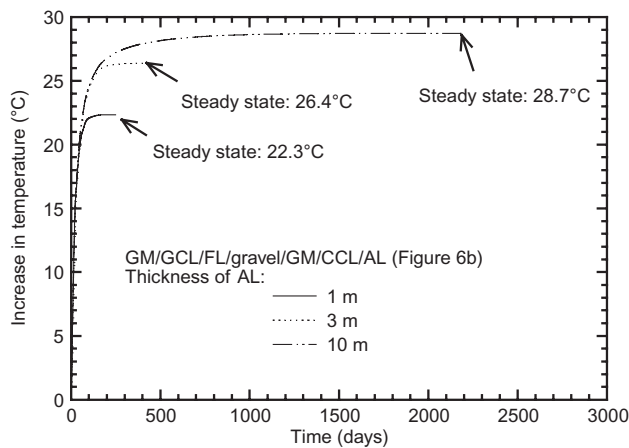


Figure 13. Effect of attenuation layer thickness on temperature of secondary geomembrane (for average thermal diffusivities)

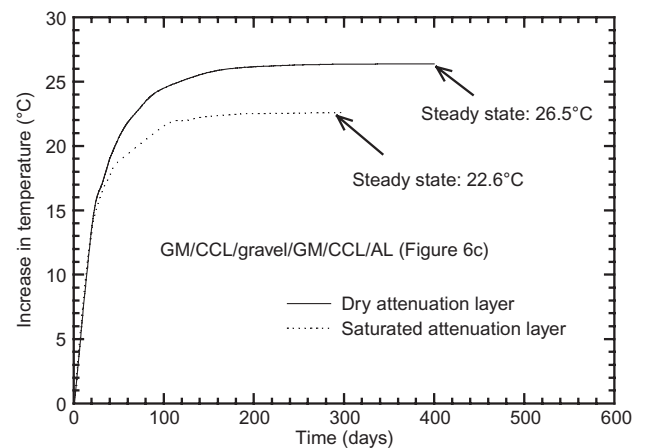


Figure 14. Temperature of secondary geomembrane for dry and saturated attenuation layer (for average thermal diffusivities)

Figure 6c. It can be seen that, for a 30°C temperature rise at the primary liner, these two cases correspond to a temperature increase at the SGM of 26.5°C and 22.6°C for the dry and saturated attenuation layer cases respectively.

Figure 15 shows the calculated temperature profile for

different modes of operation of landfill with a barrier system such as that shown schematically in Figure 6b. For all cases, the temperature in the aquifer is assumed to be 10°C. For the case representing a landfill with an operating leachate collection system the temperature at the top

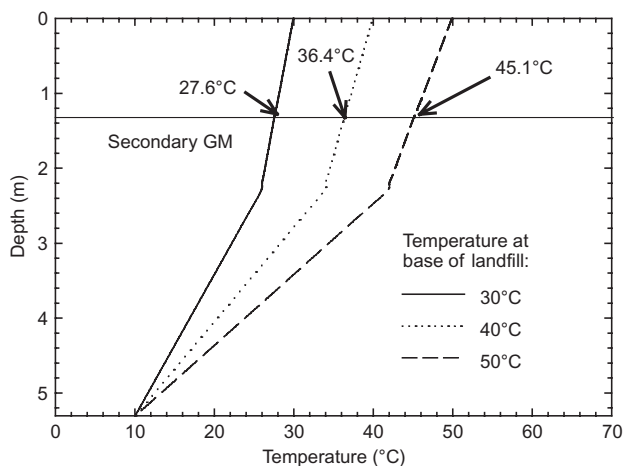


Figure 15. Temperature profile for different modes of operation (for barrier systems shown in Figure 6b and average thermal diffusivities)

of the primary liner is set to be 30°C. The case where the primary liner temperature is 40°C is considered to represent a landfill being operated as a bioreactor, and 50°C represents a landfill where leachate collection has been terminated, or where there was failure of the leachate collection system that allowed leachate to mound into the waste. For the cases examined, the temperature on the SGM is predicted to be 2.5–5°C lower than that at the PGM.

6. IMPLICATIONS FOR SECONDARY GEOMEMBRANE SERVICE LIFE

Figure 16 and Table 3 summarise the calculated temperatures of the secondary geomembrane (SGM) for different landfill liners and a range of primary liner temperatures. The results given in Figure 16 for Cases 6a and 6d (as defined in Figure 6 and Table 2) are, to all practical purposes and plotting accuracy, identical. Thus, with respect to SGM temperature, it did not matter whether the secondary clay liner was a GCL or a CCL, provided that the distance from the SGM to the aquifer was the same.

The data presented in Figure 16 and Table 3 were used for making preliminary estimates of secondary liner service lives (SL) for a range of primary GM liner (PGM) temperatures and the barrier configurations shown in Figure 6. These estimates were based on the methodology described by Rowe (2005). The predicted service lives considered all three stages of degradation of a GM (Viebke *et al.* 1994; Hsuan and Koerner 1998): Stage 1, depletion of antioxidants; Stage 2, induction time to the onset of polymer degradation; and Stage 3, degradation of the polymer to decrease some property (or properties) to an arbitrary level (e.g. to 50% of the original value).

Stage 1 times were based on recent data on OIT depletion for simulated composite liners with leachate above the GM and a GCL and foundation layer below the GM, as published by Rowe and Rimal (2008a, 2008b) for a GM with standard OIT of 135 min and HP-OIT of 660 min. For the PGM, these data are from the same tests but supersede the preliminary data used by Rowe (2005)

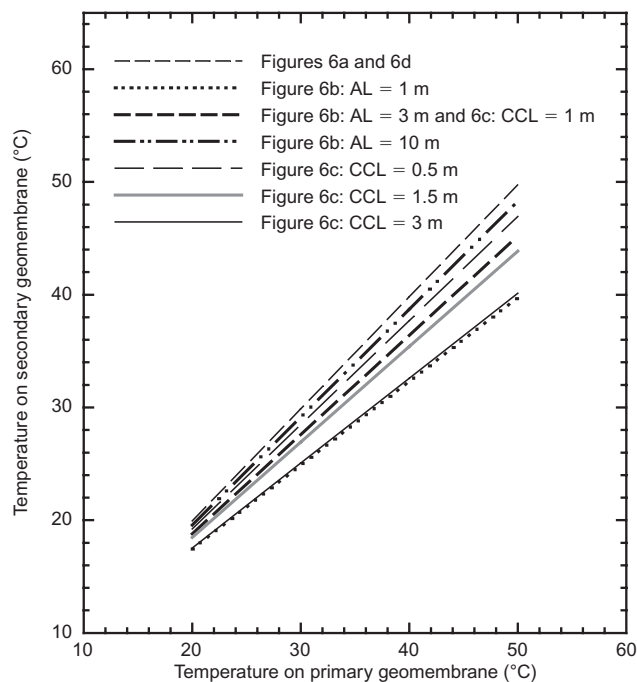


Figure 16. Temperature of secondary GM liner for different landfill barrier systems and a range of temperatures of the primary GM liner (aquifer temperature = 10°C)

since they are based on two additional years of data collection, and lead to slightly longer predicted service lives than those given by Rowe (2005). Assuming that any leachate reaching the SGM will have had to pass through the primary clay liner, some attenuation of surfactants and trace metals that may impact on the SL of the GM (Rowe *et al.* 2008) is expected, and so for the estimates of SGM SL the data obtained from Rowe and Rimal (2008b) for a GM separated from the leachate by a GCL were used. As shown by Rowe and Rimal (2008b), the time for OIT depletion for a GM separated from the leachate by a GCL is longer than that for a GM with just a geotextile protection layer between it and the leachate (e.g. a typical PGM, as examined by Rowe and Rimal 2008a), and hence even for the same temperature the Stage 1 times for the SGM are greater than for the PGM. Any difference in temperature between the PGM and SGM (as per Table 3) will further increase this difference in SL.

The data published by Viebke *et al.* (1994) for both the induction (Stage 2) and polymer degradation (Stage 3) stages of degradation for polyethylene gas pipe with minimal antioxidant and a wall thickness of 2.1 mm provided the basis for estimating Stages 2 and 3. Their tests involved having stagnant deionised water inside the pipe and circulating air around the outside of the pipe. Based on their tests, activation energies of 75 kJ/mol and 80 kJ/mol were used to infer the times for the induction (Stage 2) and degradation stage (Stage 3) respectively for their air/water system. This, combined with the estimate of Stage 1 based on the tests of Rowe and Rimal (2008a, 2008b) give what is referred to herein as the 'unadjusted' SL and is considered to give an upper-bound estimate to the likely SL of a primary GM liner (PGM). Since the interaction with leachate may influence degradation of the

GM, a second estimate of the times for Stages 2 and 3 was obtained by adjustment, based on the difference in the effect of air/water exposure and water/leachate exposure observed in the tests conducted by Sangam and Rowe (2002), as described by Rowe (2005). This adjusted time is considered to give a lower-bound estimate of the SL. Thus for the purpose of illustrating the potential effects of the difference in liner temperature on the SL of the PGM and SGM in this paper, the PGM SL at a given temperature was taken to be the mean of the adjusted and unadjusted values calculated as described above: this gives values of 270 years, 105 years and 45 years at 30°C, 40°C and 50°C respectively. For the SGM liner SLs were calculated in two ways. The unadjusted values were used to obtain an estimate of the SL for the case where the surfactants and trace metals in the leachate reaching the GM are largely attenuated by passing through the primary liner (column 4 in Table 3). The second estimate of the SGM SL was based on the mean of the unadjusted and adjusted values in the same way as was done for the PGM, and these numbers are given in column 6 of Table 3. The difference between the numbers in columns 4 and 6 illustrates some of the uncertainty associated with predictions of GM SL based on currently available data. Because of the uncertainty in predicting service lives, the SLs in Table 3 have all been rounded to the nearest 5 years to avoid giving the impression of unjustified accuracy. Table 3 also summarises the difference in estimated SL of the SGM (both unadjusted and mean) and PGM.

The geosynthetic double composite liner system shown in Figure 6a gives temperatures on the secondary liner very close to that on the primary liner. Thus the difference in the PGM and SGM SLs is due largely to the assumptions about leachate exposure: using the mean estimates of PGM and SGM SLs, the difference ranges from 40 years (310 years for SGM as against 270 years for PGM) at a PGM temperature of 30°C to about 5 years (50 years for SGM as against 45 years for PGM) at a PGM liner temperature of 50°C. However, if the SGM has only intermittent contact with leachate, the SGM SL (365 and 60 years at 30°C and 50°C respectively) may be between 95 and 15 years longer than the PGM SL (Table 3).

The use of either a GCL with a 1 m thick foundation layer or a CCL as part of the primary composite liner (Figure 6b or 6c) can reduce the temperature on the secondary liner, relative to the configurations shown in Figures 6a and 6d, by between 2.3°C and 4.6°C over the range of cases considered. While apparently small, this difference can still have a notable effect on the SGM SL. For a PGM at 30°C the SL of the SGM is 390 years (for cases 6b2 and 6c3; Table 3). This is 80 years longer than for Case 6a (310 years). At 50°C, the use of a 1 m thick CCL or foundation layer extends the SL by 25 years (SL of 75 years compared with 50 years for the 'all-geosynthetic' barrier system).

The results discussed above and presented in Table 3 highlight the potential significance of temperature for the SL of the SGM liner. The service lives may be adequate for some situations but not for others (depending on the

contaminating lifespan of the landfill). For PGMs at 30°C, the SGM SL ranges between 310 and 605 years (310 to 515 years based on the 'mean predictions' and 365 to 605 years based on the unadjusted predictions), depending on the barrier system. At 40°C the SGM SLs range between 125 and 290 years and at 50°C between 50 and 145 years, depending on the barrier system.

The service lives presented in Table 3 are intended to give an indication of the magnitude of the primary and secondary geomembrane service lives, and to highlight the importance of the type of liner system for the temperature and hence the SL of the SGM liner. When there is a small difference in temperature, one should not ascribe much significance to the predicted difference in service lives based on Arrhenius modelling. In fact the difference in exposure conditions between the primary liner and the secondary liner may be more significant than the effect of small differences in temperature.

For the analyses conducted herein it has been assumed that no heat is removed through the leak detection system (LDS). This is the worst-case scenario, and results in conservative service lives. In the event of significant heat loss from the LDS, the temperature of the SGM will be lower and the service life longer.

The predictions given in Table 3 assume that the temperature remains constant over the period of time being considered. In reality the temperature will change, and hence the values given represent 'lower bound' estimates for a given peak liner temperature. As shown by Rowe (2005), consideration of a temperature–time history will give longer estimates of service life for a given peak liner temperature. In situations where the SL calculated as presented in this paper is not adequate, one would first conduct a more detailed analysis and consider the effect of the likely time–temperature history on the service life. If the SL is still too short, options include: (1) changing the method of operations so as to reduce heat generation; (2) revising the type of barrier design (e.g. thickening the primary liner); (3) cooling the primary liner (Rowe *et al.* 2007; Hoor *et al.* 2008); or (4) cooling the secondary liner.

The values given in Table 3 should be used with caution. Only the results for Stage 1 are based on actual tests on a GM typically used in landfill application in a simulated liner configuration. The uncertainty regarding the Stage 2 and 3 components highlights the need for additional testing to examine their contributions to SL: these tests have been under way for several years, but as yet there are insufficient data to provide improved predictions. However, the data at 85°C where Stage 2 and 3 have been completed in the laboratory suggest that the methodology used to give estimates presented here is likely to be conservative (i.e. underestimates Stages 2 and 3 of the SL) for the type of GM examined (Rowe and Rimal 2008a). Once longer-term testing data become available, the predictions will be updated. It should also be noted that the predictions are relevant only to a GM with properties similar to, or better than, those for which the test data were derived (standard OIT (ASTM D3895) of 135 min and HP-OIT (ASTM D5885) of 660 min, single-point

stress crack resistance greater than 400 h (ASTM D5397: appendix)). Geomembranes with lower values may have lower service lives.

7. CONCLUSIONS

As part of a broader study of the long-term performance of landfill liners, this paper has focused on the temperature of secondary geomembrane (SGM) liners and its associated effects on the service life (SL) of the SGMs. The temperatures of the SGM liner have been predicted for different liner configurations and modes of landfill operation. It has been shown that, for the liner materials studied, the steady-state temperature profile is not very sensitive to the thermal properties of the liner materials. However, the geometry and thickness of the liners considerably affect the SGM temperature. In particular, the thicker the primary liner, the lower the temperature in the SGM. Also, the shallower the aquifer, the lower the temperature of the SGM liner (other things being equal). In this study, soil has been used as thermal insulator between the primary and secondary liners. It should be noted that in geotechnical applications soil is not considered to be an effective thermal insulator. This is due to its relatively high thermal conductivity compared with other common insulation materials. Soil has high specific heat, and is commonly used in thermal mass applications, and situations where the temperature changes quickly: this is not the case in landfills. Ideally, a material with lower thermal conductivity should be used. Research is ongoing to study the issues associated with the use of more effective thermal insulators as part of a barrier system. Meanwhile, a thick layer of soil can be an intermediate alternative whose performance in the landfill environment is reasonably well known.

The SL of the SGM was minimum for an all-geosynthetic system, ranging from 310 years if the PGM temperature was at or below 30°C to 50 years when the PGM was at 50°C. This SL could be improved to 390 years at 30°C and 75 years at 50°C by the use of a primary composite liner involving a GM and either a GCL and a 1 m thick foundation layer or a 1 m thick CCL. This study highlights the need to consider the temperature of the SGM in the design of MSW landfills, to ensure that the SL of the system is likely to exceed the contaminating lifespan for a particular design.

Based on the limited available data, it is considered that the service lives predicted in this paper are likely to be conservative for a high-quality geomembrane. The predictions assume that: (1) there is no cooling of the secondary liner due to airflow in the leak detection systems; and (2) the temperature of the primary liner remains constant over the period of time being considered. In reality, the temperature of the primary liner will change with time. As shown by Rowe (2005), consideration of a temperature–time history will give longer estimates of service life for a given peak liner temperature. In situations where the service life calculated as presented in this paper is not adequate, one would first conduct a more detailed analysis and consider the effect of the likely time–temperature

history on the service life. If the service life is still too short, options include: (1) changing the method of landfill operations so as to reduce heat generation; (2) revising the type of barrier design (e.g. thickening the primary liner); (3) cooling the primary liner; or (4) cooling the secondary liner.

The results presented herein are preliminary, and long-term service life experiments on and monitoring of PGMs and SGMs are recommended.

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NOTATIONS

Basic SI units are given in parentheses.

c	specific heat (J/kg °C)
c_a	specific heat of air (J/kg °C)
c_s	specific heat of solid particles (J/kg °C)
c_w	specific heat of water (J/kg °C)
c_i	specific heat of the i th constituent (J/kg °C)
n	porosity (dimensionless)
\dot{q}	volume energy addition (J/m ³ s)
S	degree of saturation (dimensionless)
T	temperature (°C)
t	time (s)
x, y, z	Cartesian coordinate system (m)
x_i	volumetric fraction of the i th constituent (dimensionless)
α	thermal diffusivity (m ² /s)
λ	thermal conductivity (J/m s °C)
λ_x	thermal conductivity in the x direction (J/m s °C)
λ_y	thermal conductivity in the y direction (J/m s °C)
λ_z	thermal conductivity in the z direction (J/m s °C)
ρ	material density (kg/m ³)
ρ_i	density of the i th constituent (kg/m ³)
ρ_a	density of air (kg/m ³)
ρ_s	density of solid particles (kg/m ³)
ρ_w	density of water (kg/m ³)

ABBREVIATIONS

AL	attenuation layer
CCL	compacted clay liner
FL	foundation layer
GCL	geosynthetic clay liner
GM	geomembrane
GN	geonet
GR	gravel
HDPE	high-density polyethylene
HP-OIT	high-pressure oxidative induction time
KVL	Keele Valley landfill
LDS	leak detection system
MSW	municipal solid waste
OIT	oxidative induction time
PGM	primary geomembrane
SGM	secondary geomembrane
SL	service life

REFERENCES

- ASTM D3895. *Standard Test Method for Oxidative-induction Time of Polyolefins by Differential Scanning Calorimetry*. ASTM International, West Conshohocken, PA, USA.
- ASTM D5397. *Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test*. ASTM International, West Conshohocken, PA, USA.
- ASTM D5885. *HP-OIT Standard Test Method for Oxidative Induction Time of Polyolefin Geosynthetics by High-Pressure Differential Scanning Calorimetry*. ASTM International, West Conshohocken, PA, USA.
- Abuel-Naga, H. M., Bergado, D. T. & Bouazza A. (2008). Thermal conductivity evolution of saturated clay under consolidation process. *International Journal of Geomechanics*, **18**, No. 2, 114–122.
- Becker, B. R., Misra, A. & Fricke, B. A. (1992). Development of correlations for soil thermal conductivity. *International Communications in Heat and Mass Transfer*, **19**, No. 1, 59–68.
- Birch F. & Clark H. (1940). The thermal conductivity of rocks and its dependence upon temperature and composition. *American Journal of Science*, **238**, No. 8, 529–558.
- Brachman, R. W. I. & Gudina, S. (2008a). Gravel contacts and geomembrane strains for a GM/CCL composite liner. *Geotextiles and Geomembranes*, **26**, No. 6, 448–459.
- Brachman, R. W. I. & Gudina, S. (2008b). Geomembrane strains from coarse gravel and wrinkles in a GM/GCL composite liner. *Geotextiles and Geomembranes*, **26**, No. 6, 488–497.
- Bristow, K. L. (1998). Measurement of thermal properties and water content of unsaturated sandy soil using dual-probe heat-pulse probes. *Agricultural and Forest Meteorology*, **89**, No. 2, 75–84.
- Bristow, K. L., Kluitenberg, G. J., Goding, C. J. & Fitzgerald, T. S. (2001). A small multi-needle probe for measuring soil thermal properties, water content and electrical conductivity. *Computers and Electronics in Agriculture*, **31**, No. 3, 265–280.
- Campbell, G. S., Jungbauer, J. D., Bidlake, W. R. & Hungerford, R. D. (1994). Predicting the effect of temperature on soil thermal conductivity. *Soil Science*, **158**, No. 5, 307–313.
- Cote, J. & Konard, J. M. (2005). Thermal conductivity of base-course materials. *Canadian Geotechnical Journal*, **42**, No. 1, 61–78.
- Dean, J. A. (1999). *Lange's Handbook of Chemistry*, 15th edn. McGraw-Hill, New York, 1999. See <http://www.knovel.com/knovel2/Toc.jsp?BookID=47&VerticalID=0> for online version. Accessed: 4 March 2009.
- Döll, P. (1997). Desiccation of mineral liners below landfills with heat generation. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, **123**, No. 11, 1001–1009.
- El-Zein, A. & Rowe, R. K. (2008). Impact on groundwater of concurrent leakage and diffusion of DCM through geomembranes in landfill liners. *Geosynthetics International*, **15**, No. 1, 55–71.
- Farouki, O. T. (1986). *Thermal properties of soils*. Series on Rock and Soil Mechanics. Trans Tech Publications, Clausthal-Zellerfeld, Vol. 11.
- Fowmes, G. I., Dixon, N. & Jones, D. R. V. (2008). Validation of a numerical modelling technique for multilayered geosynthetic landfill lining systems. *Geotextiles and Geomembranes*, **26**, No. 2, 109–121.
- Ghuman, B. S. & Lal, R. (1985). Thermal conductivity, thermal diffusivity, and thermal capacity of some Nigerian soils. *Soil Science*, **139**, No. 1, 74–80.
- Gottheil, K. M. & Brauns, J. (1994). Das Austrocknungsverhalten von mineralischen Dichtungsschichten unter Kunststoffdichtungsbahnen bei erhöhten Temperaturen. *Geotechnische probleme bei bau von abfalldeponien*, Prühs, H., Editor, Nürnberger Deponieseminar, Eigenverlag LGA Nürnberg, pp. 299–306.
- Hanson, J. L. & Yesiller, N., Swarbrick, G. E. (2005). Thermal analysis of GCLs at a municipal solid waste landfill. *Waste Containment and Remediation, Proceedings of Geo-Frontiers 2005 Congress*, Austin, TX, USA, ASCE, Reston, VA, pp. 3269–3283.
- Heibrock, G. (1997). Desiccation cracking of mineral sealing liners. *Proceedings of the 6th International Landfill Symposium*, Cagliari, 1994, pp. 101–113.
- Holzlhöner, U. (1990). *Langzeitverhalten von mineralischen Abdichtungsschichten in Deponieabdichtungen hinsichtlich Austrocknung und Ribbildung*. Bundesanstalt für Materialforschung und –prüfung, Berlin, Forschungsbericht 10203412, Teil III.
- Hoor, A., Rowe, R. K. & Pollard, A. (2008). A method for reducing the temperature of landfill liners in MSW landfills. *Proceedings of the 1st Global Waste Management Symposium*, Copper Mountain Conference Center, CO (CD-ROM).
- Hopmans, J. W. & Dane, J. H. (1986). Thermal conductivity of two porous media as a function of water content, temperature, and density. *Soil Science* **142**, No. 4, 187–195.
- Hsuan, Y. G. & Koerner, R. M. (1998). Antioxidant depletion lifetime in high density polyethylene geomembranes. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **124**, No. 6, 532–541.
- Joint Departments of the Army and Air Force (1988). *Arctic and Subarctic Construction—Calculation Methods for Determination of Depths of Freeze and Thaw in Soils*. Joint Departments of the Army and Air Force, Washington, D.C., USA, TM 5-852-6/AFR 88-19, Volume 6.
- Kersten, M. S. (1949). *Thermal Properties of Soil*, Engineering Experiment Station Bulletin No. 28, University of Minnesota, Minneapolis, MN, 227 pp.
- Koerner, G. R. & Koerner, R. M. (2006). Long-term temperature monitoring of geomembranes at dry and wet landfills. *Geotextiles and Geomembranes*, **24**, No. 1, 72–77.
- Koerner, R. M., Koerner, G. R., Eith, A. W. & Ballod, C. P. (2008). Geomembrane temperature monitoring at dry and wet landfills. *Proceedings of the 1st Global Waste Management Symposium*, Copper Mountain Conference Center, CO (CD-ROM).
- Konard, J. M. (2001). Cold region engineering. *Geotechnical and Geoenvironmental Engineering Handbook*, Rowe, R. K., Editor, Kluwer Academic Publishing, Norwell, USA, pp. 593–613.
- McInnes, K. (1981). *Thermal Conductivities of Soils from Dryland Wheat Regions in Eastern Washington*, MSc thesis, Washington State University.
- Penner, E., Johnston, G. H. & Goodrich, L. E. (1975). Thermal conductivity laboratory studies of some Mackenzie Highway soils. *Canadian Geotechnical Journal*, **12**, No. 3, 271–288.
- Philip, L. K., Shimell, H., Hewitt, P. J. & Ellard, H. T. (2002). A field-based test cell examining clay desiccation in landfill liners. *Quarterly Journal of Engineering Geology and Hydrogeology*, **35**, No. 4, 345–354.
- Rowe, R. K. (1998). Geosynthetics and minimization of contaminant migration through barrier systems beneath solid waste. *Proceedings of the 6th International Conference on Geosynthetics*, Atlanta, GA, pp. 27–103.
- Rowe, R. K. (2005). Long-term performance of contaminant barrier systems. *Géotechnique*, **55**, No. 9, 631–678.

- Rowe, R. K. & Booker, J. R. (2005). *POLLUTEv7: Pollutant migration through a nonhomogeneous soil*, GAEA Environmental Engineering Ltd, Whitby, Ontario, Canada.
- Rowe, R. K. & Rimal, S. (2008a). Depletion of antioxidant from HDPE geomembrane in a composite liner. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, **134**, No. 1, 68–78.
- Rowe, R. K. & Rimal, S. (2008b). Aging of HDPE geomembrane in three composite liner configurations. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, **134**, No. 7, 906–916.
- Rowe, R. K., Quigley, R. M., Brachman, R. W. I. & Booker, J. R. (2004). *Barrier Systems for Waste Disposal Facilities*, Taylor & Francis (E and FN Spon), London.
- Rowe, R. K., Pollard, A., Chong, A., Chisholm, E., Toda, R. & Tomson, C. (2007). Sustainable landfills : a technique for extracting heat to prolong service-life of geomembrane liners. *Proceedings of the 60th Canadian Geotechnical Conference*, Ottawa, Vol. 2, pp. 1310–1315.
- Rowe, R. K., Islam, M. Z. & Hsuan, Y. G. (2008). Leachate chemical composition effects on OIT depletion in HDPE geomembranes. *Geosynthetics International*, **15**, No. 2, 136–151.
- Saidi, F., Touze-Foltz, N. & Goblet, P. (2008). Numerical modelling of advective flow through composite liners in case of two interacting adjacent square defects in the geomembrane. *Geotextiles and Geomembranes*, **26**, No. 2, 196–204.
- Salomone, L. A. & Kovacs, W. D. (1984). Thermal resistivity of soils. *Journal of Geotechnical Engineering, ASCE*, **110**, No. 3, 375–389.
- Salomone, L. A. & Marlow, J. I. (1989). *Soil Rock Classification According to Thermal Conductivity*, EPRI CU-6482, Electric Power Research Institute, Palo Alto, CA.
- Salomone, L. A., Kovacs, W. D. & Kusuda, T. (1984). Thermal performance of fine-grained soils. *Journal of Geotechnical Engineering, ASCE*, **110**, No. 3, 359–374.
- Sangam, H. P. & Rowe, R. K. (2002). Effects of exposure conditions on the depletion of antioxidants from HDPE geomembranes. *Canadian Geotechnical Journal*, **39**, No. 6, 1221–1230.
- Sepaskhah, A. R. & Boersma, L. (1979). Thermal conductivity of soils as a function of temperature and water content. *Soil Science Society of America Journal*, **43**, No. 3, 439–444.
- Schön, J. H. (1998). *Physical Properties of Rocks: Fundamentals and Principles of Petrophysics*. Handbook of Geophysical Exploration: Seismic Exploration series, volume 18, Elsevier Science, Oxford.
- Sorour, M. M., Saleh, M. M. & Mahmoud, R. A. (1990). Thermal conductivity and diffusivity of soil. *International Communications in Heat and Mass Transfer*, **17**, No. 2, 189–199.
- Southen, J. M. & Rowe, R. K. (2004). Investigation of the behavior of geosynthetic clay liners subjected to thermal gradients in basal liner applications. *Journal of ASTM International*, **1**, No. 2, ID JA111470 (available: www.astm.org), 13 pp.
- Southen, J. M. & Rowe, R. K. (2005a). Laboratory investigation of geosynthetic clay liner desiccation in a composite liner subjected to thermal gradients. *Journal of Geotechnical and Geoenvironmental Engineering*, **131**, No. 7, 925–935.
- Southen, J. M. & Rowe, R. K. (2005b). Modelling of thermally induced desiccation of geosynthetic clay liners. *Geotextiles and Geomembranes*, **23**, No. 5, 425–442.
- Take, W. A., Chappel, M. J., Brachman, R. W. I. & Rowe, R. K. (2007). Quantifying geomembrane wrinkles using aerial photography and digital image processing. *Geosynthetics International*, **14**, No. 4, 219–227.
- Thusyanthan, N. I., Madabhushi, S. P. G. & Singh, S. (2007). Tension in geomembranes on landfill slopes under static and earthquake loading: centrifuge study. *Geotextiles and Geomembranes*, **25**, No. 2, 78–95.
- Viebecke, J., Elble, E., Ifwarson, M. & Gedde, U. W. (1994). Degradation of unstabilized medium-density polyethylene pipes in hot-water applications. *Polymer Engineering and Science*, **34**, No. 17, 1354–1361.
- Yesiller, N. & Hanson, J. L. (2003). Analysis of temperatures at a municipal solid waste landfill. *Proceedings of the 9th International Landfill Symposium*, Cagliari (CD-ROM).
- Yoshida, H., & Rowe, R. K. (2003). Consideration of landfill liner temperature. *Proceedings of the 9th International Landfill Symposium*, Cagliari (CD-ROM).
- Yoshida, H., Tanaka, N. & Hozumi, H. (1997). Theoretical study on heat transport phenomena in a sanitary landfill. *Proceedings of the 6th International Landfill Symposium*, Cagliari, pp. 109–120.
- Zhou, Y. & Rowe, R. K. (2003). Development of a technique for modelling clay liner desiccation. *International Journal for Numerical and Analytical Methods in Geomechanics*, **27**, No. 6, 473–493.

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