LONG-TERM BASAL TEMPERATURES AT BEDDINGTON FARMLANDS LANDFILL AND TEMPERATURE INFLUENCES ON HDPE LINER SERVICE LIFE

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Abstract: This paper presents and discusses results of more than 7 years of temperature monitoring using 19 thermistors integral with vibrating wire piezometers located at the top of the basal clay liner of a mainly MSW landfill in southeast England. Leachate recirculation was carried out during and after waste disposal. The development of elevated temperature in landfilled wastes is considered and the paper discusses the controlling effects of high liner temperatures and the lifetime temperature profile on the durability and service life of HDPE geomembrane liners.

Keywords: temperature, HDPE geomembrane, landfill, liner, service life, instrumentation.

INTRODUCTION

Elevated temperatures in landfills are generally caused by the biodegradation of the organic constituents of the waste or by exothermic chemical reactions within certain waste types. Localised hot spots can, and frequently do, occur from various causes. Concurrently with biodegradation, landfill gas is generated and leachates are created. The correlation of these indicators of biodegradation is complex and will change with the factors controlling the biodegradation process but, where the rates of biodegradation or chemical reactions change, it is to be expected that waste temperatures and landfill emissions will be commensurately affected.

The temperature at a HDPE geomembrane liner has a crucial influence on the long-term integrity and service life of the liner as elevated temperatures greatly accelerate the rate of depletion of the protective antioxidants added to the geomembrane during manufacture. A greater understanding of the factors controlling the liner temperature profile with time from installation through to the peak temperature and the post-peak stage is important to designers, operators and regulators to enable reliable estimations to be made of the average liner temperature throughout the period that the wastes remain of environmental concern. With this knowledge, the service life of the HDPE liner can then be estimated.

This paper presents temperature records over a 7.3 year period from a landfill in southeast England, and discusses factors that affect landfill temperatures and the key influence of the lifetime temperature profile on estimating the HDPE geomembrane liner service life.

BASAL LINER TEMPERATURES AT BEDDINGTON LANDFILL

The Site

The study was undertaken in Cell 1B of the Beddington Farmlands landfill, located in the London Borough of Sutton, England. The surface formations consist of sand and gravel deposits overlying tertiary London Clay. Landfill cells have been developed by excavating the sand and gravel down and into the London Clay, then compacting the clay to form a basal liner. London Clay has also been used to form sidewall seals. No geomembrane liner was installed. A photograph of the cell prepared for waste disposal is shown in Figure 1.

Figure 1. Cell 1B prepared for waste deposition

Cell 1B lies immediately west of a part-filled cell, 1A, and was separated from it by a basal clay bund running north-south. The side walls slope at 1:2.5 and contain two benches. The cell base falls at a gradient of ~2% from SE to NW. The cell has a basal area of ~9000 m^2, rising to ~27,000 m^2 at ground level. A layer of ~300mm of drainage stone was placed on the base of the cell. A leachate collection pipe was laid within the drainage stone, running diagonally SE to NW to an abstraction sump in the north-west corner of the cell.

The cell was filled with predominantly domestic waste, plus some non-hazardous commercial and industrial waste. Subsequent lifts were placed in a conventional manner using a steel-wheeled compactor. Infilling began at the start of October 2000 and waste deposition was completed by the end of October 2001. By this time the waste depth had reached a maximum depth of ~23m. The wastes were then capped with at least 2m of compacted clay.

Instrumentation

Vibrating wire piezometers (VWPs) were installed on the base of the cell, prior to infilling. The VWPs used in the study were supplied by Soil Instruments Ltd, Uckfield, East Sussex, UK. The model was the HAE Ceramic VWP (ref.981-520X) fitted with a NTC type thermistor with an accuracy of ±0.5ºC. The working range for this model of VWP is 0–15m water. The integral thermistor, as well as being necessary for temperature correction of the signal, allowed the long term logging of the development of temperatures on the base of the new landfill cell. All data from the VWPs were collected by a data logger. The model used was the Campbell Scientifics CR10X Data-logger, placed in a protective metal enclosure.

The VWPs were placed directly on top of the basal clay liner and were connected to the data logger by armoured cable. The drainage gravel was backfilled directly over the piezometers and armoured cable on the base of the cell. Where the armoured cable ran up the cell wall to the data-logger, it was protected by placing it in HDPE pipe. The prepared cell and locations of VWPs are illustrated in Figure 2, with Figure 3 showing a plan of the base of the prepared cell. Routine visits were made at approximately monthly to 2-monthly intervals to download data, change the logger battery and check that the equipment was working. Since June 2006, data have been downloaded by telemetry and the battery was supplemented by a solar panel. There have been seven significant interruptions to data logging caused by malfunctions, battery failures and re-location of the logger. These added up to a loss of 67 weeks data in the period October 2000 to January 2008. Readings are recorded every one hour.

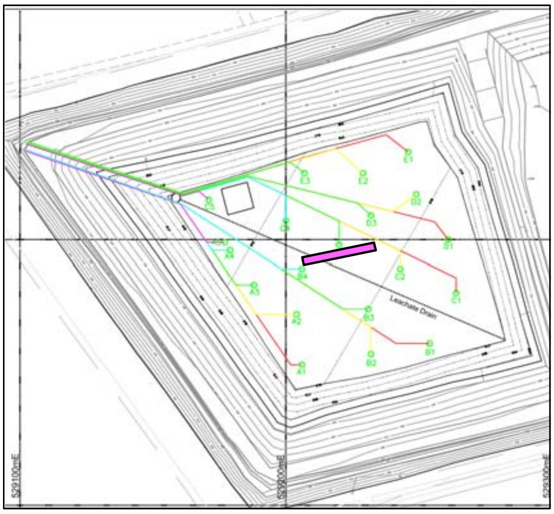

Figure 2. Layout of Cell 1B, showing positions of piezometers and cables and approximate location of leachate injection trench in cap centrally located over cell base

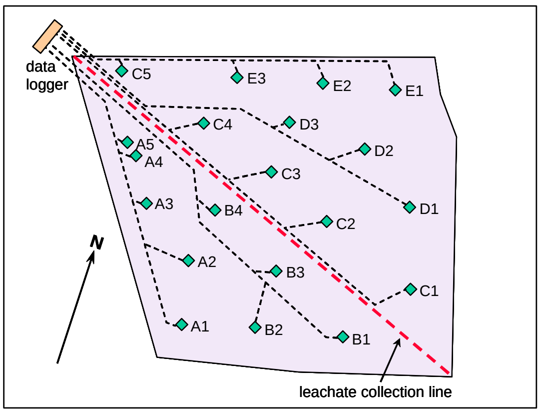

Figure 3. Cell 1B base - layout of VWPs and integral thermistors

All the probes have continued to generate a signal whenever interrogated by the data logger, with the exception of C2, thought to have been damaged by a compactor driving over the first shallow lift of waste even though the first lift of waste was placed with minimal compaction, using only a tracked bulldozer, to minimise the risk of damage to the piezometers and cables. Some initial high levels of 'noise' and anomalous readings on several VWPs were traced to a faulty multiplexor board, which was replaced in July 2001. Other problems, particularly the long term drift due to gas diffusion, have affected the VWP readings of leachate head but have not affected temperature readings.

Leachate and gas management

The start of infilling, in October 2000, coincided with the start of one of the wettest winters on record in the UK. It became necessary within one month to remove leachate from the sump in Cell 1B. This was achieved by recirculating directly into the wastes within Cell 1B. Following capping of the waste (November 2001), recirculation was achieved via a 30 m long gravel filled trench installed into the waste just below the cap, on the crown of the cell, shown on Figure 2. Recirculation continued to be the sole method used to control leachate head on the base up to January 2005, when the facility to discharge to sewer became available. Since January 2006, no recirculation has been carried out, mainly due to clogging of the re-injection trench.

As there is only one trench of limited length, the proportion of the waste in the whole cell influenced by the recirculation will have been relatively small. Figure 4 shows the leachate elevation in metres above Ordnance Datum (OD) at the abstraction sump. The elevation of the top of the clay liner was 14.6 m above OD at the sump, rising to 17 m above OD at the southeast corner. As the hydraulic continuity across the cell was shown by the VWPs to be good, when the leachate level is depressed at the sump, much of the higher southeastern part of the base will have no leachate head.

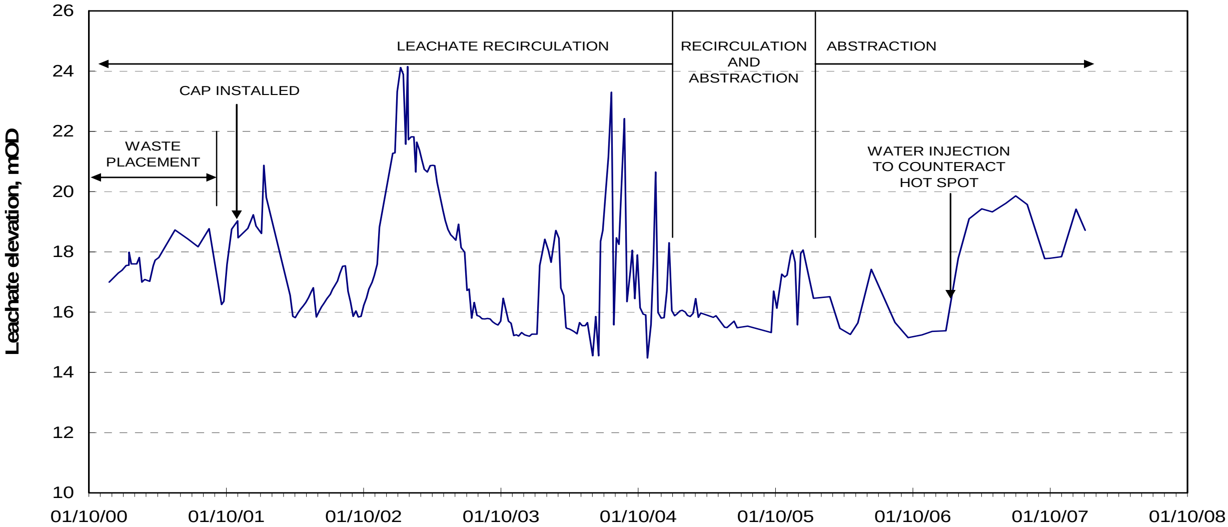

Figure 4. Leachate elevation at the abstraction sump

Gas wells were installed shortly after capping in November 2001. Some of the wells are located quite close in plan position to several of the VWPs (A2, A4, C3 and E3) in the drainage blanket. There has been active abstraction of gas continuously since then from the wells and from the leachate abstraction sump. The layout of the gas extraction system has not enabled an assessment of the gas production from Cell 1B to be separately identified or related to temperature or leachate management indicators.

Measured Temperatures

Time series graphs of temperature data from all working thermistors are shown in Figure 5 for the 7.3 year period October 2000 to January 2008.

Following the commencement of waste placement, the temperatures with little discernible delay rose quite rapidly due to biological activity from the initial ambient temperature range of 15 - 20ºC to reach a maximum of 32 - 40ºC at the various thermistor positions across the cell base after about seven years. The rate of temperature increase has reduced with time and temperatures in January 2008 have levelled off or reduced to a very low rate of rise, with an average temperature at the 19 thermistors of 34.5°C.

A spatial variation of 8°C has developed across the base of the cell. There was a generally consistent pattern of temperature rise until November 2006 (except at thermistors D1 and D2) The period at the peak temperatures at the VWPs has so far been approximately 9 months. It remains to be seen whether the present temperatures will remain stable, increase further or start to decline as the rate of biological activity falls. As a result of the 2.4 m slope of the base from the southeast down to the northwest, the northwest part of the cell will have been continuously covered by leachate while the southeast will have frequently had little or no head of leachate. Inspection of the temperature records shows there is a trend for temperatures to increase from the southeast to the northwest as the depth of leachate will have increased (e.g. B1 to B3, C1 to C4 (no readings from C2)), a feature noted by Rowe (2005). Anomalies to this trend do occur with C5 in the northwest consistently recording the lowest temperature of all 19 thermistors, currently being 31.2°C. The reason for this is not known but C5 is the VWP located closest to the leachate abstraction sump and this position may influence its temperature.

Other reasons for the temperatures at some locations being consistently lower than at others may be a reflection of the mixed waste stream, with less biodegradable waste deposited in some locations, leading to lower biological activity and temperatures. Such waste would not only generate less heat but would also act as insulation from warmer wastes. The thermistors at the edge of the cell (E1 to E3) did not exhibit lower temperatures than those located further into the cell, indicating no material boundary effect on basal temperatures.

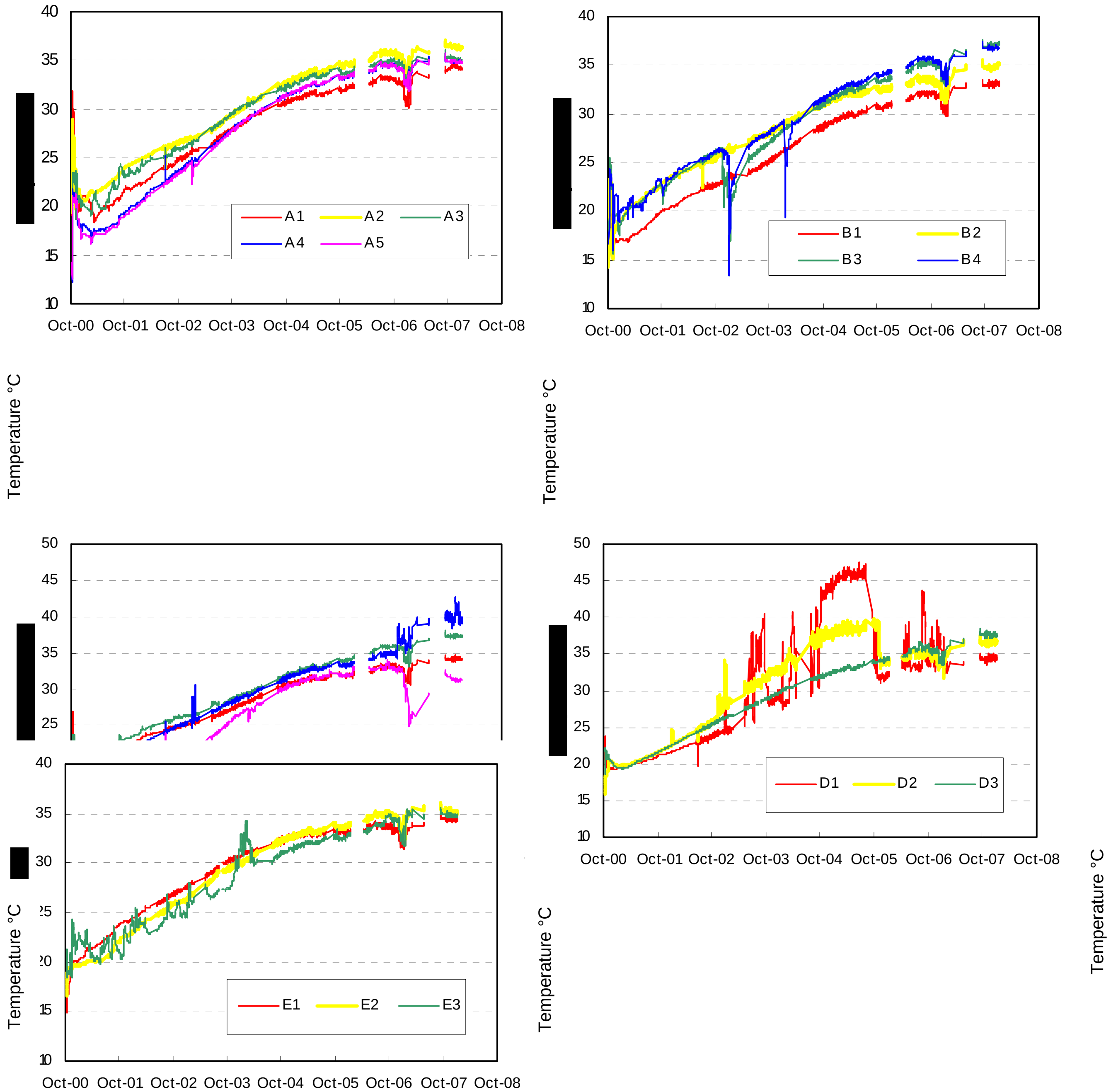

Figure 5. Time series data for temperatures on the base of Cell 1B

There have been periods of erratic measurements at some locations, e.g. B3, B4, C5, D1, D2 and E3. Initially, there were considerable temperature fluctuations while the cover over the VWPs comprised only the drainage gravel or a shallow waste cover but subsequently, the temperature fluctuations do not appear to be related to external climatic temperature variations, indicative of the insulation provided by the rapid increase in waste depth. The thermistors show only slightly higher temperatures in those located below the sub-cap recirculation trench.

Aside from some very short term temperature spikes (positive or negative) which may be ignored as reading malfunctions or aberrations, sharp temperature movements were recorded at several of the thermistor positions. No member of the research team was on-site and the causes of the rapid temperature movements has been interpreted from information received. Where there were sharp increases, they may have been caused by the formation of localised 'hotspots' in the waste. Rapid temperature drops are considered to be related to cooling effects of recirculated leachate where it rapidly infiltrates and percolates down through the waste to the drainage gravel, or from the injection of cold water to control suspected or identified hotspots. For example, a short-lived fall of ~3°C occurred during January 2007, caused by an influx of cold water injected to control a 'hot spot' in the waste. The 'hotspot' was not recorded by the thermistors (it may have been located between them or have been restricted to a zone several metres above the base) but the cold water could have spread across the base of the cell through the highly permeable drainage blanket, being recorded in almost all the thermistors. Temperatures then recovered rapidly to their former values, except for anomalies at C4 and C5.

Abnormally high temperatures up to 47°C were recorded at D1 and D2 from January 2003 (D2) and August 2004 (D1) to October / November 2005 when the temperature abruptly reduced to below 35°C. After November 2005, a period of more erratic temperatures was observed but, over the last six months, temperature readings have stabilised and generally levelled off. The reasons for the temperature fluctuations are not known to the authors but they may be related to hotspots in the waste which were treated with water injection.

TEMPERATURE DEVELOPMENT IN LANDFILLS

Elevated temperatures can occur in landfills for several reasons. The most common is from the biodegradation of the organic fraction in the waste materials but can also occur from exothermic reactions in mineral waste materials such as incinerator ash. Background temperatures for non-hazardous landfills within the body of the waste, as opposed to the base of the landfill, are typically in the range of 40–45ºC for the first five years, stabilising in the majority of landfills to an optimum of 35–45ºC (Environment Agency 2002).

Exothermic activity can lead to high temperatures in excess of 85°C in bottom ash waste (Klein *et al.*, 2001) but the period of high temperatures (> 40°C) is generally of shorter duration than as a result of biodegradation. For the case described by Klein *et al.* (2001), it is estimated that the temperature at the geomembrane liner would have been above 40ºC for a total of only about 20 months, a short period of near-peak temperatures compared to many reported time-temperature profiles for biodegradable wastes, but with higher peak temperatures.

It is reasonable to conclude that the reducing content of biodegradable MSW in landfilled wastes as required by the Landfill Directive will lead to lower temperatures from biological activity in newer waste streams but attention to the potential for exothermic reactions to take place will be necessary in incinerator and other non-inert mineral wastes.

The occurrence of landfill fires or deep-seated zones "hot spots" of raised temperatures in landfilled wastes was examined by Hall *et al.* (2007). Air ingress to the waste as a result of active gas extraction systems and the over-abstraction of landfill gas was suspected to be the principal contributing factor for the majority (62 per cent) of sites examined. An additional 10 per cent of sites identified air ingress at exposed waste flanks as a major contributing factor to the occurrence of the hot spot. Materials within the waste were suspected of causing 20 per cent of the incidents, and tyres were considered to be a contributing factor in 8 per cent of the incidents. The Environment Agency of England and Wales confirmed the widespread occurrence of hot spots throughout the geographical regions of the UK and the relatively common occurrence is also seen at sites outside the UK (Hall *et al.*, 2007). The core of a hot spot can have a temperature of several hundred degrees centigrade but many wastes are good insulators of heat with temperatures reducing rapidly away from the centre of the hot spot, with the result that the influence of the hot spot can be quite restricted. Localised high temperatures may occur at geomembrane liners caused by a nearby hot spot and could remain unknown for a considerable period of time with serious consequences to the integrity of the liner, especially if the centre is close to the liner where it may have the potential to melt the geomembrane.

Leachate recirculation will normally enhance biodegradation and lead to increased temperatures in the waste but where there are preferential drainage paths through the waste allowing rapid percolation of the leachate to the basal drainage blanket, this could reduce temperatures on the basal liner. This effect would be accentuated where cold water was used.

TEMPERATURE EFFECTS ON POLYETHYLENE GEOMEMBRANES

Oxidative degradation and polyethylene longevity

As observed by Hsuan & Koerner (1998), oxidative degradation of HDPE geomembranes is considered to occur in three distinct phases:

- Phase 1 – time for the complete depletion of antioxidant additives;
- Phase 2 – an induction period to the onset of polymer oxidative degradation; and
- Phase 3 – time for degradation of the polymer to decrease a selected property to 50% of the original value (the "half life").

The antioxidant depletion stage is the most important in terms of the long-term retention of the functionality of the geomembrane liner. The induction period is relatively short, estimated by Rowe (2005) to extend for only 10 to 1 year for constant operating temperatures of 20ºC to 40ºC when exposed to leachate. Once oxidative degradation in Phase 3 is underway, it is expected that stress cracking, which is the geomembrane property that is likely to have the greatest effect on the ability of a liner to act as a barrier, will increase markedly. As discussed in Needham & Knox (2007), it is therefore considered prudent for landfill designers to exclude any contribution from the Phase 3 "half life" period from the estimated service life of HDPE geomembranes. Thus, the antioxidant depletion stage (Phase 1) is the critical element in polyethylene liner longevity and service life.

As described by Hsuan & Koerner (1998), the time required to deplete the antioxidants at any given temperature for the same exposure conditions can be estimated by using the Arrhenius equation:

$$s = A\exp\left(\frac{-Ea}{RT}\right) \quad \text{.....................(1)}$$

Where s is the OIT depletion rate obtained from oxidative induction time tests; A is a constant; E_a is the activation energy of the antioxidant depletion mechanism (J/mol); R is the universal gas constant (8.314 J/mol K); and T = absolute temperature (K).

The activation energy represents the necessary minimum energy that must be provided for the antioxidant depletion mechanism to commence and is dependant on the characteristics of the polymer resin, the antioxidant additive package in the geomembrane and the exposure conditions in which the loss is occurring. A lower value indicates that antioxidant depletion will commence earlier than for a geomembrane using a polymer with a higher activation energy.

The antioxidant depletion rate, represented by the OIT depletion rate, is exponentially dependant on both the geomembrane temperature and the activation energy. It follows that the reliability of the estimation of the length of the depletion stage depends upon reasonably accurate estimates of the lifetime temperature at the geomembrane liner as well as on the activation energy. The derivation of activation energy values requires a programme of very long-term tests at a range of elevated incubation temperatures and so only limited published values are available. Needham and Knox (2007) discuss the lack of consistency in the published values of activation energy which makes the selection of suitable values problematic.

The rapid reduction in antioxidant depletion time with rising liner temperatures has been discussed in several papers, for example Rowe (2005), and is illustrated in Figure 6, the estimated antioxidant depletion times in landfill exposure conditions being adapted from the procedure in Needham *et al.* (2004). The severe reductions in antioxidant depletion time in warmer landfills will result in much reduced service lives of the HDPE geomembranes

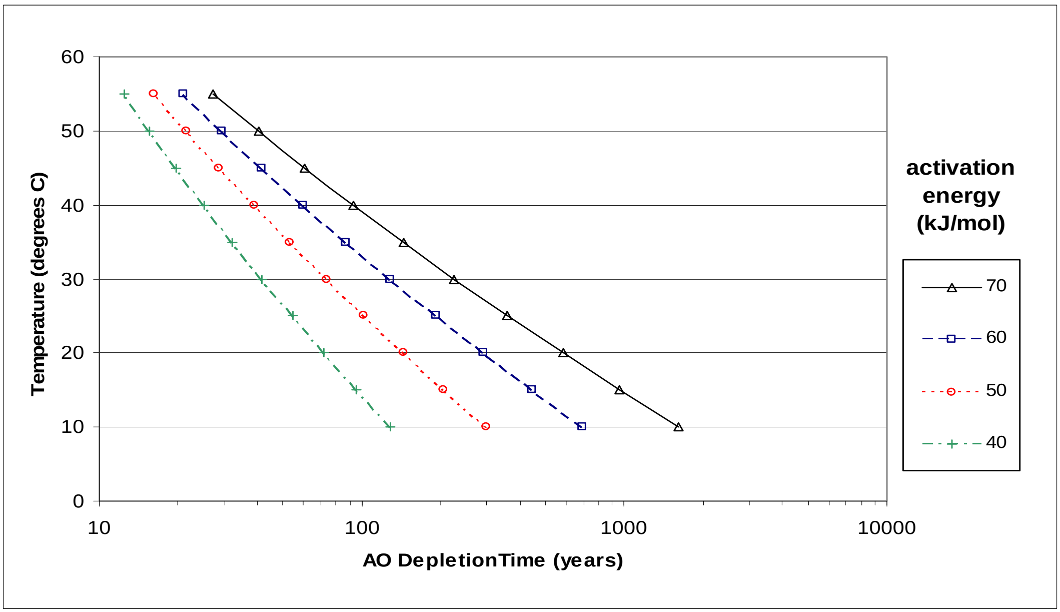

Figure 6. Temperature effect on antioxidant depletion time for different activation energies

Temperature profile with time

The temperature at any point on a landfill liner is not constant with time, rising from a natural background figure (T_o) to a peak (T_p) during the most active period of biological (or exothermic) activity. After some time close to this maximum value, the temperature will slowly decline eventually to reach a residual value being the initial background temperature (T_o) of the adjacent natural ground (12ºC on average at 50 m depth in the UK). The variable temperature, especially the period at the maximum temperature T_p, will strongly influence the antioxidant depletion time and thus the service life of the geomembrane liner. Rowe (2005) presents a procedure to take account of the variation in temperature with time for use in estimating antioxidant depletion rates during the periods of increasing and decreasing temperatures, enabling an assessment to be made for a predicted or measured temperature profile.

Published temperature monitoring of basal landfill temperatures has not been carried out for long enough to identify all the elements of the temperature profile - the period and rate of temperature increase, the peak temperature, the duration at the peak temperature, rates of temperature decline and the time when the temperature has dropped to background levels of the adjacent natural ground. Koerner & Koerner (2006) report on up to 10.5 years of basal temperature monitoring at two MSW cells (one a 'wet' cell with recirculation and the other a 'dry' cell) with temperatures in both cells still rising slowly. The temperatures recorded at Beddington Farmlands landfill for over seven years may have reached a peak but that will not be confirmed until further monitoring results become available with time; alternatively, temperatures may yet rise further. The period at or close to peak temperatures is unknown and the duration of the decline in temperature to background values can only be educated speculation at present. It is expected that there will be a link between gas generation and settlement (as indicators of continuing biodegradation activity and mass loss) and temperature.

Where the waste is not biodegradable but subject to exothermic reactions, the rise and fall in temperatures is more rapid and, as described by Klein *et al.* (2001), definite peak and declining temperatures can be seen within a three year period. In such wastes, the temperature profile with time can be estimated with more confidence.

CONCLUSIONS

1. Results of basal temperature monitoring for over 7 years at the liner of a mainly MSW landfill are presented and show present peak values of 32-40ºC across the landfill base.
2. For biodegradable wastes, elevated liner temperatures depend on high moisture contents of the wastes, which are controlled by infiltration and leachate management.
3. Temperature records from landfilled wastes with higher biodegradable content should therefore be used with caution in the prediction of landfill temperatures with newer waste compositions with lower biodegradable fractions.
4. The severe effect of higher liner temperatures on the service life of polyethylene liners has been discussed. Mitigation measures could comprise the inclusion of an inert layer above the drainage layer and liner as additional insulation or the provision of a double HDPE liner, the lower liner being subject to lower temperatures and slower antioxidant depletion, increasing the service life of the liner.
5. Few basal liners have temperature monitoring programmes and given the importance of temperature to the service life of HDPE containment barriers, more sites with long-term temperature monitoring covering a range of waste types would provide valuable data for landfill designers, operators and regulators.

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