Factors Affecting the Service-life of HDPE Geomembranes in an LLW Disposal Facility-19320

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ABSTRACT

The assessment of a suitable maximum allowable strain (MAS) for high density polyethylene (HDPE) geomembranes (GMBs) considered suitable for a proposed low level radioactive waste engineered containment mound with a 550-year design-life is described in the context of the available literature and data in 2018. Consideration is given to both the material properties and the factors contributing to the development of sustained tensile strain in the GMB. The assessment is based on the service-life of the GMB eventually being reached due to stress cracking after depletion of the protective antioxidants to a residual value. With respect to the selection of a GMB with a suitable stress crack resistance (SCR), it is noted that morphological changes can result in a substantial reduction in SCR with time, from the initial just manufactured value (SCR_o) to a more representative value (SCR_m), as the material tends to a thermodynamically more stable post-manufactured state. Thus, SCR_m should be considered more representative of the true SCR of the material than the value obtained from the off-roll material just after manufacture. SCR_m of can be estimated by aging the candidate GMBs in liquid at 55°C for 270 days. Considering the potential implications of failure of the textured GMB to be used at this facility, and the potential for repair and replacement if it does fail, it is recommended that a maximum allowable strain (MAS), from all sources, of 3%, 4% and 5% be adopted on the base, side slopes, and cover GMBs, respectively. These maximum allowable strain values were selected considering the nature of the waste to be contained and the design-life that is required; they may be too conservative for some other applications with a much shorter design-life or lower consequence of premature failure. It is also indicated that the most critical locations on the GMB are often the welded seams where GMB panels are joined or repaired. Welds act a stress-raisers (increasing the stress and strain the GMB compared to that on either side of the weld). To minimize the need for patching areas damaged by the removal of samples for destructive tests, it is recommended that destructive tests on welds should generally be restricted to the minimum possible. It is also recommended that the German limits on welded GMB thickness be adopted in construction. Since strains can be significantly increased by failure to construct in accordance with the design drawings and specifications, it is recommended that there be Construction Quality Assurance (CQA) by very experienced personnel with a good knowledge of compacted clay liners, Geosynthetic Clay Liners (GCLs), and GMBs and the facility design, and that there be an experienced individual watching the construction work at all times prior to completion of the liner system.

INTRODUCTION

Canadian Nuclear Laboratories (CNL) are proposing to develop a Near Surface Disposal Facility (NSDF) at the Chalk River Laboratories (CRL) site in Ontario, Canada for disposal of Canadian Nuclear Laboratories' Low Level Radioactive Waste (LLW) and other suitable wastes [1]. The proposed Engineered Containment Mound (ECM) includes both base liner and final cover systems which incorporate 2 mm-thick textured, white, high-density polyethylene (HDPE) GMBs. The barrier system in the Engineered Containment Mound of the Near Surface Disposal Facility (NSDF ECM) to be discussed here performs a function the same as to that in municipal and hazardous waste disposal facilities (typically called "landfills") with the difference between them and the LLW application considered here being the nature of the waste (low level radioactive waste) and leachate, and the length of the design-life. In this paper "landfill" is used generically for waste containment facilities (including that consider here) and "facility" is used specifically for the NSDF ECM.

For the following discussion of the longevity of a HDPE GMB liner there are three terms that warrant some definition at the outset:

- Time to nominal failure: This is a material characteristic for a given GMB under a defined set of exposure conditions. It is often taken to be when the break elongation reaches 50% of its initial value or the stress crack resistance reaches 50% of the specified value (or initial value in some other contexts).
- Service-life is an ultimate limit state value for a given application: In a landfill it is when the GMB is so cracked that it no longer limits the leakage to a reasonable (design-related) value. It is directly related to material behaviour under field conditions and is related to, but not the same as, the time to nominal failure.
- Design-life is the time the GMB is required to meet it design function (e.g., to limit leachate escape at or below the design level or a level that does not cause an unacceptable impact on the environment). It is often based on considerations such as the contaminating-lifespan of the landfill that are not directly related to the geomembrane material behaviour. One often expects the service-life to exceed the design-life.

Canadian Nuclear Laboratories are conducting an extensive study to evaluate the relative performance of five different HDPE GMBs using a leachate simulant comparable to that expected in the Near Surface Disposal Facility leachate and a reference simulant used for testing many GMBs. The results of the tests are intended to provide insight into the likely relative time to the end of the first stage of the time to nominal failure (antioxidant depletion) and will be used to select the candidate GMB(s) from those with a high probability of exceeding the design-life of 550 years at the expected field temperature [1].

The study described by [1] considers the effect of chemical exposure and temperature on the aging of the five GMBs. This is indeed a necessary consideration since the service-life is related to the material properties (i.e., to the time to nominal failure). However, in and of itself, this is not sufficient. One must also consider the sustained tensile strains and these will depend on design and construction considerations.

The proposed Near Surface Disposal Facility's base liner (Figure 1) incorporates, from top to bottom: 300 mm thick Granular 'A' filter, nonwoven geotextile filter, 300 mm thick layer of 19-mm relatively uniformly graded gravel (clear stone), woven geotextile separator, 200-mm-thick sand cushion, 2 mm- thick textured primary HDPE GMB liner, geosynthetic clay liner (GCL), 300 mm thick layer of 9.5-mm relatively uniformly graded gravel (clear stone), woven geotextile separator, 200-mm-thick sand cushion, 2 mm-thick textured secondary HDPE GMB liner, GCL, and 750-mm-thick compacted clay liner (CCL). The total thickness of base liner system is approximately 2.05 m. To have a service-life that exceeds the desired 550-year design-life it is necessary that the GMBs selected have adequate long-term performance characteristic from a materials perspective but also that the design and construction are such that as to limit the long-term tensile strain to below the maximum allowable strain (MAS). This paper addresses the question as to what represents a suitable maximum allowable strain for the Near Surface Disposal Facility.

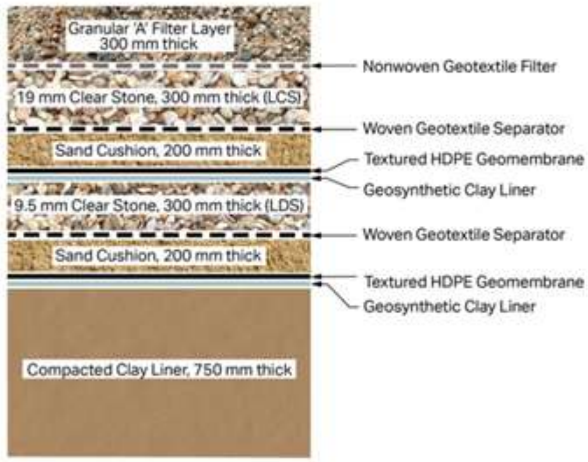

Figure 1. Base Liner System Components with Leachate Collection System (LCS) and Leak Detection System (LDS) (after [1])

BACKGROUND

This paper deals solely with what is commonly referred to as a high density polyethylene (HDPE) GMBs which typically contains a medium density resin. Since only HDPE GMBs are being considered, any reference to a "GMB" is implicitly to a HDPE GMB. The word "geomembrane" is used more generically and includes other types of polyolefin geomembranes.

Provided that the barrier system is correctly designed and installed with appropriate attention by a full-time experienced construction quality assurance (CQA) inspector together with an electrical leak location survey, and that the placement of the waste is carefully controlled to minimize the risk of damage to the liner, then there should be minimal holes and leakage (i.e., not exceeding the design values) through the primary composite liner and negligible leakage through the secondary composite liner at the time of landfill commissioning and closure (i.e., after about 50 years). Under these circumstances, the service-life of the GMBs will be dictated by stress cracking at locations where there are sustained tensile strains at the maximum allowable strain (MAS) value. Stress cracking is distinct from a puncture with which most people may be familiar. A puncture is typically a hole that forms in a ductile manner relatively quickly and is associated with strains well in excess of the yield strain of the GMB (Figure 2a). Stress cracks are brittle ruptures that develop with time at a locations of sustained tensile stress/strain. The time to stress cracking will depend on the magnitude of the sustained tensile stress and the properties of the GMB (specifically its stress crack resistance, SCR). A severely stress cracked sample is shown in Figure 2b.

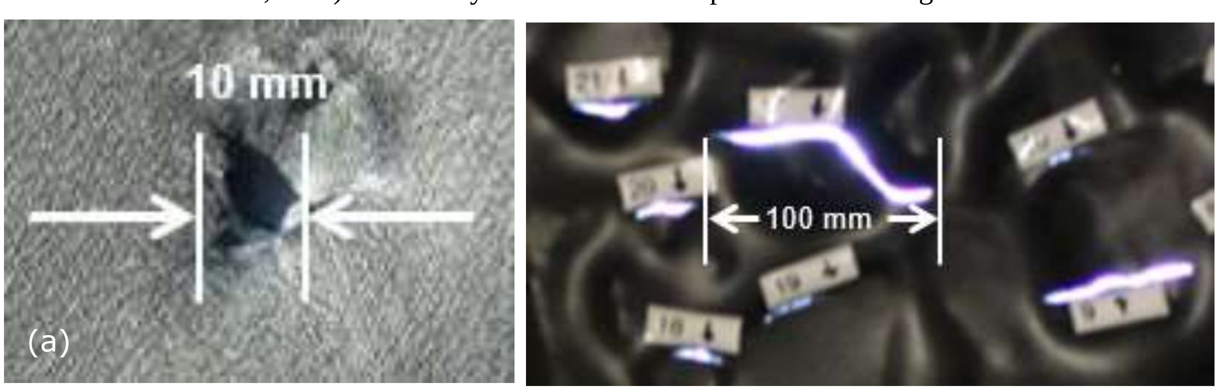

Figure 2: HDPE GMB with (a) a puncture formed during construction (detected by CQA and repaired), and (b) Stress cracks at the end of its service-life (modified from [2]).

In a landfill, sustained tensile strains can develop in a GMB from a number of sources but most notably: (a) indentions from protrusions (usually gravel particles) in a compacted clay liner or the overlying leachate drainage layer, (b) down-drag of the GMB on slopes due to the weight of the waste and subsequently due to consolidation/degradation of the waste, and (c) differential settlement of the material below the GMB. Rowe and Yu [3, 4] provided a recent review of the first two mechanisms. All three mechanism can be mitigated by design, appropriate construction, appropriate CQA, and controlled placement of the waste to minimize voids and the risk of significant differential settlement. There are other additional mechanism for developing sustained tensile strains (e.g., placing material over a GMB with what is known as trampolining, placing a GMB over a significant rut in the subgrade, excessive wrinkles and especially folding of wrinkles) that can arise during construction but can be avoided by experienced full-time construction quality assurance.

The service-life of a GMB will depend on the leachate chemistry, temperature, the sustained tensile strain/stress in the GMB, and the GMB stress crack resistance (SCR). The SCR is obtained from the single point notched constant tensile load (SP-NCTL) test (ASTM D5397, Appendix) conducted on specimens of GMB with a precut notch under a stress of 30% of the short-term yield stress in an aqueous solution containing 10% surface-active reagent (Igepal CO-630) at 50 ± 1°C. The notch, reagent, and temperature all accelerate the stress cracking and hence the values obtained are strictly only applicable to those test conditions but are a useful index to the relative stress crack characteristics of different GMBs or a GMB with different amounts of aging. The SCR test can only be readily performed for smooth sheet and hence for a textured GMB it is usually obtained for the smooth edge of the textured sheet.

In the stress crack test, the GMB specimen is subjected to a constant load of 30% of the yield stress. For the GMB tested by [2, 5] to be discussed later, the short-term tensile strain in the specimen was about 5-6%. This load is sustained and with time there will be some creep (increase in strain with time) until rupture occurs. However, this test shows that stress cracking can and does occur for a short-term tensile strain of 5-6% if the stress is maintained. Had the specimen been subjected to a fixed strain corresponding to that at 30% of the yield stress, with time some stress relaxation would occur and it would be expected to take longer before stress cracking would occur. Thus, the tensile stress/strain behavior of a GMB is a complex issue since strains can increase due to creep and stresses can reduce due to relaxation. In the field, both can occur and what governs will depend on the subgrade. At the Near Surface Disposal Facility there is a 750 mm CCL and a GCL below the secondary GMB, then a protection layer, a leak detection system, and a GCL below the primary GMB which is overlain by a protection layer and a leachate collection system. For the cover, there is waste, 300 mm of sand, and a GCL, below the GMB which is overlain by a sand protection layer and the rest of the cover system. These subgrades will have time dependent properties related to primary and secondary compressions as well as local deformations that will affect the tensile strains/stresses in the GMB. In cases like this one cannot assume that stress relaxations will manage the strains in the GMB and, as clearly illustrated by [2,5], stress cracking can occur with time in a liner system where a GCL is the only significant time dependent component of the subgrade (Figure 2b). One can however envisage a situation where the loads associated with the deformation are low enough, as represented by the short-term maximum allowable tensile strain (MAS) in the GMB, that the relative rates of subgrade creep and GMB stress relaxation are such that at some point stress cracking is delayed, if it even occurs, for a very long period of time until the stress crack resistance drops so low that stress cracking eventually occurs. All these factors need to be considered and are implicitly considered in geosynthetic liner longevity simulator tests to be discussed later.

DISCUSSION AND IMPLICATIONS OF PREVIOUS MAS RECOMMENDATIONS

There is limited advice in the literature as to the maximum allowable tensile strain (MAS) in a GMB. The recommendation most commonly adopted in most parts of the world (Germany a notable exception to be discussed) is that proposed by Peggs et al. [6] and given in Table 1. It is important to place Table 1 in the context for which it was developed.

These recommendations were developed specifically with respect to Waste Management's American Landfill near Canton, OH, where a geomembrane was being proposed as part of a separation lining system for a vertical expansion on an existing unlined cell. The geomembrane was to be covered by a geonet/geotextile drainage composite or a drainage sand and to rest either a compacted clay or a geosynthetic clay liner (GCL) underlain by the waste in the exiting landfill cell. The primary source of tensile strain being considered was differential settlement expected to develop over approximately 80 years with a maximum of 60% of the settlement within 5 years.

Table 1: Peggs et al.'s Maximum allowable strain (MAS) values for confined geomembranes (GMBs) where the GMB is slowly strained (adapted from [6])

Case	**MAS**
Smooth HDPE (SCR > 1500 hours)	8%
Smooth HDPE (SCR < 1500 hours)	6%
Textured HDPE	4%

As indicated by Peggs et al. [6], stress cracking is an intrinsic characteristic of the semi-crystalline HDPE GMB but can be accelerated by certain chemical environments (e.g., detergents/surfactant, oxidizing acids, and chlorinated solvents) and temperature. In selecting the maximum allowable strain, [6] discusses the German Federal Institute for Materials Research and Testing (BAM) [7, 8] recommended maximum global strain (i.e., MAS) of 3% and includes the associated maximum local strain of 0.25% due to indentations where they are calculated by a very specific method specified by BAM (this number should only be used in that very specific context and is low, in part, because the calculation method ignores bending strains; it should not be applied to other methods of calculating indentation strain which consider bending strain). This BAM approach considered the stress at which the stress relaxation history of a specimen initially rapidly strained to 3% and maintained at 40°C (a typical MSW landfill liner temperature) intersects the brittle segment of the 40°C stress rupture curve at a projected 50 years. Based on the same figure, the present authors projected the intersection of the stress relaxation history of a specimen initially rapidly strained to 3% and maintained at 20°C to occur at about 800 years.

Peggs et al. [6]:

- discuss stress relaxation in context an examination of stress relaxation for a 1.5 mm-thick GMB with initial stresses of 40, 50, and 60% of yield stress and initial strains of 1, 3, and 5% for a wide range of temperature (–10 °C ≤ T ≤ 70°C). At a temperature of 10°C (i.e., at or above that expected at the Near Surface Disposal Facility) the stress induced by an initial 3% strain eventually reduced to an equilibrium value of about 30% of the initial stress.
- quote private communications from Dr. W. Müller of BAM as stating:

  " ….. *A strain limit of about 3% is an extremely conservative estimate from pipe pressure data for environmental conditions (base lining) with temperatures up to 40°C. At room temperature (cap lining) a limit of up to 6% seems to be acceptable*."

  and indicate that the German BAM Institute allows a maximum general strain of 6% in cover/capping GMBs.
- conclude, for smooth GMBs, that

  "*The allowable general strain figure of 3% was generated from pipe tests in which the stress was maintained constant (stress relaxation does not occur) and Janson's (1981) recommendation of a maximum 5% strain is in a service situation where applied stresses (internal gas pressure) are active and constant. And in none of these situations is the material intimately confined between two masses holding the material "together" – and controlling its strain history. For instance, the confining soil will prevent the local ballooning of a thin spot that would otherwise occur if the geomembrane were pressurized on one side and unsupported on the other side. Under equilibrium settlement conditions the confining soils will not allow a geomembrane to further deform to allow a crack to open up.*

Therefore, if an active strain of 3% is felt sufficient to induce a potential critical stress in an HDPE geomembrane, but loading is very slow so that stress relaxation (by a factor of 2) can occur, the critical stress will actually be achieved at a strain of 6% or more, by the time stress relaxation has accumulated. Therefore, on consideration of the various test data, the opinions expressed by those involved with the regulations and specifications, the contributions of confining pressure, the occurrence of stress relaxation, and the nature of the soils on each side of the liner in the American Landfill, it is my calculated opinion that maximum allowable biaxial strains be conservatively set at 6% and 8% for HDPE geomembranes with 400 hr < SCR < 1500 hr and SCR > 1500 hr, respectively."

These conclusions and Table 1 are drawn with respect to: (a) a specific municipal solid waste landfill and application with a design-life likely substantially shorter than that for the Near Surface Disposal Facility but where the liner is likely to be at a much higher temperature than the Near Surface Disposal Facility bottom liner or cover, (b) the strains of concern are to be induced by differential settlement, and (c) a cut-off base strain was 3% based on test data that was increased to 6% on the basis of an inferred creep-stress reduction factor of 2. The increase from 6% to 8% for higher SRC appears arbitrary and was unexplained (but likely reflects the reasonable expectation that the service-life will be longer for higher SCR, other things being equal, and hence for the same service-life a higher strain could be tolerated for a GMB with a higher SCR). Thus, without questioning the validity of the recommendation for the specific situation for which they were made, it is valid to ask if they are suitable for the different design-life and temperature of Near Surface Disposal Facility. This question will be addressed later in the paper.

With respect to textured GMBs, [6] stated:

"*As a consequence of the changes and potential changes in mechanical performance characteristics of … textured materials it is proposed that MAS be set … at 4% for the randomly textured products, … regardless of geomembrane/resin SCR values*."

As acknowledged [6], there is no real data upon which to assess an appropriate reduction. The 33% reduction (from 6% to 4%) is a professional opinion based on the judgement of (the very experienced and well respected senior author of [6]), with the stated expectation that the given reduced value is conservative.

SOURCES OF TENSILE STRAIN (STRESS)

The tensile strain at any point will be the total tensile strain from all sources. The objective of design <u>and</u> construction for the Near Surface Disposal Facility is to limit the maximum such total strain to below the maximum allowable strain (MAS) to be discussed subsequently. The common sources of tensile strain for a buried liner include: (i) gravel in an overlying drainage layer, (ii) gravel in an underlying layer (e.g., compacted clay liner), (iii) down-drag forces on side slopes both on initial loading and with subsequent consolidation and settlement of the waste, (iv) "trampolining" or tensile membrane strains/stresses induced by poor construction practice, (v) wrinkles, (vi) differential settlement of subgrade/waste with time, and (vii) any permanent strains induced by seismic events. Tensile strains may be magnified by the presence of welds/seams. These will each be discussed below.

Tensile Strain/Stress Induced by Gravel Drainage Layers

Most of the research and discussion of allowable tensile strains relates to indentations due to gravel [9, 10]. This is because in a landfill with a gravel drainage layer there is potential for a very large number of indentations unless there is an adequate protection layer between the drainage layer and the geomembrane. With respect to indentations, Peggs et al. [6] noted that:

"*It was this susceptibility to stress cracking that prompted German regulators to limit the strains to which HDPE geomembranes could be subjected. This was driven by the need to prevent damaging puncture stresses by drainage stones, and therefore to define the type of test required to assess the protection capabilities of geotextiles and other protection systems.*

It is important to note the differences between the German and US approaches to geomembrane protection as it affects the limiting strain. The Germans were concerned about a deformation in the geomembrane causing premature failure of the geomembrane by stress cracking sometime in the future. The US approach is to assess puncture protection by determining whether complete geomembrane penetration occurs at the time of the test. Hence, the German emphasis is on limiting strain, a concern that has not appeared until recently in the US."

In the 13 years since this statement, the predominate US attitude has not changed significantly and their remains a significant difference between the common approach in the US which involves design of protection layers based on factored puncture resistance rather than the German approach which focuses on limiting tensile strain. However, over the past 13 years, the data supporting the German focus on the importance of strain with respect to long-term performance has increased substantially and strongly supports their general approach (see [3 and 4] for a review of the literature). This topic was the subject of much discussion at a session at the recent *International Geosynthetics Society Barriers Workshop* held in Munich in June 2018 where the US delegate continued to strongly advocate the US approach. The other presenters (which included the senior author of this paper) did not share the US delegate's view. In his introductory comments on the engineering mechanics of geomembrane deformations from coarse gravel, the session chair (Dr. R.W.I. Brachman):

"*emphasized that the geomembrane is part of a system, meaning that long-term deformations of one or more components of the system can lead to additional deformation of another. As such, the geomembrane is not under pure creep, but restrained by soil or other materials beneath the geomembrane; nor is it under pure relaxation, if strains increase with time. Rather, it is an interaction problem that could be impacted by the gravel / geotextile / geomembrane / material(s)-beneath-the-geomembrane components of the system. He also explained the need to distinguish between large- versus small-displacement problems. Short-term geomembrane puncture from cover-soil placement and construction equipment loading is a large-displacement problem as the geomembrane response is ductile (relatively large elongations prior to break). Long-term geomembrane rupture from gravel indentations under sustained burial pressure is closer to a small-displacement problem if the geomembrane response can become more brittle (relatively small elongations prior to break) with time. Proper consideration of engineering mechanics was encouraged to understand limitations of past empirical approximations; resolve why some tests show no long-term rupture, while others do; and select an appropriate protection layer to ensure long-term environmental protection.*"

The subtext to this comment is that the test data being relied on in the US approach does not adequately consider the interactions that occur in a real field situation and while it considers relaxation in the GMB, it does not consider the effects of creep in the subgrade over which GMBs are placed when in a composite liner.

In any discussion of GMB strain due to indentations, it is important to distinguish how the strain is assessed. As indicated by [3], the method can greatly affect the inferred strain. The German BAM recommended a limiting the global strain to 3% and the arch elongation strain due to an indentation to 0.25% [7-9]. This latter (0.25%) value must be interpreted in the context of the method used in its assessment that involves calculating the membrane strain by fitting a circular segment to the indentation in the lead sheet below the GMB. The Germans realized that this approach considerably underestimated the strain developed due to bending (especially for the 2.5 mm-thick GMB used in Germany) and it is understood that the role of the 0.25% limit for indentations was (a) to limit the strain to as small as reasonably possible (zero is not reasonable) due to indentations from the gravel drainage layer (since this could be controlled by the choice of protection layer) and (b) to ensure that the strain induced by bending and membrane elongation remained below 3%. All the indentation strains discussed in this paper were obtained with the Tognon et al. [10] method that provides much more realistic strains than the arch elongation method and includes both the bending and membrane strains in its evaluation and so no adjustment is needed to make allowance for their method of strain calculation and the strain can be directly compared to the maximum allowable strain.

Given the differences in available approaches, some justification for the focus on strain and assessment of strains at which stress cracking (rupture) will occur is required. Ewais et al. [2] pre-aged a smooth 1.5-mm thick GMB to the end of the lag stage (end of Stage II in the typical three stage degradation process considered relevant to HDPE [11]) to where the physical properties were just beginning to degrade (start of Stage III in the three stage model of GMB degradation). They placed the pre-aged GMB in a composite liner (GMB over a GCL and sand foundation) with an approximately 560 g/m^2 geotextile protection layer between the GMB and the 50-mm gravel drainage layer containing leachate in a geosynthetic liner longevity simulators [2]. The system was then subjected to a pressure of 250 kPa at 85ºC. No punctures or ruptures were observed in the GMB after 10 and 16 months. Ruptures (i.e., fully penetrating stress cracks) were observed for the cells aged for 20 (1 rupture), 24.5 (12 ruptures), 25 (40 ruptures) and 25.5 (61 ruptures) months when the stress crack resistance (SCR) of the GMB was about 760 hours [2]. The test was repeated for a GMB aged to full depletion of antioxidant (end of Stage I as defined by [11]) and consistent result were obtained after allowing for a 5.5 month lag time in Stage II.

Abdelaal et al. [5] tested the same GMB as [2] under these same conditions except that the GMB had been pre-aged to about 75 hours SCR (i.e., 10% of that tested by [2]). At 85ºC, the GMB ruptured at a tensile strain of 12 ± 2% of sustained loading (measured after 48 hours since the test was allowed to run for 24 hours after the leak detection system detected the first hydraulically significant crack). This can be compared to over 600 days before the first rupture at a strain of 24 ± 6% when the SCR was 760 hours [2] (i.e., a 10-fold decrease in SCR reduced the time to cracking by a factor of about 600). The 12 ± 2% strain reported in [5] after 48 hours at 85ºC was not significantly different to the 11% value [12] obtained from a similar short-term (10 hour) test at room temperature suggesting very little creep or relaxation during that period. Thus the factor of two difference in the rupture strain at 1-2 days and 600 days suggests that (i) there was much more creep and relaxation of both the GMB and underlying materials (primarily a GCL since relatively little time dependent movement would be expected for the sand subgrade) in 20 months at 85ºC for SCR = 760 hours than in the 48 hour test for SCR=75 hours under the same applied load. This supports the argument (implicit in Table 1) that higher SCR is better (other things being equal) but it is essential to remember that with time the SCR will decrease for all GMBs and hence even for a sustained stress the resistance to stress cracking will eventually reduce with time; this is considered in evaluating the performance of GMBs discussed in [1]. This comparison also highlights the relevance of Dr. Brachman's quote (above) about the importance of the mechanics of the problem. Although the overall stress field involved is a compression under 250 kPa of vertical stress, the vertical stress varied locally and for a gravel particle, it will be greatest at the tip pressing into the GMB and least between adjacent gravel particles. The load at the top of the gravel is partly carried by membrane tension and bending in the GMB and part is transferred to the bentonite in the GCL below the gravel. In the short-term a stress equilibrium is reached (at 24-48 hours) at 11-12% strain in the GMB. If cracking had not occurred (e.g., due to higher SCR), stress relaxation and creep would occur in the GMB and creep would occur in the bentonite (moving away for the high load); however, the stress equilibrium must be maintained and so a significant stress is maintained in the GMB despite the creep/relaxation until failure occurred at 24% strain after about 600 days when SCR was 760 hours. Had the GMB been directly on a firm sand subgrade (no GCL) one can expect that there would be less creep and more stress reduction due to relaxation – thus cracking would take longer; however when it did occur the leakage would be very substantial. Similarly, the failure time would be longer with a better protection layer [3, 4]. Note also, that only a third (34%) of the cracks reported by [2] were at the tip of the gravel, half (48%) were on the side slopes, and 18% (and the largest and most open cracks/ruptures) were between gravel particles due to the bending of the GCL when pinned by adjacent gravel particles; the latter were the most hydraulically significant (see 100 mm long crack on right of Figure 2b).

The experiments reported by [5] had a leak detection system that signaled when a crack had formed. To confirm that a rupture had indeed occurred, the geosynthetic liner longevity simulator experiment was continued for 24 hours after detection of the first hydraulically significant crack before termination.

During this 24-hours period, the number of fully penetrating stress cracks increased from 1 crack (35,000 holes/ha) at 55ºC to 7 at 65ºC, 16 at 70ºC, 34 at 75ºC and 41 (~1.5 million holes/ha) at 85ºC. Thus, failure is progressive and accelerated by temperature, *T*.

The failure times given above are not the service-life of the GMB. Rather, they reflect the time to rupture after the SCR had reduced to 75 hours. Nevertheless, they show that there is a strong correlation between rupture time and temperature. Also a relationship was established between average rupture strain and temperature [5] which suggests that the strain at which ruptures (stress cracks) could occur in this test decreases with temperature (even though the time to rupture increases). The hydraulically significant tensile strain at rupture was 8% for the geosynthetic liner longevity simulators at 55ºC, however there were ruptures at strains lower than 8% in 75% of the other experiments with the lowest rupture strain being 6% for the experiment at 75ºC. The cracks observed by [5] were only those that occurred over 24 hours from the first detection of leakage. Had more time been allowed before test disassembly there likely would have been more cracks.

The strains that develop in a GMB are a function of: (i) the type and nature of the clay liner and/or subgrade below the GMB, (ii) the nature of the drainage layer above the GMB and especially its particle size, (iii) GMB thickness, (iv) applied stress, (v) expected liner temperature, (vi) the length of the period of sustained loading, and (vii) the nature of the protection layer. For the conditions examined by [2, 5], one would expect the short-term (10-hour) maximum strain at room temperature to be about 11% and to be higher for tests conducted for a longer time and/or at a higher temperature. However, ruptures do not always occur at the locations of highest strain and can occur at much lower strains in some directions due to the anisotropy of the GMB. For example [2] reported that ruptures were observed to be generally in the machine direction with 51% being ± 15º for the machine direction (0º), and 96% ± 45º to the machine direction and they did not necessarily occur at the locations of maximum strain but rather could occur at smaller strain in the cross-roll direction. Given the length of the tests at 75, 70, 65, 55, 40ºC and the elevated temperature, the maximum strains all exceed 11% yet many of the ruptures occurred at much smaller strains. Thus, as indicated by [3, 4], in design it is important to (a) project the strain for the anticipated temperature and time of exposure, and (b) limit the maximum projected tensile strain from all sources (those above were only for indentations from the drainage layer) to below the maximum allowable strain (MAS).

Projecting the best-fit curve to the average rupture strains reported by [5] has risk since the relationship between the strain at rupture and temperature may change from the linear trend at temperature below which the data was established and hence extrapolations should be viewed with some caution. With this caveat, the projected average rupture strain from the relationship given by [5] is about 2% at 10ºC and hence the strain at rupture can be expected to certainly exceed 2% at 10ºC (it can be demonstrated that 2% errs on the conservative side). Fitting an Arrhenius relationship to same data in terms of the reciprocal of strain (1/strain vs 1/Temperature (K)) gives a predicted (eventual) rupture strain of 5% at 10ºC. Plotting ln (strain) vs 1/Temperature (K) gives a predicted (eventual) rupture strain of 3.6% at 10ºC. The three values are given to demonstrate the uncertainty associated with the interpretation of the same data when extrapolating to lower temperatures depending on the method of extrapolation. The average of the three methods is 3.4%. Based on these numbers, a conservative estimate of the strain at which rupture can occur is 3% and a more likely value relevant to Near Surface Disposal Facility is considered around 4% at to 10ºC. At this 4% strain the length of time until rupture will depend on the GMB and its exposure conditions but can be expected to exceed the time to nominal failure (often taken to be the time for SCR to reduce to 250 hours and sometimes to 150 hours) for the GMB under anticipated field conditions at the Near Surface Disposal Facility. The 3% strain was arrived at from recent data on modern GMBs in liner systems under simulated field conditions and hence from considerations different to those used by [7-9] and, thus, the convergence of approaches adds confidence to it being a reasonable but conservative value.

The foregoing discussion of cracks in geosynthetic liner longevity simulators is based on published papers. Unpublished work (Abdelaal, Rowe & Brachman, pers. comm.) is being conducted with different gravel sizes, protection layers, and stresses.

Of particular note is a test on the same GMB with a 2440 g/m^2 geotextile protection layer but other conditions as for the tests reported above at 85°C ruptured occurred at 5% tensile strain when the GMB stress crack resistance was 75 hours. This shows that rupture can occur at tensile strains (in unnotched smooth sheet) at strains less than 6% in a liner system.

Gravel in an Underlying Layer

Of relevance to the Near Surface Disposal Facility design is the potential for gravel (stones) in the compacted clay liner (CCL) proposed for the secondary composite liner. Brachman and Sabir [13] performed in large geosynthetic liner longevity simulators tests on liner systems which included a CCL and demonstrated that for a CCL compacted at a typical 2-4% wet of standard Proctor optimum water content (w_{opt}) required to get a low permeability CCL, a single 35 mm gravel particle in the upper lift but below the surface of the CCL (i.e., not visible) could induce tensile strains of 3.6 to 14% in the GMB depending on the compaction water content and applied stress up to 1000 kPa (Table 2). The larger strains were developed for the clay compacted at a water content w =16% which is at, or close to, the plastic limit (PL). They also showed that even in this case (CCL compacted at of 16% = w_{opt} + 4% ~ PL) and a 1000 kPa vertical pressure) there was negligible strain in the GMB due to the gravel particle when a GCL was placed between the CCL and the GMB (Table 2).

Down-drag Forces on Side Slopes

As discussed by Rowe and Yu [3,4], numerical models are currently the only practical tool for assessing the potential down-drag tensile strains and forces that can develop in the GMB due to placement and subsequent consolidation/degradation of the waste when designing the geosynthetic liner system. The down-drag strains are a function of the slope angle, the waste properties, liner design, thickness of the waste and subgrade. Down-drag forces are especially significant since they are induced by equilibrium requirements and while the GMB can be expected to creep under the corresponding stress, relaxation can only relieve these stresses if there is another loadbearing element (e.g., reinforcement) that has adequate stiffness and is less susceptible to creep than the GMB that can sustain the transfer of these loads throughout the design-life of the GMB (550 years in this case).

Table 2: Maximum geomembrane strains reported for a CCL with a 35 mm gravel particle below the surface (not visible) of 150 mm-thick CCL below a 1.5 mm HDPE GMB with a 540 g/m^2 protection layer and overlying sand protection at different applied vertical pressures at room temperature (adapted from [13])

Liner	CCL compacted w (%)	Applied vertical pressure (kPa)	Maximum strain (%)
GMB/CCL	14 (w_{opt} + 2%)	600	3.6
GMB/CCL	14 (w_{opt} + 2%)	1000	6.3
GMB/CCL	16 (w_{opt} + 4%)	200	5.2
GMB/CCL	16 (w_{opt} + 4%)	600	10.0
GMB/CCL	16 (w_{opt} + 4%)	1000	14.0
GMB/GCL/CCL	16 (w_{opt} + 4%)	1000	< 0.1%

Tensile Membrane Strains/Stresses Induced by Poor Construction Practice

Sustained tensile strains/stresses can arise when a GMB is placed and welded at one temperature and the cooling causes thermal contraction. This can be especially problematic at changes in grade (e.g., toe of side slopes) where it can cause what is known as trampolining. These tensile stresses can be exacerbated by placing material over a GMB subject to exiting membrane strains due to trampolining. Tensile strains can also be developed by placing material over a GMB underlain by a significant rut in a compacted clay liner or in the subgrade beneath a GMB/GCL composite liner.

Wrinkles

Excessive wrinkles in the GMB and especially when the wrinkling leads to folding of wrinkles can give rise to tensile strain.

Strains from Differential Settlement and Permanent Strains from Seismic Events

As for down-drag tensile strains in the GMB, numerical models are the best means of assessing the GMB strains induced by short and long-term differential settlement of the waste.

Seams

Rowe and Shoaib [14, 15] showed that the material adjacent to the seam could degrade about twice as fast as the adjacent sheet in MSW leachate. Giroud et al. [16] reported that tensile strain concentrations near seams can give rise to failure adjacent to seams. Laboratory testing reported by Kavazanjian et al. [17] indicated that the tensile strain magnification induced by a seam was even greater than estimated by [16]. Based on [17], for a sheet tensile strain of about 3% the strain magnification ranged between 2.3 to 4.0, depending on sheet thickness and type of seam, with an average of 3.2. Thus if the average seam strain was 3%, the strain at the weld would be about 9.6% and any defect, such as a scratch, in the heat affected zone adjacent to the weld assumes a much higher significance than it would in the sheet well away from the weld.

MAXIMUM ALLOWABLE STRAIN (MAS) FOR THE NEAR SURFACE DISPOSAL FACILITY

The service-life of the proposed 2mm-thick textured GMB will be longer the (a) lower the liner temperature, (b) the higher the operational SCR (SCR_m) of the GMB, and (c) lower the sustained tensile strain. These will be addressed below.

Temperature: For the Facility GMB's, the long-term temperature is dictated by its location and will likely be very close to the long-term average annual temperature (i.e., around 6ºC at present). Thus 10ºC would appear to be a conservative design value even allowing for global warming.

SCR: The manufacturers of the five candidate GMBs selected for detailed examination [1] were requested to provided GMBs with an off-the-roll SCR greater than or equal to 1000 hours [1]. The preferred candidate geomembrane will be based on the basis of relative performance with respect to OIT depletion and changes in physical parameters in immersion tests in three simulant fluids at a range of temperatures. Research has shown morphological changes can result in a substantial reduction in SCR with time to SCR_m as the material tends to a thermodynamically more stable post-manufactured state. For example [18] give an example where SCR decreased from an initial SCR_o = 680 hours to $SCR_m \approx 0.5\ SCR_o$ while [19] cite an example where it drops from SCR_o = 500 hours to $SCR_m \approx 0.38\ SCR_o$ (indeed the SCR of this GMB reduced from 500 to 330 hours in only four years on the roll in the laboratory). These two data points show that the ratio of SCR_m/SCR_o is GMB dependent. It is SCR_m and not the initial SCR_o from the off-roll material just after manufacture that will control the GMB service-life and this should be considered. SCR_m of can be estimated by aging the candidate GMBs in liquid at 55ºC for 270 days. Because of the effects of morphological change [18], more weight will be given to the relative SCR values after 270 days at 55ºC than to the initial values in making the final selection of the GMB to be used.

The total tensile strain from all sources will be held as low as practical (see next section). However, it is not reasonable to expect negligible strain and nor is it required to achieve the desired design-life of 50+500=550 years. Given that temperature is fixed by site location, the candidate GMBs have already been selected and are subject to a detailed study to select the most suitable, the remaining issue to be addressed is the maximum allowable strain (MAS).

Base

The most critical location with respect to minimizing the GMB strain is the bottom of the Near Surface Disposal Facility. This represent a large area where leachate will pass over the liner and is inaccessible for repairs or replacement once the waste is in-place and so a conservative approach is warranted.

Based on (i) the justification adopted by the Germans which (based on the present authors' assessment) gives a conservative estimated time to rupture of 800 years at 20^{o}C for a 3% strain, (ii) the conservative rupture strain at 10^{o}C being about 3.4% based on various interpretation of data from [5], it is recommended that if the base were to be covered by a smooth GMB, a maximum allowable strain MAS = 3% be adopted.

The present design uses a textured GMB on the base and so consideration must be given to the effect of texturing on this recommendation. It is known that the break strength and elongation of GMBs textured by the nitrogen-injection blown film method adopted for all five candidate GMBs is considerably reduced compared to similar smooth sheet. However, the strains in the GMB will be a very small fraction of the break strain and indeed only a small fraction of the yield strain. Since the SCR is related to the tensile stress as a proportion of the yield stress, the effect of texturing on yield strength is examined.

The yield strength of the candidate textured GMBs is equal to or exceeds that of the smooth GMB for all five GMBs in the machine direction and for four GMBs in the transverse direction [1]. For the one exception in the transverse direction, the yield strength of the textured GMB is only 5% lower than for the smooth edge. Given the generally similar to better yield strength for the textured material compared to smooth, together with conservative assumptions used to establish 3% maximum allowable strain for smooth GMB, it is not considered necessary to apply any additional factor for the five textured GMBs being considered and so it is recommended that a maximum allowable strain MAS = 3% be adopted.

Slopes

Like the base, the GMB liners side slopes below the waste are essentially inaccessible for repairs or replacement once the waste is in-place. However, unlike the base, they represent a relatively small area, very little leachate is expected to pass over the liner on the side slopes and, assuming good construction quality assurance (CQA), there is minimal potential for leachate mounding. Thus, while it is still highly desirable to keep strains as low as possible ($\leq$ 3%), the same high level of conservatism adopted for the base is not required. Because the side slope (at 3 horizontal : 1 vertical or 18^{o}) is steeper that the base, tensile stress due to down-drag is likely to be greater on the side slopes than on the base and a small stress from this source must be accommodated within the maximum allowable strain. Based on the available information reviewed in the previous sections, it is considered that for a suitably selected GMB, it is very highly likely that a maximum allowable strain MAS = 4% would provide the design life required for the Near Surface Disposal Facility. Thus, while every reasonable effort will be made to limit the long-term tensile strains from all sources to 3%, a MAS = 4% (from all sources) is recommended for the five candidate GMB being considered for the side slopes.

Cover

The cover GMB should have little exposure to leachate and is primarily to limit the ingress of water. In the cover, the GMB is confined between a GCL and 0.3 m (minimum) below and about 1.75-2.35 m of soil above. The cover slope has a maximum of 4 horizontal: 1 vertical (25% or 14^{o}) and a minimum of 5% (<3^{o}) with only the weight of the 1.75-2.35 m of overlying soil to induce down-drag stress and so down-drag is far less significant for the cover than the side slopes or the 10% slope on the base.

The primary source of tensile strain for the cover will be that induced by differential settlement of the waste over the 550-year design life. Unlike the GMB below the waste, the cover can be repaired (if needed), replaced (if needed), or an additional cover could be constructed should it ever be needed. Therefore, the GMB in the cover, while important, is the least critical of those in the Near Surface Disposal Facility liner systems and a larger maximum allowable strain could be tolerated.

Based on the available information reviewed in the previous sections, it is considered that for a suitably selected GMB, it is highly likely that a maximum allowable strain MAS = 5% would provide the design-life required for the Near Surface Disposal Facility. Nevertheless to the extent practical, every reasonable effort should be made to limit the long-term tensile strains from all sources to 4%.

MINIMIZING TENSILE STRAIN IN THE NEAR SURFACE DISPOSAL FACILITY GMBs

The following steps will be taken to minimize strain in the Near Surface Disposal Facility GMBs to keep the maximum expected strain to less than the recommended maximum allowable strain.

Protection of the GMB from Gravel in the Drainage Layer

The bottom base liner for the Facility design (Figure 1) has, from bottom up: (i) CCL, (ii) GCL, (iii) secondary GMB (iv) sand cushion [i.e., protection layer] (v) 9.5 mm gravel leak detection layer, (vi) GCL, (vii) primary GMB, (viii) sand cushion, and (ix) 19 mm gravel leachate collection drainage layer. By testing the system the interaction between the components is implicitly assessed. The specification for the sand cushion is intended as the protection layer but for other reason the designers require $D_{50} \geq$ 2mm, $D_{10} \geq$ 0.35mm, with maximum size being fine gravel $D_{100} \leq$ 6.4 mm. This specified sand with $D_{50} \geq$ 2mm is potentially much coarser than the comparator sand for which published tests have been conducted. On the side slope the sand cushion is replaced by a thick (tentatively 2000 g/m^2) in contact with the drainage gravel. Thus, once the source of the sand and clay is identified it is recommended that geosynthetic liner longevity simulator test be conducted to simulative the critical portion of proposed secondary liner system tests be constructed under the maximum proposed load (increase by a factor to account of time dependent effects) to check that the indentation strains are sufficiently small that, together with the other anticipated strains, they are unlikely to exceed the maximum allowable strain of 3% on the base and 4% on the side slope. If the indentation induced tensile strains exceed allowable limits (when combined with other expected strains) then:

(a) on the base, the grain size distribution of the sand cushion can be adjusted to get an acceptable low strain. Reported test [12, 20, 21] with a poorly graded sand (e.g. with D_{100} = 5.5 mm, D_{90} = 3 mm, D_{60}= 0.58 mm, D_{50} = 0.45 mm, D_{10}= 0.15 mm) cushion have given maximum tensile strains ≤ 0.2%.

(b) on the side slope, the 50 mm gravel might be replaced by the 19 mm gravel to be used on the base, and/or the protection layer modified.

Protection of the GMB from Gravel in the Compacted Clay Liner

The specification for the compacted clay liner requires $D_{50} \leq$ 0.075 (so the majority of the soil is fine grained) but allows $D_{100} \leq$ 100 mm and thus there may be coarse particles in the soil. The secondary liner has, for a variety of reasons, including this, been designed with a GCL between the GMB and CCL. It is anticipated [13] that this GCL will mitigate the effect of gravel in the CCL on GMB tensile strains. However, it is recommended that in the geosynthetic liner longevity simulator tests proposed above for the assessing the cushion layers also use CCL material that is representative in terms of gravel content with that proposed for the Facility and be compacted at the upper limit of the acceptable moisture content range. This will allow confirmation that the GCL will provide the required protection for the proposed CCL material.

Design to Accommodate Down-drag Forces

Calculation have been performed by the designers to assess the likely down-drag strain. With respect to these calculations, the relative friction angles of the layers above and below the GMB are critical in assessing the tensile strains in the GMB.

For the waste in the facility, the primary source of down-drag strain is likely to be that due to the initial loading since the magnitude of subsequent deformation due to settlement are likely to be far smaller than for MSW landfills. For this design down-drag induced stains are not considered to be a major contributor to the total tensile strain on the side slope.

Design to Minimize Tensile Strain at Seams

Following general good practice, seams will not be placed perpendicular to the 3H: 1V slopes of the Facility or within 2 m from the toe of the slope. Care will be taken to avoid wherever possible seam or welds in areas of higher expected tension. Destructive tests on welds will generally be restricted to the start and end of a welding run to avoid the need for patching of areas damaged by the removal of samples for destructive tests. To minimize loss of antioxidants in the heat affected zone during welding, it is recommended that the German DVS [22] limits of weld thickness be applied as an acceptance criteria for welds in addition to the usual peel and shear.

Management of Construction Related Tensile Strains (Stresses)

The tensile strains that can be induced by “trampolining” and other tensile membrane strains/stresses induced by poor construction practice, wrinkles, and differential settlement of subgrade with time can all be kept to negligible levels at this site by good construction quality assurance (CQA). Thus, it is recommended that there be construction quality assurance by very experienced personnel with a good knowledge of compacted clay liners, GCLs, and GMBs and the Facility design, and that there be an experienced individual watching the construction work at all times prior to completion of the liner system.

CONCLUSIONS

The factors contributing to the development of sustained tensile strain in the GMB and ultimately to the service-life of HDPE GMBs based on stress cracking have been considered. Based on a review of the relevant literature including the latest findings from geosynthetic liner longevity simulators, recommendations were made for the maximum allowable strain to be permitted in the proposed 2-mm thick textured HDPE GMB liners in a low level radioactive waste disposal site proposed for Ontario, Canada. The recommendations are made in the context of the site location (liner temperature) and 550-year design-life. Specifically, to achieve a service-life of the GMB that can be expected to greatly exceed the required design-life it was recommended that:

- the selection of the final candidate GMBs be based on the performance of the five candidate GMBs with respect to antioxidant depletion in three simulated leachate solutions together with the equilibrium stress crack resistance (SCR) reached after 270 days immersion in the leachate at 55-75ºC.
- the maximum allowable tensile strain to be permitted from all sources be 3% in the bottom base liner, 4% in the bottom side slope liner, and 5% in the cover GMBs
- geosynthetic liner longevity simulator tests be conducted to simulate the critical portion of proposed secondary liner system both on the with 250 mm of compacted clay proposed for the facility, the proposed GCL, 2-mm secondary GMB, and sand cushion, the GCL, 2-mm primary GMB, and for the base a sand cushion and for the side slope the proposed geotextile protection layer, and lastly the gravel under the maximum proposed load (increased by a factor to account of time dependent effects) to check that the indentation strains are sufficiently small that, together with the other anticipated strains, the maximum strain from all anticipated sources < 3% and 4% respectively .
- since strains can be significantly increased by failure to construct in accordance with the design drawings and specifications, there be construction quality assurance (CQA) by very experienced personnel with a good knowledge of compacted clay liners, GCLs, and GMBs and the Near Surface Disposal Facility design and that there be an experienced individual watching the construction work at all times prior to completion of the liner system.

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