GEOMEMBRANE LINER DURABILITY: CONTRIBUTING FACTORS AND THE STATUS QUO

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Abstract
Regulators and engineers have sufficient confidence in the durability and long-term integrity of geomembrane lining systems to require their use as barriers between potential contaminants and groundwater. Yet experience with such lining systems covers only about 30 years. However, in that period adequate performance has been demonstrated. But how long will such geomembrane materials last before ultimate degradation or failure?

In the case of municipal solid waste landfills chemical dissolution and degradation of the typical high density polyethylene (HDPE) geomembrane is considered to be a non-issue. Ultimate durability will be a function of the stress cracking resistance of the specific HDPE resin used, the effectiveness of its antioxidation additives, the stresses generated in the geomembrane during installation and landfill operation, and the stress relaxation rate. The potential influences of each of these phenomena individually, and synergistically, on the lifetime of geomembranes are considered.

Introduction
It is interesting to note that environmentalists frequently claim that the plastic bags that float around in the oceans are a peril to wildlife forever, yet they also claim that specially formulated and designed plastic based landfill lining systems are bound to fail in a relatively short time!

In our technical world the lifetimes of HDPE geomembranes in landfill lining systems have been variously estimated to be between 200 and 750 years. At the other end of the scale installed HDPE lining systems in other applications, typically exposed pond liners or cast-in concrete liners, have not lasted 6 months without failing. “Failing” is practically defined as developing a leak.

Of the many HDPE geomembrane liners that have “failed” in the past 20 years, all have failed in a very limited number of ways, but none have just “worn-out” or generally degraded to nothing, nor is it expected that they will. However, our practical experience with HDPE geomembranes is limited to about 25 years. Polyvinyl Chloride (PVC) has been evaluated after 30 years, and polypropylene (PP) is quite young at about 10 years. North American municipal solid waste (MSW) leachate is typically quite benign, as shown by the model for a standard testing leachate in Appendix A, to the extent that in the USA chemical resistance tests of HDPE are now rarely required. Many EPA 9090 “Compatibility Test for Wastes and Membrane Liners” tests have been performed with MSW leachates and none have been shown to damage the geomembrane – the degradative effect of MSW leachate on HDPE can practically be ignored.

HDPE liners in landfills and other applications fail or are made to fail as follows:

- Inadequate welding and attachment to structures
- Imposed stresses during construction
- Mechanical damage during construction
- Stress cracking at stress points
- Service stresses that separate welds
Except for poor welding and damage induced during installation HDPE geomembranes have generally only failed by stress cracking (a fundamental performance characteristic of HDPE), or as a combination of oxidation followed by stress cracking (SC). Stress cracking is essentially a brittle cracking phenomenon that occurs at a constant stress lower than the short term yield strength or break strength of the material. It is a consequence of the semi-crystalline microstructure that gives the HDPE its good chemical resistance and high strength. PVC liners have cracked from loss of plasticizer at elevated temperatures and under ultraviolet radiation (UV) exposure, and PP has also experienced cracking at elevated temperatures but without UV exposure. However, PVC, PP, and LLDPE, are not susceptible to SC in the as-manufactured condition as is HDPE. Break times as a function of constant stress for five as-manufactured HDPE geomembranes are shown in Figure 1. At the higher stresses close to the yield stress, break occurs in a ductile manner. At lower stresses, below the knee in the curve, break occurs in a brittle manner - the ductile slope cannot be extrapolated to give a lifetime at a lower stress.

![Stress rupture curves for five HDPE geomembranes (Hsuan et al. 1992)](image)

Figure 1 Stress rupture curves for five HDPE geomembranes (Hsuan et al. 1992)

It is frequently stated by some in the geomembrane and gas pipe industries (Peggs (2003), Thomas (2002) Brown (1993)) that the only meaningful parameter that requires specification for HDPE is its stress cracking resistance (SCR). This is the only parameter that reflects the wide range of mechanical durabilities of geomembranes made from the different HDPE resins. All other index properties (tensile, puncture, and tear) are essentially identical in all HDPE geomembranes. Fortunately, as a result of the failures that have occurred, resins, geomembranes, and welding equipment/procedures used in landfill lining systems have significantly improved. LLDPE and PP do suffer from SC, but only when their antioxidants are depleted and they oxidize.
Such failures have been more evident in exposed lining systems in ponds, lagoons, and concrete basins where restrained contraction stresses are cyclic as temperatures change, where the geomembrane is not confined between two layers, where leakage is more evident, and where the damage can be seen. There have effectively been no known in-service failure events that have occurred in solid waste facilities in North America that cannot be ascribed to external influences. However, HDPE and PP have cracked on wrinkles under a hydrostatic head and there has recently been cracking in reinforced PP (RPP) on the underside of floating covers at the bottom of drainage troughs.

Double lining systems in US landfills that allow continuous monitoring of leakage flow rates through primary liners into the leakage collection, drainage, and removal systems (LCDRS) have shown no spikes related to punctures or liner degradation in service caused by events solely within or very close to the lining system. However, HDPE liner lifetimes considerably in excess of those experienced to date (maximum about 25 years) are desired and obtaining such lifetimes is the subject of this paper.

Discussion
Geomembrane liners are ideally designed to be installed without stress. They are simply intended to act as a barrier. Clearly, a zero stress installation is practically impossible to achieve – wrinkles are unavoidable. But without mechanical tensile stress a liner cannot be made to break and leak, making such an objective, or the means to tolerate it, desirable. However, while general chemical degradation due to leachate does not occur, the presence of chemicals such as chlorinated solvents, acids, and detergents in contact with a stressed HDPE geomembrane may result in environmental stress cracking (ESC) where the chemical accelerates the fundamental stress cracking phenomenon. ESC is taken advantage of in laboratory tests that are performed in a surface active detergent at elevated temperature (50°C) to accelerate failures so they occur in a reasonable time, but without changing the fracture mechanism and morphology.

Impermeability
It must be recognized that nothing is absolutely impermeable. Apparent “leakage” may also occur through diffusion of vapor (solvent and water) through amorphous regions of the HDPE geomembrane, which then recondenses on the opposite side. Sangam and Rowe (2002), Park et al. (1995), and others have shown the diffusion rates of various organic liquids and solutions through geomembranes, but while these liquids are absorbed by the HDPE, which causes it to soften they do not cause a continuing and permanent degradation. When the liquid environment is removed the solvent vapors volatilize out of the geomembrane which recovers its original properties. In general the softening of the geomembrane while in service will be beneficial in allowing the liner to better conform to subgrade profiles and differential settlement without significant stress, thereby reducing the possibility of stress cracking. In fact the diffusing/absorbed organics act as a plasticizer for PVC which, when it dries out may then crack. Thus it remains flexible in service, but becomes brittle when exposed and tested. However, a similar phenomenon may have occurred in one case in which HDPE was exposed to creosote in a chemical resistance test - a 70% reduction in SCR was observed when the HDPE was removed from the creosote and all organics had desorbed. It is not known if this is a standard occurrence after exposure to organic liquids. In another case, in the presence of sulphuric acid, wrinkles in 3 mm and 5 mm thick HDPE liners caused by naphthalene, kerosene, and aromatic hydrocarbon absorption did suffer stress cracking as a result of oxidation caused by the acid at temperatures of about 70°C.

Giroud and Bonaparte (1989) have shown (Table 1) that water vapor diffusion through 1 mm HDPE geomembrane with a head of 300 mm (the maximum allowed in MSW landfills), is
approximately 0.8 lphd. Therefore no individual HDPE geomembrane can be considered absolutely leak free. This is the reason for the philosophy of double lining systems. Equivalent diffusion rates through LDPE and PVC geomembranes would be approximately factors of 45 and 115 higher due to their different densities and more amorphous microstructures. However, such diffusion “leakage” pales into insignificance compared to stone punctures and bulldozer blade rips.

Table 1: Water vapor diffusion through a 1 mm HDPE geomembrane

<table>
<thead>
<tr>
<th>Water depth on top of the geomembrane, $h_w$</th>
<th>0 m</th>
<th>0.003 m</th>
<th>0.03 m</th>
<th>0.3 m</th>
<th>3 m</th>
<th>&gt;10 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0 ft)</td>
<td>(0-01 ft)</td>
<td>(0-1 ft)</td>
<td>(1 ft)</td>
<td>(10 ft)</td>
<td>(&gt;30 ft)</td>
<td></td>
</tr>
<tr>
<td>Coefficient of migration, $m_g$ (m$^2$/s)</td>
<td>0</td>
<td>$9 \times 10^{-20}$</td>
<td>$9 \times 10^{-18}$</td>
<td>$9 \times 10^{-16}$</td>
<td>$9 \times 10^{-14}$</td>
<td>$3 \times 10^{-13}$</td>
</tr>
<tr>
<td>Unitized leakage rate, $q_g$ (m/s)</td>
<td>0</td>
<td>$9 \times 10^{-17}$</td>
<td>$9 \times 10^{-15}$</td>
<td>$9 \times 10^{-13}$</td>
<td>$9 \times 10^{-11}$</td>
<td>$3 \times 10^{-10}$</td>
</tr>
<tr>
<td>(lphd)</td>
<td>0</td>
<td>$8 \times 10^{-5}$</td>
<td>0.008</td>
<td>0.8</td>
<td>80</td>
<td>260</td>
</tr>
<tr>
<td>(gpad)</td>
<td>0</td>
<td>$8 \times 10^{-6}$</td>
<td>0.0008</td>
<td>0.08</td>
<td>8</td>
<td>28</td>
</tr>
</tbody>
</table>

In US landfills, analyses of primary leachates have shown them (Table 2) to be relatively benign, with pH values close to 7 and no high concentrations of any damaging components. By the time the components of the compacted bottle of detergent or solvent in the waste have drained to the level of the liner they are well diluted and do not cause an environmental stress cracking problem in the HDPE.

Table 2. Analysis of MSW landfill leachates (Tchobanoglous et al, 1993)
Oxidation
The major environmental agency of concern in US landfills is oxidation. The Geosynthetic Research Institute has performed a number of thermal aging studies (Hsuan and Koemer (1998), Hsuan and Guan (1998)) to develop an estimated liner lifetime. Samples of different HDPE geomembranes were placed in ovens or simulated landfill environments at temperatures between 55 and 115°C for up to 2 years. Typical mechanical properties were periodically measured. The depletion of antioxidants was determined by measuring standard oxidation induction times (OIT) at 200°C and high pressure oxidative induction times (HP-OIT) at 130°C. Hsuan and Koemer (1998) heated five different geomembrane samples in forced-air ovens. The as-received OIT and HP-OIT values varied widely, again demonstrating the differences in durability between geomembranes from different manufacturers. Retained OIT values after aging at 65°C are shown in Figure 2, and changes in OIT and mechanical properties at 95°C are shown in Figure 3. The latter shows that mechanical properties are not changing as AO depletion occurs. Hsuan and Guan (1998) state that mechanical properties do not change until all AO has been consumed. An Arrhenius plot for OIT test data is shown in Figure 4 from which the activation energy for depletion of AO indicates that all AO is depleted at a service temperature of 20°C in three of the geomembranes after approximately 60, 80, and 100 years. Note, again, that the different HDPE geomembranes behave quite differently. At the point of complete AO depletion the mechanical properties start to degrade. Thus there is another period after AO depletion during which the polymer itself degrades (oxidizes) and during which the measured property degrades to a defined critical level, often considered to be 50% of its original value. The time at which this occurs is termed the half-life.

![Figure 2 Aging at 65°C](image-url)
Figure 3  Aging at 95ºC

Figure 4  Arrhenius plot for OIT test data
Hsuan and Koerner (1998) report data on one HDPE geomembrane exposed in a simulated landfill environment as shown in Figure 5. The geomembrane sample was confined between two sand layers at a pressure of 260 kPa. A 300 mm head of water was maintained above the sample and the complete assembly was heated. Similar changes in properties were observed as shown in Figure 6. In this case the estimated time to AO depletion was calculated to be between 200 and 215 years. It is longer than in the laboratory tests because of the more limited access of fresh oxygen to the surface of the geomembrane in the confined environment. Aging procedures are still underway to assess the post-AO-depletion degradation of the material's properties.
Hsuan and Koerner’s (1998) hypothesis is that degradation of the geomembrane is a three stage process, as shown in Figure 7: 1) depletion of AO; 2) induction time to onset of polymer degradation, and; 3) degradation of the polymer and loss of mechanical properties. This will likely occur when samples are exposed without stress in an oven and under a uniform compressive stress in a simulated field environment. However, when the geomembrane is under tensile stress or has shear stresses imposed on/in surface layers at the same time as oxidation is occurring, the kinetics of degradation will not be as simple to model. Oxidation and SC will interact synergistically. Hessel (1990) indicates that when an HDPE specimen is thermally aged under stress it fails completely when the AO is consumed, as shown in Figure 8. At the higher stresses close to the yield stress the material fails in a ductile mode before oxidation occurs. At the intermediate stresses a premature (compared to ductile region extrapolation) brittle SC break occurs before oxidation occurs. But at the lower stresses when the AO is fully consumed and oxidation occurs before the extrapolated SC curve, break is even more premature. Therefore, there is a constant competition between the rate of depletion of AO and parallel or subsequent oxidation and the initiation of stress cracking as to which initiates failure first. In practice, oxidation within a continuously propagating and opening crack tip will further accelerate the crack growth rate.

Figure 7  Stages of aging and degradation

![Figure 7: Stages of aging and degradation](image)

Figure 8  Stress rupture curves as a function of temperature

![Figure 8: Stress rupture curves as a function of temperature](image)
In fact, a conventional measurement of OIT will not indicate the true situation since oxidation will first occur on the surface where cracks will be initiated as soon as there is an adequately thick surface layer for the local stress to initiate a crack. When a conventional OIT test is performed, using the full thickness of the geomembrane as the specimen, the measured OIT will not be an indicator of the condition of the surface of the material. For instance if 10% of the thickness is fully depleted of AO the measured OIT will indicate a 90% retention of OIT, the same as if the complete thickness of the geomembrane were oxidized only 10% – not something that would normally cause concern. But, a completely oxidized surface layer and the cracks that would be initiated in it would be of concern. Thus there will be a continuing synergism between the kinetics of oxidation through the thickness of the geomembrane and the kinetics of stress cracking.

Stress Cracking Resistance
The significance of the rates of initiation of stress cracks on the surface of a geomembrane followed by crack propagation into the body of the geomembrane was further shown by Cadwallader (2001). He found that coextruded textured material made with a surface layer of low stress cracking resistance (apparently recycled polymer) would cause the accelerated cracking of core material with otherwise high SCR. Thus a core material that had a single point notched constant tensile load stress cracking resistance of over 1000 hr failed in 324 hr in an unnotched test when coextruded with a textured surface layer made with inferior quality resin. The cracks were easily initiated in the textured surface layer but did not slow down when they met the core layer. Thus it is easier for a crack to propagate into a core layer than it is for a crack to initiate and propagate within that material alone. In general it was concluded that random surface textures may reduce the SCR of the basic smooth geomembrane. This will not occur in structured-surface geomembranes with their designed reproducible profiles on sheet of a uniform thickness.

In practice a confined HDPE geomembrane will only fail in the long term either by stress cracking at points of constant stress – stone protrusions, stresses across seams, creased wrinkles, textured surfaces. Stressed areas have also been seen at temporary dividing berms where the vertical pressure of waste has caused the berm to spread laterally on the continuous liner – there may be wrinkling on one side of the berm and significant tension on the other side.

The author clearly has concerns about double textured liners on side slopes where there is a higher shear resistance on the top surface than on the bottom surface of the geomembrane with the result that the geomembrane becomes a load-bearing member of the system due to the induced shear stress. This is a major disconnect since on one hand the liner is designed to be without stress but on the other hand it is textured to hold soil on slopes. And, as indicated above, the presence of the surface texture will, at the same time, cause a reduction in the SCR of the geomembrane itself – to different degrees in the different types of textured and structured profiles. When a slide occurs on a slope and the geomembrane tears, it is always assumed that the geomembrane tears as a result of the soil movement. It is equally possible that the geomembrane may experience stress cracking, as a consequence of the induced shear stress, that initiates critical movement of the soil. All such geomembrane tears should be examined for regions of stress cracking within more extensive overload tears with their ductile elongations. Shear stresses induced in textured surfaces will be of much more significance in the forthcoming bioreactors with their higher temperatures and more extensive settlement along side slopes. The use of smooth top surfaces on geomembranes will have significant positive impact on the service life of a geomembrane – covering soils would better be provided with veneer stability by geogrids or high strength geotextiles, or by using an HDPE geomembrane with much higher SCR.
The kinetics of stress crack initiation and propagation increase at elevated temperatures as shown schematically in Figure 8. However, stress relaxation also increases as temperature increases resulting in a permanent race between stress cracking and stress relaxation as to which will prevail. If the induced stresses can be sufficiently reduced before cracking is initiated cracking will not occur. Also to be factored into this argument is oxidation of the geomembrane, for all HDPE geomembranes have required antioxidant additives that protect them against oxidation at the elevated temperatures during and after extrusion, during welding, during weld repairs, and during service. Once the additives are all consumed in providing protection, only very small tensile stresses will be sufficient to cause fracture.

The influences of the different textures and performance characteristics on the durabilities of HDPE geomembrane are reflected in recent work performed by Peggs et al. (2003b) to evaluate the maximum allowable strain in HDPE and other geomembrane materials used as a separation barrier between old waste and new waste in an MSW landfill vertical expansion. This work was done in response to the regulators requiring no more than 1% strain in the separation geomembrane independent of the polymer used. At another project the engineer was requiring an HDPE geomembrane in a lining system to experience no more than 0.25% strain at any location. This is practically impossible to achieve. These specifications are clearly a misunderstanding of the German BAM requirements (Seeger and Müller, 1996) for a maximum global strain of 3% and maximum local strain (at individual stone protrusions, for example) of 0.25%. More realistically, the following maximum strains are being recommended:

- HDPE smooth SCR<1500 hr  6%
- HDPE smooth SCR>1500 hr  8%
- HDPE random texturing  4%
- HDPE structured profile  6%
- LLDPE density <0.935 g/cm³  12%
- LLDPE density >0.935 g/cm³  10%
- LLDPE random texture  8%
- LLDPE structured profile  10%
- PP unreinforced  15%

The measurement of strain is used as an indirect measure of the stress that exists in a geomembrane that might result in stress cracking. While this is clearly important for HDPE, it is not as significant for other materials that are not susceptible to SC unless oxidized. The objective is to limit stress to a subcritical value where stress cracking will not be a practical problem. However in a confined situation the stress will be applied very slowly to the geomembrane as the adjacent soils move, and the geomembrane will be able to relax resulting quite rapidly in geomembrane stresses that are maybe 50% of the value implied by the deformation.

Stress Relaxation
While the benefits of stress relaxation are apparent it is not a topic that has been thoroughly studied for geomembranes. Soong et al. (1994) investigated stress relaxation in a 1.5 mm thick HDPE geomembrane with initial stresses of 40, 50, and 60% of yield stress (at test temperature) and initial strains of 1, 3, and 5% at temperatures between -10 and 70°C. These were quasi-biaxial tensile tests using 100 mm wide by 50 mm gage length “wide width” tensile specimens. Initial loading was done quite quickly to minimize stress relaxation on loading. As shown in Figure 9 whatever the starting conditions, there was a trend to a very narrow range of final, but still significant stresses, after about 100 days. The relaxation modulus curves (stress/strain as a function of time) for a given starting condition could be superimposed into a master curve for a given relaxation temperature, as shown in Figure 10 for an initial 3% strain and a temperature of 10°C.
Figure 1  Results of stress relaxation test of 1.5 mm HDPE geomembrane started initially at 50% of yield stress at various temperatures.

Figure 2  Stress relaxation modulus of 1.5 mm HDPE geomembrane corresponding to initial stress level of 50% of yield stress at various temperatures.

Figure 3  Normalized time-dependent stress of 1.5 mm HDPE geomembrane corresponding to initial stress level of 50% of yield stress at various temperatures.

Figure 4  Results of stress relaxation test of 1.5 mm HDPE geomembrane started initially at 3% of strain at various temperatures.

Figure 5  Stress relaxation modulus of 1.5 mm HDPE geomembrane corresponding to initial strain level of 3% of strain at various temperatures.

Figure 6  Normalized time-dependent stress of 1.5 mm HDPE geomembrane corresponding to initial strain level of 3% of strain at various temperatures.

Figure 9  Geomembrane stress relaxation data
In this case 50% of the applied stress is removed by relaxation after 50 minutes with final equilibrium being achieved at about 30% of applied stress after 11.4 years. At higher temperatures the stress would relax more quickly. The equilibrium residual stress is between 2500 and 4000 kPa, between about 13 and 21% of the room temperature yield stress. Note that the strain was applied far more quickly than will occur during subgrade settlement, so in the landfill significant stress relaxation will occur during deformation. Soong et al. (1994) stated:

"Trial tests were performed initially to determine the suitable loading rate. The results suggested a rate of 12.7 mm/min as being appropriate. At slower rates a very significant amount of stress relaxation occurred during the loading process."

Also, note that Soong et al. (1994) concluded:

"... other HDPE geomembranes will undoubtedly respond differently than the HDPE studied..."

Thus all HDPE geomembranes are not the same, just as their SCR performances are not the same.

These stress relaxation rates compare well with those generated by Soong and Koemer (1997) for stress relaxation in waves in HDPE geomembranes under a uniform vertical loading. After 1000 hr at temperatures of 23, 42, and 55°C they found stresses relaxed between 60 and 78% leaving residual stresses of between 1% and 22% of the yield stress. Recollect that SC occurs below about 40% of the yield stress, in the range of these residual stresses. However, these tests were done under semi-confined conditions (waves raised off a flat support surface) while the Soong et al. (1994) tests were done under unconfined conditions. Under semi-confined conditions the residual stresses were lower than for unconfined specimens, possibly a result of the...
stress relaxation occurring during loading. Under fully confined conditions the residual stresses would probably be even lower.

Fracture Mechanics
The HDPE natural gas distribution pipe research supported by the Gas Research Institute (now part of the American Gas Association) since the late 1970s has involved the development of fracture mechanics methodology to forecast lifetimes of high and medium density PE pipe and joints for system operating conditions - typically a well established internal pressure and temperature. Slow crack growth tests on laboratory specimens at elevated temperatures are used to develop empirical relations for the initiation and rate of crack growth as a function of a measure of the crack driving force and temperature. Kanninen et al. (1993) found that biaxial stress and temperature shifting rather than conventional uniaxial time temperature shifting (superpositioning) was more appropriate for gas pipe materials. This is because the semi-crystalline microstructure causes a change in strength of HDPE as temperatures change and this change also contributes to changes as a function of time. The shift functions for pipe HDPEs are very simple:

\[
a_T = \exp[-0.109(T_s - T_r)] \quad \text{for horizontal (time) shifting} \\
b_T = \exp[0.016(T_s - T_r)] \quad \text{for vertical (dependent variable) shifting}
\]

where \( T_s \) is an arbitrary (service) temperature (°C) relative to a reference (test) temperature \( T_r \). However, note that while these shift functions are the same for all MD/HDPEs tested the reference behaviors of the various PEs were different. As shown in Figure 11 rate curves and ductile/brittle transitions can be reproducibly shifted to any temperature within the variability of data generated at that temperature.

![Figure 11](image-url)
The small amount of testing performed on geomembranes implied the same behaviour as for pipes and with very similar simple shifting functions. The mechanical durability of HDPE geomembranes would be a function of the resin used to manufacture the geomembrane, the geometry of the liner feature being evaluated (plain geomembrane, extrusion seams, fusion seams, textures/structures), the stress distributions, and the temperature. All these parameters synergistically influence the stress intensity factor responsible for crack initiation and propagation. They would be very difficult to predict for geomembranes, although simplifications could be made to assure lifetimes in excess of 100 years relatively quickly (Popelar et al. 1998).

The potential lifetime of an HDPE geomembrane as a result of crack initiation and propagation under a given set of environmental parameters has been initiated but is far from being finished. Along with the rate of AO depletion at service temperatures, this is the testing that will provide the data necessary to predict the durability of any given HDPE geomembrane. A start on applying the lessons learned from studies on HDPE gas pipe has been made by Kanninen, et al. (1992, 1993) who investigated the fracture mechanics of HDPE geomembranes and the possibility of performing accelerated tests at elevated temperatures then shifting rate curves to lower service temperatures. Two heuristic calculations were made of the lifetimes of a seamed geomembrane with stress cracks in the center of the weld and in the geomembrane at the edge of the seam (Figure 12) simply as a result of a lower service temperature compared to the installation temperature - i.e. as a result of contraction stresses. As shown in Figure 13, a stress crack approximately 0.2 mm deep would propagate through a liner at a temperature 3°C lower than the installation temperature in approximately 1.5 yr. At a temperature difference of 12°C final failure would occur in 0.3 yr. And at a 12°C difference a stress crack 0.08 mm deep would have a failure time of about 0.4 yr, while a 0.3 mm deep crack would have a failure time of about 0.2 yr. While these scoping calculations generate very short crack penetration times it should be noted that baseline measurements were made on a material with low stress cracking resistance. The calculations also assume a constant load (no stress relaxation) and no confining pressures. Nevertheless, these calculations do show the ability of fracture mechanics, accelerated testing, and shifting of data to predict the failure times of specific HDPE geomembranes with given flaws in specific environments. Then, armed with a definition of critical flaw sizes, CQA monitors will become more effective and equipment can be developed to quantify observed defects and to mark them as critical or sub-critical. The latter need not be repaired. This is far better than the present blanket specifications which typically require no surface defect to exceed 10% of the thickness of the geomembrane while not having an instrument to easily measure it.

![Figure 12 Model used in lifetime calculations](image-url)
Specifications

At present protection against SC is typically considered to be provided if the geomembrane has a break time exceeding 200 hr in the ASTM D5397 notched constant tensile load test as promulgated in the Geosynthetic Research Institute GRI.GM13 standard “Test Properties, Testing Frequency and Recommended Warrant for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes” Revision 2, 1999. Some materials have break times of 250 hr, others have passed 10,000 hr without breaking. Thus, all HDPE’s are not identical – some are far superior to others in their resistance to SC. These are the ones that should be used for maximum durability. Specifying “HDPE” for a critical geomembrane is akin to specifying “Steel” for bridge construction without identifying types and grades.

In the same GRI.GM13 standard adequate oxidation resistance is assumed if a decomposition time exceeding 100 min is obtained in the ASTM D3895 oxidation induction time (OIT) test. But this test performed at 200°C does not necessarily reflect the oxidation resistance at lower service temperatures, since different AO packages have different components that protect the geomembrane over different temperature ranges, as shown in Figure 14. For example, phosphates only protect above 150°C while hindered amine light stabilizers (HALS) only protect below 150°C. Thus, a passing OIT at 200°C does not necessarily guarantee acceptable behaviour at 80°C, and vice versa. However, in most instances GRI has shown a relationship between oxidation rates at the two temperatures, but Peggs (2003) reports two instances where adequate SCR and OIT values did not result in adequate long term performance. In the first case an SCR of 240 hr and an OIT of 101 min did not prevent cracking of an HDPE geomembrane on exposed landfill liner slopes after 8 years. Cracks occurred on the longitudinal folds of the round-die manufactured geomembrane, in and along seams, and in the covering patch at burn-through protrusions. The material had lost all of its AO additives and had measured OITs of zero and 3 min.
In the second case, a new HDPE geomembrane that had an SCR of 540 hr and an OIT of 240 hr, far exceeding the GRI.GM.13 specifications, just met the specification for thermal aging (at 85°C) but miserably failed the UV resistance test with a retained OIT of 35% compared to the specified >50% retained OIT. Thus there is much that we do not yet know about the oxidation rate of HDPE geomembranes at different temperatures.

Peggs et al. (2002) are attempting to develop a single material durability factor (MDF) that combines the SCR with an oxidation factor determined at 85°C. A Fourier Transform Infrared Spectroscopy specimen (simulating a thin surface layer on a bulk sample) is heated in an oven for a given time then the change in carbonyl group content, representative of oxidation, is monitored. It was found necessary to heat the specimen in an oxygen rich air stream at 90°C for at least 24 hr in order to start seeing significant changes in the carbonyl group peak. More recent testing by Thomas (2003) suggests that testing at 85°C in a high-pressure oxygen atmosphere may be necessary to generate sufficient oxidation in a thin specimen in a reasonably short time – 20 to 50 hr. Such an MDF will not quantify the time at which leaks will occur in a given lining system but it will facilitate a qualitative ranking of the durabilities of HDPE geomembranes made from different resins and with different AO packages. Then when experiments and calculations are made to determine the lifetime of one or two product, others can be scaled accordingly.

However, to further complicate matters, the exact combinations of circumstances that generate stress cracking are also not well established. In a pulp mill black liquor pond (effectively a confined situation) at an incoming liquor temperature of about 70°C environmental stress cracking (due to detergent in the liquor) occurred at the tops of wrinkles in an indiscriminate fashion - small wrinkles on the floor were cracked but large kinked wrinkles at the toes of slopes were not. Intermediate wrinkles on the slopes also cracked indiscriminately. Therefore, it is impossible to predict the combinations of parameters that will generate environmental stress cracking.

Wrinkles have also caused problems in HDPE liners in concrete basins in mining facilities where cast-in liner has been used on walls and around the periphery of the floor, and loose liner has been used on the floor. Absorption of organic components of heap leach process solutions and swelling of surface layers has caused large wrinkles to build up against the peripheral weld between loose and anchored liner with the result that every millimeter of weld experiences a
significant peel stress. The weakest segments of the welds have separated. That this happens may not be too surprising when liner seam specifications often allow one of the five peel and shear specimens to fail—a 20% failure rate. When such a seam has separated the long term durability of the liner is compromised even more because it is very difficult to make an effective repair weld on liner containing absorbed organics. Such repair/peel/repair/peel behavior continues. Ultimately the acid component of the elevated temperature solution might oxidize the liner with resultant stress cracking on the tops of wrinkles and along the edges of welds.

A survey of many colleagues reveals that none are aware of any leakage that has developed in a landfill bottom liner after a facility has been placed in service that is not due to external influences. However, a landfill in Minnesota had a bulldozer nick near a sump during construction that was repaired. The system, with waste on the floor, operated without any leak indication for about three months. Leakage then started at a rate of about 5000 lpd, equivalent to a hole of about 6 mm diameter under a 300 mm hydraulic head (Giroud and Bonaparte (1989)). Electrical leak surveys on top of 9 m of waste and die testing suggested that the leak was not at the same location as the sump and the repaired patch. Unfortunately, the suspected leak was not excavated to confirm its existence and to determine its cause. There have been a number of instances where leakage rates have suddenly increased after some time, but these have generally been found due to an increase in the primary leachate level above original defects in the liner that previously were not leaking.

Surveys by Bonaparte and Gross (1990) and others since then have showed that leakage rates through the primary liners of ponds and landfills vary significantly from effectively zero to quite significant values (3300 lphd). A typical Action Leakage Rate in US landfills at which leaks must be found and repaired is 200 lphd. This is not difficult to achieve. However, when a requirement for 70 lphd was not met at one hazardous waste project attempts to make repairs only resulted in a higher leakage rate. At a double lined concrete basin project a few drips from the leakage detection system was not considered satisfactory performance by the owner who insisted that repairs be made; the drips increased to a steady flow which could not be stopped. Surveys performed by Koemer et al. (2000) have shown (Figure 15) leakage rates at different stages of a landfill lifetime in different types of lining systems to taper off during closure to be very low—less than 1 lphd Koemer (2003—personal communication) is not aware of any HDPE landfill liner that has developed a hole in service from anything other than an external influence, such as a bulldozer.
Figure 15 Primary liner leakage rates at different stages of landfill lifetime.

Stage 1: Initial life  Stage 2: Active life  Stage 3: Post-closure

Nosko et al. (1996, 2000), and Rollin (1999) have clearly shown the locations, frequency, and causes of leaks made in liners during their installation, covering, and early stages of operation. Their data are summarized in Table 3 and Figure 16. In covered liners most damage (over 70%) is caused during placement of the cover soil, and only 24% of leaks occur in seams. However, in exposed liners almost 80% of leaks are on seams.
Table 3: Statistics of Liner Damage

<table>
<thead>
<tr>
<th>WHEN/WHERE</th>
<th>AMOUNT</th>
<th>DETAILS</th>
<th>AMOUNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner installation</td>
<td>24%</td>
<td>Extrusion</td>
<td>61%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Melting</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stone Puncture</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cuts</td>
<td>4%</td>
</tr>
<tr>
<td>Covering</td>
<td>73%</td>
<td>Stone Punctures</td>
<td>68%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy Equipment</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grade Stakes</td>
<td>16%</td>
</tr>
<tr>
<td>Post-Construction</td>
<td>2%</td>
<td>Heavy Equipment</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Construction</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weather, etc.</td>
<td>2%</td>
</tr>
<tr>
<td>Flat Floor</td>
<td>78%</td>
<td>Stones</td>
<td>81%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy Equipment</td>
<td>13%</td>
</tr>
<tr>
<td>Comer, Edge</td>
<td>9%</td>
<td>Stones</td>
<td>59%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy Equipment</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Welds</td>
<td>18%</td>
</tr>
<tr>
<td>Under Pipes</td>
<td>4%</td>
<td>Stones</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Welds</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy Equipment</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Worker</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cuts</td>
<td>14%</td>
</tr>
<tr>
<td>Pipe Penetrations</td>
<td>2%</td>
<td>Welds</td>
<td>91%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Worker</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cuts</td>
<td>1%</td>
</tr>
<tr>
<td>Road, Storage, etc.</td>
<td>7%</td>
<td>Heavy Equipment</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stones</td>
<td>21%</td>
</tr>
<tr>
<td></td>
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<td>Worker</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Welds</td>
<td>17%</td>
</tr>
</tbody>
</table>

Figure 16 Frequency of leaks in primary geomembrane liners
Summary
In summary, an HDPE geomembrane used in a landfill is most unlikely to fail due to conventional chemical degradation as a result of being in contact with MSW leachates. HDPE geomembranes have adequate chemical resistance to endure and retain their integrity well beyond other factors that will cause a liner to fail. However, if the leachates contain unusually high concentrations of oxidizing acids, chlorinated solvents, or detergents that remain constantly on the liner for considerable times, environmental stress cracking may occur. By far the predominant mode of failure is due to man-induced damage during construction, such as stone punctures, bulldozer damage, and depth stake puncturing. When this type of damage is precluded or stabilized, premature failures will then only occur by simple stress cracking, or oxidation followed by stress cracking at regions of induced stress such as creases and wrinkles, stone protrusions, seams, textured surfaces, etc. The susceptibility of the liner to these kinds of stresses will be a function of the SCR of the specific resin used, and such resistances presently vary by a factor of about 500.

The durability of an HDPE geomembrane is a function of the following;

- The SCR and OIT of the resin used and of the geomembrane itself
- The knowledge of the design engineer in selecting and specifying the most appropriate HDPE, and designing the liner for minimum stress on slopes, at sumps, at penetrations, and in anchor trenches.
- The knowledge of the engineer in designing the system to accommodate the interim stresses between installation and design operating conditions
- The knowledge of the engineer in specifying adequate puncture protection for the geomembrane.
- The ability of the manufacturer to produce a consistent homogeneous material with a minimum number of internal and surface flaws and with effective antioxidation additives
- The smoothness, uniformity, and density of the subgrade
- The quality of the installation - lack of wrinkles, intimate contact with subgrade, seams, penetrations, minimum extrusion welding, minimum shear stress on slopes.
- Quality of CQA
- Placement of cover layers
- Operation of equipment on cover layers
- Placement of first layer of waste

If all of these items are optimized it is expected that an HDPE geomembrane in an MSW landfill should last for about 400 yr. Exposed liners are another matter altogether, clearly depending on the exposure conditions and requiring a better understanding of oxidation rates. Perhaps 75 years is an appropriate place to start. But lifetimes exceeding 100 years may not be necessary since, by then, there will be better things to do with present waste and it will be being mined with unusable components disposed of in better ways - maybe even atomized to nothing. Future generations will not want to maintain sealed cells of their forebears' waste, in the same way that there are presently very few infrastructures that we are using that are in their 1875-1900 as-installed condition. We delude ourselves if we think we have the ultimate solution to waste containment and disposal. Nevertheless we should still target the maximum geomembrane and liner durability within existing technology.

Once a liner has successfully been installed and there is no leakage the only internal influences that can cause additional leaks are such things as:

- Wrinkles and protrusions causing SC before stress relaxation can occur
• Wrinkles at seams causing slow peel separation and propagation of critical, but not then penetrating, flaws in seams

• Crazes induced by peel separation initiating stress cracking at the stressed seam prior to stress relaxation occurring

• Shear and peel stresses at overheated and over-ground seams adjacent to wrinkles initiating stress cracking.

• Elevated geomembrane temperatures causing oxidation and accelerating stress cracking if stress relaxation is not accelerated in proportion.

• Stress cracking on slopes with randomly textured liner on the top surfaces prior to waste stabilization.

All of these possibilities can be minimized by the use of an HDPE geomembrane with high stress cracking resistance and good oxidation resistance. In practice, if settlement stabilizes and if no failures have already occurred it is unlikely that any subsequent failures will occur.

Conclusion

In practice, while one can make any number of aging and degradation calculations of lifetimes, half lives of specific index mechanical and physical properties, and activation energies, the practical performance of a lining system is presently controlled by human activities. Once the liner is installed and working without leakage the development of further leakage is a function of its stress cracking resistance, its oxidation resistance, the stresses generated, and the stress relaxation rate. The synergism between these performance characteristics is extremely difficult to predict. The most meaningful technique would be to use a fracture mechanics approach. However, as is evident, this still requires a significant amount of research effort. In assessing the development of flaws the most important thing to note is that all HDPEs are not the same - their mechanical durabilities can vary by a factor of 500. Specifying “HDPE” for a critical lining system is somewhat akin to specifying “Steel” for a bridge without identifying types or grades. Should the golf course decorative pond be lined with the same liner as a hazardous waste liquid pond as is presently done?

In the meantime, the best solution is to select a geomembrane with the highest stress cracking resistance and the best performance in the GRI.GM13 thermal aging test, and to install it carefully. Exposed liners will also require the UV resistance test. With a high SCR HDPE liner the emphasis will even more be on the care of design engineers, installation contractors, general contractors, CQA firms, and owners to ensure that the liner has no holes in it when it is placed in service.

References


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APPENDIX A

Model for Standard MSW Leachate for Chemical Resistance Testing (TRI/Environmental)