Determining the Remaining Lifetime of Exposed HDPE Geomembrane Liners

I.D. Peggs. I-Corp International, Inc., United States of America, icorp@geosynthetic.com

ABSTRACT
Many exposed HDPE geomembrane liners are approaching service lifetimes of 30 and 35 years. When these liners reach end-of-life (EOL) they will likely fail quite quickly by stress cracking (SC) as a result of thermal and photo-oxidation of the surface. Undoubtedly these failures will be considered "premature" and catastrophic. This has already been seen in one installation after only 15 years. Associated and remediation costs will be very high. It therefore becomes of interest to be able to assess the remaining lifetime of any specific lining system. Time to EOL is very much a function of the site-specific conditions, such as temperature range, UV exposure, chemistry of facility contents, and operating stresses. It will also be a function of specific HDPE resin used, co-monomer used to improve SC resistance, stabilizer formulation, manufacturing process parameters, and installation/weld quality. All HDPEs are not the same. Therefore, laboratory models cannot predict a generic EOL for exposed HDPE geomembranes. The reasons why not are clarified. Then, from these data a test program will be generated that should provide two or three years notice of EOL, otherwise known as the "mature" failure.

1. INTRODUCTION

The generally accepted three-stage model for HDPE geomembrane aging/degradation is that proposed by Hsuan et al. (2008) as depicted in Figure 1. Stage A is loss/consumption of stabilizing additives that protect the PE from thermal oxidation and UV radiation. When all protective additives are lost Stage B is an induction period to the onset of degradation or loss of properties. During Stage C a loss of the monitored property occurs. The degradation process is most frequently monitored by changes in break strength and/or elongation, with end-of-life (EOL) being defined as the time at loss of 50% of the relevant property, i.e. 50% retained (ret). At this point, of course, physical break, or loss of geomembrane integrity has not occurred, but it might, or might not, be close. It would be helpful to be more certain of time to EOL.

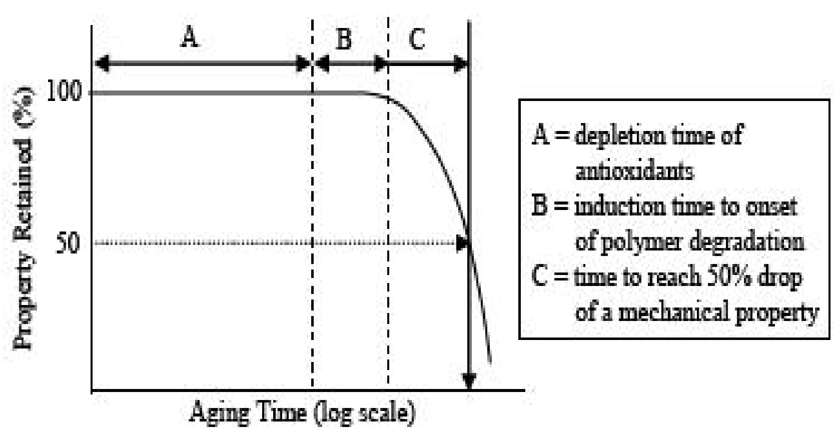

Figure 1. Three stages of degradation

At the same time the loss of stabilizer is monitored by the measurement of the standard oxidation induction time (S-OIT, ASTM D3895) or high-pressure oxidative induction time (HP-OIT, ASTM D5885).

Both measure the time to the start of oxidation of a small specimen of the material in an oxygen atmosphere. S-OIT is performed at 200°C in oxygen at normal atmospheric pressure while HP-OIT is performed at 150°C in a high-pressure oxygen atmosphere. The OIT times are a measure of the amount of effective stabilizer remaining in the material and, therefore, of the remaining lifetime. On a general note, it is acceptable to assess relative remaining lifetimes of a single material under different conditions on the basis of OIT, but it is not acceptable to predict the degradation performances of two different materials on the basis of their OITs.

However, it can be seen in Figure 2 that laboratory test results show the reduction in mechanical properties to commence, not when all the OIT times are zero and all additives have been consumed, but when OIT has been reduced to about 20% of the original. This is because there are probably still some stabilizers in the centre of the specimen but all have been consumed on the surface layers. Thus the surface has degraded and affected the test results. Tensile break properties and impact resistance are significantly affected by surface condition, such as scratches (even extrusion die lines), notches (grinding for extrusion welding), and oxidation. At zero OIT the tensile properties are not just starting to decrease but have been extensively reduced.

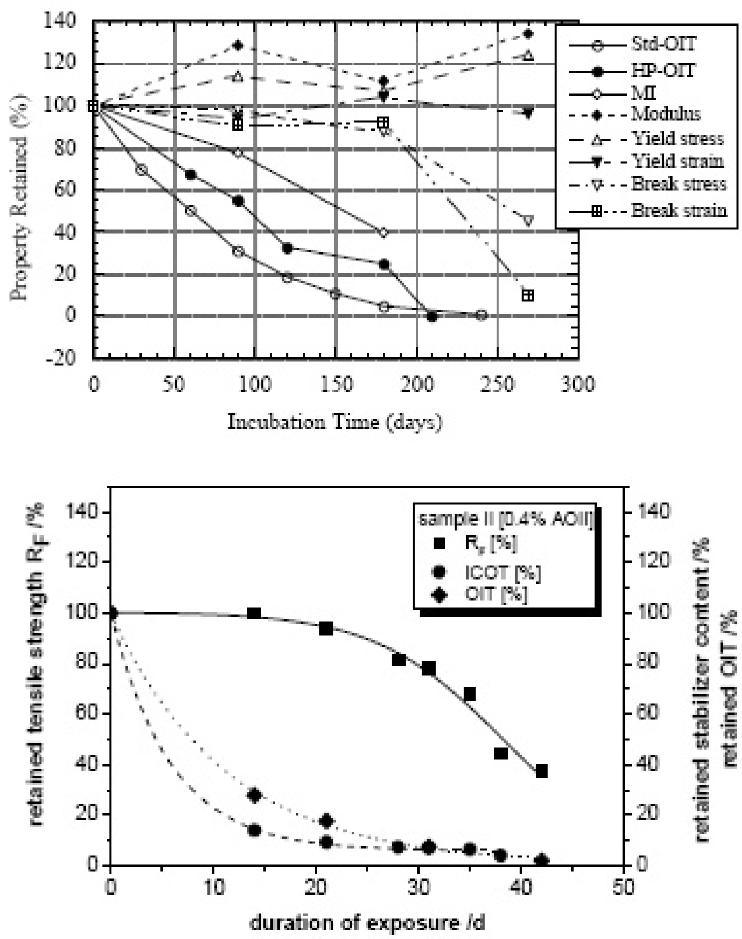

Figure 2. Changes in tensile properties and OIT while aging. (Hsuan et al., 2008, top; Boehning et al., 2008, bottom).

A measure of the time to EOL of any exposed PE or PP geomembrane lining system would provide owners with an increased level of risk management such that unexpected costly catastrophic failures that might be termed "premature", but that are really EOL that could be expected (a "mature" failure?), are totally avoided. Replacement can be planned before EOL. It is expected that a few years notice of EOL could be obtained. After investigating several liners, floating cover, and exposed landfill cap failures, a protocol for the assessment of EOL is becoming apparent. While the general principals of the laboratory model of liner degradation/weathering are observed, the rate at which field failures occur is accelerated. However, it is most important that relevant tests be performed to assess aging, as demonstrated by the example below.

An exposed reinforced polypropylene (RPP) geomembrane cap (EGC) on an 18 ha landfill was evaluated after almost 10 years of service prior to application for an operating permit for a further ten years. Conventional mechanical property tests (grab tensile, wide width tensile, puncture, tear) were performed on samples removed from the cap and all were essentially found to be acceptable. Some increased monitoring was proposed on the south facing (sun exposed) side due to a larger, but not unacceptable, reduction in properties. However, not long after the permit application was submitted, but before it was issued, significant degradation of the liner became visually apparent. Reinforcing yarns were exposed on the sunny side as the exposed PP layer cracked and spalled (Figure 3), and as the other sides were found to have become powdery or “chalked” on the surface (Figure 4). Even with good surface cleaning it was not possible to thermally weld a patch of RPP to the surface to make a repair. The surface of the FPP had become oxidized and would not melt to facilitate a repair.

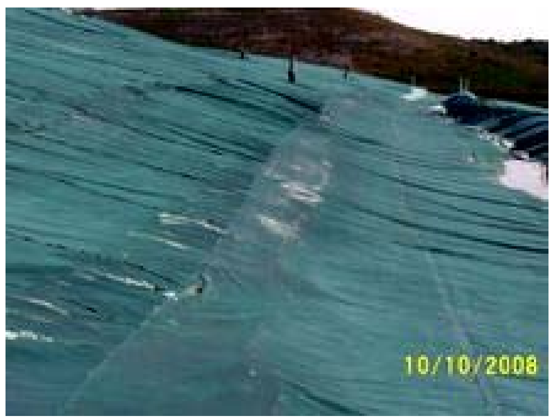

Figure 3. Exposed reinforcement (white) on sunny side (Courtesy DSWA)

Figure 4. Chalking on surface (Courtesy DSWA)

So, why was this degradation not reflected in the testing program when it was known that there had been many other similar PP geomembrane failures (Peggs, 2008). Quite simply, the conventional mechanical tests only evaluated the condition of the reinforcing polyester geotextile (scrim) that carried the PP liner material. The PP polymer was not challenged in the tests. Ultimately, of course, after sufficient loss of surface polymer, the reinforcing polymer would be affected, as shown in the extreme case in Figure 5. However, the integrity of the EGC was compromised before mechanical properties so indicated. After the previous failures, tests to evaluate the condition of the PP polymer surface layer should have been performed.

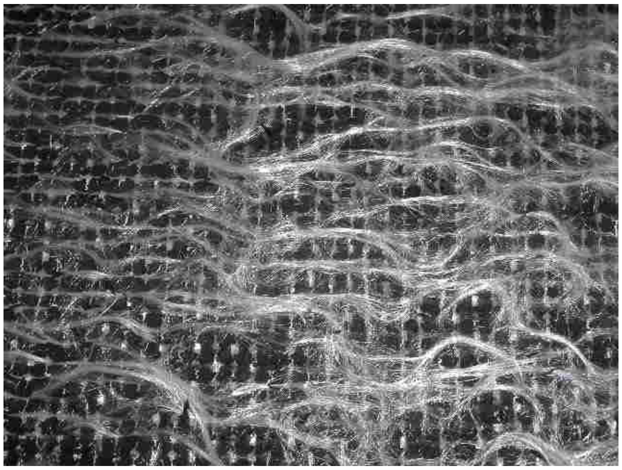

Figure 5. Exposed PP layer fully exfoliated after 9 years UV radiation in hot environment to reveal polyester reinforcing yarns.

1.1 Polyethylene

Another example is a single exposed HDPE liner in a pond in a hot/cold environment in the Midwest USA. It was installed in 1993. It failed in late 2008 (Peggs 2009). Material from the anchor trench, unaffected by high temperatures and UV exposure still met 1993 geomembrane specifications (National Sanitation Foundation International standard NSF 54). It also met the Geosynthetic Research Institute (GRI) GM13 stress cracking resistance (SCR) specification of >200 hr (ASTM D 5397) introduced a few years later. In fact, the conventional mechanical properties of the exposed material still met those specifications. However, the SCR had decreased, and both Standard Oxidative Induction Time (S-OIT) and High Pressure Oxidative Induction Time (HP-OIT) fell by about 50%. Failure was by SC along some, but not all, of the round die extrusion manufacturing fold marks at the quarter and three-quarter roll width locations of the sheet (Figure 4), and at subgrade stone protrusions (Figure 7).

Figure 6. Stress cracking (screwdriver) along apex-down manufacturing fold. Anomalous apex-up folds (arrowed) are not cracked.

Figure 7. Stress cracking along extrusion die lines at subgrade stone protrusion.

The cracking was initiated on the exposed surface. The fold failures only occurred in the few folds with the apex down (a V cross section). No SC occurred in the majority of folds with the apex up (an inverted V). The stresses that induced cracking were those due to thermal contraction at low temperatures. Thus, the surface conditions on the exposed and unexposed surfaces of the geomembrane at the folds are shown in Table 1.

Table 1. Surface Stress and oxidation conditions at fold marks

FOLD PERFORMANCE				
Fold Orientation	**Surface**	**Oxidized**	**Stress**	**Cracked**
Apex down	Exposed	Yes	Tension	Yes
	Unexposed	No	Compression	No
Apex Up	Exposed	Yes	Compression	No
	Unexposed	No	Tension	No

This shows that only the apex-down creases have both tensile stresses and oxidation on the surface, both being needed to initiate SC. Similarly the stone protrusions generate a tensile stress on the oxidized surface and SC is initiated at the stress concentrating surface die marks. These stresses are exacerbated at low ambient temperatures. SC was also seen along the edges of both extrusion welds (added oxidation and grinding gouge stress concentrations) and fusion welds (added oxidation). Thus, there was more cracking, as expected, at extrusion welds.

It was also found that the HP-OIT of the exposed material was much lower than the anchor trench material, although it was still far from zero. Therefore, despite the fact that the conventional mechanical properties were still acceptable, and despite the fact that there was a significant OIT, the surface itself had probably been fully oxidized, stress cracking had been initiated, and the liner had failed. This was, therefore, not a “premature” failure but a “mature” EOL failure of that specific material in that specific application in that specific environment. That same HDPE in another application could have lasted longer, or another HDPE in that application could have lasted longer. All HDPE geomembranes are not the same.

Thus, the durability of any given HDPE geomembrane in any exposed application is a synergistic function of:

- the specific PE resin and co-monomer used which affect SCR.
- the stabilizer formulation used – proprietary to resin and geomembrane manufacturers, which provides thermal and UV resistance.
- the service temperature range which affects rate of thermal oxidation and magnitude of contraction stresses.
- the service UV exposure, which affects photo-oxidation, and
- Residual, installation, and service induced stresses that cause cracking.

Thus, time to EOL can only be projected by properly evaluating the field material itself. Clearly, the same material installed in Central Africa and in the Arctic will behave quite differently and have quite different lifetimes at the two locations.

With reference to stress cracking, Figure 8 (Hessel et al., 1988), shows the typical HDPE stress rupture curve in which the shallowest slope (<B) at the higher stresses is the region of ductile breaks and the steeper slope is the region of fundamental HDPE brittle stress cracking (BC). At the end of this region the vertical slope (>C) represents break at any stress when the material is fully oxidized. Thus, when oxidation occurs on an exposed surface, stress cracking can be initiated. Once initiated, such cracks can relatively easily propagate into unoxidised interior material, ultimately causing complete fracture.

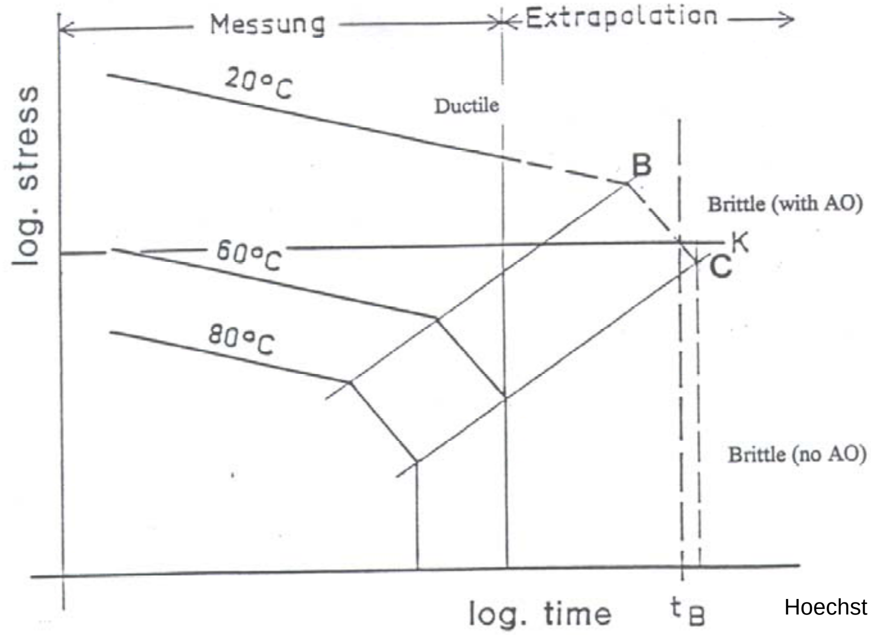

Figure 8. Stress rupture curve showing ductile (<B), stress cracking (BC), and oxidized (>C) regions (Hessel et al., 1988).

Therefore, the important durability monitoring parameters are not the conventional mechanical properties but are the polymer microstructural analytical properties:

- Stress cracking resistance
- Initial HP-OIT
- Thermal aging as monitored by surface layer HP-OIT
- UV aging as monitored by surface layer HP-OIT

The HP-OIT of the surface layer (~0.5 mm thick) is measured to get closer to the conditions of the exposed surface and away from the bulk material.

Properties such as Melt Index (representing molecular weight), density (representing crystallinity), and carbon black dispersion (potential SC initiation at agglomerates) may also be useful, but are of lesser interest.

However, none of these tests indicate definitively whether or not actual oxidation of the surface has occurred. Clearly such knowledge is important. This information can fairly simply be obtained by measurement of the carbonyl index (CI) using the attenuated total reflectance (ATR) technique of Fourier Transform Infrared spectroscopy (FTIR) on the exposed surface. The CI is derived as shown in Figure 9. It represents a measure of the degree of oxidation by monitoring the increase in the products of oxidation (carbonyl groups) as a function of a reference PE spectral peak.

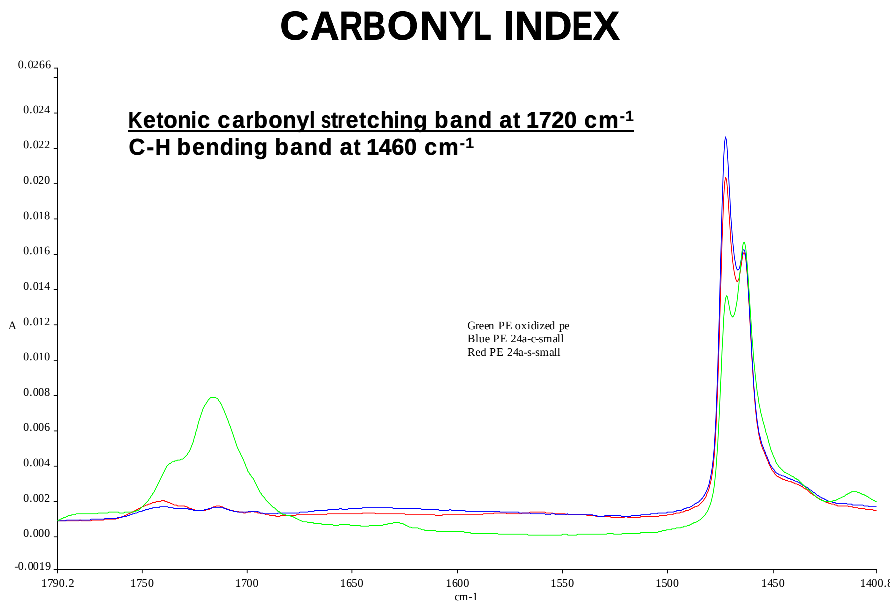

Figure 9. FTIR-ATR spectral peaks (carbonyl left, PE right) and definition of CI.

In HDPE natural gas distribution pipe failure investigations Broutman and Duval, (1989) and Duval (2002) have proposed that if CI exceeds 0.1 there is a high probability of SC being initiated. It is proposed that this also be used in the evaluation of HDPE geomembranes.

1.2 Field Evaluation

Therefore, the first stage of liner evaluation is a site visit with appropriate liner inspection and removal of samples for testing. A reference as-manufactured archive sample that has been kept indoors and cool will be obtained if possible, or a benchmark sample that has not been exposed to UV radiation or elevated temperatures will be removed from within the anchor trench. The reduction in SCR of a melted and cast plaque will be determined as will changes in HP-OIT of the bulk material and of the surface layer. The change in HP-OIT will be compared to the thermal aging and UV resistances as measured on the archive material according to GRI.GM13. The CI of the surface layer will assess the degree of oxidation. Extensions of the test data will be made to determine when surface HP-OIT will become zero and when the CI will exceed 0.1. Two, or three at the most, site samplings should be sufficient to determine when EOL will occur.

With time to EOL known the lining system can be replaced, or repaired in appropriate locations, such as on high UV exposure slopes, before catastrophic failures occur.

The database that is generated by these investigations will provide relationships between bulk HP-OIT and surface layer HP-OIT, between surface layer HP-OIT and the extent of oxidation (CI), and between CI and the initiation of SC. Each of these relationships will ultimately allow the specification of HDPE geomembranes for maximum durability in specific environmental applications. Thus, commodity HDPEs can be used for decorative ponds and other noncritical applications, while the hazardous liquid waste pond will use a known more durable HDPE geomembrane.

2. CONCLUSIONS

- As exposed HDPE geomembrane lining systems continue to age we will begin to see an increasing number of end-of-life (EOL) stress cracking failures as the material oxidizes.

- The time to failure will be a synergistic function of resin used, stabilizer formulation, range of service temperature, UV exposure, and induced stress in the liner.
- Each installation will be unique.
- A program to assess the remaining time to EOL of any installation in any environment has been proposed based on measurements of stress cracking resistance, high pressure oxidative induction time, and surface carbonyl index.
- The data generated will facilitate the specification of HDPE geomembranes with maximum durability.

REFERENCES

Boehning, M., Robertson, D., and Schroeder, H.F., (2008). Autoclave Testing: A New Approach to the Evaluation of Oxidative Long-Term Resistance of Geosynthetics, Fourth European Geosynthetics Conference, Edinburgh, Scotland, IGS UK Chapter.

Broutman L.J., Duvall, D.E., So, P.K., (1989). Fractographic Study of a Polyethylene Sewer Pipe Failure, SPE Antec, pp 1599-1602.

Duvall, D.E., (2002). Analyses of Large Diameter Polyethylene Piping Failures. Proceedings of the Society of Plastics Engineers 60th Annual Technical Conference, Brookfield, Connecticut, USA.

Hsuan, Y.G., Schroeder, H.F., Rowe, K., Mueller, W., Greenwood, J., Cazzufi, D., and Koerner, R.M. (2008), Performance and Lifetime Prediction of Geosynthetics, Fourth European Geosynthetics Conference, Edinburgh, Scotland, IGS UK Chapter.

Hessel, J., Koch, R., Gaube, E., Gondro, C., and Heil, H. (1988) Langzeitfestigkeit von Deponiedichtungsbahnen aus Polyethylen, Kunststoffe Hoechst, Sonderdruck 6312 d, Frankfurt, Germany.

Peggs, I.D., (2006) “Investigation of Stress Cracking in a Reinforced Polypropylene Floating Cover”, 8 International Conference on Geosynthetics, Yokohama, Japan, September 2006.

Peggs, I.D., (2009) “HDPE Geomembranes – Reaching 30 years, What’s Next: or How Much Longer Will My Liner Last?” Geo09, IFAI, Roseville, MN, USA, pp 357-364.