



# BERLIN 2 – HDPE GEOMEMBRANE WORKSHOP

Technical Notes From The Berlin 2 HDPE Geomembrane Workshop:  
*ASSESSING REMAINING SERVICE LIFE*

## Technical Notes from the Berlin 2 HDPE Geomembrane Workshop: Assessing Remaining Service Life

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### 1.0 INTRODUCTION

Nearly all engineered systems have a finite service life. This includes geomembrane (GMB) barriers (liners) as part of the system for the containment of valuable product (potable water, gold solutions, etc.) and contaminated/obnoxious liquids/solids (coal ash, meat processing waste, etc.). All exposed high-density polyethylene (HDPE) GMBs will degrade by oxidation in service and fail by quasi-brittle stress cracking. Clearly, facility owners need to know when a liner will no longer perform its containment function.

On 26 September 2014, the day after the end of 10<sup>th</sup> International Conference on Geosynthetics (ICG) in Berlin, Germany, a workshop of international experts was held at the Federal Institute for Materials Research and Testing (BAM) to discuss “**development of a protocol to determine the remaining service life of an already exposed HDPE geomembrane liner**”. This followed two shorter workshops on the same topic at EuroGeo 5 in Valencia, Spain (2012) and at Geosynthetics 2013 in Long Beach, USA.



Figure 1. The "BAM Leak Detector." Dr. JP Giroud (Berlin 2 Facilitator) pauses outside the proceedings to appreciate the intersection of engineering and art.

### 2.0 OBJECTIVES OF WORKSHOP

The ultimate workshop objective was to develop a protocol that would describe the actual condition of an exposed HDPE GMB, to predict its remaining service life, i.e. the time before the GMB can be expected to fail, and consequently needs to be repaired or replaced to prevent such failure. The discussion was limited to HDPE because of its globally common use in major sectors such as waste and mining and because its durability characteristics are better understood than those for other liner materials.



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A skeleton protocol to catalyze the discussion was proposed as follows, based on the assumption that final failure of HDPE GMB would occur by surface oxidation and stress cracking:

1. Measure oxidative induction time (OIT) to assess whether or not oxidation protection is still available.
2. Measure carbonyl index (CI) to assess extent of any oxidation that has occurred.
3. Determine if there is a critical CI at which stress cracking (SC) is initiated.
4. Measure stress cracking resistance (SCR) to determine the time until SC is initiated.

Note well that the intent was to discuss barriers already installed that have been exposed to the environmental synergisms that cannot possibly be reproduced in the laboratory. It was not to discuss accelerated testing on virgin materials in an artificially generated environment to determine their expected service lives.

## 3.0 DIFFERENTIATION BETWEEN BURIED AND EXPOSED APPLICATIONS

### 3.1 Buried GMBs

- Mechanical stresses in GMBs occur only during installation (under “ideal conditions”) and if we ignore folded wrinkles (according to “North American practice”).
- After installation, stresses in GMBs relax and GMBs are practically “stress-free” (under “ideal conditions”).
- The classical “3-stage aging model” (antioxidant {AO} depletion time + induction time + polymer degradation resulting in a modification of the mechanical behavior of the GMB) described by Hsuan & Koerner (1998) is reasonable because the service life, often presented as time to reduce mechanical properties, defined with an acceptance criteria of the original value is sufficient for an ideally designed and ideally installed, buried GMB.

However, buried GMBs are not the topic of this workshop!

### 3.2 Exposed GMBs

- The full designed stress (or more) may occur at any time – even after many years in service! Therefore, End of Life (EoL) should be based on 100% retained or design-based strength as 100% of the expected stress may occur at any time.
- “2-stage model” (AO depletion time + induction time) is relevant:
  - A reduction of mechanical properties cannot be considered as part of the service life of an exposed GMB.
  - First cracks occur in the surface after oxidation of the surface (OIT is close to zero at the exposed surface of the GMB)

Mechanical properties are close to 100% (e.g. in case of phenol based stabilization).



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### 3.3 Examples of functions of exposed GMBs

- Snow pond (Example 1):  
GMB is as a barrier to leakage because leakage water can lead to instability of the earth dam surrounding the snow pond.
- Water canal for a hydropower station (Example 2):  
GMB is used as a barrier to water loss, as leakage will reduce the efficiency of the hydropower station.
- Containment of acid or soda in ponds and reservoirs in mining (Example 3):  
GMB is specified as a barrier because groundwater or environmental pollution from unlined leakage would represent inefficient (i.e. less profitable) operation.
- Tailing reservoirs in mining (Example 4):  
GMB is specified as a barrier because leakage from an unlined facility would be detrimental to groundwater or the environment, or such leakage would lead to financially inefficient operations. Regarding tailings ponds, many of them are now designed to bury the geomembrane under a volume of material that may make monitoring impractical or impossible.

It was originally expected that there would be much discussion on the difficulty of making meaningful comparisons between parameters measured on the full thickness of the GMB and parameters that assess surface layer properties. For instance, to compare CIs (typically measured on a surface layer) and OITs, the OITs should also be measured on surface layers and not on full thickness GMB specimens as is usually done. The OIT of a surface layer may be zero while that measured on the full thickness could be quite significant.

Similarly, should GMB specimens used for SCR tests be notched on the exposed/oxidized side or the opposite unexposed side? Or should all GMB specimens for SCR tests be made from melted material and solidified plaques? Or, should a test on an un-notched specimen be performed?

The most serious discussion was on a definition of EoL, for without a definition of EoL, a remaining service life cannot be determined. This varied from appearance of the first stress crack, through appearance of the first penetrating hole (but holes can be repaired, to extend service life), and even to the need for each application to have its own EoL. Certainly most people felt that a more practical EoL than time to 50% of a retained parameter could be developed.

### 4.0 PARTICIPANTS

The workshop was organized by Ian D. Peggs (USA) and Helmut Zanzinger (Germany), with the assistance of Elizabeth Peggs (USA), Chris Kelsey (USA), Werner Müller (Germany) and Andreas Wöhlecke (Germany). Experts were invited from different sectors of the industry and from different countries.



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Those in attendance:

• Ian D. Peggs	(co-chairman)	I-CORP INTERNATIONAL, USA	Consultant
• Helmut Zanzinger	(co-chairman)	SKZ – Testing GmbH, Germany	Research
• J.P. Giroud	(facilitator)	J.P. Giroud, Inc., USA/France	Consultant
• Mike Sadlier		Geosynthetic Consultants Australia, Australia	Consultant
• John Cowland		GeoSystems Ltd., Hong Kong, China	Consultant
• Daniel Tan		Solmax International Asia Pacific Sdn. Bhd, Malaysia	Manufacturer
• Vera Olischläger		NAUE GmbH & Co. KG, Germany	Manufacturer
• Sebastian Hausmann		SKZ – Testing GmbH, Germany	Research
• José Miguel Munoz		Sotrafa S.A., Spain	Manufacturer
• Robert Kienzl		OFI, Austria	Research
• Fred Gassner		Golder Associates Pty Ltd., Australia	Designer
• Mauricio Ossa		GSE Lining Technology, Chile	Manufacturer
• Ana M. Noval		CEDEX, Spain	Research
• Catrin Tarnowski		GSE Lining Technology GmbH, Germany	Manufacturer
• Werner Müller		BAM, Germany	Research
• Marcus Grob		BASF, Switzerland	Research
• Amr Ewais		Queens University, Canada	Research
• Hyun-Jin Koo		FITI, Korea	Research



Figure 2. Berlin 2 group photo. Front row (from left): Werner Müller, John Cowland, Mike Sadlier, Fred Gassner J.P. Giroud, Ian D. Peggs, Helmut Zanzinger, Andreas Wöhlecke, Daniela Robertson. Back row (from left): Daniel Tan, Hyun-Jin Koo; Chris Kelsey; Robert Kienzl; Mauricio Ossa; Catrin Tarnowski; Amr Ewais; Ana M. Noval; Marcus Grob; Montse Garcia Estopá, Sebastian Hausmann, Vera Olischläger, Franz-Georg Simon

It was Dr. Giroud's responsibility to keep the discussions on track and to try to identify, at the end of the day, three or four topics that could be researched before the next meeting.



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### 5.0 WORKSHOP INVITATION OUTLINE

Invited participants were sent a skeleton proposed protocol and were requested to prepare and submit a 400 word “abstract” of a relevant topic prior to the workshop to stimulate discussion. The abstracts were circulated to all participants before the workshop.

*The day after the INTERNATIONAL GEOSYNTHETICS CONFERENCE in Berlin ends, I-CORP INTERNATIONAL (USA) and SKZ – Testing GmbH (GERMANY) are co-chairing a workshop to develop a protocol for the determination of remaining service life in in-service exposed HDPE Geomembranes. The objective is to determine when liners need to be replaced before a catastrophic failure occurs.*

*Pre-service lifetime estimates based on testing virgin materials at specific temperatures, in specific environments, cannot possibly reproduce all the synergisms that can occur in the field, but once a material has been in service for some time it should be more appropriate to assess remaining service life in that continuing environment.*

*The outline of a remaining service life assessment protocol follows and abstracts/papers will be invited from about 35 experts modifying that proposal or proposing another protocol. About 15 of these papers will be briefly presented to initiate extensive discussion. All papers and the discussion will be recorded and published electronically.*

*The skeleton of a proposed reference protocol is:*

- *Definition of EoL*
- *Measure OIT of exposed surface layer to assess stabilizer remaining*
- *Measure carbonyl index to assess extent of surface oxidation*
- *Measure stress cracking resistance of unnotched specimen or of melted/solidified plaque*
- *Determination of critical carbonyl index at which SC is initiated*
- *Assess impact of SCR on SC initiation after critical CI is reached*

*Consider surface properties vs. bulk properties. Consider use of thin film specimens. Consider novel testing techniques - impact resistance, autoclave oxidation, strain-hardening modulus.*

*Remember, we are seeking remaining service life of already installed material, not the expected life of virgin material.*

*BERLIN 2: One target. Multiple methodologies. Lively discussion.*

One commonly heard comment was,

*“I have no test results, so I have nothing I can contribute to the discussion”.*

Clearly, there are little data available, hence the reason for the Workshop. The objective of the discussion was to identify the data that are needed. Thus, forward-looking, out-of-the-box thinking, rather than hard data, was required. Many participants had difficulty with this.



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### **6.0 INDIVIDUAL INTRODUCTORY ABSTRACTS**

There are several recurring questions that can be followed during the initial presentations and the subsequent discussion. They are:

- Definition(s) of failure in individually measured parameters that individually or together can define EoL.
- What combination of parameters is required to define EoL?
- Monitoring changes in measured parameters and extrapolating them as a function of time to determine remaining service life, as opposed to taking a sample, measuring relevant parameters, then performing accelerated aging tests to determine time to EoL.
- Perform tests relevant to the service environment of each facility, as opposed to doing standard tests applicable to all installations.
- Focus on tests on past performance of the liner to extrapolate to EoL rather than focus on tests that show the future performance of the liner and time to EoL.
- Test seams as well as liner material since most failures occur at seams.

Selected abstracts submitted by the invited experts follow:

#### **6.1 Abstract of Mike Sadlier:**

The obvious answer to the EOL question is when it “ceases to perform the required function” but that can mean different things in different situations. Much of this will depend on what is going on around a liner. A liner buried under tailings or waste and immobilized may lose properties but continue to reasonably perform its required function. However a pond liner or floating cover that loses properties will quickly cease to function.

The other important question is what HDPE are we talking about? To me there are three very broad categories of HDPE with distinctly different properties and this brings into question whether our current definition of HDPE is adequate:

- The “old time” HDPE with carbon black and little else had its difficulties with welding and stress cracking but it brought excellent chemical resistance and excellent UV resistance as can be seen on some older installations.
- The “current standard” HDPE intended to meet GM13 is easier to work with and has better stress cracking properties along with what seems to be reasonable chemical resistance and good UV resistance.
- The “new world” HDPE that shows much improved mechanical properties (e.g. multiaxial elongation at over 40%, NCTL approaching 1500 h). With good high-pressure OIT (HP-OIT) we can anticipate good UV performance but with mechanical properties similar to linear low-density polyethylene (LLDPE) what do we expect of chemical resistance?

We also need to know more about the real world of exposure of a HDPE or other GMB material which may well involve influences beyond those considered at design. Some examples include acidic ash from certain coal fired power stations, active radiation and other minerals in the general environment, especially at mining sites. There have been occasions when deterioration



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due to the intended exposure was minimal but other more general exposures have caused damage.

In assessing the performance of a GMB in service we are often limited by the capacity to extract samples from exposed locations and the capacity to generate a “benchmark” for the performance of unexposed material. Does material sampled from an anchor trench really represent unexposed material? This is where archived materials and exposure coupons can enable a much better informed answer to the perennial question “how much time do we have left?”

### **6.2 Abstract of John Cowland:**

The expected life of GMBs will depend on their intended applications, which can be quite different for different projects, such as mining projects, solid waste landfills, the containment of water and the containment of hazardous liquids. Expected life can also be affected by exposure to high and low temperatures, and UV light.

All too often, the design engineer is required to take responsibility for the future performance of a GMB manufactured with additives that the design engineer knows little about. Indeed, it is my experience from many factory inspections that some manufacturers do not know as much about the additives they have been sold to add to their GMBs as they should do to safeguard their own liability. I have experienced unfortunate cases where additives have been used to protect the GMB against exposure to acids where the project will expose the GMB to alkalis.

The skeleton of the proposed reference protocol is excellent, and in my view the workshop should also discuss how this protocol can help design engineers.

Finally, in my opinion, this workshop should be expanded to include all types of GMB, not just HDPE, or medium-density polyethylene (MDPE).

### **6.3 Abstract of Fred Gassner:**

In response to the request for an opinion on life of HDPE GMB, I provide the following points from the point of view of a designer:

- The operational or functional life of a GMB is related to when the effect of the GMB is materially different to what it was intended. It is my opinion this is when the seepage rate through the liner due to defects has changed by one order of magnitude compared to the design intent.
- In my experience the degradation/failure of GMB liners occurs or starts at welds. A defect formed due to degradation is usually a long split along the edge of seam of the GMB and its seepage effect can be assessed similar to a wrinkle. The impact of failures along weld edges is most marked in ponds, where usually no or minor confinement exists over the GMB. The consequence of failures along seam edges in landfills may be less due to the confinement effect on the GMB.



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- Much analysis and research is aimed at intact GMB. Consideration should be given to the weld conditions and their durability as welding results in degradation of stabilizers/AO from the welding heating effect and hence is likely to be the first area of age failure of GMB liners.
- Stress cracking can occur while the GMB still has a moderate level of OIT time. Probably worthwhile to get a better understanding of current stabilizer packages and their effect on SCR. Some GMBs plateau at certain OIT values, and is possibly linked to mobility of stabilizers molecules within the GMB sheet. So OIT values may no longer be a reliable way to assess the degradation status of the GMB.
- The remaining service life of an exposed GMB can be assessed by a simple tensile test on coupons across the welds, compared to strength values achieved referenced from installation quality control records. These residual strength values can be compared to design strength requirements for wind uplift etc. Once values drop to unacceptable factors of safety this liner has reached its end of life, as a design wind effect is likely to result in large extent of liner seam separation at the panel seams. Failed seams along panel edges are likely to result in seepage rates similar to no liner being present, in most situations. This can be assessed on a case by case basis.
- With advances in the GMB industry, is there a basis to develop a GMB with most of the chemical resistance of HDPE but with a resin that is not prone to stress cracking? The majority of projects do not need the very high chemical resistance of HDPE.

### 6.4 Abstract of Catrin Tarnowski:

In the recent years the focus on the relevant long-term performance parameter of HDPE GMBs has changed: Whereas for several years the community talked on stress crack resistance nowadays the focus is getting back to oxidative stability. It seems that with having established the performance parameter for NCTL being > 300 h acc. to ASTM D5397, Appendix, that the problem of early failure is solved. Also considering that GMBs shall be installed in relaxed conditions, stress cracking should not be an issue.

But just for exposed applications we cannot exclude external stresses like wind action for example. When failures are reported the failure mechanism is a brittle one – stress cracking.

Thus not only the stage of oxidation, but also the stress crack performance related to the specific conditions of use has to be considered. The topic – when does a liner need to be replaced before a catastrophic failure does occur – is just for exposed applications a very challenging one. So what is the stress crack resistance value needed to overcome possible stress?

From the authors point of view a protocol addressing critical/relevant points in projects would be a starting point rather than knowing the GMB performance only. This might possibly be leaching, wind speeds, points and number of wind action, critical weld areas or bridging problems, initial performance of the liner, kind of raw materials used and various others.



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With such a protocol one might find similarities in different projects related to the aging stage of a GMB and possible time to failure or necessary point of replacement. Thinking about failures which have occurred after short time period only, whereas in other cases HDPE GMBs are exposed for more than 30 years and still in service. Also a database on the properties of these GMBs itself might be a helpful tool.

### 6.5 Abstract of Ian Peggs:

Many studies have been done on the expected service life of a given as-manufactured HDPE GMB material in a given environment usually covered by soil. Lifetime is usually presented as time to reduce a given parameter, often tensile strength, to 50% of its original value. This is quite an arbitrary parameter. And most researchers will clarify that the results apply only to that specific HDPE formulation in that specific environment. Unfortunately no laboratory test environment can reproduce the field environment and synergisms of temperature (expansion/contraction), chemistry (environment/internal), and stresses (expansion/contraction, wind uplift), and UV exposure. And field failures rarely occur as a result of the material losing its tensile strength.

Most usually it is recognized EoL occurs as a result of thermal oxidation and UV photo-oxidation which causes the initiation of stress cracks in the exposed surface which ultimately propagate through the GMB by slow crack growth or rapid crack propagation. Since it is not possible to predict the propagation rate of a stress crack through a given thickness of GMB EoL is therefore considered to be when stress cracks first occur in an exposed surface. So, how can we assess the oxidation "degradation" rate in an exposed GMB, provided of course it will remain in the same environment? Two or three samples taken after different service times will be compared to the uninstalled GMB. The following parameters will be measured for the following reasons, remembering that oxidation is a surface process:

- HP-OIT to assess the rate of consumption of anti-oxidants in the stabilizer formulation. This will be done on a surface layer of the exposed liner, not on the complete thickness as is usually done.
- When the HP-OIT effectively reaches a plateau in the surface layer, oxidation may not immediately occur. Therefore CI will be measured to determine the extent and rate of oxidation. The use of an attenuated total reflection (ATR) crystal in a Fourier transform infrared spectrometer (FTIR) will enable the CI of a surface layer to be measured.
- Researchers in HDPE gas pipe have proposed there to be a critical CI at which SC is initiated. To determine this relationship in the exposed material the surface CI measured above will be compared to the unnotched SCR of a thin plaque prepared from the full thickness sample.
- This will require data to be generated on the relationship between CI and unnotched SCR on variably oxidized specimens to determine the critical CI at which SC occurs on the GMB surface.
- Thus the measured CI at different service times can be extrapolated to the time to critical CI and the initiation of SC, therefore the time to end of practical service life.



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Knowing the time to EoL should allow the owner to plan for appropriate repairs or replacement of the liner and to avoid an unexpected catastrophic failure.

### **6.6 Abstract of Werner Müller:**

The remaining service life of exposed HDPE GMBs depends (1) on the type and amount of AOs, which are still present, (2) on the loading conditions, i.e. to which extent tensile forces are regularly imposed onto the GMB due to thermal shrinkage at low temperatures, wind suction, deformations, indentations, etc., (3) the surface properties, i.e. occurrence of critical stress initiation points, deep scratches and grooves, local stress concentration at geometric discontinuities associated with seems, etc. Typically HDPEs are stabilized by a combination of phenolic and phosphitic AO. These AOs are primarily consumed by UV accelerated oxidation processes and hydrolytic degradation at the surface, by extraction and evaporation of the AO molecules and their degradation fragments from the surface. This will be discussed in detail. Two regimes of AO depletion have been found. Regime A: Accelerated loss of AOs due to exudation. Regime B: loss by normal diffusion. Since the AOs get lost at the surface, there is a concentration gradient between surface and bulk which drives the diffusion of AOs from the bulk to the surface. If AO concentration in the bulk becomes very low and concentration at the surface is therefore essentially zero, then a heterogeneous oxidation process starts at various spots on the surface, which are depleted from AOs (regime C). With tensile force present, cracks are initiated at these spots. Failure of the whole product will then be imminent. The depth profile of such AO concentration can be measured by OIT. From such measurements, one may deduce remaining service life. Nowadays, hindered amine stabilizers (HAS) are sometimes added to the “classical” stabilization. Since HAS are less extractable and not sensitive to hydrolysis, HAS may still be present even after extended loss of phenolic and phosphitic AO components. However, HAS do not prevent oxidation, even though, oxidative degradation is significantly decelerated. What happens to HAS stabilized HDPE GMBs? To which extend is stress cracking initiation prevented? How can a depth profile of HAS be determined, since neither Std-OIT nor HP-OIT are applicable?

### **6.7 Abstract of Amr Ewais:**

There are a number of challenges to creating a protocol for assessing the remaining service life of exposed GMBs. First, it is anticipated that the GMB resistance required will differ from one application to another. Second, the rate degradation of the GMB would not only depend on the GMB properties (resin) but also on the exposure conditions. Third, there are difficulties associated with the techniques used to assess the remaining resistance of a GMB. For



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example, one of the techniques used to assess the GMB resistance is the stress crack resistance (SCR, ASTM D5397) of the GMB. To use the SCR to assess the end of life for the GMB, the following questions need to be answered: (a) is this a useful technique, and (b) if so, what is the critical SCR at which the liner will rupture and when will this critical SCR will be reached? To address these questions, two studies were conducted to investigate the degradation of polyethylene GMBs under different loading conditions (demand). The first study, considered the degradation of different GMBs exposed to very different climatological conditions. It was shown that: (a) SCR may decrease significantly without any evidence of chemical degradation, and (b) the GMB installed on a 3H:1V, 22 m high, slope had not ruptured after 16 years despite a reduction in SCR to about 70 hours. In the second study, three sets of polyethylene GMB samples (14 different polyethylene GMB) were left exposed on a wooden rack inclined at 2H:1V in southern Ontario Canada. The first set of the GMB samples were exhumed from leachate lagoon after 14 years in service before being placed on the rack for an additional 17 years (a total of 31 years aging to date). The second set of GMB samples were taken from an initially un-aged GMB and have been exposed since 1997. The third set of GMB samples were taken from 12 different polyethylene GMBs of different thicknesses and resins and have been exposed since 2010. The temperature of the GMBs from different sets was monitored and it was found that: (a) there was no significant difference in the temperatures of the black GMBs regardless the difference in resin and thickness, (b) in Kingston, Canada, the temperature of the black GMB may exceed 70 °C in the summer where the temperature of the white GMB did not exceed 40 °C, and (c) minimum temperature of the GMB in winter may reach -20 °C. Although the GMB (from which the samples of the first set was taken) extensively ruptured in the lagoon during 14 years of service; intact samples taken from the lagoon and aged on the roof were observed to rupture after 12 years exposure on the roof (26 years of aging in total for these samples). This highlights the role of load-demand on the rupture of the GMB. Although the GMB samples in the second set still have a standard OIT (Std-OIT) of ~40 minutes (30% of the initial value) and a HP-OIT of 1200 minutes after being exposed to the elements for 16 years, several severe surface cracks have developed and the stress crack resistance has decreased from ~ 6000 hours to ~ 3000 hours (possibly due to surface aging). Comparing the depletion of the Std-OIT from the GMBs of third set in the second study, it was found that: (a) an increased HP-OIT correlated with a decreased depletion of Std-OIT, (b) thicker GMBs had slower Std-OIT depletion, (c) the depletion of AOs from high density and linear low density polyethylene GMBs depended more on the AO package than the polyethylene resin, and (d) the white GMB had the slowest Std-OIT depletion. The SCR measured for the black GMBs in the third set of samples decreased by 30 to 70% although they still had significant Std-OIT and HP-OIT; in contrast, the stress crack resistance of the white GMB has not decreased over three years of monitoring this GMB. The results of these studies highlight the challenges of assessing the EOL of a GMB and the need to better understand the different factors that may affect the time to GMB rupture.



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### **6.8 Overview**

Few participants addressed the immediate topic of developing an integrated testing protocol to assess remaining service life. Several addressed the need for durability in specific applications and several addressed different individual test methods that might be used as a part of an overall protocol but few addressed the integration of a number of tests. For instance, stress crack resistance test methods, and the data they generated were discussed but there was no discussion on how these data would or could be used to define a remaining service life. Nevertheless, it was interesting to see how the various experts interpreted the topic and the depth of their knowledge of HDPE GMBs.

## **7.0 MORNING DISCUSSION SESSION**

### **7.1 Ian Peggs: General introduction**

In his general introduction to the workshop, Ian Peggs identified what he expected would be some of the more lively topics of discussion. These included:

- Confirming the “natural” mode of failure of an exposed HDPE geomembrane at the end of its service life, assuming no negative mechanical, physical, and chemical agencies were acting upon it.
- How to describe a practical EoL so that the “natural” mode of failure does not occur.
- Identify parameters and test methods that allow for a practical EoL to be determined.
- Giving owners and engineers confidence that a geomembrane’s end of life is approaching, but that there is still has time to repair/replace the liner so that failure does not occur.
- Identify research that is needed to provide data that is presently not available to determine EoL.

### **7.2 Mike Sadlier asked:**

“What is the function of a GMB in a specific project and how is the GMB used?” EoL could be seen as “end of function”. In most projects it is difficult to cut large samples. Only small samples can be taken. On these samples only OIT measurements can be made. Therefore tensile tests and NCTL tests are not done. It is difficult to find archived samples (baseline samples). Such samples should be stored in a controlled climate without stress and unaged. Samples from anchor trenches are often used as the best baseline samples available in a project. Old and new HDPE GMBs have different formulations. New HDPE GMBs have ‘enhanced’ performances. OIT or HP-OIT is not always appropriate. The exposure of a GMB can be very different. The GMB can be exposed to UV or to chemicals. Even at the same site a GMB may have different locations with other exposures.

### **7.3 John Cowland mentioned, that**

... different project owners tolerate and accept differential leakage rates. For prevention of water ingress into an earthen dam suffering piping problems, zero leakage might be insisted



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upon. For solid waste landfills with double GMB layers, the leakage rates resulting from up to 15 defects per hectare in one layer might be accepted. How can an all-encompassing EoL be defined if some projects can tolerate more leakage than others?"

GMB in floating covers for wastewater are designed to withstand mechanical stresses at the anchor trenches. Various (hazardous) chemicals (cyanide and caustic soda in gold mining, sulphuric acid in copper and nickel mining, caustic soda in processing of alumina) are used in the mining industry and operating temperature has been increased from 30°C to 60°C in some mines. Laboratory tests are often carried out at 20°C but in mining projects the temperatures are higher! Scratches on the surfaces of a GMB can reduce service life. Joints and connections of GMB to rigid structures can overstress a GMB.

Testing protocol is needed to be tailored to the function of the GMB containment.

### **7.4 Daniel Tan stated, that**

... most studies are made with GMB with thicknesses of 1 mm and thicker. Thin GMB with thicknesses of 0.5 mm and 0.75 mm are not studied regarding durability. There is a need for research on thin GMBs. The highest depletion of stabilizers (in other words: lowest remaining OIT) is at the crest. The AO depletion rate is significantly higher for thin GMBs. The increase is exponential. In tropical areas the washing off of dust accelerates the aging of GMB compared with arid regions. Dust can act as a protector of a GMB against UV-aging.

Periodical testing of OIT, HP-OIT, tensile properties and SCR at facilities across the world is recommended.

### **7.5 Vera Olischläger noticed, that**

... the meaning of the thickness for the lifetime of GMB shall be studied. Research is needed for GMB thicker than 1.5 mm.

### **7.6 Sebastian Hausmann proposed, that**

EoL of exposed GMB could be defined as the time when mechanical properties start to change, when OIT is 'zero' or in high-pressure autoclave test (HPAT) at the onset of oxygen pressure decrease – in other words, when the polymer starts to degrade.

### **7.7 Helmut Zanzinger required, that**

...for the evaluation of the surficial aging of exposed GMBs, the unexposed GMB surface shall be notched in notched constant tensile load (NCTL) tests or in accelerated NCTL (ANCTL) tests. Failure times at different stresses, other than 30% of yield stress, should be determined in NCTL tests. NCTL tests at temperatures other than 50°C would be of interest. In a certain depth of a GMB stabilizers are not completely consumed as it could be the case at the exposed surface. Inside the GMB the polymer could still be protected from aging and



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the original reference curves of SCR tests are kept valid for the deeper section in the exposed GMB.

### **7.8 Jose Munoz informed, that**

... the SCR of HDPE GMB is good for resins with low density and wide molecular weight distribution.

### **7.9 Robert Kienzl observed, that**

... cracks occur preferably near extrusion welds. They are found after 15 to 25 years in service on GMB installed in the late 1980s. Three-mm-thick HDPE concrete protection liners (CPL) showed no failures after 10 years in service as containment of landfill waste water.

### **7.10 Fred Gassner believes, that**

... EoL depends on the functional intent of the liner. He experienced long cracks next to weld due to heating effects. SC may occur due to wind load and thermal cycling effects above water line in ponds but pond may still function to hold liquid. There are stress concentrations by seams. Therefore, research on SCR of seams is necessary.

*Editor's Note:* Later on it became clear that other design engineers made the experience that is often very difficult taking even small samples from the side or it is not even allowed by the owner to take any sample, because it is the client's desire to keep the facility operational. And exposure coupons are much rarer than they should be in the real world.

### **7.11 Mauricio Ossa found, that**

... white surface of a GMB reduces the temperature differential to minimize wrinkles and AO depletion of white GMBs is lower than of black GMBs.

### **7.12 Anna M. Noval showed, that**

... the performance of a 1.5 mm thick HDPE GMB in San Isidro reservoir, Gran Canary Island, has been shown for water tightness after 22 years – even when OIT decreases, CI increases and the retained mechanical properties are around 70 to 75% of the original mechanical properties.

### **7.13 Catrin Tarnowski realized, that**

... there are different perspectives and challenges of project owners, designers, manufacturers and installers. Different protocols are needed for different formulations/products and for different applications/projects and for different aging and for different installations. Which information on the formulation can be made available? Which are the relevant properties (OIT, NCTL, carbonyl index (CI), performance of welds) to be monitored? Are the current test procedures adequate? These tests should focus on



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remaining service life. Should we do tensile creep tests, stress relaxation tests and the old impact strength tests? Is there information available on the product in its initial stage?

Such information should be stored together with retained samples for future projects. We have to define the needed relevant information for future evaluations of exposed GMBs. Such application related information includes:

- external forces at critical point of the application
- amount of UV-radiation
- average temperature and peak temperature
- bearing layer influence
- chemical influence
- leaching by contained water or rain
- wind actions or even uplift in connection with lying flat
- quality of welding works
- points of possible stress concentrations of the above
- AND: Can samples be retrieved at critical areas?

The best practice (design, product, installation, quality control / quality assurance (QC/QA) and allowance for monitoring) for an exposed application of a GMB should be described and respected by all involved parties of a project.

### **7.14 Ian Peggs remarks, that**

... SC occurs after a certain degree of oxidation. The major concern is on bulk performance vs. surface performance. The OIT is to be measured on the surface, but how thick is the “surface” to be tested? The SCR notch must not penetrate the surface layer. Should SCR tests be made on un-notched specimens? Could trial tests be made on thin films? Most failures occur as a result of SC at extrusion seams. A simple approach for EoL would be a first appearance of stress cracks.

### **7.15 Werner Müller stated, that**

... exposed GMBs are always affected by some kind of mechanical stress. Exposed GMBs will fail in the long run by stress cracking primarily located at seams. Ductile failure always indicates errors in design or installation or it may be triggered by accidents or disasters. Oxidative degradation will strongly reduce SCR. Even high SCR GMBs will finally become susceptible to SC triggered by oxidative degradation. A protocol has to refer to the state of oxidative degradation. The lifetimes of buried GMBs are very long as AO depletion process is extremely slow. Exposed GMBs degrade faster due to UV-radiation and additionally by the input of solar heat radiation primarily in a small surface layer. Oxidation starts at “oxidation spots” in the surface. SC are initiated at those spots. Once initiated they will propagate through the intact bulk material within years (depending in field site conditions). OIT over thickness should be measured. Survey of any indication of crack formation at



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seams is necessary. An evaluation of the change of the SCR is needed by determining the whole curve. Get also the information about type and amount of AO, measure the Std-OIT profiles through the thickness of the GMB and evaluate these profiles.

### **7.16 Marcus Grob noted, that**

... OIT and even HP-OIT measurements are far away from real thermal stresses on GMBs. OIT is measured in the liquid/molten state but the final application is in the solid state. In a molten state thermal/processing history has been cancelled, mobility of the stabilizers is much too high, solubility of the stabilizers strongly influenced by the temperature, volatility of the stabilizers is different, inhomogeneity of the stabilizers in the polymer (crystalline regions/amorphous regions) are not considered and reactions in a solid phase or in a highly viscous liquid with a gas depend on the diffusion of the gas/partial pressure of the gas. OIT depends strongly on the sample preparation, surface to volume ratio. Different stabilizers show different activity at the OIT testing temperatures. OIT depends not only from the polymer and the stabilizers but also on the rest of the formulation (fillers, pigments, antacids), but reactivity is not linear at the end-use conditions and at OIT temperature. Failure criterion for HAS or for phenol could create completely different EoL. Accelerated aging should be done under similar conditions as the final application (e.g. extractive, light exposed), with the same concentration as in the final application, at not too elevated temperatures to have similar degradation patterns, with a well-defined EoL criterion and the disadvantage is: It is time consuming.

### **7.17 Amr Ewais reported, that**

...50% retained strength and 50% retained elongation are not the appropriate failure criterion for an exposed GMB. The presence of high OIT values does not necessary mean that the GMB is resistant against chemical oxidative degradation. The surface of a GMB may degrade before the core increasing the susceptibility of the GMB to SC. GMB resistance is significantly affected by the morphological changes that take place in the GMB decreasing its SCR before AO depletion or chemical degradation has occurred.

### **7.18 Overview**

It very quickly became apparent that the definition of a single EoL would be very difficult if not impossible. A general definition such as “when the GMB ceases to perform its design function” moves us no further forward. Since the function of the liner is containment, one could argue that the first appearance of a leak is EoL. However, leaks can be repaired and allowable leakage rates (ALR) are specified in several projects to accommodate some leakage that will not further damage the subgrade or the lining system.

One could argue that the first appearance of a stress crack (the mode of ultimate failure) on an exposed slope could be EoL. But cracks on a slope do not mean there are cracks under the liquid level that are leaking.



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When the leakage rate reaches the ALR could also be considered the EoL, but repairs can be made to extend service life. However, if repairs do not reduce leakage below the ALR, that too could be defined as EoL.

To further complicate the issue, most liner failures are initiated at seams that have been overheated, suffered overgrind, or were improperly applied, and which have little to do with the degradation rate of the GMB material itself.

It therefore appears that EoL could consist of two components. The basic component would be for liner material degradation processes and based on first cracking, first in-service leak, critical OIT, etc. The second component would be a modification for the specific application of the liner and seaming quality, etc.

To counter the complexity of a definition of EoL it was expected that if the physical-chemical environment did not significantly change while the liner was in service, it would not matter, for instance, what the relative contributions of chemistry, temperature, and UV exposure would be to the oxidation degradation rate, all that would be required would be a measure of the extent of oxidation. Thus, there would be no need for complex considerations of environmental parameters. Detailed knowledge of the make-up of the environment would not be necessary.

### **8.0 SUMMARY OF MORNING SESSION**

The morning session concluded with the identification of the major topics of concern which were to be addressed in the afternoon. As identified by JP Giroud and Chris Kelsey, they were:

#### **8.1 Definition of EoL**

The morning session of Berlin 2 was dedicated to 17 presentations by workshop participants and a brief session focused on defining EoL and outlining goals for remaining discussion in the day. The DEFINITION AGREED UPON, for the sake of guiding the day's continuing conversation, was: "End of Life is when a GMB is no longer acceptable for its intended fluid containment function as a result of degradation."

ISO/PDTS 13434 describes EoL in the following:

A geosynthetic is intended to perform a particular function for a minimum expected time, called the design life. Impermeability to liquids is the functional property for a geosynthetic barrier.

Assessment of the durability of structures using geosynthetics requires a study of the effects of time on the functional properties. The physical structure of the geosynthetic, the nature of the polymer used, the manufacturing process, the physical and chemical environment, the conditions of storage and installation, and the load supported by the



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GSY are all parameters which govern the durability. The main task is to understand and assess the evolution of the functional properties over the entire design life. This problem is quite complex due to the combination and interaction of numerous parameters present in the soil environment and the lack of well documented experience.

It is necessary to differentiate between the available and required values of a functional property. **Figure 3** is a schematic representation of the evolution of the available property of a material as a function of lifetime, represented by the curves on the graph. The functional property may be a mechanical or a hydraulic property such as tensile strength or permeability. The events that happen between manufacture of the product and the end of product life can be indicated along the time axis. After installation, the operating life of the material starts. Failure implies that the geosynthetic can no longer perform the function for which it is being selected.

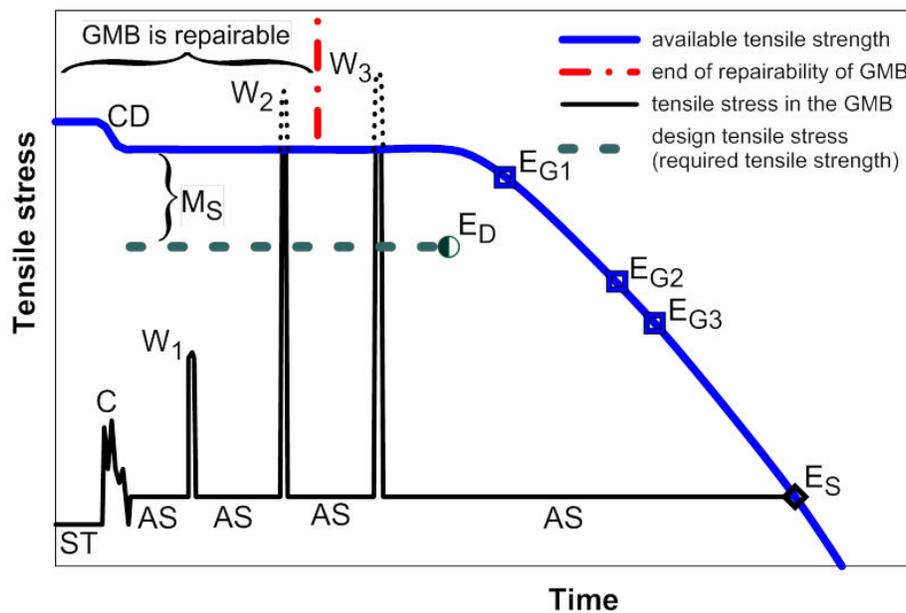


Figure 3. Functional property of an exposed GMB as a function of time (Courtesy: JP Giroud)

ST:	Tensile stress in storage and transportation
C:	Tensile stress during construction
AS:	Actual tensile stress in service without wind
$M_s$ :	Margin of safety
$W_1$ :	Wind less strong than design wind
$W_2$ :	Unforeseen strong wind causing rupture and repair of the geomembrane
$W_3$ :	Unforeseen strong wind causing premature end of service because the geomembrane is not repairable
CD:	Construction damage
$E_D$ :	End of design life
$E_S$ :	End of service life
$E_{G1}, E_{G2}, E_{G3}$ :	End of GMB life (defined by criteria)



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*Editor's note:* As a definition for EoL could not be agreed during the workshop the discussion among the design engineers continued and ended in Figure 3 (above) being developed by JP Giroud in March 2018. It became obvious that we have to distinguish between end of design life, end of service life and end of product life. The later one is project specific and depends and the criteria applied, because some projects may tolerate more leakage than others.

Prediction for EoL is described by Greenwood et al. (2012):

EoL prediction can be based on experience, on the extrapolation of measured properties, or on tests intended to simulate the whole lifetime of a GSY by accelerated testing. Experience is simply not available for the long design life expected of GSY. Measurements have to be made for at least ten to twenty years in order to detect with sufficient accuracy the changes that will lead to failure after more than a century. Many processes occur non-linearly, showing little evidence of change in their early stages and then reaching a threshold where degradation sets in emphatically. In others one process of degradation follows another. Life prediction is not as simple as measuring the progressive wear of a car tire to determine when it will need replacement.

"End of life" is a more appropriate description than failure. EoL depends on the function for which the geosynthetic has been chosen. The function determines the end of life.

To make a numerical life prediction, the end of life has to be defined as a number. Vague general statements are not sufficient. Examples of a quantitative and measurable criterion are as follows:

- 50% reduction in strength,
- increase (e.g., 10%) in permeability,
- visible holes in a GMB, whether the GMB is a single or double liner or a composite, in which case the quality of contact between the GMB and the underlying mineral liner has to be considered or whether the leachate source is persistent, leachate head, and the chemical nature of the leachate and the sensitivity of the site to groundwater quality.

Thus the end of life criterion can vary from one site to the next. Lifetime of a geosynthetic, as defined by its end of life criterion, is greater than its design life. In other words, the geosynthetic will continue to do its job.

### **8.2 Prediction of remaining service life on the basis of control or reference samples**

The use of control samples is a GOOD SOLUTION, but control samples from the identical batch are hardly available.



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The use of unexposed samples from the same site as reference samples is the SIMPELEST SOLUTION but it has many uncertainties:

- Samples from a weld are very small.
- Samples from an anchor trench might be damaged during installation.
- Often only OIT can be determined, but mechanical properties would be interesting.
- “Unexposed” samples from a site are also aged to a certain extent.

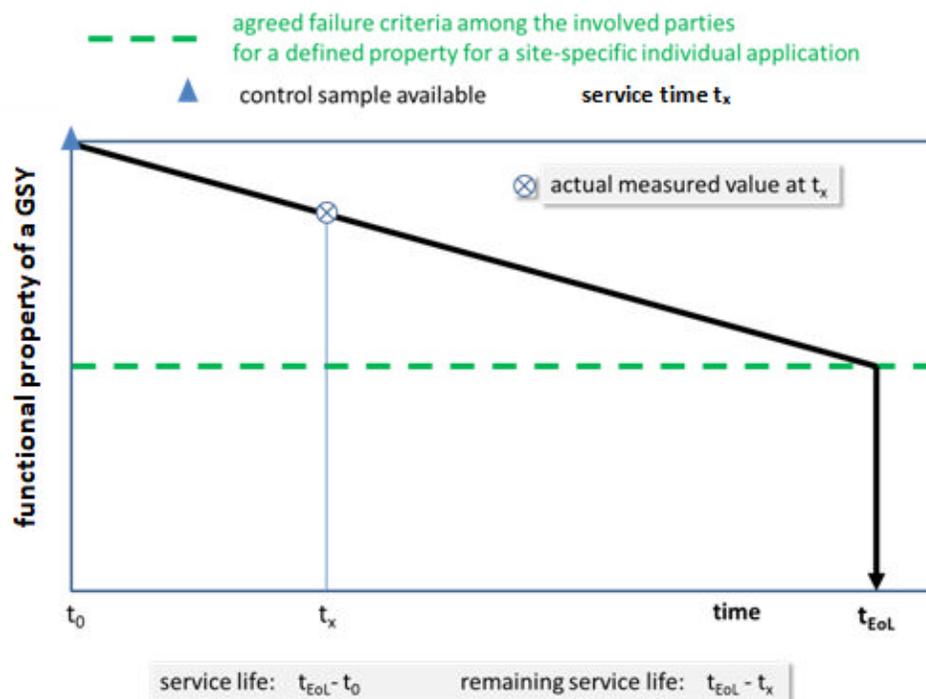


Figure 4. Prediction of EoL based on “unaged” control samples

Evaluation should be better based on two ways:

- Periodic short-term tests on samples from the site in a monitoring program. This is the best way to predict the remaining service life.
- The second best solution might be accelerated tests in the laboratory on samples from the site, to determine the remaining service life for which a modeling for lifetime prediction is necessary. (NOTE: Not all attendees are in agreement about the utility of accelerating testing for creating an EoL protocol.)



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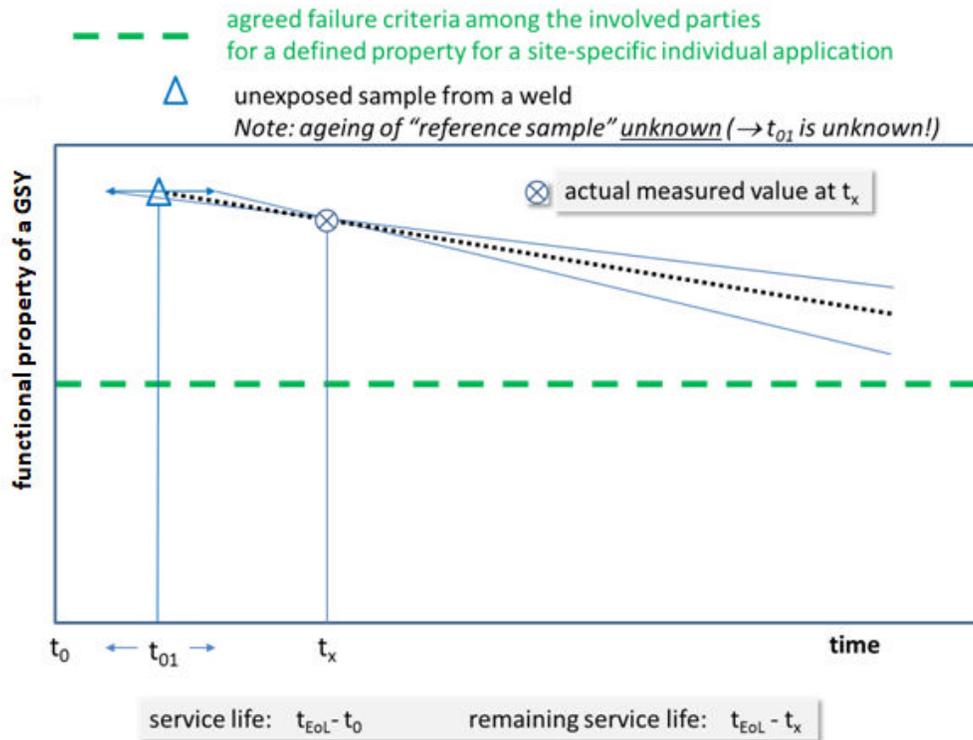


Figure 5. Prediction of EoL based on unexposed samples from the site

### 8.3 Sampling for monitoring of samples exposed under real site conditions

The use of samples from periodic sampling during a monitoring program is the BEST SOLUTION but monitoring programs are rarely installed – only owners of huge projects run monitoring programs from time to time.

Where and how to take on-site samples is a matter of debate. Buried liner at the top of an installation, for example, may be more representative of the virgin liner than an archived sample (as there are no standard controls on storage of archived material). Sampling from first and last installed panel may smartly assess any change in materials from beginning to end of delivery on large projects.



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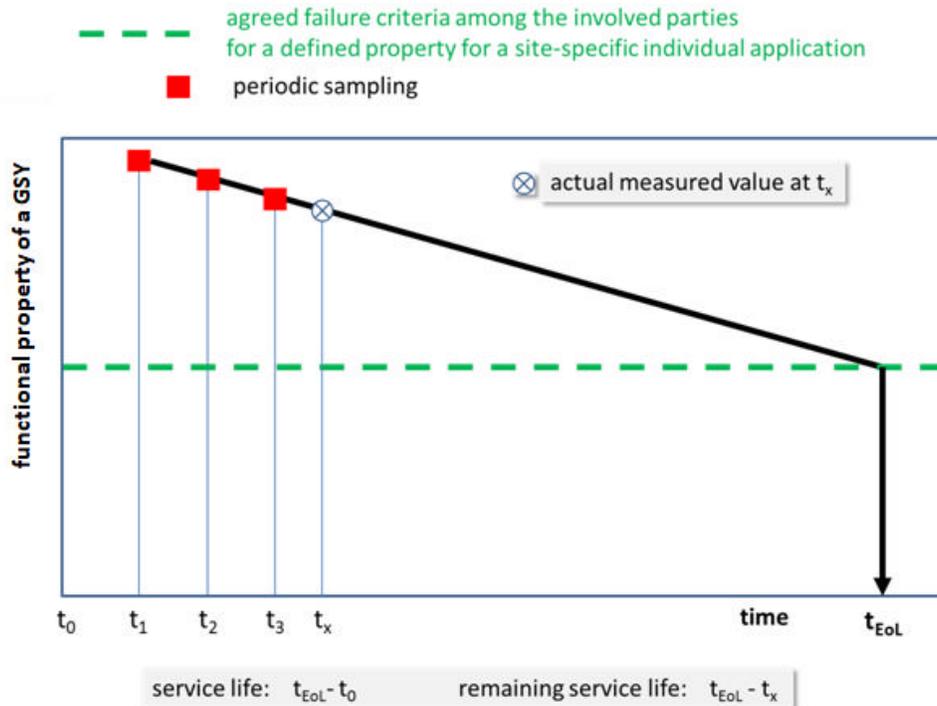


Figure 6. Prediction of EoL based on periodic monitoring

Some sites will deteriorate much faster than others due to the type of liquid contained and the on-site environmental conditions, etc.

- All influences of a specific project are involved.  
Changes in the monitored/measured properties can be detected.
- From where to take the samples?  
From the most critical location in a site?
- From welded seams?
- Which tests shall be performed?
- Which sample sizes are needed?
- Which reference values shall be used?
- Where and how shall reference samples be stored?
- Which sampling frequencies?
- Which failure criteria?
- Monitoring programs have to be prepared parallel with the installation of the GMB.  
The monitoring programs shall run as long as the intended lifetime of the GMB.



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## 8.4 Simulation of remaining service life using accelerated aging tests

IF neither control samples nor “unexposed site samples” nor “periodic samples” are available, accelerated tests in the lab on samples from the field might be considered for use as an ALTERNATIVE SOLUTION to EoL prediction.

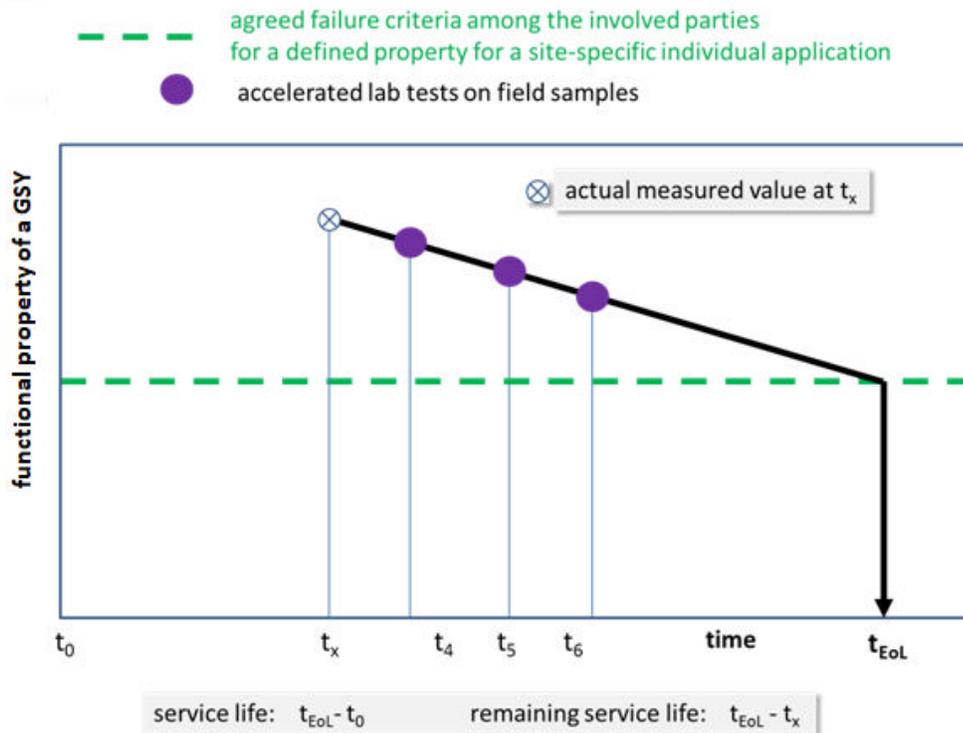


Figure 7. Prediction of EoL based on accelerated tests in the lab

However, workshop participants were not in agreement on whether this would be practical. Consider: Should an accelerated aging test be conducted on a 20-year-old liner still in service? More discussion is needed here, but laboratory work in this area is worth visiting.

As such, IF aging tests shall be performed, they should be performed under defined accelerated conditions with the real media from the specific project simulating singular aging processes or simulating combinations of different aging tests one after the other. The test parameters for each single aging test must to be considered and the project specifically defined.



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### 8.3.1 Oxidation resistance tests in oven

Test temperature, test duration, fresh air exchange, circulation of air, position of specimen

### 8.3.2 Chemical resistance tests

Test temperature, test duration, media exchange, pH value, stress, circulation/stirring, position of specimen

### 8.3.3 Leaching resistance tests in water

Temperature, test duration, water exchange, pH value, circulation/stirring, position of specimen

### 8.3.4 HPAT

Test temperature, oxygen pressure, duration, water exchange, stirring, pH value

### 8.3.5 Weathering resistance tests

Xenon arc or Fluorescent weatherometer (spectrum of light), black standard test temperature, rain simulation or condensation, cycles, UV doses: Stress cracking resistance tests

### 8.3.6 Stress cracking resistance tests

Full NCTL/SP-NCTL, full ANCTL/SP-ANCTL (with testing even at different temperatures)

*NOTE: Notching of unexposed surface, as the aged surface shall be included in the evaluation.*

*NOTE: Some research indicates which side is notched (exposed or non-exposed) is less relevant than the integrity of the sample. Scratches on a specimen surface can greatly affect the test. Microscopic evaluation of scratches might be required to assess a scratch pattern indicative of a mechanism of failure; it was also pointed out that CMD and MD testing can help determine if the “scratch damage” in question was the result of degradation or installation.*

### 8.3.7 Strain Hardening Modulus

*NOTE: Un-notched specimens are tested. Aged surface of GMB is included.*

## 9.0 POSSIBLE MONITORING TESTS

See **Table 1** on next page for a list of possible monitoring tests and affiliated parameters that might be measured in order to assess the rate of degradation.



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Table 1. Parameters that might be measured in order to assess the rate of degradation

TEST	STANDARD	REMARKS
Tensile Test	ISO 527-3	Yield tensile stress and elongation at yield
		Tensile strength at break and elongation at break
		A “design tensile strength” $T_d$ has to be given in kN/m (force per unit width). Thickness is involved in this consideration, if it is given in kN/m. The thickness of the tested specimen will not be measured. The width of the specimen has to be measured. The basis must be tensile strength at yield for HDPE GMB. Evaluation is based on tensile strength T vs. time (logarithmic scale) log t. What is the tensile stress in kN/m which a GMB can withstand – ignoring whether it is textured or smooth, new or already single-sided partly oxidized?
Std. OIT at temperatures of 180°C and at 210°C, and HP-OIT at 150°C	ISO 11357-6, ASTM D3895 and ASTM D5885	OIT distribution profile through the geomembrane thickness:
		- at the exposed surfaces (e.g. upper 300 μm) of the sample?
		- at the center of the sample?
Oxidation onset temperature (OOT)	ISO 11357-6	- from the entire cross section of the sample?
Stabilizer content (e.g. HPLC, UV/IR-spectroscopy)		
Strain hardening modulus	prEN 17096:2017	Recent research has shown a relationship between the strain hardening modulus determined by uniaxial tensile testing and the SCR of the materials.
Carbonyl Index (CI)	ASTM E334	In plastic pipe, it has been proposed that a CI $\geq 0.10$ is the threshold for SC to be initiated.
Multiaxial tensile test (burst test)	EN 14151, DIN 61551, ASTM D5617	
Water tightness	EN 14150	
Tensile strength of welded seam	DVS 2226-2 and DVS 2226-3	Shear elongation (DVS 2226-2) and peel separation (DVS 2226-3)
Burst strength and elongation of welded seam	DIN 61551	
Impact strength of welded seam	ISO 8256	Impact strength tests can provide much information on the presence of mechanical defects in seams and sheets and their influence on the susceptibility to stress cracking failures, both slow crack growth (SCG) and rapid crack propagation (RCP).
Puncture impact energy	EN 12691	



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## 10.0 J.P. GIROUD'S SUMMARY OF ITEMS DISCUSSED IN MORNING SESSION

NOTE: These summary comments are only in relation to what was discussed *during* the workshop. They are not interpretations of or commentary on any of these issues by Dr. Giroud.

This document, prepared by J.P. Giroud, comprises two parts.

The first part, presented at the end of the morning session, summarizes the various items mentioned in the presentations made in the morning session.

The second part, presented at the end of the afternoon session, summarizes the various discussions topics addressed in the afternoon session.

1

## Part 1

### SUMMARY OF ITEMS MENTIONED IN THE MORNING PRESENTATIONS

2

### FOCUS

- Exposed geomembranes only
- Remaining time to end of life of field geomembranes rather than studying virgin materials
- No need to know how oxidation occurred
- Practical goal: providing owner with predicted end of life, so appropriate measures can be taken (noncritical consequences of geomembrane failure are acceptable)

3

### FAILURE MECHANISMS

- Oxidation followed by stress cracking
- At what degree of oxidation will stress cracking occur ?  
(what about stress cracking that occurs due to repeated stresses on extrusion seams a few years after installation? Obviously antioxidants are present in this case.)
- Hydrolysis in addition to oxidation ?

4

### HDPE GEOMEMBRANE

- Variety of HDPE geomembranes
- Variety of stabilizers
- Difference between past and present geomembranes

5

### DEFINITION OF END OF LIFE

- Goal of meeting: agree on definition.
- Definition should depend on application and/or function  
(which may vary depending on location in the liner: e.g. slopes vs bottom, above water level vs below).
- Linked to leakage rate ?
- Onset of polymer degradation ?  
End of functionality ? Functional reserves ?

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## DETERMINATION OF END OF LIFE (continued)

- 50% retained property ? Arbitrary
- Which property ?
- Knowledge of the antioxidant package is necessary to predict end of life.
- Monitor antioxidants on a regular basis.

7

## EXPOSURE CONDITIONS

- Should be precisely described.
- UV radiation is often mentioned, but UV radiation is only a part of solar energy.
- Environment: solar radiation, rain, temperature
- Emptying-filling, wind, temperature variations, surface condition of supporting layer, differential settlement

8

## SAMPLING

- Sample size. Difficult. Do not waste samples.
- Sacrificial geomembrane (also called coupons) may be irrelevant.
- Take samples in delicate areas: seams, wrinkles.

9

## INCUBATION

- Must simulate field conditions.
- How to accelerate ?
- But, incubation irrelevant today because we focus on samples taken from the field.

10

## TESTING

- What tests ? HPAT ? Tensile ? Need better indicator than OIT. Concerns about HP OIT “not good instrument to predict end of life”
- Tests take too much time.
- Correlation between tests
- Notching which side ? Or not notching ?
- What percentage of yield stress in NCTL test ? 30% ? 20% ?

11

## TESTING

(continued)

- SCR tests on un-notched specimens ? Or on melted-solidified plaque ?
- Trial tests on thin films ?
- OIT profile over thickness gives antioxidant profile.
- Defining end of life from OIT profiles
- Mechanical tests: Tensile, Impact, Bending

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### **PARAMETERS**

- **Influence of thickness**  
Influence of density
- **Consequence: report density and thickness, do research on influence of these parameters.**
- **Influence of temperature**

13

### **11.0 AFTERNOON DISCUSSION SESSION**

The afternoon session focused on the question raised in the summary of J.P. Giroud. Much information is needed to ensure a GMB has optimum performance. Research work to be done was described.

#### **11.1 Liner integrity**

A lot of information is needed for a good design of a GMB in any application.

- Raw material
- Additive formulation
- Manufacturing of GMB
- Factory Production Control (FPC)
- Third party control
- Design:
  - Installation
  - Storage
  - Loads (confining pressure, wind loads, thermal stresses, ...)
  - Environment (UV-radiation, chemicals, ...)
  - Ambient temperature
  - Liner Temperature
  - Surrounding soil (particle size, angularity, ...)
  - Protection of GMB (e.g. use of GTX or sand layers)
  - Welding (welding standards, techniques, ...)
  - Anchorage
  - Ballasting
- Construction Quality Control (CQC)
- Construction Quality Assurance (CQA)



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As previously stated, many experts felt that samples of the aged liner should be incubated for accelerated aging tests in order to predict remaining service life. However, as stated in Dr. Giroud’s summary:

“..... incubation is irrelevant today because we focus on samples taken from the field.”

In other words, we focus on the past real world performance and extrapolate to the future and EoL. The intent is not to perform complex incubation and aging prediction tests to determine future degradation rates. EoL is determined by historical performance rather than by laboratory aging tests.”

### 11.2 End of Life

Only a broad definition of EoL was reached. EoL occurs when the GMB fails to perform its required function. However, there was no agreement on what constitutes a “failure” to perform. It was felt there is no single definition based on technical performance that could be applied to any lining system. There was a strong feeling that any definition should consider the structural functions of the site-specific geomembrane and the criticality of the installation. For instance, the contribution of surface texture to stability of the liner on slopes is a factor that impacts the geomembrane’s EoL.

Several people believe the definition of EoL should be based on “ideal” conditions, i.e. ideal design and ideal installation, which, of course, rarely happens. Others believe that in the real world it should be possible to find appropriate parameters that monitor material changes and that can be combined in some way to track the overall degradation rate independently of quality of installation and specific environmental conditions.

The difficulty in settling upon a definition of failure for the field can be seen in one of the example definitions provided to the workshop. It comes from a real litigation case in which the Final Judgment document cited the following:

*“Failure is a condition or state that prevents the liner from fulfilling its intended purpose. Failure of the lining therefore refers to a leak that permits process liquids to contact a concrete tank (in this case) in significant quantities”.*

From the perspective of End of Life and the mechanisms involved in the deterioration and (potential) failure of an exposed HDPE geomembrane, we can immediately observe that this actual “definition” of failure from a real legal document does not consider any aging or use of the geomembrane. It does not consider any “ideal” conditions. Rather, it is entirely focused on leakage—which could be present at the inception of an installation (e.g., design, installation, or operation conditions that are not ideal). Also, how do we interpret “significant” quantities? Certainly, it is useful word: significant means in quantities that have such an impact on the considered project that service is interrupted. Still, this definition is far too inexact to move the field towards a useful EoL definition.



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### 11.3 Testing

The tests considered relevant for assessing time to EoL include SCR (possibly un-notched specimens), OIT including stabilizer profiles through the thickness of the liner, HP-OIT when HAS are in the stabilizer package, and carbonyl index (CI). However, applicability of CI was seriously questioned. This may be because it is a surface layer property while most other tests are full thickness properties - but a surface layer property may be what we need most.

Regarding SCR, un-notched specimen tests seem to be very important here. Yet, a test with a specimen notched on the *non*-exposed side may be useful—if failure occurs from the exposed face. Such an occurrence would indicate that the exposed face is in critical condition.

If the end of life is to be characterized by onset of stress cracking, the test specimen must not be notched on the exposed side. Test with an un-notched specimen must be run. A test with a specimen notched on the non-exposed side may be useful if failure occurs from the exposed face: this would indicate that the exposed face is in critical condition.

Standard mechanical tests are relevant, but can require large samples (e.g. multiaxial tensile tests). The question of the introduction of impact testing that can reflect surface conditions and such as has been used to introduce and study RCP cracks in HDPE pipe was raised.

Further physical tests of interest are melt flow rate (MFR), density, and discoloration. Basic physical characteristics that should be reported to describe the GMB are thickness, additives and whether the material is smooth, textured, or structured.

### 11.4 Sampling Frequency

A constant frequency of monitoring such as every 5 years for “ordinary” projects and every 2 years for critical containment projects was suggested.

### 11.5 Sampling Location

Tests could be performed on samples from all relevant locations such as on slopes above and below liquid level, at the waterline, at the crest of slopes, on the floor, and at the anchor trench. However, this is not a research program. Therefore, samples should be removed from what is considered to be the most aggressive environment location. Welds must be included.

If as-manufactured archive samples have not been retained and maintained in a cool, dark location the best baseline sample would be from the anchor trench, bearing in mind that installation damage can negatively influence parameters such as impact resistance and tensile elongation at break.



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### 12.0 OVERALL RESEARCH WORK TO BE DONE

Topics and areas of general research required to provide data to help development of a protocol to determine EoL are as follows:

- Is the 3-stage model relevant for exposed GMB?
  - If we agree that onset of cracking is the criterion, then 2-stage model is right.
- Lifetime of GMB in mining
  - High temperatures (up to 60°C)
  - Aggressive chemicals:
    - Cyanide and caustic soda
    - Sulphuric acid
- Relevance of thickness of a GMB on durability  
(need of research on the service life of GMB with various thicknesses)
  - In which condition can a thicker GMB compensate the oxidation in the surface?  
Is the AO package of a thinner GMB ( $\leq 1.5$  mm) consumed earlier than the identical AO package and concentration of a thicker GMB ( $> 2$  mm)? (For the applications cited in the workshop's discussions and the sensitivity of EoL in these applications, it's likely that geomembranes  $< 1.5$  mm are not relevant to this EoL protocol and not to be encouraged in these applications.)
  - Will SC in a thicker GMB occur later than in a thin GMB?
  - Can a thicker GMB withstand higher external loads than thinner GMB?
  - What is the minimum thickness of a GMB for a specific application?
  - Does the thickness represent a "factor of safety"?
  - Can a thicker GMB compensate mistakes in the installation better?
  - Can scratches in a thicker GMB be tolerated rather than scratches in a thin GMB?
  - Do thicker GMBs provide a wider "temperature window" for welding?
  - Is the welding of thicker GMBs easier?
  - Do thin GMBs have to be welded in a factory to panels and only thick GMBs can be welded on site?
- What are the relevant tests for the evaluation of EoL? And how is EoL to be defined?
- Lifetime of welded seams
  - Cyclic loading of GMB to simulate wind loads?
  - Tensile creep?
  - Stress relaxation?
  - Impact strength?
  - SCR of seams?
- Accelerated aging tests—if they are to be considered—on samples from the field:
  - under similar conditions as in the field (e.g. extractive media, light exposed ...)
  - with the same concentration as in the field
  - at not too elevated temperatures, to have similar degradation patterns
  - with a well-defined EoL criterion



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- Evaluation of GMB based on OIT-measurements:
  - From where should a specimen be taken from a sample?
  - How shall the specimen be prepared?
  - Check OIT profile over thickness.
  - OIT can give only an indication but for many AO the OIT test temperature are unrealistic and then the OIT measurement may be irrelevant.
- Where are the critical locations to be monitored?
  - Near extrusion welds?
  - Near overheated areas?
- Which test data are necessary for the evaluation?
  - Full NCTL curve?
  - NCTL curve for different temperatures?
  - Notching of the aged side of the GMB or the opposite side?
- Data base from periodically testing at facilities across the world
- Development of function-tailored testing protocols
- Service life of joints between GMB and rigid structures (concrete, metal and plastics)
- Effects of colored GMB on temperature in the GMB (thermo-oxidative aging, thermal expansion effects)
- Relevance of density to SCR
- Development of failure criteria for phenol stabilized GMB
  - Phenol stabilized materials show no change in strength or elongation for a long time and then mechanical properties drop rapidly.
- Development of a failure criteria for HAS-stabilized GMB
  - HAS show a steady loss in strength or elongation.

### 13.0 J.P. GIROUD'S SUMMARY OF ITEMS DISCUSSED IN AFTERNOON SESSION

NOTE: These summary comments are only in relation to what was discussed *during* the workshop. They are not interpretations of or commentary on any of these issues by Dr. Giroud.

#### Part 2

#### SUMMARY OF AFTERNOON DISCUSSIONS

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#### END OF LIFE

- We agreed on some of the items to be included in a definition (details to be provided separately).
- We may amend the definition to include structural functions of the geomembrane (e.g. contribution of geomembrane surface roughness to liner system stability on slopes).
- The definition and resulting protocol are based on "ideal conditions" (ideal design and ideal installation).

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## TESTING

- Un-notched CTRL, OIT profile, carbonyl index
- HP OIT: many questions, difficult to interpret, but good test for HAS
- Mechanical tests: yes, but problem because large specimens needed, especially for multiaxial
- Recommended mechanical tests: tensile, impact, multiaxial

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## TESTING

*(continued)*

- Recommended physical tests / evaluations: discoloration, melt flow rate (but thickness change considered not relevant)
- Characteristics to be reported for identification: thickness, smooth/textured

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## PERIODICITY OF SAMPLING AND TESTING

- Constant frequency recommended
- 5 years for ordinary projects
- Greater frequency (e.g. 2 years) for critical situations

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## SAMPLING LOCATION

- Perform tests on coupons located at all relevant locations (e.g. above and under liquid level, on crest / anchor trench / slope / bottom).
- Include welds in sampling/testing.
- Keep archived samples stored in a cool, dark place.

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## FUTURE WORKSHOPS

- The results of the Berlin 2 Workshop should be evaluated for applicable extension to other geomembrane types and amended, as needed, for those types.
- Workshops could be organized for other geomembrane types.

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### 14.0 SPECIFIC ACTION ITEMS

At the end of the day the four topics that clearly needed additional work and discussion were as follows as agreed by all attendees:

- **Better definition(s) of End of Life.** Can there be one overarching definition but with secondary definitions depending on application, if necessary? Without question, the field needs something other than “half-life” to work with.



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- **Comparisons of bulk OIT and surface layer OIT** (or distribution of OIT from one surface to the other).
- **Relevance of OIT, CI and impact testing** to determination of EoL.
- **Stress cracking resistance and location of notch, or whether to notch**

It is hoped that all participants, and others in the field, will continue to consider these items and to include them in research projects and in forensic investigations.

### **15.0 WORKSHOP SUMMARY**

A one-day workshop of international experts was held on 26 September 2014, in Berlin, Germany to discuss the development of a protocol to determine the End of Life (e.g., the remaining service life) of an already installed HDPE GMB liner. These technical notes provide an overview of the discussions.

While all agreed that a half-life of some mechanical property should be improved upon there was no description of EoL that was generated other than “when the liner fails to perform its intended function” which, by default, implies that each lined facility has its own EoL. In this, the meaning of EoL was most closely agreed upon as the “end of a functional service life.” Service life and EoL, however, are not thought to be interchangeable terms.

The objective of trying to identify the threshold for an unacceptable degraded condition of an exposed HDPE GMB, was far from achieved. An important point made at the meeting was that the end of life is site specific and is based on continuation of same exposure conditions. In other words, history was considered essential. However, a few research topics that would go some way to achieving this objective were proposed.

The complete workshop was videotaped and audio recorded.

### **16.0 ACKNOWLEDGEMENTS**

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- The BAM Institute for recording the workshop.
- The BAM Institute for coffee breaks and lunch.
- J.P. Giroud for acting as Facilitator (and as a reviewer of this report).
- Elizabeth Peggs and Chris Kelsey for arrangements before, during, and after the workshop.
- All the participants.



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### **17.0 DOCUMENTATION**

The following documents and media are available from the workshop:

- Presenter abstracts (~400 words) from (list names and titles). [Contact Geosynthetica](#)
- Extended abstracts from (list names and titles). [Contact Geosynthetica](#)

### **RECOMMENDED READING**

John H. Greenwood, Hartmut F. Schroeder, Wim Voskamp (2012). *Durability of Geosynthetics*, CUR Building & Infrastructure Report 243

Hsuan, Y. G. and Koerner, R. M. (1998). *Antioxidant depletion lifetime in high density polyethylene geomembranes*. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(6), 532–541.

ISO/TS 13434. Geosynthetics -- Guidelines for the assessment of durability