



NOTE TECHNIQUE

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OBJET :	Durée de vie des géomembranes en PEHD et garantie du manufacturier
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1. MISE EN CONTEXTE

Il est important de ne pas confondre la garantie offerte par le manufacturier de la géomembrane en PEHD par rapport à la durée de vie réelle de ce type de géomembrane une fois en service. Les manufacturiers de géomembrane en polyéthylène ont l'habitude de fournir une garantie de fabrication de 20 ans. Cette garantie est d'ailleurs demandée pour le lieu d'enfouissement technique (LET) de Sainte-Sophie.

Le document *GSI White Paper #9* du Geosynthetic Institute (GSI) joint en annexe explique la provenance de cette garantie de fabrication de 20 ans et la raison pour laquelle le GSI l'a enlevée de ses exigences depuis le 10 juillet 2006.

Pour le LET de Sainte-Sophie, la fourniture de cette garantie est tout de même demandée pour chacune des phases de travaux d'imperméabilisation par rigueur. Cette garantie ne touche que le matériau en lui-même pour garantir qu'il respecte les exigences spécifiées au devis technique. Le manufacturier n'a aucun contrôle sur l'usage final et la mise en place de la géomembrane. De plus, aucune compagnie d'assurance ne peut endosser une garantie sur plusieurs centaines d'années.

La responsabilité de spécifier une géomembrane permettant de respecter les objectifs de performance à long terme incombe à l'ingénieur en se basant sur la recherche scientifique disponible dans la littérature, le tout en conformité avec les réglementations en vigueur.

Un autre point important à considérer est le contrôle d'assurance qualité de la géomembrane qui est effectuée en respect aux normes du Geosynthetic Institute GRI GM #13 et #17 qui recommandent les méthodes, propriétés et fréquences de contrôle à respecter pour ce type de produit. Cette méthodologie est utilisée pratiquement partout sur le continent nord-américain et dans plusieurs pays européens.

La performance globale d'un système d'imperméabilisation mise de plus sur la redondance des géomembranes en incluant deux systèmes d'imperméabilisation, le second étant composite associant une géomembrane PEHD avec un géocomposite bentonitique, la bentonite étant une argile naturelle hautement imperméable. Ces deux systèmes sont supportés par des systèmes de drainage performant qui permettent une évacuation rapide des eaux de lixiviation, évitant ainsi leur accumulation sur les géomembranes.

Au total, le système multicouche d'imperméabilisation inclut donc cinq géosynthétiques, dont deux niveaux de géomembrane PEHD 1,5 mm d'épaisseur et un géocomposite bentonitique pour assurer la protection de l'environnement. De plus, une protection supplémentaire est mise en place lors du recouvrement final progressif du lieu d'enfouissement avec la mise en place d'une géomembrane supplémentaire pour limiter, à la source, l'infiltration des eaux et la production de lixiviat.

2. DURÉE DE VIE EN SERVICE DES GÉOMEMBRANES EN PEHD

La géomembrane en polyéthylène est utilisée depuis plus de 40 ans dans des lieux d'enfouissement et sa pérennité est validée notamment par ces organismes reconnus : l'EPA (Environmental Protection Agency) et le GRI (Geosynthetic Research Institute).

Par sa résistance chimique reconnue, de tous les types de membrane disponibles, la géomembrane en PEHD est de loin celle qui a été le plus utilisée, entre autres pour l'enfouissement de matières résiduelles, mais également dans une multitude d'applications différentes incluant, notamment l'élimination des déchets dangereux et des résidus miniers, l'imperméabilisation des bassins de traitement d'eau, la protection des bassins de confinement secondaire, etc.

La membrane en PEHD est par conséquent celle dont l'utilisation est la mieux documentée et supportée par 40 années d'observation sur le terrain et de recherche scientifique. Sa performance est d'ailleurs reconnue par l'EPA qui recommande spécifiquement l'utilisation d'une géomembrane en PEHD depuis 1991 pour l'imperméabilisation des lieux d'enfouissement de matières résiduelles.

La durée de vie de ce type de membrane est optimisée lors de sa fabrication par l'ajout d'antioxydants spécifiques au polymère. Ces antioxydants permettent d'accroître la durée de vie du système d'imperméabilisation bien au-delà de la période requise pour la stabilisation de l'ensemble des matières enfouies.

Pour une utilisation de confinement, le principal facteur influençant la dégradation d'une géomembrane en PEHD est la température. Cette dernière sera variable dans le temps, s'accroissant durant la période de biodégradation active puis diminuant progressivement pour revenir vers la température usuelle des sols, autour de 10 °C. La température maximale atteinte est fonction de plusieurs paramètres dont le climat local, l'épaisseur de matières résiduelles, la proportion de matières organiques facilement dégradables, etc. Au LET de Sainte-Sophie, en se basant sur des données antérieures jugées sécuritaires, la température maximale atteinte directement sur la membrane est de l'ordre de 25 °C et la température moyenne se situerait sécuritairement entre 20 et 25 °C.

Le document *GRI White Paper #6* du GSI également joint en annexe démontre que pour ces températures moyennes de 20 °C, la demi-vie prévue de la géomembrane non exposée est estimée entre 265 et 446 ans. Il est important de considérer que la demi-vie en service correspond à la période pour que la membrane perde 50 % de certaines de ses propriétés mécaniques, mais la membrane est toujours en place et fonctionnelle. De plus, les températures affectant la membrane inférieure sont moindres que celles sur le niveau de protection supérieure, ajoutant à la sécurité du système.



Nous espérons le tout à votre entière satisfaction et nous vous prions d'agr er, Monsieur,
l'expression de nos sentiments les meilleurs.

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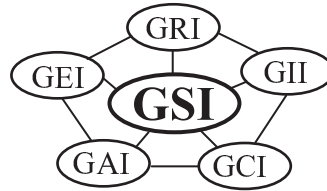
p. j. Annexes A et B



ANNEXE A
DOCUMENT « GSI WHITE PAPER #9 »
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GRI White Paper #9

On the Topic of Geomembrane Warranties

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July 10, 2006

GSI White Paper #9

On the Topic of Geomembrane Warranties

Introduction

GSI began its research efforts on geomembrane durability and lifetime prediction in 1985 and it cumulated in a lifetime prediction of 450-years for a soil or waste covered HDPE geomembrane (see GSI White Paper #6). In 1995 we began our efforts in developing and writing generic specifications. In this regard the following specifications are the topic of this White Paper.

- GRI-GM13 Specification for HDPE Geomembranes
- GRI-GM17 Specification for LLDPE Geomembranes
- GRI-GM18 Specification for fPP Geomembranes
- GRI-GM21 Specification for EPDM Geomembranes

All of the above specifications contained a suggested warranty for 5-years duration. This White Paper attempts to explain why the warranties appeared in the specifications in the first place, as well as why they have been removed as of July 10, 2006.

Background

Geomembranes are certainly related to, and have somewhat followed, the use of polymeric waterproofing membranes in the roofing industry; particularly flat roofs on commercial and industrial buildings. The roofing industry has given a 20-year warranty for its products for many years. It should be recognized however, that roofing membranes are either fully exposed to sunlight and high temperatures, or covered with a thin layer of gravel or light paving material. Thus, ultraviolet light and/or extremely high temperatures are always present. If, and when, degradation of a roofing membrane occurs, repairs or replacement material can usually be readily made. Thus, a 20-year material warranty is considered worthwhile since the field lifetime of roofing membranes

is often challenged within this time frame. In such exposed and generally high temperature roofing environments, lifetime is decidedly shorter than in the buried environments that geomembranes usually are placed without UV exposure and typically at 20°C temperatures or lower. Obviously, the exposed conditions are in drastic contrast to covered geomembranes when 450-years of halflife are anticipated. As a result, a 20-year warranty for a geomembrane is of little value since it only represents 4.4% (20/450) of the anticipated halflife of the material.

Wasteful Burden for Manufacturers

With the advent of major geomembrane use in the USA in 1980's, owners and specifiers began requesting 20-year warranties of geomembranes as was the custom for roofing membranes. Yet, to our knowledge there has never been a degradation issue (such as oxidation, hydrolysis, etc.) on covered geomembranes to date. This cannot be said for punctured or torn geomembranes (these are installation issues) or for containment of aggressive liquids as in some surface impoundments (these are chemical compatibility issues).

The implications of a 20-year warranty in the eyes of a geomembrane manufacturer's insurance company is clearly a financial burden due to the required escrowed money that must be sequestered for the 20-year period. Thus, the paradox is readily seen in that funds must be sequestered for an event that will simply never occur within the allocated time frame. It is indeed a financial burden for manufacturers with no benefit to the owners, specifiers, or anyone else involved in the process.

After discussions with the manufacturers' group within GSI it was decided to suggest a warranty on our geomembrane specifications with a 5-year time frame instead of 20-years. This was done on the geomembrane specifications noted in the introduction

(beginning with the HDPE geomembrane specification in 1997) and clearly had the effect of lowering the amount of escrowed funds required of the manufacturers. And yet one must ask, “What does a warranty for 5-years represent for a material with a halflife of 450-years durability prediction”? In short, the entire scenario is foolish at best, and financially wasteful at worst.

An added point bears mentioning and concerns geomembrane installation warranties (in contrast to the material, per se). In this regard it is customary to require a 1-year installation warranty. While this time frame is curious in comparison to the longer material warranty, the entire process of warranties in light of the rigor of manufacturing quality control (MQC), manufacturing quality assurance (MQA), construction quality control (CQC), and construction quality assurance (CQA) is simply an outmoded and useless activity.

GSI's Response

In light of this discussion, GSI has entirely removed its warranties from the four specifications mentioned in the introduction as of July 10, 2006. They were added appendages from the outset and they never provided any realistic added security for the user. In each of the four specifications a note has been added accordingly in the respective revision schedule. Additional discussion on the warranty issue is available from the authors at the following e-mail addresses.

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ANNEXE B
DOCUMENT « GSI WHITE PAPER #6 »
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GRI White Paper #6

- on -

**Geomembrane Lifetime Prediction:
Unexposed and Exposed Conditions**

by

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Geomembrane Lifetime Prediction: Unexposed and Exposed Conditions

1.0 Introduction

Without any hesitation the most frequently asked question we have had over the past thirty years' is "how long will a particular geomembrane last".* The two-part answer to the question, largely depends on whether the geomembrane is covered in a timely manner or left exposed to the site-specific environment. Before starting, however, recognize that the answer to either covered or exposed geomembrane lifetime prediction is neither easy, nor quick, to obtain. Further complicating the answer is the fact that all geomembranes are formulated materials consisting of (at the minimum), (i) the resin from which the name derives, (ii) carbon black or colorants, (iii) short-term processing stabilizers, and (iv) long-term antioxidants. If the formulation changes (particularly the additives), the predicted lifetime will also change. See Table 1 for the most common types of geomembranes and their approximate formulations.

Table 1 - Types of commonly used geomembranes and their approximate formulations
(based on weight percentage)

Type	Resin	Plasticizer	Fillers	Carbon Black	Additives
HDPE	95-98	0	0	2-3	0.25-1
LLDPE	94-96	0	0	2-3	0.25-3
fPP	85-98	0	0-13	2-4	0.25-2
PVC	50-70	25-35	0-10	2-5	2-5
CSPE	40-60	0	40-50	5-10	5-15
EPDM	25-30	0	20-40	20-40	1-5

HDPE = high density polyethylene PVC = polyvinyl chloride (plasticized)
 LLDPE = linear low density polyethylene CSPE = chlorosulfonated polyethylene
 fPP = flexible polypropylene EPDM = ethylene propylene diene terpolymer

* More recently, the same question has arisen but focused on geotextiles, geogrids, geopipe, turf reinforcement mats, fibers of GCLs, etc. This White Paper, however, is focused completely on geomembranes due to the tremendous time and expense of providing such information for all types of geosynthetics.

The possible variations being obvious, one must also address the degradation mechanisms which might occur. They are as follows accompanied by some generalized commentary.

- Ultraviolet Light - This occurs only when the geosynthetic is exposed; it will be the focus of the second part of this communication.
- Oxidation - This occurs in all polymers and is the major mechanism in polyolefins (polyethylene and polypropylene) under all conditions.
- Ozone - This occurs in all polymers that are exposed to the environment. The site-specific environment is critical in this regard.
- Hydrolysis - This is the primary mechanism in polyesters and polyamides.
- Chemical - Can occur in all polymers and can vary from water (least aggressive) to organic solvents (most aggressive).
- Radioactivity - This is not a factor unless the geomembrane is exposed to radioactive materials of sufficiently high intensity to cause chain scission, e.g., high level radioactive waste materials.
- Biological - This is generally not a factor unless biologically sensitive additives (such as low molecular weight plasticizers) are included in the formulation.
- Stress State – This is a complicating factor which is site-specific and should be appropriately modeled in the incubation process but, for long-term testing, is very difficult and expensive to achieve.
- Temperature - Clearly, the higher the temperature the more rapid the degradation of all of the above mechanisms; temperature is critical to lifetime and furthermore is the key to

time-temperature-superposition which is the basis of the laboratory incubation methods which will be followed.

2.0 Lifetime Prediction: Unexposed Conditions

Lifetime prediction studies at GRI began at Drexel University under U. S. EPA contract from 1991 to 1997 and was continued under GSI consortium funding until ca. 2002. Focus to date has been on HDPE geomembranes placed beneath solid waste landfills due to its common use in this particular challenging application. Incubation of the coupons has been in landfill simulation cells (see Figure 1) maintained at 85, 75, 65 and 55°C. The specific conditions within these cells are oxidation beneath, chemical (water) from above, and the equivalent of 50 m of solid waste mobilizing compressive stress. Results have been forthcoming over the years insofar as three distinct lifetime stages; see Figure 2.

Stage A - Antioxidant Depletion Time

Stage B - Induction Time to the Onset of Degradation

Stage C - Time to Reach 50% Degradation (i.e., the Half-life)

2.1 Stage A - Antioxidant Depletion Time

The dual purposes of antioxidants are to (i) prevent polymer degradation during processing, and (ii) prevent oxidation reactions from taking place during Stage A of service life, respectively. Obviously, there can only be a given amount of antioxidants in any formulation. Once the antioxidants are depleted, additional oxygen diffusing into the geomembrane will begin to attack the polymer chains, leading to subsequent stages as shown in Figure 2. The duration of the antioxidant depletion stage depends on both the type and amount of the various antioxidants, i.e., the precise formulation.

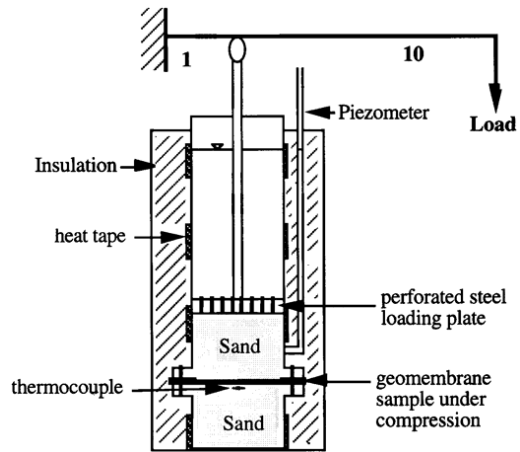


Figure 1. Incubation schematic and photograph of multiple cells maintained at various constant temperatures.

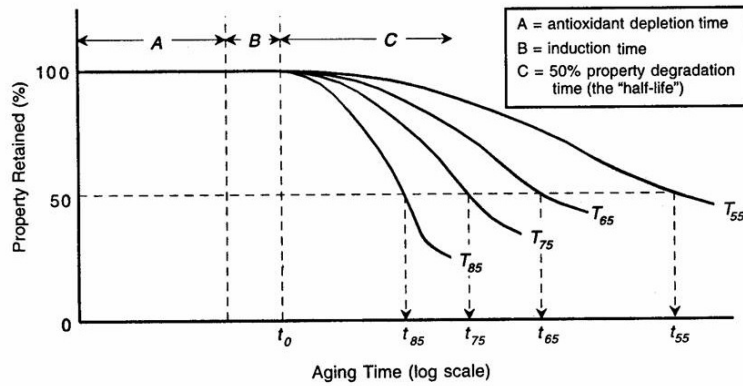


Figure 2. Three individual stages in the aging of most geomembranes.

The depletion of antioxidants is the consequence of two processes: (i) chemical reactions with the oxygen diffusing into the geomembrane, and (ii) physical loss of antioxidants from the geomembrane. The chemical process involves two main functions; the scavenging of free radicals converting them into stable molecules, and the reaction with unstable hydroperoxide (ROOH) forming a more stable substance. Regarding physical loss, the process involves the distribution of antioxidants in the geomembrane and their volatility and extractability to the site-specific environment.

Hence, the rate of depletion of antioxidants is related to the type and amount of antioxidants, the service temperature, and the nature of the site-specific environment. See Hsuan and Koerner (1998) for additional details.

2.2 Stage B - Induction Time to Onset of Degradation

In a pure polyolefin resin, i.e., one without carbon black and antioxidants, oxidation occurs extremely slowly at the beginning, often at an immeasurable rate. Eventually, oxidation occurs more rapidly. The reaction eventually decelerates and once again becomes very slow.

This progression is illustrated by the S-shaped curve of Figure 3(a). The initial portion of the curve (before measurable degradation takes place) is called the induction period (or induction time) of the polymer. In the induction period, the polymer reacts with oxygen forming hydroperoxide (ROOH), as indicated in Equations (1)-(3). However, the amount of ROOH in this stage is very small and the hydroperoxide does not further decompose into other free radicals which inhibits the onset of the acceleration stage.

In a stabilized polymer such as one with antioxidants, the accelerated oxidation stage takes an even longer time to be reached. The antioxidants create an additional depletion time stage prior to the onset of the induction time, as shown in Figure 3(b).

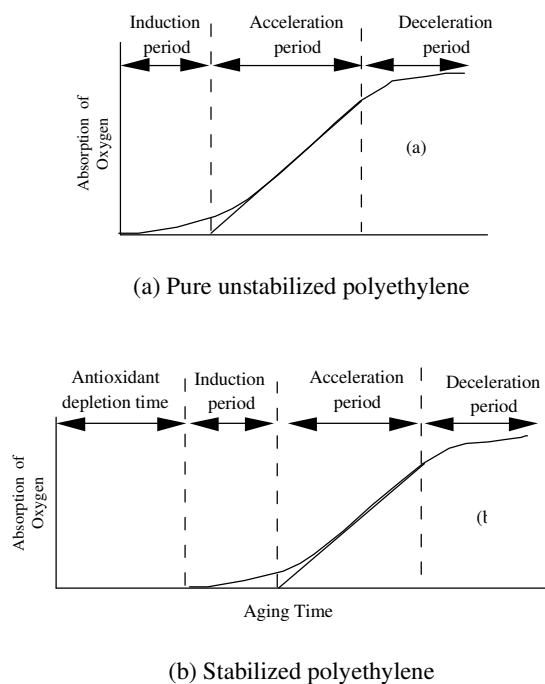


Figure 3. Curves illustrating various stages of oxidation.



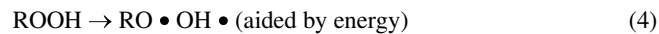
(aided by energy or catalyst residues in the polymer)



In the above, RH represents the polyethylene polymer chains; and the symbol “•” represents free radicals, which are highly reactive molecules.

2.3 Stage C - Time to Reach 50% Degradation (Half-life)

As oxidation continues, additional ROOH molecules are being formed. Once the concentration of ROOH reaches a critical level, decomposition of ROOH begins, leading to a substantial increase in the amount of free radicals, as indicated in Equations (4) to (6). The additional free radicals rapidly attack other polymer chains, resulting in an accelerated chain reaction, signifying the end of the induction period, Rapoport and Zaikov (1986). This indicates that the concentration of ROOH has a critical control on the duration of the induction period.



A series of oxidation reactions produces a substantial amount of free radical polymer chains ($R\bullet$), called alkyl radicals, which can proceed to further reactions leading to either cross-linking or chain scission in the polymer. As the degradation of polymer continues, the physical and mechanical properties of the polymer start to change. The most noticeable change in physical properties is the melt index, since it relates to the molecular weight of the polymer. As for mechanical properties, both tensile break stress (strength) and break strain (elongation) decrease.

Ultimately, the degradation becomes so severe that all tensile properties start to change (tear, puncture, burst, etc.) and the engineering performance is jeopardized. This signifies the end of the so-called “service life” of the geomembrane.

Although quite arbitrary, the limit of service life of polymeric materials is often selected as a 50% reduction in a specific design property. This is commonly referred to as the half-life time, or simply the “half-life”. It should be noted that even at half-life, the material still exists and can function, albeit at a decreased performance level with a factor-of-safety lower than the initial design value.

2.4 Summary of Lifetime Research-to-Date

Stage A, that of antioxidant depletion for HDPE geomembranes as required in the GRI-GM13 Specification, has been well established by our own research and corroborated by others, e.g., Sangram and Rowe (2004). The GRI data for standard and high pressure Oxidative Induction Time (OIT) is given in Table 2. The values are quite close to one another. Also, as expected, the lifetime is strongly dependent on the service temperature; with the higher the temperature the shorter the lifetime.

Table 2 - Lifetime prediction of HDPE (nonexposed) at various field temperatures

In Service Temperature (°C)	Stage “A” (years)			Stage “B” (years)	Stage “C” (years)	Total Prediction* (years)
	Standard OIT	High Press. OIT	Average OIT			
20	200	215	208	30	208	446
25	135	144	140	25	100	265
30	95	98	97	20	49	166
35	65	67	66	15	25	106
40	45	47	46	10	13	69

*Total = Stage A (average) + Stage B + Stage C

Stage “B”, that of induction time, has been obtained by comparing 30-year old polyethylene water and milk containers (containing no long-term antioxidants) with currently

produced containers. The data shows that degradation is just beginning to occur as evidenced by slight changes in break strength and elongation, but not in yield strength and elongation. The lifetime for this stage is also given in Table 2.

Stage "C", the time for 50% change of mechanical properties is given in Table 2 as well. The data depends on the activation energy, or slope of the Arrhenius curve, which is very sensitive to material and experimental techniques. The data is from Gedde, et al. (1994) which is typical of the HDPE resin used for gas pipelines and is similar to Martin and Gardner (1983).

Summarizing Stages A, B, and C, it is seen in Table 2 that the half-life of covered HDPE geomembranes (formulated according to the current GRI-GM13 Specification) is estimated to be 449-years at 20°C. This, of course, brings into question the actual temperature for a covered geomembrane such as beneath a solid waste landfill. Figure 4 presents multiple thermocouple monitoring data of a municipal waste landfill liner in Pennsylvania for over 10-years, Koerner and Koerner (2005). Note that for 6-years the temperature was approximately 20°C. At that time and for the subsequent 4-years the temperature increased to approximately 30°C. Thus, the half-life of this geomembrane is predicted to be from 166 to 446 years within this temperature range. The site is still being monitored, see Koerner and Koerner (2005).

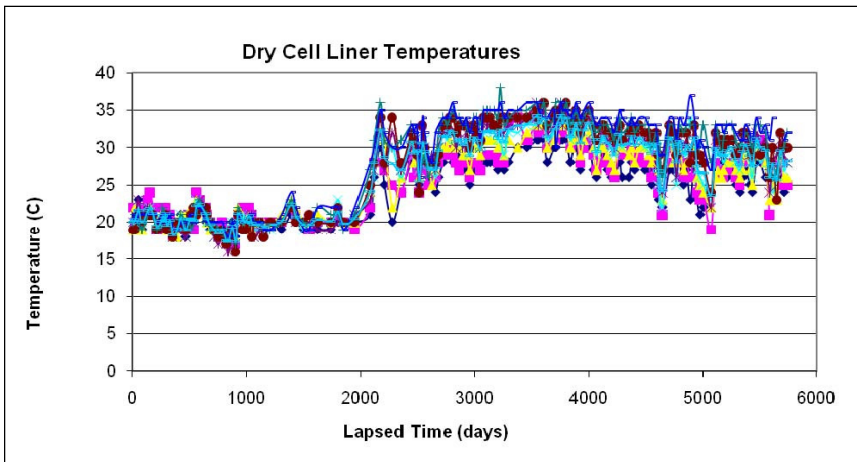


Figure 4. Long-term monitoring of an HDPE liner beneath a municipal solid waste landfill in Pennsylvania.

2.5 Lifetime of Other Covered Geomembranes

By virtue of its widespread use as liners for solid waste landfills, HDPE is by far the widest studied type of geomembrane. Note that in most countries (other than the U.S.), HDPE is the required geomembrane type for solid waste containment. Some commentary on other-than HDPE geomembranes (recall Table 1) follows:

2.5.1 Linear Low Density Polyethylene (LLDPE) geomembranes

The nature of the LLDPE resin and its formulation is very similar to HDPE. The fundamental difference is that LLDPE is a lower density, hence lower crystallinity, than HDPE; e.g., 10% versus 50%. This has the effect of allowing oxygen to diffuse into the polymer structure quicker, and likely decreases Stages A and C. How much is uncertain since no data is available, but it is felt that the lifetime of LLDPE will be somewhat reduced with respect to HDPE.

2.5.2 Plasticizer migration in PVC geomembranes

Since PVC geomembranes necessarily have plasticizers in their formulations so as to provide flexibility, the migration behavior must be addressed for this material. In PVC the plasticizer bonds to the resin and the strength of this bonding versus liquid-to-resin bonding is significant. One of the key parameters of a stable long-lasting plasticizer is its molecular weight. The higher the molecular weight of the plasticizer in a PVC formulation, the more durable will be the material. Conversely, low molecular weight plasticizers have resulted in field failures even under covered conditions. See Miller, et al. (1991), Hammon, et al. (1993), and Giroud and Tisinger (1994) for more detail in this regard. At present there is a considerable difference (and cost) between PVC geomembranes made in North America versus Europe. This will be apparent in the exposed study of durability in the second part of this White Paper.

2.5.3 Crosslinking in EPDM and CSPE geomembranes

The EPDM geomembranes mentioned in Table 1 are crosslinked thermoset materials. The oxidation degradation of EPDM takes place in either ethylene or propylene fraction of the co-polymer via free radical reactions, as expressed in Figure 5, which are described similarly by Equations (4) to (6).

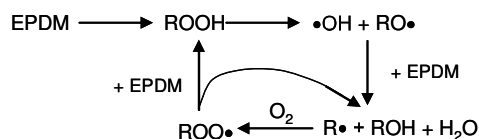


Figure 5. Oxidative degradation of crosslinked EPDM geomembranes, (Wang and Qu, 2003).

For CSPE geomembranes, the degradation mechanism is dehydrochlorination by losing chlorine and generating carbon-carbon double bonds in the main polymer chain, as shown in Figure 6.

The carbon-carbon double bonds become the preferred sites for further thermodegradation or cross-linking in the polymer, leading to eventual brittleness of the geomembrane.

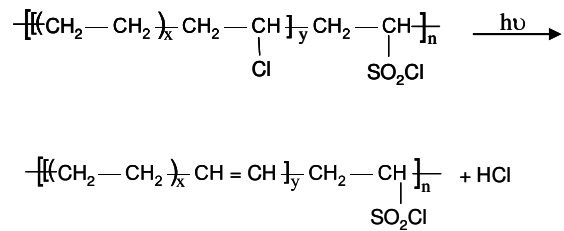


Figure 6. Dechlorination degradation of crosslinked CSPE geomembranes (Chailan, et al., 1995).

Neither EPDM nor CSPE has had a focused laboratory study of the type described for HDPE reported in the open literature. Most of lifetime data for these geomembranes is antidotal by virtue of actual field performance. Under covered conditions, as being considered in this section, there have been no reported failures by either of these thermoset polymers to our knowledge.

3.0 Lifetime Prediction: Exposed Conditions

Lifetime prediction of exposed geomembranes have taken two very different pathways; (i) prediction from anecdotal feedback and field performance, and (ii) from laboratory weathering device predictions.

3.1 Field Performance

There is a large body of anecdotal information available on field feedback of exposed geomembranes. It comes from two quite different sources, i.e., dams in Europe and flat roofs in the USA.

Regarding exposed geomembranes in dams in Europe, the original trials were using 2.0 mm thick polyisobutylene bonded directly to the face of the dam. There were numerous problems encountered as described by Scuero (1990). Similar experiences followed using PVC

geomembranes. In 1980, a geocomposite was first used at Lago Nero which had a 200 g/m² nonwoven geotextile bonded to the PVC geomembrane. This proved quite successful and led to the now-accepted strategy of requiring drainage behind the geomembrane. In addition to thick nonwoven geotextiles, geonets, and geonet composites have been successful. Currently over 50 concrete and masonry dams have been rehabilitated in this manner and are proving successful for over 30-years of service life. The particular type of PVC plasticized geomembranes used for these dams is proving to be quite durable. Tests by the dam owners on residual properties show only nominal changes in properties, Cazzuffi (1998). As indicated in Miller, et al. (1991) and Hammond, et al. (1993), however, different PVC materials and formulations result in very different behavior; the choice of plasticizer and the material's thickness both being of paramount importance. An excellent overview of field performance is recently available in which 250 dams which have been waterproofed by geomembranes is available from ICOLD (2010).

Regarding exposed geomembranes in flat roofs, past practice in the USA is almost all with EPDM and CSPE and, more recently, with fPP. Manufacturers of these geomembranes regularly warranty their products for 20-years and such warrants appear to be justified. EPDM and CSPE, being thermoset or elastomeric polymers, can be used in dams without the necessity of having seams by using vertical attachments spaced at 2 to 4 m centers, see Scuero and Vaschetti (1996). Conversely, fPP can be seamed by a number of thermal fusion methods. All of these geomembrane types have good conformability to rough substrates as is typical of concrete and masonry dam rehabilitation. It appears as though experiences (both positive and negative) with geomembranes in flat roofs should be transferred to all types of waterproofing in civil engineering applications.

3.2 Laboratory Weatherometer Predictions

For an accelerated simulation of direct ultraviolet light, high temperature, and moisture using a laboratory weatherometer one usually considers a worst-case situation which is the solar maximum condition. This condition consists of global, noon sunlight, on the summer solstice, at normal incidence. It should be recognized that the UV-A range is the target spectrum for a laboratory device to simulate the naturally occurring phenomenon, see Hsuan and Koerner (1993), and Suits and Hsuan (2001).

The Xenon Arc weathering device (ASTM D4355) was introduced in Germany in 1954. There are two important features; the type of filters and the irradiance settings. Using a quartz inner and borosilicate outer filter (quartz/boro) results in excessive low frequency wavelength degradation. The more common borosilicate inner and outer filters (boro/boro) shows a good correlation with solar maximum conditions, although there is an excess of energy below 300 nm wavelength. Irradiance settings are important adjustments in shifting the response although they do not eliminate the portion of the spectrum below 300 nm frequency. Nevertheless, the Xenon Arc device is commonly used method for exposed lifetime prediction of all types of geosynthetics.

UV Fluorescent devices (ASTM D7238) are an alternative type of accelerated laboratory test device which became available in the early 1970's. They reproduce the ultraviolet portion of the sunlight spectrum but not the full spectrum as in Xenon Arc weatherometers. Earlier FS-40 and UVB-313 lamps give reasonable short wavelength output in comparison to solar maximum. The UVA-340 lamp was introduced in 1987 and its response is seen to reproduce ultraviolet light quite well. This device (as well as other types of weatherometers) can handle elevated temperature and programmed moisture on the test specimens.

Research at the Geosynthetic Institute (GSI) has actively pursued both Xenon and UV Fluorescent devices on a wide range of geomembranes. Table 3 gives the geomembranes that were incubated and the number of hours of exposure as of 12 July 2005.

Table 5 - Details of the GSI laboratory exposed weatherometer study on various types of geomembranes

Geomembrane Type	Thickness (mm)	UV Fluorescent Exposure*	Xenon Exposure*	Comment
1. HDPE (GM13)	1.50	8000 hrs.	6600 hrs.	Basis of GRI-GM13 Spec
2. LLDPE (GM17)	1.00	8000	6600	Basis of GRI-GM-17 Spec
3. PVC (No. Amer.)	0.75	8000	6600	Low Mol. Wt. Plasticizer
4. PVC (Europe)	2.50	7500	6600	High Mol. Wt. Plasticizer
5. fPP (BuRec)	1.00	2745**	4416**	Field Failure at 26 mos.
6. fPP-R (Texas)	0.91	100	100	Field Failure at 8 years
7. fPP (No. Amer.)	1.00	7500	6600	Expected Good Performance

*As of 12 July 2005 exposure is ongoing

**Light time to reach halflife of break and elongation

3.3 Laboratory Weatherometer Acceleration Factors

The key to validation of any laboratory study is to correlate results to actual field performance. For the nonexposed geomembranes of Section 2 such correlations will take hundreds of years for properly formulated products. For the exposed geomembranes of Section 3, however, the lifetimes are significantly shorter and such correlations are possible. In particular, Geomembrane #5 (flexible polypropylene) of Table 3 was an admittedly poor geomembrane formulation which failed in 26 months of exposure at El Paso, Texas, USA. The reporting of this failure is available in the literature, Comer, et al. (1998). Note that for both UV Fluorescent and Xenon Arc laboratory incubation of this material, failure (halflife to 50% reduction in strength and elongation) occurred at 2745 and 4416 hours, respectively. The comparative analysis of laboratory and field for this case history allows for the obtaining of acceleration factors for the two incubation devices.

3.3.1 Comparison between field and UV Fluorescent weathering

The light source used in the UV fluorescent weathering device is UVA with wavelengths from 295-400 nm. In addition, the intensity of the radiation is controlled by the Solar Eye irradiance control system. The UV energy output throughout the test is 68.25 W/m².

The time of exposure to reach 50% elongation at break was as follows:

$$\begin{aligned} &= 2745 \text{ hr. of light} \\ &= 9,882,000 \text{ seconds} \end{aligned}$$

$$\begin{aligned} \text{Total energy in MJ/m}^2 &= 68.25 \text{ W/m}^2 \times 9,882,000 \\ &= 674.4 \text{ MJ/m}^2 \end{aligned}$$

The field site was located at El Paso, Texas. The UVA radiation energy (295-400 nm) at this site is estimated based on data collected by the South Florida Testing Lab in Arizona (which is a similar atmospheric location). For 26 months of exposure, the accumulated UV radiation energy is 724 MJ/m² which is very close to that generated from the UV fluorescent weatherometer. Therefore, direct comparison of the exposure time between field and UV fluorescent is acceptable.

Field time vs. Fluorescent UV light time: **Thus, the acceleration factor is 6.8.**
= 26 Months = 3.8 Months

3.3.2 Comparison between field and Xenon Arc weathering

The light source of the Xenon Arc weathering device simulates almost the entire sunlight spectrum from 250 to 800 nm. Depending of the age of the light source and filter, the solar energy ranges from 340.2 to 695.4 W/m², with the average value being 517.8 W/m².

The time of exposure to reach 50% elongation at break

$$\begin{aligned} &= 4416 \text{ hr. of light} \\ &= 15,897,600 \text{ seconds} \end{aligned}$$

$$\begin{aligned} \text{Total energy in MJ/m}^2 &= 517.8 \text{ W/m}^2 \times 15,897,600 \\ &= 8232 \text{ MJ/m}^2 \end{aligned}$$

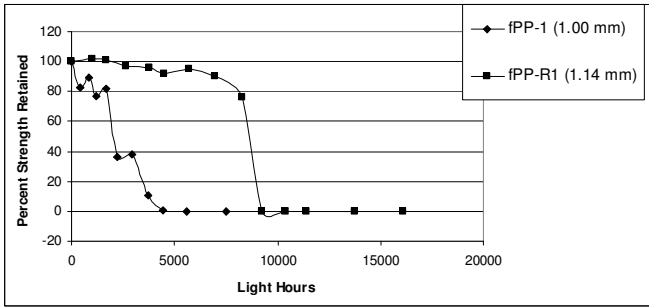
The solar energy in the field is again estimated based on data collected by the South Florida Testing Lab in Arizona. For 26 months of exposure, the accumulated solar energy (295-800 nm) is 15,800 MJ/m², which is much higher than that from the UV Fluorescent device. Therefore, direct comparison of halflives obtained from the field and Xenon Arc device is not anticipated to be very accurate. However, for illustration purposes the acceleration factor based on Xenon Arc device would be as follows:

Field vs. Xenon Arc : **Thus, the acceleration factor is 4.3.**
= 26 Months = 6.1 Months

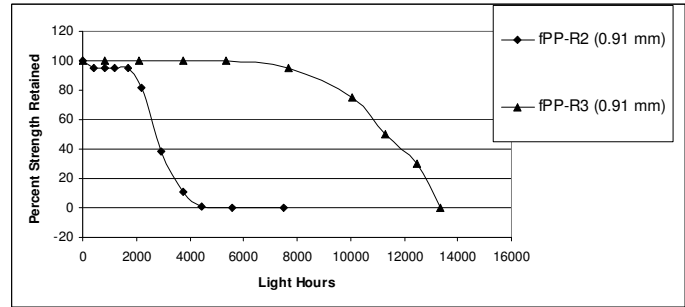
The resulting conclusion of this comparison of weathering devices is that the UV Fluorescent device is certainly reasonable to use for long-term incubations. When considering the low cost of the device, its low maintenance, its inexpensive bulbs, and ease of repair it (the UV Fluorescent device) will be used exclusively by GSI for long-term incubation studies.

3.3.3 Update of exposed lifetime predictions

There are presently (2011) four field failures of flexible polypropylene geomembranes and using unexposed archived samples from these sites their responses in laboratory UV Fluorescent devices per ASTM D7328 at 70°C are shown in Figure 5. From this information we deduce that the average correlation factor is approximately *1200 light hours* \simeq *one-year in a hot climate*. This value will be used accordingly for other geomembranes.



(a) Two Sites in West Texas



(b) Two Sites in So. Calif.

Lab-to-Field Correlation Factors
(ASTM D7238 @ 70°C)

Method	Thickness (mm)	Field (yrs.)	Location	Lab (lt. hr.)	Factor (lt. hrs./1.0 yr.)
fPP-1	1.00	≈ 2	W. Texas	1800	900
fPP-R1	1.14	≈ 8	W. Texas	8200	1025
fPP-R2	0.91	≈ 2	So. Calif.	2500	1250
fPP-R3	0.91	≈ 8	So. Calif.	11200	<u>1400</u>
					1140*

*Use 1200 lt. hr. = 1.0 year in hot climates

Figure 5. Four field failures of fPP and fPP-R exposed geomembranes.

Exposure of a number of different types of geomembranes in laboratory UV Fluorescent devices per ASTM D7238 at 70°C has been ongoing for the six years (between 2005 and 2011) since this White Paper was first released. Included are the following geomembranes:

- Two black 1.0 mm (4.0 mil) unreinforced flexible polypropylene geomembranes formulated per GRI-GM18 Specification; see Figure 6a.
- Two black unreinforced polyethylene geomembranes, one 1.5 mm (60 mil) high density per GRI-GM13 Specification and the other 1.0 mm (40 mil) linear low density per GRI-GM17 Specification; see Figure 6b.
- One 1.0 (40 mil) black ethylene polypropylene diene terpolymer geomembrane per GRI-GM21 Specification; see Figure 6c.
- Two polyvinyl chloride geomembranes, one black 1.0 mm (40 mil) formulated in North America and the other grey 1.5 mm (60 mil) formulated in Europe; see Figure 6d.

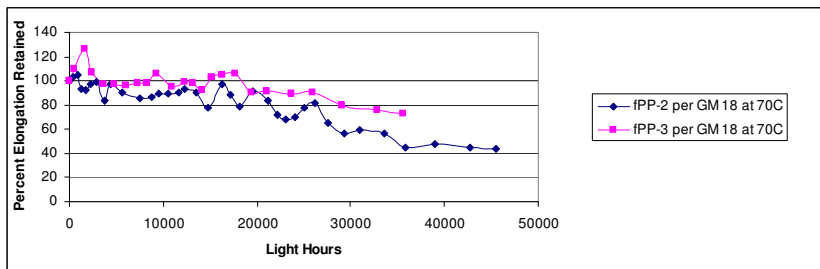
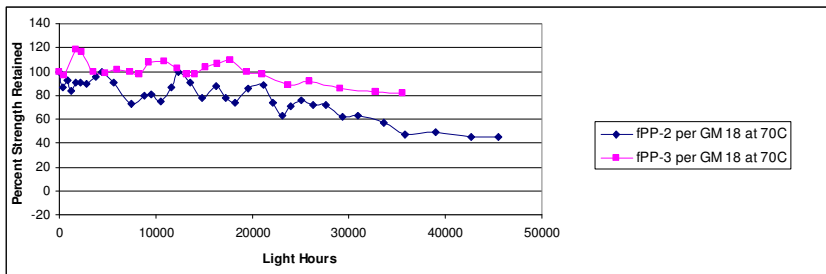


Figure 6a. Flexible polyethylene (fPP) geomembrane behavior.

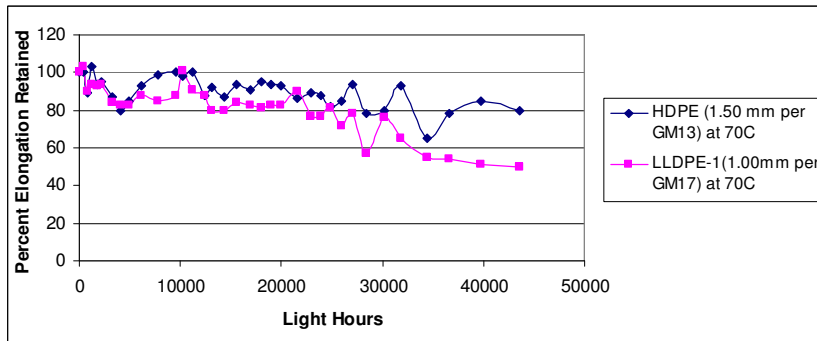
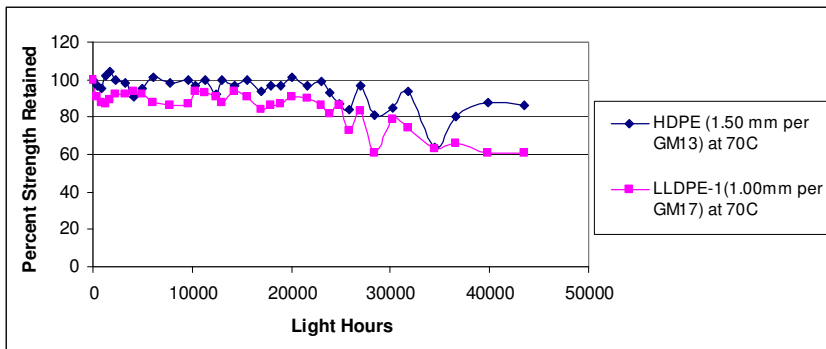


Figure 6b. Polyethylene (HDPE and LLDPE) geomembrane behavior.

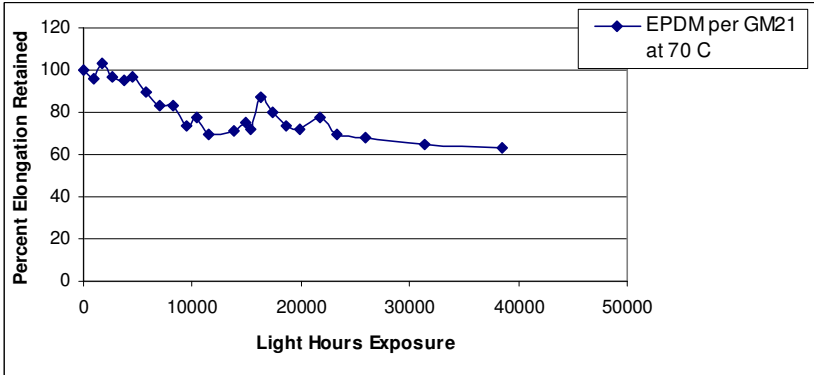
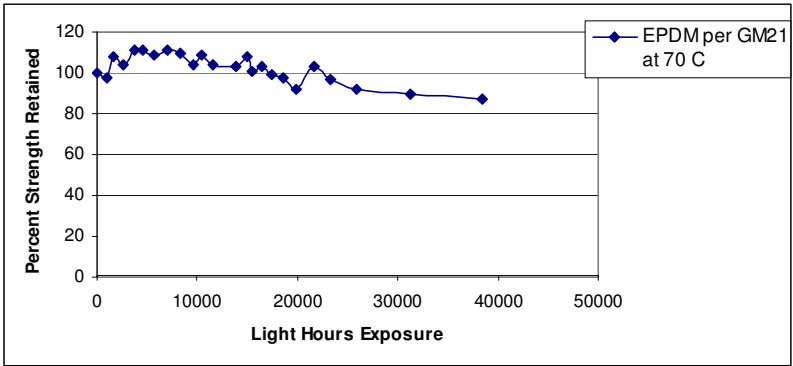


Figure 6c. Ethylene polypropylene diene terpolymer (EPDM) geomembrane.

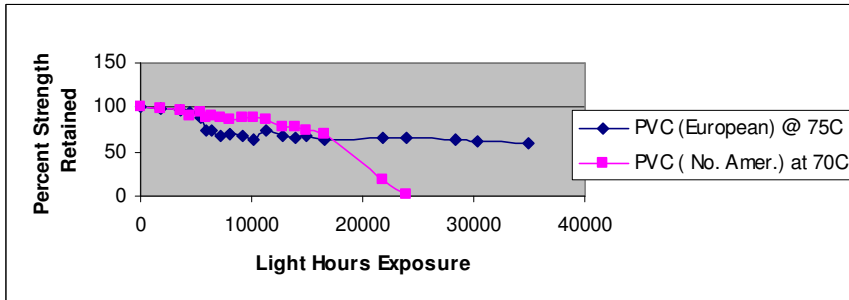


Figure 6d. Polyvinyl chloride (PVC) geomembranes.

From the response curves of the various geomembranes shown in Figure 6a-d, the 50% reduction value in strength or elongation (usually elongation) was taken as being the “half-life”. This value is customarily used by the polymer industry as being the materials lifetime prediction value. We have done likewise to develop Table 6 which is our predicted values for the designated exposed geomembrane lifetimes to date.

Table 6 – Exposed lifetime prediction results of selected geomembranes to date

Type	Specification	Prediction Lifetime in a Dry and Arid Climate
HDPE	GRI-GM13	> 36 years (ongoing)
LLDPE	GRI-GM17	≈ 36 years (half-life)
EPDM	GRI-GM21	> 27 years (ongoing)
fPP-2	GRI-GM18	≈ 30 years (half-life)
fPP-3	GRI-GM18	> 27 years (ongoing)
PVC-N.A.	(see FGI)	≈ 18 years (half-life)
PVC-Eur.	proprietary	> 32 years (ongoing)

4.0 Conclusions and Recommendations

This White Paper is bifurcated into two very different parts; covered (or buried) lifetime prediction of HDPE geomembranes and exposed (to the atmosphere) lifetime prediction of a number of geomembrane types. In the covered geomembrane study we chose the geomembrane type which has had the majority of usage, that being HDPE as typically used in waste containment applications. Invariably whether used in landfill liner or cover applications *the geomembrane is covered*. After ten-years of research Table 2 (repeated here) was developed which is the conclusion of the covered geomembrane research program. Here it is seen that HDPE decreases its predicted lifetime (as measured by its half-life) from 446-years at 20°C, to 69-years at 40°C. Other geomembrane types (LLDPE, fPP, EPDM and PVC) have had

essentially no focused effort on their covered lifetime prediction of the type described herein.

That said, all are candidates for additional research in this regard.

Table 2 - Lifetime prediction of HDPE (nonexposed) at various field temperatures

In Service Temperature (°C)	Stage "A" (years)			Stage "B" (years)	Stage "C" (years)	Total Prediction* (years)
	Standard OIT	High Press. OIT	Average OIT			
20	200	215	208	30	208	446
25	135	144	140	25	100	265
30	95	98	97	20	49	166
35	65	67	66	15	25	106
40	45	47	46	10	13	69

*Total = Stage A (average) + Stage B + Stage C

Exposed geomembrane lifetime was addressed from the perspective of field performance which is very unequivocal. Experience in Europe, mainly with relatively thick PVC containing high molecular weight plasticizers, has given 25-years of service and the geomembranes are still in use. Experience in the USA with exposed geomembranes on flat roofs, mainly with EPDM and CSPE, has given 20⁺-years of service. The newest geomembrane type in such applications is fPP which currently carries similar warranties.

Rather than using the intricate laboratory setups of Figure 1 which are necessary for covered geomembranes, exposed geomembrane lifetime can be addressed by using accelerating laboratory weathering devices. Here it was shown that the UV fluorescent device (per ASTM D7238 settings) versus the Xenon Arc device (per ASTM D 4355) is equally if not slightly more intense in its degradation capabilities. As a result, all further incubation has been using the UV fluorescent devices per D7238 at 70°C.

Archived flexible polypropylene geomembranes at four field failure sites resulted in a correlation factor of 1200 light hours equaling one-year performance in a hot climate. Using this

value on the incubation behavior of seven commonly used geomembranes has resulted in the following conclusions (recall Figure 6 and Table 6);

- HDPE geomembranes (per GRI-GM13) are predicted to have lifetimes greater than 36-years; testing is ongoing.
- LLDPE geomembranes (per GRI-GM17) are predicted to have lifetimes of approximately 36-years.
- EPDM geomembranes (per GRI-GM21) are predicted to have lifetimes of greater than 27-years; testing is ongoing.
- fPP geomembranes (per GRI-GM18) are predicted to have lifetimes of approximately 30-years.
- PVC geomembranes are very dependent on their plasticizer types and amounts, and probably thicknesses as well. The North American formulation has a lifetime of approximately 18-years, while the European formulation is still ongoing after 32-years.

Regarding continued and future recommendations with respect to lifetime prediction, GSI is currently providing the following:

- (i) Continuing the exposed lifetime incubations of HDPE, EPDM and PVC (European) geomembranes at 70°C.
- (ii) Beginning the exposed lifetime incubations of HDPE, LLDPE, fPP, EPDM and both PVC's at 60°C and 80°C incubations.
- (iii) With data from these three incubation temperatures (60, 70 and 80°C), time-temperature-superposition plots followed by Arrhenius modeling will eventually provide information such as Table 2 for covered geomembranes. This is our ultimate goal.

- (iv) Parallel lifetime studies are ongoing at GSI for four types of geogrids and three types of turf reinforcement mats at 60, 70 and 80°C.
- (v) GSI does not plan to duplicate the covered geomembrane study to other than the HDPE provided herein. In this regard, the time and expense that would be necessary is prohibitive.
- (vi) The above said, GSI is always interested in field lifetime behavior of geomembranes (and other geosynthetics as well) whether covered or exposed.

Acknowledgements

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