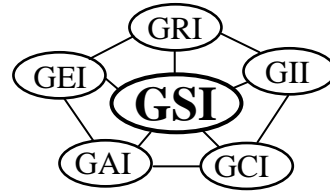


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GRI Report #42

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**Lifetime Prediction of Laboratory UV Exposed Geomembranes:
Part I - Using a Correlation Factor**

by

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Executive Summary

It is almost universally accepted that properly formulated geomembranes, when covered or backfilled, will last or even outlast other components in most engineered systems. Lifetime predictions of hundreds of years have been estimated by several research institutions; GSI being included in this regard. However, when the same geomembranes are exposed to the atmosphere (i.e., with elevated temperatures, ultraviolet light and full oxygen exposure) the lifetimes will significantly decrease. How much so is the focus of this report.

The geomembrane incubation technique to be used in such an assessment is that of using laboratory weatherometers and our selection in this regard is the ultraviolet fluorescent device, per ASTM D7238. Coupons of the selected geomembranes are incubated at a constant temperature until mechanical properties (strength or elongation) are decreased to 50% of their original values. This is the so-called “half-life” of the material.

In this Part I report of a two-part study, we were fortunate enough to have four field failures of flexible polypropylene geomembranes for which unused and archived parent material was available. Samples were incubated at 70°C temperature until half-life values of retained strength were obtained. The averages were then used to obtain a correlation factor as follows:

1200 light hours exposure at 70°C in D7238 device	~	1.0 year service life in a hot climate
--	---	---

Selecting six different commercially available geomembranes we incubated samples under these same laboratory conditions until their halflives of either strength retained or

elongation retained were reached. We then applied the above correlation factor which resulted in the following lifetime predictions.

Table 6 - Predicted Geomembrane Lifetimes Based on 50% Reduction of Strength and/or Elongation

Geomembrane Type	Nominal thickness (mm)	Applicable Specification	50% reduction* (light hours)	Predicted lifetime
fPP	1.00	GRI-GM18	40,000	33
HDPE	1.50	GRI-GM13	~ 60,000	~ 50
LLDPE	1.00	GRI-GM17	40,000	33
EPDM	1.14	GRI-GM21	37,000	30
PVC-N.A.	0.75	ASTM D7171	8,000	7**
PVC-Euro	2.50	proprietary	38,000	32

*Using ultraviolet fluorescent weathering devices at 70°C set at 350 nm wavelength for a daily cycling of 20 hours light and 4 hours dark with condensation.

**Only recommended for “buried applications”.

As expected, the predicted lifetimes are considerably shorter than when the similar geomembranes are covered or buried, but they are reasonable and are much higher than 20-year warranty which is common within the industry. Also to be noted is that the PVC-North American formulation is not recommended for exposed use and yet still gives reasonable predicted lifetime. Also, note that the HDPE is very robust in its behavior at approximately 50-years for its halflife. Interestingly, the covered predicted lifetime for HDPE is estimated at approximately ten-times this exposed lifetime value.

The expressed concern over the approach taken in this report is using a correlation factor for one resin type to be applied to many different resin types. In this regard, the Part II of this two-part study will use time-temperature-superposition at 60, 70 and 80°C incubation temperatures and then use Arrhenius modeling for a more rigorous approach toward lifetime prediction of these same geomembranes. An illustration of the approach is given in this report.

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**Lifetime Prediction of Laboratory UV Exposed Geomembranes:
Part I - Using a Correlation Factor**

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Lifetime Prediction of Laboratory UV Exposed Geomembranes: Part I - Using a Correlation Factor

1.0 Introduction and Background

Estimates of geomembrane lifetime prediction under exposed atmospheric conditions are required in many civil engineering applications. For example, surface impoundments and canal liners above their liquid levels, floating covers on reservoirs, waterproofing of dams, large megabags for liquid containment, exposed geomembrane landfill covers, etc., are all major applications for such exposed geomembranes. Comments such as a “long time” or “very long time” are usually inadequate in that an estimate of the expected number of years is required. This first section of the report describes the laboratory weathering devices used, reflections on past research lifetime prediction of covered (i.e., nonexposed) high density polyethylene geomembranes for comparison purposes, alternative methods available to extrapolate laboratory elevated temperature data, and the focus of the report itself.

1.1 Ultraviolet Weathering Devices

The lifetime of currently formulated and manufactured geomembranes is such that a “wait-and-see” attitude is generally unacceptably too long for the parties involved. Properly formulated geomembranes used in exposed applications have shown good field results in the past. For example, 17-year performance by Case, et al. (2010), 20-year performance by Yako, et al. (2010), and 25-year performance by Rohe, (2004) have been reported. In light of these long field times, there has been no past research focused on the utilization of laboratory weathering devices for geomembrane lifetime prediction purposes since the times involved are so long. In this regard, three mechanisms are

included in laboratory weathering devices; ultraviolet light, elevated temperature and moisture. The goal in such laboratory weathering devices is to incubate samples sufficiently long (it will be seen that it takes *years of incubation* for geomembranes) so as to reach a given change in mechanical properties from the as-manufactured material. In this regard, a 50% change in strength or elongation, i.e., the “half-life”, is a common target value. Other criteria such as excessive chalking, cracking or peeling have also been used. That said, the specifics of the incubation device are critical. The goal is to not only replicate the electromagnetic energy spectrum, see Figure 1, but also to ensure that light of a wavelength equal or shorter than the threshold causing photochemical reactions is available. The released photons cause the breaking of chemical bonds leading to the sample’s degradation of properties over time. The well known critical wavelengths of the resins used to manufacture geosynthetics are as follows:

- polypropylene (PP) = 370 nm
- polyester (PET) = 325 nm
- polystyrene (PS) = 315 nm
- polyvinyl chloride (PVC) = 312 nm
- polyethylene (PE) = 300nm

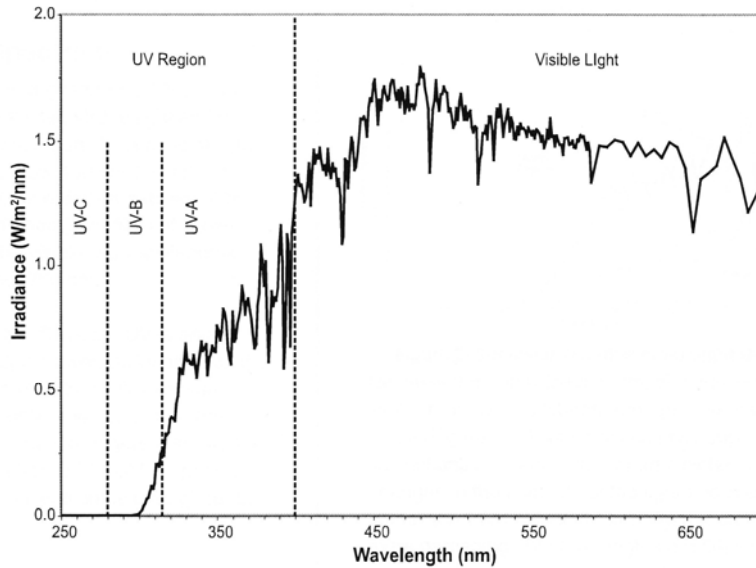
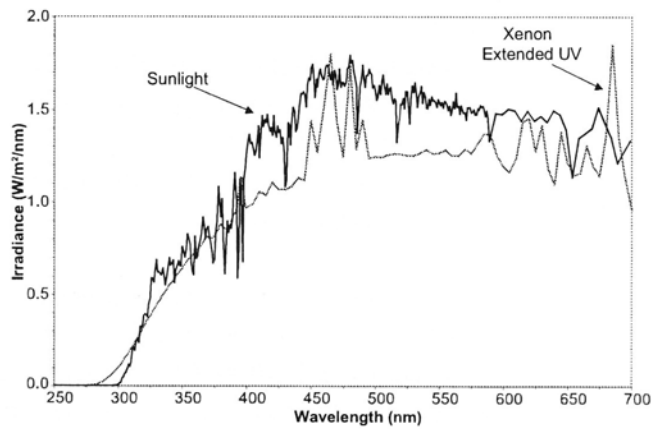
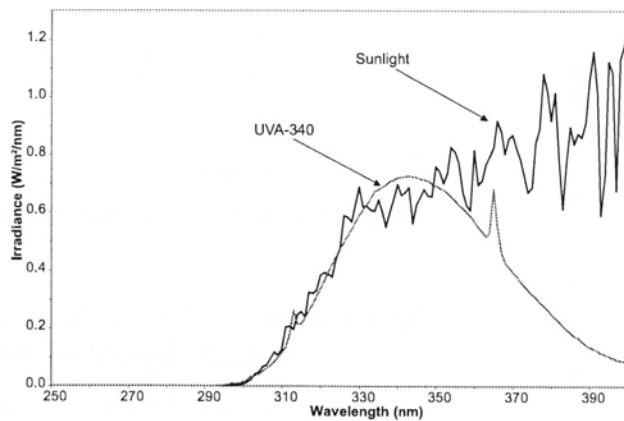


Figure 1 - Electromagnetic energy from sunlight; Q-Lab Technical Bulletin LU-0822.

In this regard, there are two competing laboratory incubation devices that meet the criteria just mentioned; the xenon arc device and the ultraviolet fluorescent device. Their respective spectra are shown in Figure 2a and 2b. Here it can be noted that both are similar in their low wavelengths so as to enter the UV region, and particularly the UV-B range where the major degradation of the resins just mentioned occurs. They are not similar in the visible light range in that the xenon arc device provides energy throughout the full spectrum of sunlight and the ultraviolet fluorescent device trails off quite abruptly. This latter approach, however, is effective because the short wavelengths cause almost all the damage to geomembrane polymers in exposed conditions.



(a) Xenon arc device with extended UV filters versus sunlight



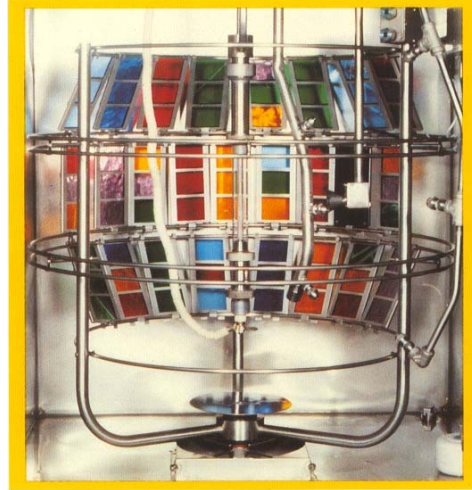
(b) Ultraviolet fluorescent UVA-340 devices versus sunlight

Figure 2 - Wavelength comparisons of the two common weathering devices used for sample incubation; after Q-Lab Technical Bulletin LU-0822.

That said, there are also practical considerations. The xenon arc device is both more expensive initially and requires considerably more operations and maintenance costs.

Figure 3 shows the two devices and Table 1 provides relative cost differences.

Considering that the incubation durations for the geomembranes of this study are 5 to 10 years, the choice of device becomes quite obvious to us. In this regard, the ultraviolet fluorescent device will be used exclusively in this study.



(a) Xenon arc device



(b) Ultraviolet fluorescent device

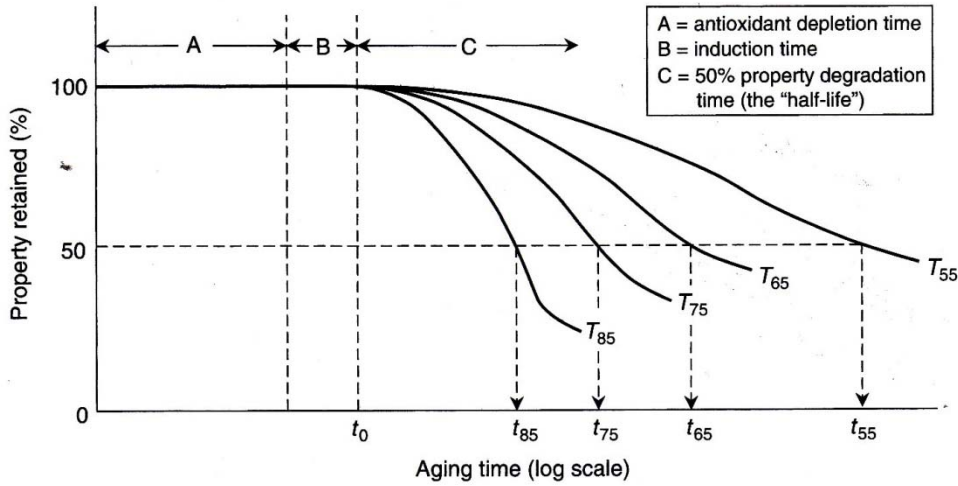
Figure 3 - Comparison and contrast of the two common laboratory weathering devices.

Table 1 - Cost Comparison of Two Common Laboratory Weathering Devices

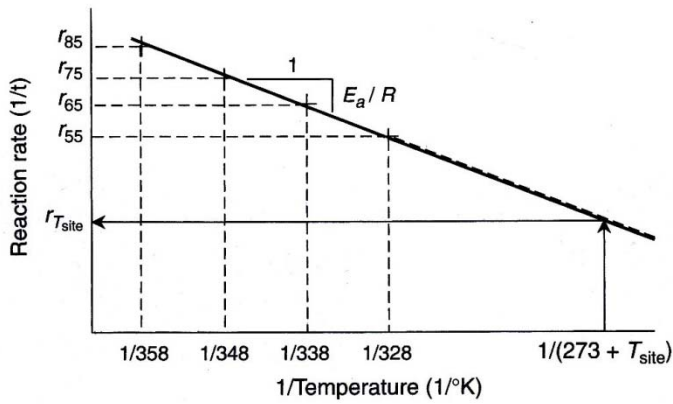
Item	Xenon Arc	Ultraviolet-Fluorescent
Standard	ASTM D4355	ASTM D7238
Conditions	90 min/light/30 min water	20 hr light/4 hr condensation
Initial Cost	≈ \$70,000	≈ \$15,000
Tube/Bulb Cost	\$15,000/year	\$300/year
Power Cost	\$5,000/year	\$400/year
Water Cost	\$3,000/year	none
Sewer Cost	\$1,000/year	none

1.2 Time-Temperature-Superposition Followed by Arrhenius Modeling

It is generally accepted that the premier laboratory method for predicting the lifetime of polymeric materials is to replicate service conditions as closely as possible at several elevated temperatures, and then extrapolate the change in properties down to a site-specific temperature. The process is called *time-temperature-superposition followed by Arrhenius modeling*. At the Geosynthetic Institute we have performed the requisite research for covered (nonexposed) HDPE geomembranes over a twelve-year period, Bonaparte, et al. (2002) and Koerner (2012). The above-mentioned concept is embodied in the following two curves, see Figures 4a and 4b. To be noted is that the calculation procedure when dealing with exposed geomembranes is exactly the same as for nonexposed except for the selection and configuration of the incubation (or containment) devices.



(a) Incubated property behavior



(b) Arrhenius plot for half-life property

Figure 4 - Arrhenius modeling for lifetime prediction using elevated temperatures.

The extrapolation of the Figure 4b curve to any lower field-specific temperature can be done graphically or analytically. The latter uses the following equation from which any (lower) field temperature can be calculated as shown in Table 2.

$$\frac{r_{T-test}}{r_{T-site}} = e^{-\frac{E_{act}}{R} \left[\frac{1}{T-test} - \frac{1}{T-site} \right]} \quad (1)$$

where

E_{act}/R = slope of Arrhenius plot,

T-test = incubated (high) temperature, and

T-site = site-specific (lower) temperature

Table 2 - Lifetime Prediction of Covered, i.e., Nonexposed, HDPE Geomembranes as a Function of Field (In-Situ) Service Temperature, Koerner (2012)

In-Service Temperature (°C)	Stage A (yrs)		Stage B (yrs)	Stage C (yrs)			Total (yrs) ¹
	Std-OIT	HP-OIT		Ref. [A]	Ref. [B]	GSI Data	
20	200	215	30	740	208	8	555
25	135	144	25	441	100	7	348
30	95	98	20	259	49	6	221
35	65	67	15	154	25	5	142
40	45	47	10	93	13	4	93

¹Total = Stage A (average) + Stage B + Stage C (average)

To be noted is that at a typical soil buried liner temperature of 20°C, the halflife of covered HDPE geomembranes (manufactured per the GRI-GM13 specification) is anticipated to be approximately 555-years. Conversely, under exposed conditions this lifetime will be greatly shortened, but how much so remains to be seen and is the subject of this study.

1.3 Alternative Methods for Lifetime Prediction

While the just discussed method for lifetime prediction using time-temperature-superposition and Arrhenius modeling is clearly the preferred method, it requires three or four incubation temperatures carried out until halflife degradation is reached. In this regard our HDPE samples incubations in the ultraviolet fluorescent weatherometer, at the temperature of 70°C are just reaching this stage and their exposure time is presently about 50,000 light hours. This is 6.8 years and the incubations at 60°C will take significantly longer. That said, this set of incubations at 60°, 70° and 80°C is presently being conducted at the Geosynthetic Institute and is ongoing. However, it will take as much as 5 to 7 years longer at 60°C to be able to replicate the covered geomembrane lifetime

prediction as was given in Table 2. As such, there are two alternative methods which are both shorter but admittedly less reliable. The second of these is the subject of this report.

The first of these *short-cut* methods is to make a correlation to world irradiation energy maps whereby published isocurves in kLy-units are used, see Figure 5. Knowing the irradiation energy for the field site in question, it can be compared to the behavior of laboratory incubated samples of the geomembrane in question. Establishing this laboratory energy (also in kLy-units) causing a given amount of degradation (like half-life) allows for a simple comparison to obtain the estimated years of lifetime. The procedure is felt to be approximate, at best, and is illustrated in the following example.

Example

Assume that a geomembrane reaches its half-life elongation in a laboratory weathering device (Energy = 517.8 W/m²) in 20,000 hr. What is the equivalent lifetime in Philadelphia with a known average exposure energy of 5021 MJ/m²-yr? Note: Joule (J) = watts (W) × seconds (sec)

Solution

$$\begin{aligned} E_{\text{test}} &= (517.8)(20,000)(3600)(1 \times 10^{-6}) \\ &= 37,300 \text{ MJ/m}^2 \\ E_{\text{Phila}} &= (5021 \text{ MJ/m}^2 - \text{yr})(1/4 \text{ sun time}) \\ &= 1255 \text{ MJ/m}^2 - \text{year} \\ T_{\text{Phila}} &= \frac{37,300}{1255} \cong 30 \text{ years} \end{aligned}$$

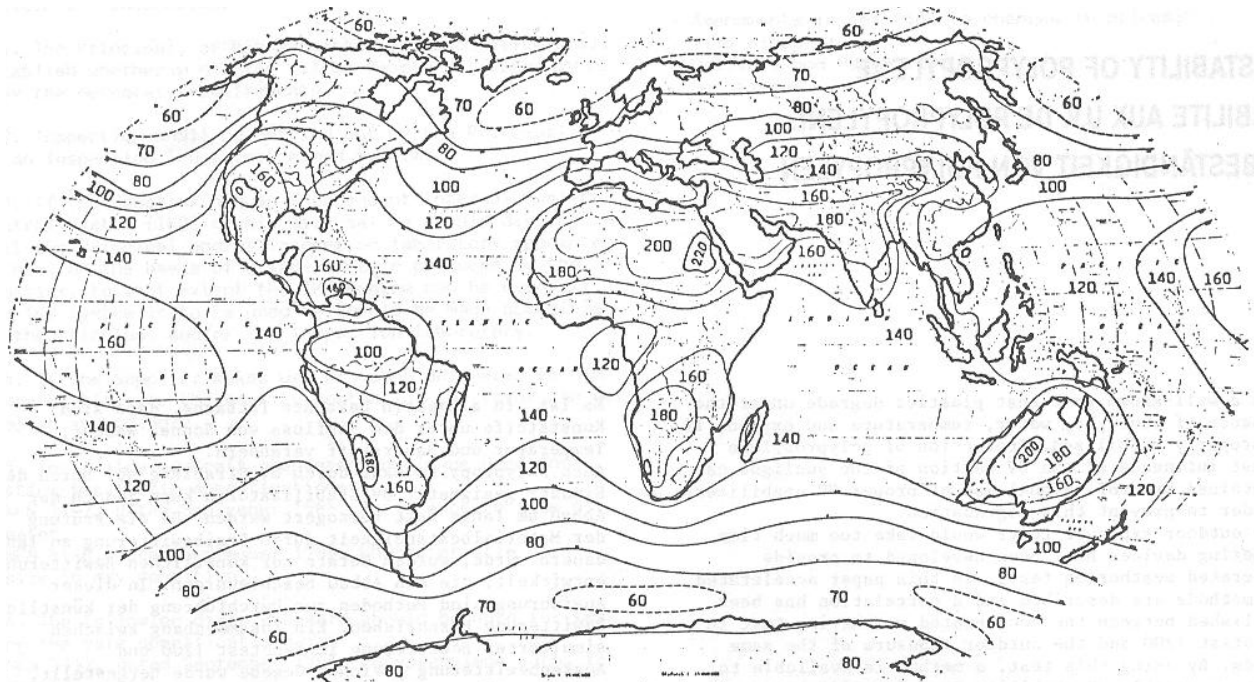


Figure 5 - Annual irradiation energy isocurves in “kLy”; where 1 kLy = 1 kcal/cm²; ref. Van Wilk and Stoezer (1986).

The second of these short-cut methods, *and the one used in this particular report*, makes use of known field failure times and when compared to the laboratory incubated failure times of the same but unexposed archived samples, allows for the establishment of a correlation factor. By having enough failures and incubation data from unexposed archived samples at those failure sites, a degree of reliance in this factor can be established. The advantage of this method is that only one incubation temperature is needed to obtain the correlation. As noted previously, this is the method selected for this report until such time that data from an additional two incubation temperatures are obtained. Then, results from time-temperature-superposition followed by Arrhenius modeling will be presented at a much later time in Part II of the study.

1.4 Focus of This Project

This report focuses on exposed lifetime performance of six different geomembrane types. They are the following along with their respective specifications:

- High density polyethylene (HDPE) per GRI-GM13
- Linear low density polyethylene (LLDPE) per GRI-GM17
- Flexible polypropylene (fPP) per GRI-GM18
- Ethylene propylene diene terpolymer (EPDM) per GRI-GM21
- Polyvinyl chloride-No. Amer. formulation (PVC-N.A.) per ASTM D7176
- Polyvinyl chloride-European formulation (PVC-Euro.) per proprietary specifications

All have been incubated at 70°C until a 50% reduction in either strength or elongation has resulted, usually the latter. The correlation factor to which this data will be compared is based on the average of four fPP field failures for which there were archived (nonexposed) samples. These were evaluated in a ultraviolet fluorescent weathering device at 70°C until their half-life was reached. The four field sites were in hot climates; two in West Texas and two in Southern California.

Use of such a correlation factor is felt to be justified for the fPP and probably the HDPE and LLDPE geomembranes as well, since all are polyolefins. The “stretch” to EPDM is obvious and particularly so for the two different PVC’s since their degradation mechanisms are quite different. Nevertheless, by having the data, the attempt will be made until such time that data for two additional incubation temperatures are available. As mentioned, this will take approximately 5-7 years longer.

2.0 Properties of Geomembrane Evaluated

Each of the six commercially available geomembranes selected for this study were characterized using ASTM test methods and compared to their respective specification values. The fPP data will be presented first, then the two polyethylenes, the EPDM and finally the two (very different) PVC's; see Table 3. A major point to be made is that the thicknesses vary in accordance to the usual usage of the materials from our perspective. In this regard, the thinner geomembranes are likely to have lower lifetimes than their thicker counterparts. However, thickness per se is not included in this study. As seen, the as-received materials generally meet their respective specification values.

Table 3 - Properties of Geomembranes Used in this Study

(a) 1.0 mm thick flexible polypropylene (fPP)

Properties	Method	Specification Value (min.)	Tested Value
Mass per unit area (kg/m²)	D5261	0.78	0.95
Thickness (mm)	D5199	0.90	0.96
Tensile	D6693		
-tensile strength (kN/m)	TypeIV	13	13.5
-tensile elongation (%)	D7004	700	798
Tear resistance (N)	D1004	53	69
Puncture resistance (N)	D4833	130	213
Carbon black content (%)	D1603	10	11.7

(b) 1.5 mm thick high density polyethylene (HDPE)

Properties	Method	Specification Value (min.)	Tested Value
Thickness - (mm)	D5199	1.35	1.60
Density (g/cm³)	D1505/D792	0.940	0.949
Tensile	D6693		
- yield stress (kN/m)	TypeIV	22	33
- break stress (kN/m)		40	53
- yield elongation (%)		12	17
- break elongation (%)		700	800
Tear resistance (N)	D1004	187	249
Puncture resistance (N)	D4833	480	667
Stress crack resistance	D5397	200	209
Carbon black content (%)	D1603	2-3	2.3
Carbon black dispersion	D5596	1 or 2	1

(c) 1.0 mm thick linear low density polyethylene (LLDPE-1)

Properties	Method	Specification Value (min.)	Tested Value
Thickness - (mm)	D5199	0.90	1.13
Density (g/cm³)	D1505/D792	0.939 (max.)	0.928
Tensile	D6693		
-break strength (N/mm)	TypeIV	27	40
-break elongation (%)		800	942
2% Modulus (N/mm)	D5323	420	613
Tear resistance (N)	D1004	100	138
Puncture resistance (N)	D4833	250	449
Carbon black content (%)	D1603	2-3	2.1

(d) 1.15 mm thick ethylene propylene diene terpolymer (EPDM)

Properties	Method	Specification Value	Tested Value
Thickness - (mm)	D5199	1.04	1.15
Tear resistance (N)	D1004	53	49
Tensile	D412		
-break strength (kN/m ²)		8300	9300
-break elongation (%)		500	910
Puncture resistance (N)	D4833	133	156
Carbon black content (%)	D1603	N/A	42.9

(e) 0.76 mm thick polyvinyl chloride-North American (PVC-N.A.)

Properties	Method	Specification Value (min.)	Tested Value
Thickness - (mm)	D5199	0.76	0.78
Density (g/cm³)	D1505/D792	1.2	1.26
Tensile	D882		
-break strength (kN/mm)		12.8	15
-break elongation (%)		380	480
Tear resistance (N)	D1004	35	53

(f) 2.50 mm thick polyvinyl chloride-European (PVC-Euro)

Properties	Method	Specification Value (min.)	Tested Value
Thickness - (mm)	D5199	prop.	2.63
Density (g/cm³)	D1505/D792	prop.	1.26
Tensile	ISO 527		
-break strength (kN/mm)		prop.	47
-break elongation (%)		prop.	450
Tear resistance (N)	D1004	prop.	153

3.0 Establishment of the Correlation Factor

Since the correlation factor to be used in this study is based on flexible polypropylene (fPP) some insight into this resin (and particularly its distinction between thermoplastic olefins, or TPO's) is warranted. The following is taken verbatim from Pasquini (2005).

In the early development of polypropylene (PP), the addition of rubber provided an improvement in impact, but results varied significantly depending on the rubber composition and morphology. The basic requirements for impact-modified brittle plastics were established with the development of high impact polystyrene (PS). Similar considerations govern rubber-modified PP, but the crystalline nature of PP complicates the achievement of the desired rubber morphology. From the PS work, it was evident that particles with about 1 micron diameter having good adhesion to the matrix were desired. PP requires a similar morphology.

In PP modification, ethylene-propylene rubber (EPR) with 30% to 60% C₂ is often used. The rubber is reactor-polymerized or introduced through compounding. As discussed earlier, the rubber composition is sufficiently different from PP homopolymer and random copolymer that it is usually immiscible even in the melt. Thus, the final rubber morphology is strongly affected by shear and deformation during melt process operations.

For polypropylene geomembranes with rubber additions, we use the term flexible polypropylene (fPP), however, others (e.g., the roofing industry) use the term thermoplastic olefin (TPO). That said, the definition for TPO's is so general (e.g., only 50% must be an olefin which is not even defined) that we prefer the GRI-GM18 specification which restricts the formulation to have at least 85% by weight of flexible polypropylene.

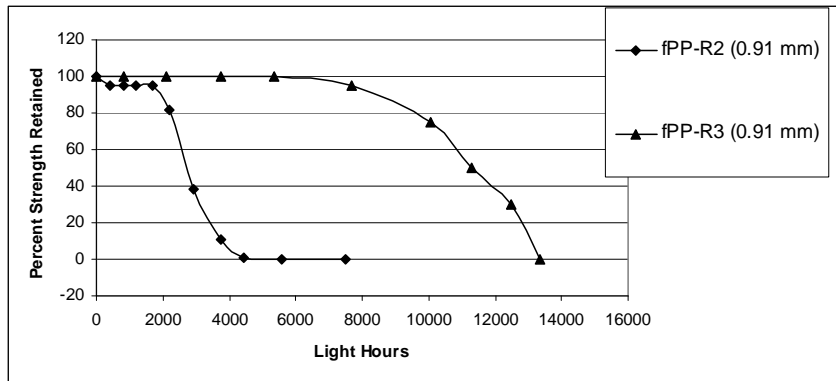
In generating the correlation factors, we were fortunate enough to have four field failures of fPP geomembranes, each of which had archived samples. These samples were incubated at GSI using the fluorescent ultraviolet device (ASTM D7238) at 70°C (20 hours light and 4 hours condensation) until the 50% strength retained value using ASTM

D6693 specimen testing was reached. Strength was used instead of the generally preferred elongation since three of the geomembranes were scrim reinforced. They were assessed on the basis of chalking and/or cracking wherein their responses were quite abrupt. The samples (with their locations and field failure times) were as follows:

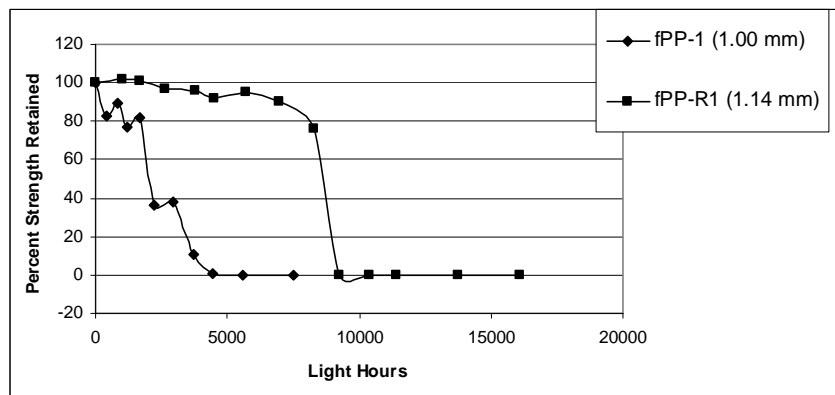
- fPP-1 (1.00 mm) in West Texas for 2-years
- fPP-R1 (1.14 mm) in West Texas for 8-years
- fPP-R2 (0.91 mm) in Southern California for 2-years
- fPP-R3 (0.91 mm) in Southern California for 8-years

Figure 6 shows the resulting laboratory data in light hours where the 50% (half-life) values are very apparent. As stated above, three of the geomembranes were scrim reinforced and thus strength (not elongation) values are indicated. In these cases, failure was decided upon on the basis of microcracks occurring (generally) above the cross-over scrim yarn locations. That said, in the work to follow all geomembranes were nonreinforced so that both strength and elongation will be presented.

Using this information a correlation factor of relating laboratory obtained half-lives to equivalent field service times in hot climates (like West Texas and Southern California) was obtained. The process is shown in Table 4 following:



(a) Two sites in West Texas



(b) Two sites in Southern California

Figure 6 - Ultraviolet incubation times versus strength retained for four archived fPP geomembrane taken from field failures sites.

Table 4 - Laboratory-to- Field Correlation Factor (using ASTM D7238 @ 70°C)

Method	Thickness (mm)	Field (yrs.)	Location	Lab halflife (lt. hr.)	Correlation Factors (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	1400
					1140 (ave.)

Thus, in the lifetime evaluations to follow, for properly formulated fPP geomembranes and on other geomembranes as well, we will use the correlation factor as follows:

1200 light hours exposure at 70°C in D7238 device	=	1.0 year service life in a hot climate
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Please note that the extension of using this correlation factor, based on fPP geomembranes, for other resin types is a “stretch” to be sure. Hopefully, the polyethylenes like HDPE and LLDPE behave similarly, but EPDM and clearly PVC have other failure mechanics and are questionable in this regard but the attempt will be made nevertheless. This caveat should be kept in mind for the next section of the report.

4.0 Ultraviolet Fluorescent Device Results

The origin of this study was to evaluate geosynthetic behavioral differences between the xenon arc and fluorescent tube weathering devices. For geotextiles, with their relatively short lifetimes, this was possible but when we began evaluating geomembranes the times to reach half-life were seen to be enormous! Furthermore, the costs involved for the xenon arc device were prohibitive. In this regard, recall Table 1 where it was seen that the equipment and operational costs of the xenon arc weathering device is such that long-term incubation with the ultraviolet fluorescent tube method was selected.

The targeted geomembranes which we selected are the most commonly used types and all are nonreinforced. In this regard, both strength retained and elongation retained could be tracked on an ongoing manner. At numerous incubation time intervals coupons were removed from the weathering device and then tensile test specimens taken accordingly; see Figure 7. The tensile testing procedures used specimen sizes and testing rates common to each geomembrane type, see Table 5 for these details. As mentioned previously the thicknesses varied greatly, i.e., from 0.76 to 2.5 mm. They were selected since they are the most common for each particular geomembrane, at least in our opinion. That said, thickness does indeed play a role in exposed durability predictions but it was not specifically evaluated in this study. Perhaps in the future it will be either from us or others, however for now it is presently a *research needs* item.

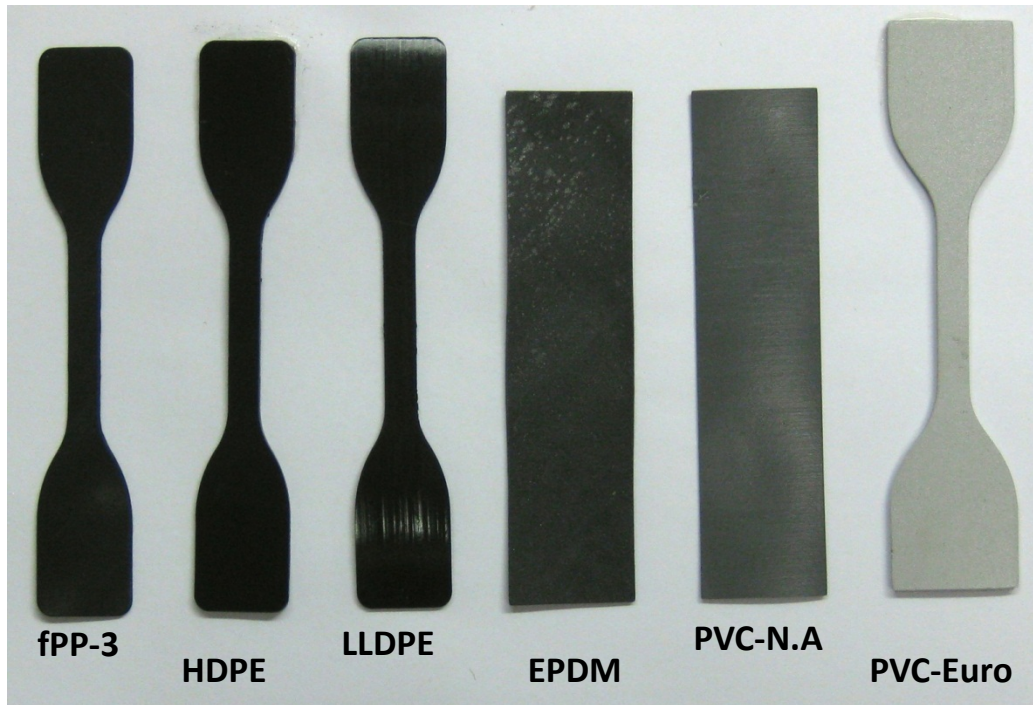


Figure 7 - Tensile test specimens of the various geomembranes used in this study.

Table 5 - Details of Tensile Test Specimens for the Different Geomembranes Evaluated

Geomembrane Type	Nominal thickness (mm)	Test method	Specimen shape	Specimen length (mm)	Gauge length (mm)	Testing rate (mm/min)
fPP	1.00	ASTM D6693	dogbone	62	50	500
HDPE	1.50	ASTM D6693	dogbone	62	50	50
LLDPE	1.00	ASTM D6693	dogbone	62	50	50
EPDM	1.14	ASTM D6693	25 mm strip	50	50	500
PVC-N.A.	0.76	ASTM D6693	25 mm strip	50	50	500
PVC-Euro	2.50	ISO 527-3	dogbone	80	25	50

The tensile strength and elongation results from the incubations of the various geomembranes are presented in Figures 8a through 8f. Here strength retained is in each upper graph and elongation retained is in each lower graph. The x-axis of all graphs is light hours of incubation at 70°C. For total hours one should multiply light hours by 1.20 (=24/20) since four hours in the device are dark each day. In this regard, it can be noted that the incubation durations of the HDPE geomembranes are over 50,000 light hours

which is equivalent to 6.8 years of total time. This time frame signifies that these are indeed long-term studies necessitating (in our opinion) the use of the ultraviolet fluorescent device over the xenon arc device for the previously discussed financial reasons only.

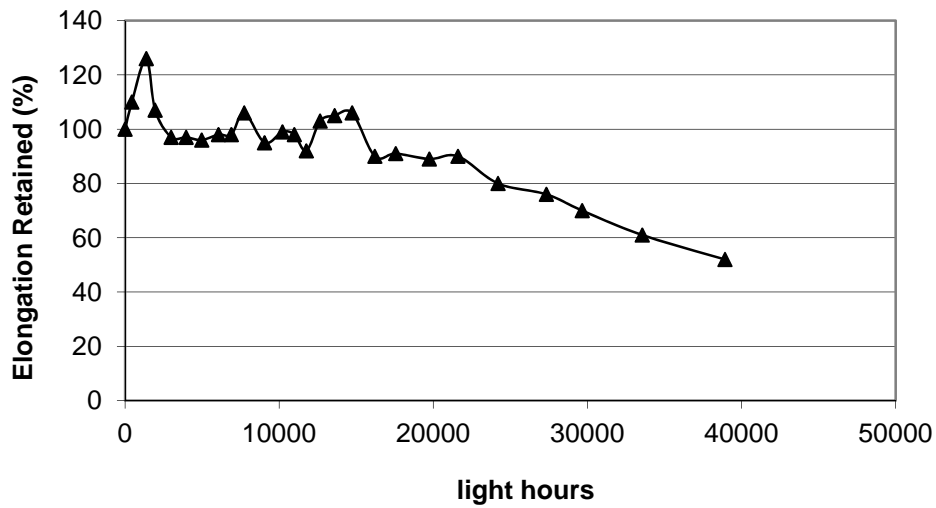
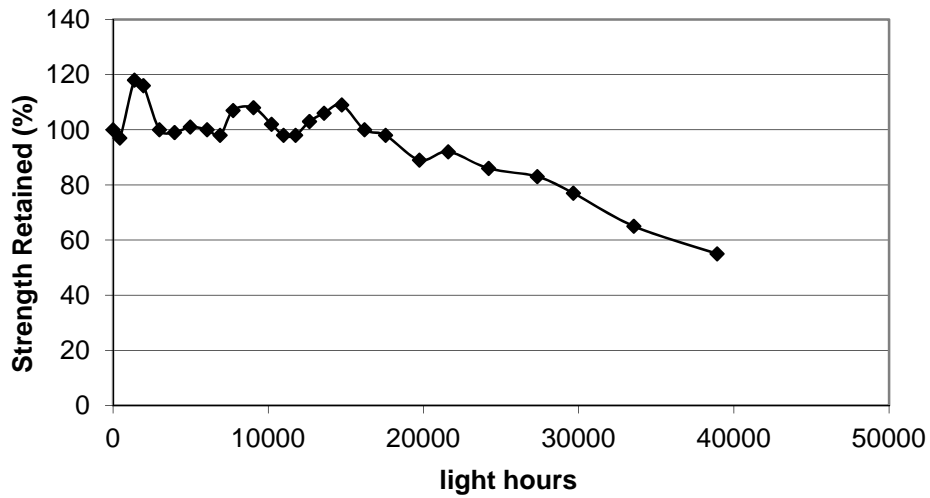


Figure 8a - UV degradation of a fPP-geomembrane at 70°C in ASTM D7238 incubation.

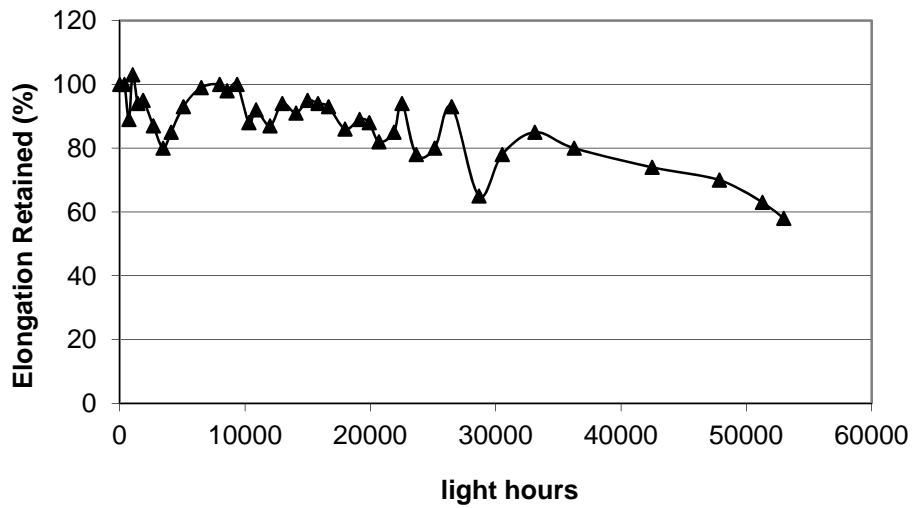
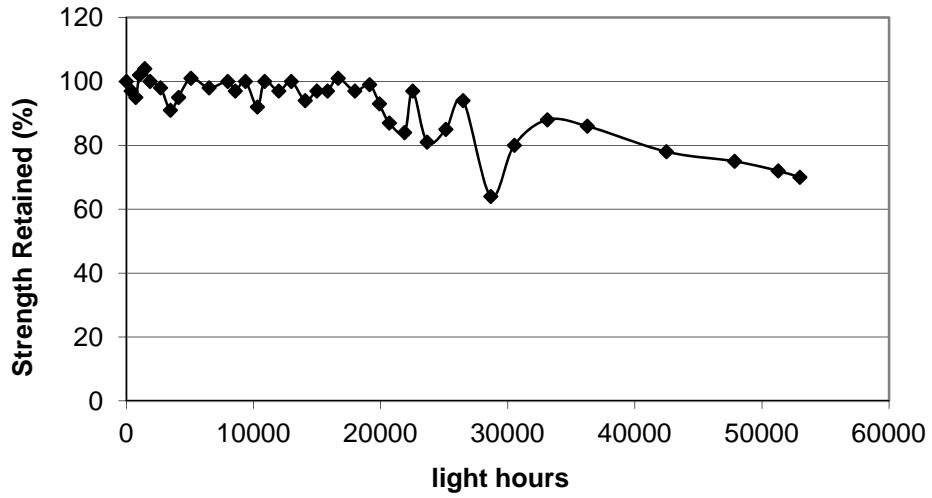


Figure 8b - UV degradation of a HDPE geomembrane at 70°C in ASTM D7238 incubation.

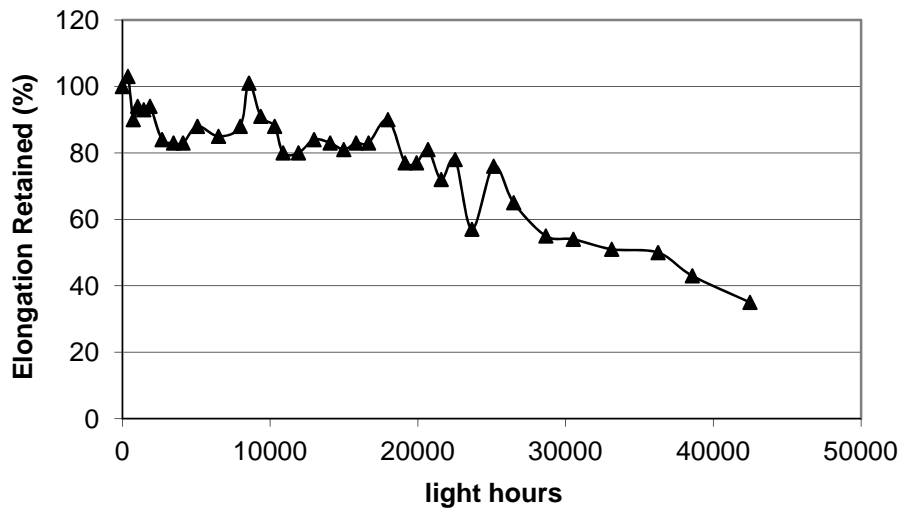
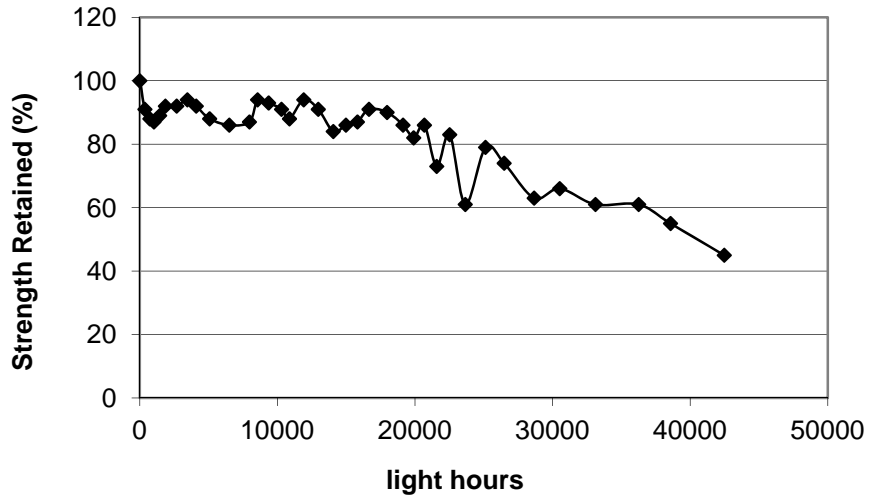


Figure 8c - UV degradation of a LLDPE-geomembrane at 70°C in ASTM D7238 incubation.

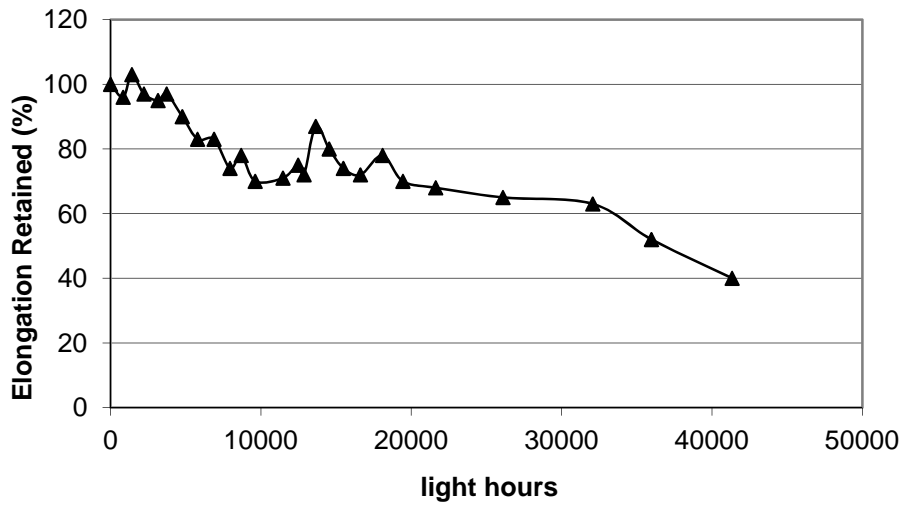
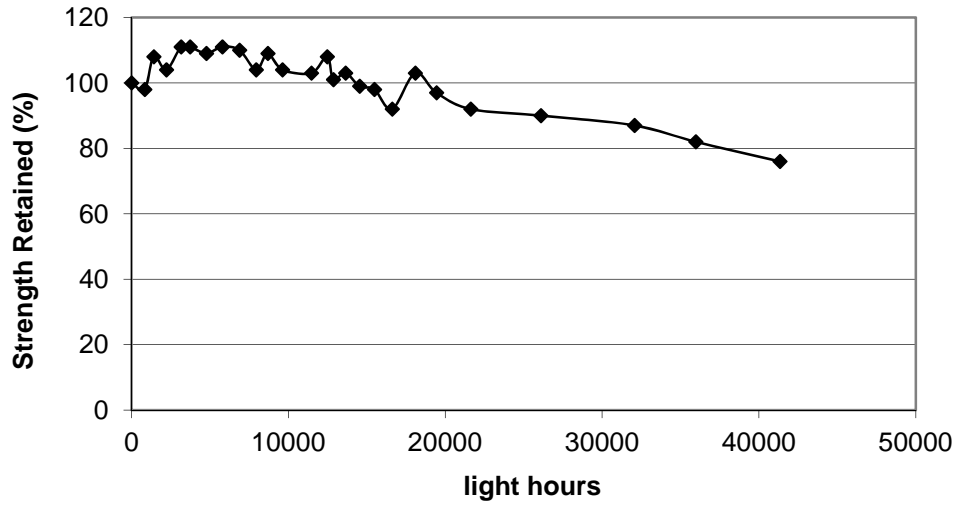


Figure 8(d) - UV degradation of an EPDM geomembrane at 70°C in ASTM D7238 incubation.

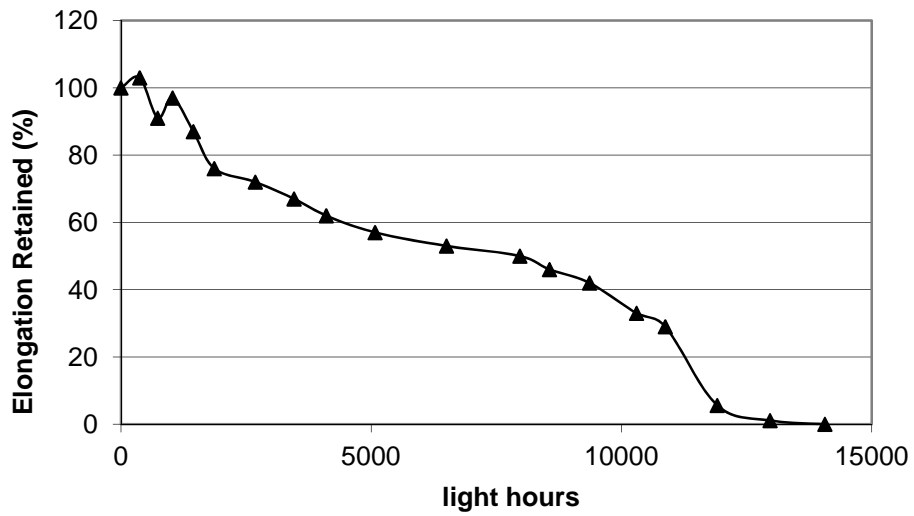
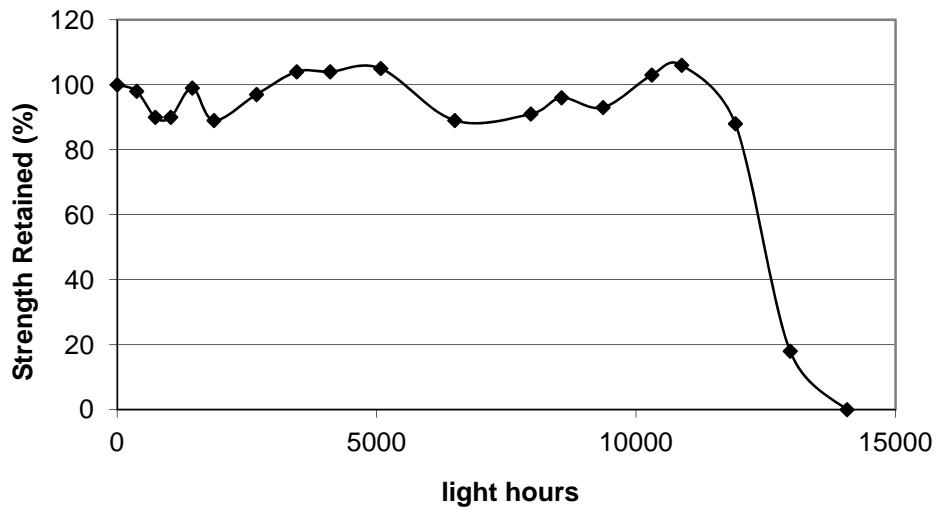


Figure 8(e) - UV degradation of PVC-N.A. geomembrane at 70°C in ASTM D7238 incubation.

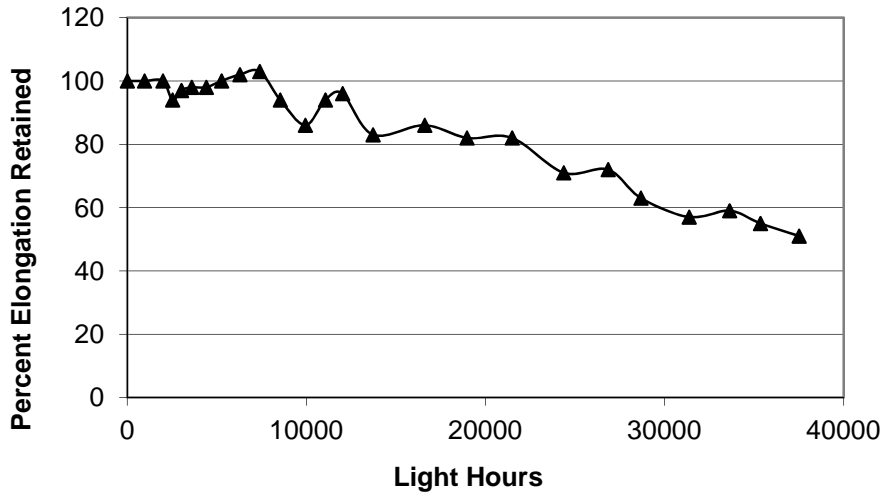
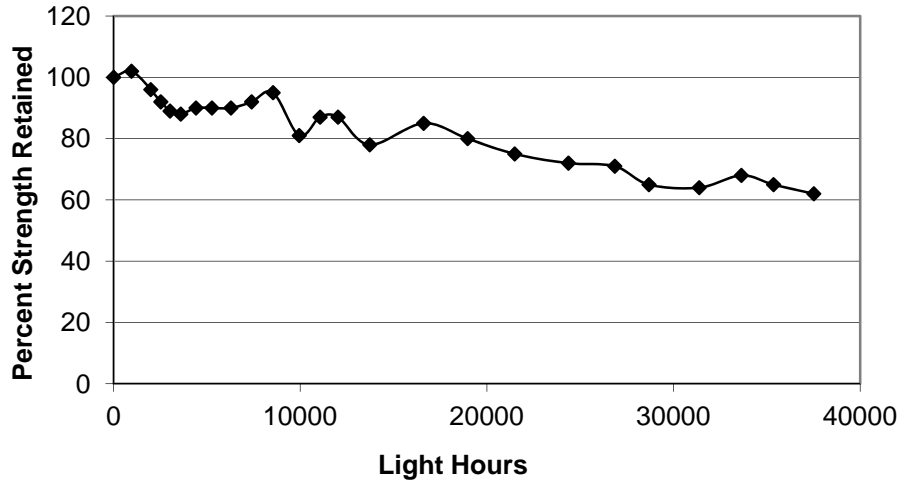


Figure 8f - UV degradation of PVC-European geomembrane at 70°C in ASTM D7238 incubation.

5.0 Lifetime Predictions and Commentary

Using the strength retained or elongation retained curves of the previous section we now are in a position to select the number of light hours for half-life of each geomembrane type evaluated. Our preference in this regard is to use elongation retained since this variable appears to degrade continuously over time. On the other hand, strength retained often behaves differently for different resins due to their unique failure mechanisms. For example, if antioxidants are being gradually depleted (as in fPP, HDPE and LLDPE) the strength decrease can indeed be gradual and somewhat track the elongation retained. For the PVC's, however, the plasticizer loss can (and often does) result in a gradual brittleness of the material and an increase in strength, sometimes beyond its original strength. When a critical amount of plasticizer is lost, however, the strength decreases abruptly indicating to us that elongation retained is clearly better to track than strength retained for PVC. Regarding EPDM, we are unsure (the material *chalks* over time) and both strength and elongation to be are considered in the assessment.

The above commentary offered, Table 6 presents our best-estimate of exposed lifetimes *in hot climates* of the geomembranes selected for this study.

Table 6 - Predicted Geomembrane Lifetimes Based on 50% Reduction of Strength and/or Elongation

Geomembrane Type	Nominal thickness (mm)	Applicable Specification	50% reduction* (light hours)	Predicted lifetime (years)
fPP	1.00	GRI-GM18	40,000	33
HDPE	1.50	GRI-GM13	≈ 60,000	≈ 50
LLDPE	1.00	GRI-GM17	40,000	33
EPDM	1.14	GRI-GM21	37,000	30
PVC-N.A.	0.75	ASTM D7171	8,000	7**
PVC-Euro	2.50	proprietary	38,000	32

*Using ultraviolet fluorescent weathering devices at 70°C set at 350 nm wavelength for a daily cycling of 20 hours light and 4 hours dark with condensation; see Figures 8a through 8f.

**Only recommended for “buried applications”.

To us, these lifetime prediction values are quite impressive and well beyond the usual warranties offered by geomembrane manufacturers of twenty years. The outlier in this regard is the PVC manufactured in North America which is specifically noted in its specification that it is for “buried applications” only. Nevertheless seven-years exposed in a hot climate is felt to be a reasonable lifetime. As will be seen in Section 6.0 of this report, however, using three temperatures and Arrhenius modeling the predicted lifetime of this particular geomembrane is apparently longer.

The other lifetime predictions shown in Table 6 range from a minimum of 30 years for EPDM to approximately 50-years for HDPE. These lifetimes are longer than most would anticipate and clearly impressive particularly when compared to our lifetime predictions of buried (or covered) applications as was shown in Table 1. Using the 20°C in-service temperature for buried HDPE of 555 years, we have a ratio of buried-to-exposed lifetime of approximately ten, a value which incidentally has been verbally suggested by others without actual data.

In reflecting on the procedures used in arriving at the prediction of Table 6 we admittedly took license with respect to the following issues.

- (i) Use of the ultraviolet fluorescent devices for incubation so as to obtain 50% reduction in strength or elongation, whereas the spectrum of the xenon arc devices is more realistic throughout the light spectrum, recall Figure 2a.
- (ii) The absence of other real-life atmosphere phenomena in the degradation of exposed geomembranes. For example, ozone, pollution, elevation, orientation, aggressive precipitation, etc., are not modeled in the incubation device.
- (iii) The use of a correlation factor based on flexible polypropylene (fPP) geomembrane failures for other types of geomembranes. This is the situation for EPDM and particularly for PVC in which failure mechanisms are different than with the polyolefins.

In this regard, the more widely accepted lifetime prediction procedure of time-temperature-superposition followed by Arrhenius modeling is clearly preferred and will be the subject of Part II of this study. A glimpse at the procedure and its contrast to this correlation factor approach follows.

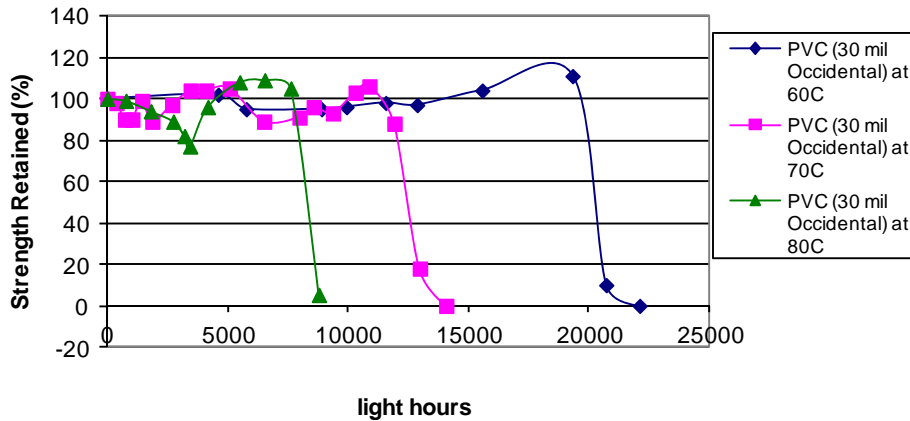
6.0 Preview of Part II of This Study

Outlined in Section 1.2 of this report was the generally accepted method of lifetime prediction used by polymer scientists and engineers; we consider this to be the justification that time-temperature-superposition is valid. This tacitly assumes that all polymer degradation mechanisms are proportionate to temperature with higher values being more aggressive and lower values less so, in a uniform (but not necessarily linear) manner. As shown in Figure 4a the procedure requires incubation at multiple temperatures which are all elevated well above the anticipated field service temperature. The higher these incubation temperatures are set, the shorter will be the time to reach a 50% property retained from which one can then plot the Arrhenius graph as shown in Figure 4b. That said, one cannot use excessively high incubation temperatures since there may be degradation mechanisms occurring which do not take place at field service temperatures. At GSI, we have limited this maximum incubation temperature to a relatively conservative value of 80°C. Note that others use higher values but we have been cautioned in this regard. Since at least three different temperatures are required, the incubation temperature sequence being used at GSI is 80, 70 and 60°C.

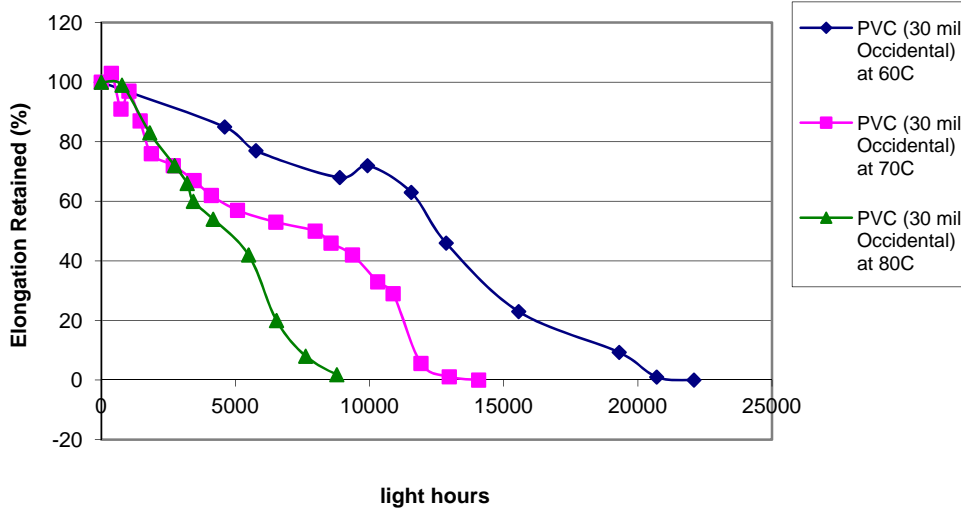
In this report, we have presented the 70°C incubation data to reach half-life in either strength or elongation. That said, we are presently incubating all of the geomembranes mentioned in this report at 80° and 60°C temperatures. While the 80°C data is now at 25,000 light hours and some geomembranes have reached their 50% retained values, the 60°C data is only out to 13,000 light hours. To start the 60°C incubations last was, of course, an unwise decision on our part since the lowest incubation temperature should have been started first. Insofar as a weak defense of this

decision is concerned, when we started the project seven-years ago we had not planned to do more than incubation at a single temperature. Clearly in hindsight we would have proceeded differently.

However, we do have one material which degraded faster than the others (recall Table 6) and it is PVC produced in North America which should only be used for buried applications. It is labeled PVC-N.A. in this report. Presently, both the 80°C and the 60°C incubations are concluded and the data is given in Figure 9. Here one can see that the strength retained curves sometimes go higher than the as-received strength. They appear to stay between 80 and 110% until they very abruptly decrease to the point where they cannot be even die-cut for test specimens without brittle cracking. Conversely, the elongation retained curves gradually decrease from their as-received elongation value, passing a well-defined 50% half-life value, and then continuing to zero. Also, to be noted is that both sets of curves for strength retained and elongation retained are well ordered among their 60, 70 and 80°C incubation temperatures.



(a) Percent strength retained curves



(b) Percent elongation retained curves

Figure 9 - Time-temperature-superposition curves of PVC-N.A. geomembranes.

Using these two data sets, the Arrhenius curves are plotted wherein the inverse of the incubation temperatures (in degrees Kelvin) are plotted against their accompanying reaction rates, which are the inverse of the respective 50% property retained values. These three data sets (one for each incubation temperature) are then plotted on the Arrhenius graph, connected by a least-squares curve fitting line, and the slope is then obtained. The slope of the curve, i.e., E_a/R , is the activation energy divided by the gas constant and is a characteristic of the ultraviolet degradation process. From this point,

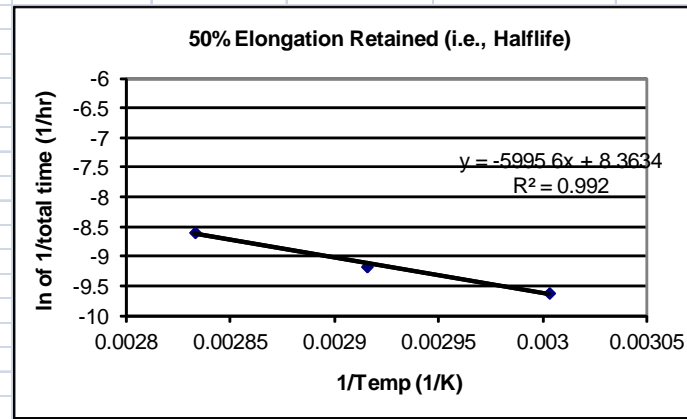
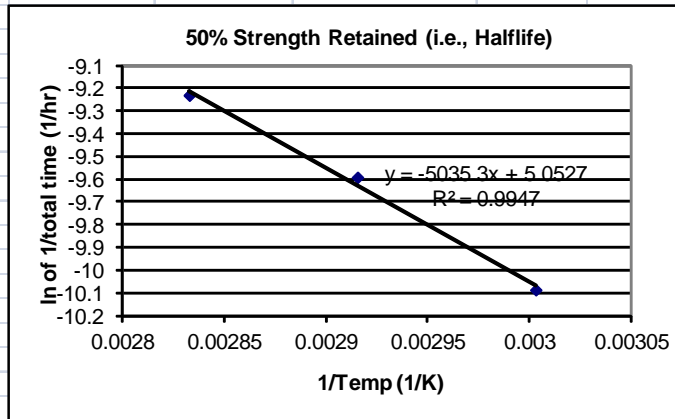
one can extrapolate the Arrhenius curve *down* to any field service temperature. This process was indeed done for the data of Figure 9 with the resulting spread sheet information that follows as Figure 10. Using this data set for comparison of predicted lifetime of this particular PVC geomembrane in the hot climates of West Texas and Southern California (with annual average maximum temperatures of 27°C) gives predicted lifetimes of 14.5 years based on strength retained and 13.0 years based on elongation retained (interpolation of this exponential data was required). These values can be compared to the 7 years given in Table 6 with the comment that this process of time-temperature-superposition followed by Arrhenius modeling is (by far) the more authoritative of the two methods. The values are also felt to be substantial for a material recommended for buried applications only. Also, recall field data by Rohe (2004) which gave 25-year performance and still no failure albeit in the cold climate of Wisconsin (which is $\simeq 13^{\circ}\text{C}$). This type of data evaluation and analysis will be the subject for all of these geomembranes in Part II of the study. Please note, however, that the Part II of the study will not be available for many years (at least 5 to 7 years) due to our lack of foresight in beginning the 60°C incubations. We will keep you posted as results become available.

Lifetime of PVC (Occidental) Based on Breaking Strength

50% Strength Retained (Half-life)					
Light Time (hr) (50% Prop.)	Total Time (hr) (50% Pro.)	1/t (1/hr) (50% Pro.)	ln(1/t) (1/hr) (50% Pro.)	Test Temp (oC)	1/T (1/K)
8500	10200	9.80392E-05	-9.230142999	80	0.002832861
12200	14640	6.8306E-05	-9.591512788	70	0.002915452
20000	24000	4.16667E-05	-10.08580911	60	0.003003003

Lifetime of PVC (Occidental) Based on Breaking Elongation

50% Elongation Retained (Half-life)					
Light Time (hr) (50% Prop.)	Total Time (hr) (50% Pro.)	1/t (1/hr) (50% Pro.)	ln(1/t) (1/hr) (50% Pro.)	Test Temp (oC)	1/T (1/K)
4500	5400	0.000185185	-8.594154233	80	0.002833
8000	9600	0.000104167	-9.169518377	70	0.002915
12500	15000	6.66667E-05	-9.61580548	60	0.003003



Equation: Y = Ax+C	
A	C
-5035.3	5.0527

Equation: Y = Ax+C	
A	C
-5995.60	8.36

Activation Calculation		
Slope	Gas Constant (MJ/mol-K)	Activation Energy (MJ/mol)
-5035.3	8.314	-41.8634842

Activation Calculation		
Slope	Gas Constant (MJ/mol-K)	Activation Energy (MJ/mol)
-5995.6	8.314	-49.8474184

Prediction		
Temperature	Lifetime (hours)	Lifetime (years)
80	10200	1.2
70	14640	1.7
60	24120	2.8
50	37664	4.3
40	61977	7.1
30	105393	12.0
20	185837	21.2

Prediction		
Temperature	Lifetime (hours)	Lifetime (years)
80	5400	0.6
70	9600	1.1
60	15000	1.7
50	26872	3.1
40	48624	5.6
30	91497	10.4
20	179764	20.5

Figure 10 - Procedure to obtain Arrhenius graphs from halflives of PVC-N.A. for different incubation times and subsequent lifetime predictions down to 20°C.

References

ASTM D4355, Standard Test Method for Deterioration of Geotextiles by Exposure to Light, Moisture and Heat in a Xenon Arc Type Apparatus.

ASTM D7176, Standard Specification for Nonreinforced Polyvinyl Chloride (PVC) Geomembranes Used in Buried Applications.

ASTM D6693, “Standard Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes.

ASTM D7238, Standard Test Method for Effect of Exposure of Unreinforced Polyolefin Geomembrane Using Fluorescent UV Condensation Apparatus.

Bonaparte, R., Daniel, D. E. and Koerner, R. M. (2002), “Assessment and Recommendations for Improving the Performance of Waste Containment Systems,” EPA/R-02/099, December, ≈ 2000 pgs.

Case, M. E., Koerner, G. R., Hsuan, Y. G. and Koerner, R. M. (2010), “Case History of a 16-Year Old Exposed HDPE Geomembrane Cover,” Proc. 9 IGS Conference, Brazil, May 23-27, pp.

GRI-GM13, Test Methods, Properties and Testing Frequency for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes.

GRI-GM17, Test Methods, Properties and Testing Frequency for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes.

GRI-GM18, Test Methods, Properties and Testing Frequency for Flexible Polypropylene (fPP and fPP-R) Nonreinforced and Reinforced Geomembranes.

GRI-21, Test Methods, Properties and Testing Frequency for Ethylene Propylene Diene Terpolymer (EPDM) Nonreinforced and Scrim Reinforced Geomembrane.

Koerner, R. M. (2012), Designing With Geosynthetics, 6th Edition, Xlibris Publishing Co., Indianapolis, Indiana, 950 pgs.

Pasquini, N. (Ed.), (2005), Polypropylene Handbook, 2nd Edition, Hanser Publishing Co., Munich, 584 pgs.

Rohe, F. (2004), “20-Year Lifetime of PVC Geomembranes for Oil Containment Reservoirs,” Federation of Solid Waste and Recycling Annual Conference, Sagamore, New York (presentation only).

Van Wijk, W. and Stoerzer, M. (1986), “UV Stability of Polypropylene,” Proc. 3rd Intl. Geosynthetics Conference, Vienna, Austria, pp. 851-855.

Yako, M. A., Koerner, G. R., Koerner, R. M. and Hsuan, Y. G. (2010), "Case History of a 20-Year Old Exposed HDPE Surface Impoundment Liner," Proc. 9th IGS Conference, Brazil, May 23-27, pp. 805-808.