LIFETIME PREDICTION OF POLYMERIC GEOMEMBRANES
USED IN NEW DAM CONSTRUCTION AND DAM REHABILITATION

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Abstract

Exposed polymeric geomembranes have been used for waterproofing dams in Europe since the 1960’s. Initial attempts were questionable, but since the 1980’s there has been considerable success. Conversely, unexposed geomembranes have performed for longer timeframes and have also had the requisite research on their lifetime prediction.

This paper presents the authors experience in lifetime prediction of unexposed HDPE geomembranes and illustrates the methodology as it applies to other types of geomembranes. It also presents the methodology of lifetime prediction for exposed geomembranes using laboratory weatherometers. This method is counterpointed by field experiences of exposed geomembranes to date. The paper concludes with recommendations for potential use of geomembranes in dam waterproofing in a manner so as to proceed with confidence.

1.0 Relevant Applications

Of the many types of hydraulic structures that are candidate applications for geomembrane waterproofing, this section will focus on three; earth and earth/rock dams, roller compacted dams and concrete/masonry dams. Both new and rehabilitated structures are involved, as are nonexposed and exposed geomembranes.

1.1 Earth and Earth/Rock Dams

The traditional construction of new earth and earth/rock dams invariably utilizes clay corewalls for their hydraulic barrier. This stems from historical precedence and has served the industry well. Only in isolated situations where clay soils are simply not available or amending on-site soils with bentonite is too expensive would a geomembrane be considered. However, this is rarely the case. On the other hand, rehabilitation of earth and earth/rock dams is another matter entirely. Such dams which have leakage through their embankment section have been retrofitted with geomembranes in a very straightforward manner. Eigenbrod, et al.(1) illustrates an early example. Shown in Figure 1(a) is a cross section of a rehabilitated structure, in which it is seen that a geomembrane is on the upstream face of the compacted tailings dam immediately beneath a crushed rock layer. A high-strength geotextile was placed between the geomembrane and the crushed rock to protect the geomembrane from puncture and provide veneer reinforcement. Sembenelli and Rodriguez(2) illustrate many additional situations. In almost all cases, the following procedure is used:

(i) The basin is emptied.
(ii) The toe is cleaned of debris and/or excavated to form an embedment trench.
(iii) A geomembrane is placed on the upstream face of the dam and anchored at the top, toe, and at both abutments.
(iv) A geotextile is placed over the geomembrane for puncture protection and, sometimes, veneer reinforcement as well.
(v) Crushed rock (rip-rap) is placed over the geotextile with thicknesses depending on the site-specific conditions.

Figures 1(b) to (d) show different case histories where the above procedure has been used.

1.2 Roller Compacted Concrete Dams

Roller compacted concrete (RCC) dams can be addressed in a manner as just described but the steep upstream slopes generally present concerns from a rip-rap stability perspective. Of course, the geomembrane could be left exposed but to do so the sheets must be individually anchored to the dam itself. This technique of rehabilitation will be described in the next section with respect to concrete and masonry dams.

Figure 1 – Geomembranes Used as Waterproofing on the Upstream Slope of Earth and Earth/Rock Dams
The focus of geomembrane use for RCC dams has been in new construction. Here the upstream face of the dam is covered by thin prefabricated concrete panels (100 to 150 mm thick) which have had geomembranes cast onto one surface. The panels are erected with the geomembrane surface against the to-be-placed RCC core. Geomembrane cap strips are welded from one panel to the next before concrete placement. The RCC is then placed against the geomembrane with the precast concrete facing being left exposed. Figure 2 illustrates the process where it can be seen that the concrete panels provide protection to the geomembrane as well as shielding from ultraviolet degradation. This technique has been used in the United States in at least one RCC dam, Gannet Fleming Inc.\textsuperscript{(3)}, and is commonly used in Europe.

Figure 2 – Geomembrane Used as Waterproofing on the Upstream Face of a RRC Dam

(a) CARPI, Inc.\textsuperscript{(4)} Anchorage Method of Panels for RCC Dams
(b) Geomembrane Faced Panel Being Erected
(c) Welding Geomembranes Cap Strips Between Panels
(d) Core Concrete Being Placed Against Geomembrane
1.3 Concrete and Masonry Dams

To our knowledge geomembrane waterproofing has never been used in new construction for concrete or masonry dams. Rehabilitation of both concrete and masonry dams, however, is another matter altogether. Table 1 gives a glimpse at such usage in Italy as of 1987. The practice has spread throughout Europe since that time and as many as 50 examples are available.

Figure 3 presents the common method of installation. While the geomembrane eventually covers the entire upstream face of the dam, it is installed in vertical strips of 2 to 4 meters in width. These strips are fixed to the dam by means of batten strips which are held by anchor bolts. (The installation of these anchor bolts are the most time consuming and expensive aspect of the installation). Several ingenuous batten strip designs are available; one designated as “profiles” by its inventor CARPI Tech S.A. (4). It consists of a patented set of back-to-back channels which tensions the geomembrane as the channels are matted to one another. The result is intimate contact of the geomembrane to the dam. Figure 4 illustrates a number of completed projects illustrating the complexity of individual situations. Scuero and Vaschetti (5) illustrate many additional case histories.

(a) Deteriorated Concrete Dam
(b) Insertion of Anchor Bolts
(c) Placement of Geomembrane Rolls
(d) Partially Completed Waterproofing

Figure 3 – Geomembranes Used as Waterproofing on the Upstream Face of a Concrete Dam
<table>
<thead>
<tr>
<th>Owner</th>
<th>Type</th>
<th>Height (m)</th>
<th>Construction</th>
<th>Geomembrane</th>
<th>Location</th>
<th>Slope (H/V)</th>
<th>Surface (m²)</th>
<th>Support</th>
<th>Protection</th>
<th>Installation</th>
<th>Type</th>
<th>Thickness (mm)</th>
<th>Piano Barbellino</th>
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</thead>
<tbody>
<tr>
<td>ENEL</td>
<td>R</td>
<td>32</td>
<td>1957-59</td>
<td>UF</td>
<td>V</td>
<td>1/1</td>
<td>2600</td>
<td>DC</td>
<td>CS</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>ENEL</td>
<td>M</td>
<td>37</td>
<td>1927-30</td>
<td>UF</td>
<td>V</td>
<td>1/1</td>
<td>3500</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>ENEL</td>
<td>M</td>
<td>11</td>
<td>1925-26</td>
<td>UF</td>
<td>V</td>
<td>1/1</td>
<td>1500</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>ENEL</td>
<td>C</td>
<td>40</td>
<td>1924-29</td>
<td>UF</td>
<td>V</td>
<td>1/2.5</td>
<td>4000</td>
<td>GT</td>
<td>-</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>CBAL</td>
<td>Coff</td>
<td>13</td>
<td>1982</td>
<td>RA</td>
<td>V</td>
<td>1/2.5-1/3.0</td>
<td>28,000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>CBM</td>
<td>C</td>
<td>67</td>
<td>1981-86</td>
<td>UF</td>
<td>V</td>
<td>1/2.5-1/3.0</td>
<td>46,000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>ENEL</td>
<td>C</td>
<td>58</td>
<td>1925-28</td>
<td>UF</td>
<td>V</td>
<td>1/2.5-1/3.0</td>
<td>10,000</td>
<td>GT</td>
<td>GT</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>ENEL</td>
<td>C</td>
<td>69</td>
<td>1926-31</td>
<td>UF</td>
<td>V</td>
<td>1/2.5-1/3.0</td>
<td>5,500</td>
<td>GT + RR</td>
<td>GT</td>
<td>-</td>
<td>UF</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: R: Rockfill Dam; M: Masonry Dam; C: Concrete Dam; Coff: Cofferdam; ENEL: Ente Nazionale Energia Elettrica; CBAL: Consorzio Bonifica Apulo-Lucano; CBM: Consorzio Bonifica Musone; UF: Upstream face; RA: Reservoir area; DC: Draining concrete; C: Concrete Dam; CS: Concrete slabs; RR: Riprap; EG: Elastomeric geomembrane; PIB: Polyisobutylene; PVC: Polyvinyl chloride; GT: Geotextile; IIR: Isoprene-isobutylene rubber.
The geomembrane is never placed directly against the deteriorated concrete or masonry face of the dam. Either a thick needle-punched nonwoven geotextile or a geonet composite is placed first and then the geomembrane placed against this dual-functioning protection and drainage material. Leakage that may pass the geomembrane is collected at the toe of the dam and properly conveyed through the dam cross section or into a drainage gallery.

The treatment at the toe of the dam, and its abutments, is critical to the success of such installations. Special care in cleaning of debris and loose rock is necessary for adequate geomembrane anchorage. Thus, dewatering of the basin is very desirable. However if not possible, this type of remediation has recently been accomplished underwater using divers and related equipment, Wilkes(6).

1.4 Summary of Applications

In this section we have presented a brief overview of geomembranes in both new and rehabilitated dams. There are many examples in the literature. This activity is perhaps exemplified by a new ICOLD document entitled: “Geomembrane Sealing Systems for Dams: An Advanced Technology” which will be released shortly.

This overview was purposely arranged into the three categories presented so as to focus on the geomembranes themselves and the general demands that must be satisfied. Clearly, the situation of the geomembrane being nonexposed or exposed is paramount.
This is not only from the perspective of ultraviolet and elevated temperature degradation but also from accidental or intentional (vandalism) damage. If at all possible the geomembrane should be covered and in the first and second categories this can be reasonably accomplished. For masonry and concrete dams, however, the geomembranes are exposed and their lifetime must be assessed accordingly.

High temperature accelerates all degradation mechanisms for geomembranes in these applications and it must be considered accordingly. Obviously, this is a site-specific consideration but one that is very important.

All of the applications mentioned will undergo wet/dry cycling on at least part of their surface. For some geomembranes this is a factor to consider.

Lastly, freeze/thaw cycling is a factor for both the geomembrane sheets and their anchorage systems. It is again a site-specific situation, but one that should be considered from both a durability perspective and a serviceability one. It is also product-specific insofar as the geomembrane selection is concerned.

### 2.0 Geomembranes and Their Formulations

It must be recognized at the outset that all geomembranes are actually formulations of a parent resin (from which they derive their generic name) and varying amounts of other ingredients. The most commonly used geomembranes for containment and waterproofing are listed in Table 2. They are listed according to their commonly referenced acronyms which will be referenced in the text to follow.

**Table 2 – Types of Commonly Used Geomembranes and Their Approximate Weight Percentage Formulations**

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

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

The additives in the above table are particularly important. For the polyethylenes and polypropylene (collectively called “polyolefins”) the additives are antioxidants which prevent degradation until they are fully consumed or dissipated. Thus, antioxidant depletion time represents the first stage in lifetime prediction of these materials. Conversely, for plasticized PVC, the stability of the plasticizer against leaching or extraction represents the first stage in lifetime prediction. For CSPE, and to a lesser extent EPDM, the initial mechanism is cross-linking which is an embrittlement process and is its first stage in lifetime prediction.
It is also critical to recognize that elevated temperature and high stress are conditions which promote the role of degradation in all geomembranes and do so in a relatively aggressive manner. Thus, elevated temperature and stress concentrations decrease lifetime exponentially from comparably less severe conditions.

Regarding elevated temperature, it is interesting to note that the degradation rate is not governed by the highest temperature that the geomembrane experiences. While this high temperature will indeed cause degradation at its corresponding rate, when the temperature decreases the rate decreases accordingly. Thus the average annual temperature is likely to be the appropriate value for lifetime prediction purposes. Hsuan, et al.\(^8\) have shown that PP and PET geotextiles which have been partially degraded using laboratory weatherometers (simulating both sunlight and elevated temperatures), did not continue their degradation when removed from such exposure. From a practical aspect, this suggests that a geomembrane exposed to a high afternoon temperature for a short period of time will only degrade during that time at the high rate. As the temperature decreases, the degradation rate decreases accordingly.

### 3.0 Lifetime Prediction

The aging of polymers implies some type of degradation process usually involving the breaking of covalent bonds, e.g., thermal-oxidation, ultraviolet-degradation, etc., Struik\(^9\). This process eventually leads to degradation of engineering properties. Thus, the polymer becomes progressively more brittle albeit in very slow stages. From an dam application point of view, aging is the important degradation mechanism. In this section, the different stages of aging of geomembranes are described.

Conceptually, the aging process of a thermoplastic geomembrane can be considered in three distinct stages, as shown in Figure 5. These stages are designated as depletion time of antioxidants; induction time to the onset of polymer degradation; and degradation of the polymer resulting in changes of some property or properties to an arbitrary level, e.g., to 50% of its original value.

![Figure 5 – Three Conceptual Stages in Chemical Aging of Polyolefin Geomembranes](image)

A = depletion time of antioxidants
B = induction time to onset of polymer degradation
C = time to reach 50% degradation of a particular property
3.1 Depletion of Antioxidants: Stage A

The purposes of antioxidants are to prevent polymer degradation during processing and to prevent oxidation reactions from taking place during the first stage of service life. Obviously, there can only be a given amount of antioxidants in any formulation. Once the antioxidants are completely depleted, additional oxygen will begin to attack the polymer chains, leading to subsequent stages as shown in Figure 5. The duration of the antioxidant depletion stage depends on the type and amount of antioxidants.

The depletion of antioxidants is the consequence of two processes: chemical reactions with the oxygen diffusing into the geomembrane and 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.

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. Since antioxidant depletion has been the subject of a companion paper, only this brief commentary is presented. See Hsuan and Koerner(10) for additional details.

3.2 Induction Time: Stage B

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 6(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. Thus, the acceleration stage of oxidation cannot be achieved.

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 6(b).

\[ RH \rightarrow R \cdot + H \cdot \]  
\[ \text{(aided by energy or catalyst residues in the polymer)} \]  
\[ R \cdot + O_2 \rightarrow ROO \cdot \]  
\[ ROO \cdot + RH \rightarrow ROOH + R \cdot \]

In the above, RH represents the polyethylene polymer chains; and the symbol “\cdot” represents free radicals, which are highly reactive molecules.
3.3 Polymer Degradation: Stage C

As oxidation continues, additional ROOH molecules are 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)-(6). The additional free radicals attack the polymer chain readily, resulting in an accelerated chain reaction, signifying the end of the induction period, Rapoport and Zaikov\(^{(11)}\). This indicates that the concentration of ROOH has a critical control on the duration of the induction period.

\[
\text{ROOH} \rightarrow \text{RO} \cdot \text{OH} \cdot \text{(aided by energy)} \quad (4)
\]

\[
\text{RO} \cdot + \text{RH} \rightarrow \text{ROH} + \text{R} \cdot \quad (5)
\]

\[
\text{OH} \cdot + \text{RH} \rightarrow \text{H}2\text{O} + \text{R} \cdot \quad (6)
\]
The oxidation produces a substantial amount of free radical polymer chains (R⋅), 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-lifetime, 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.

3.4 Plasticizer Migration

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 water-to-plasticizer 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 and vice versa. See Miller, et al.\textsuperscript{(12)} and Hammon, et al.\textsuperscript{(13)} for more detail in this regard.

4.0 Geomembrane Lifetime Prediction

4.1 Nonexposed Geomembranes

Most of the laboratory lifetime prediction studies on nonexposed geomembranes have been associated with landfills. The liners beneath solid waste must be serviceable by federal regulations for times exceeding 30-years. Some agencies require substantially longer lifetimes. Since HDPE is usually the geomembrane type, most studies have focused on this particular material.

Sangam and Rowe\textsuperscript{(14)} investigated the antioxidant depletion time (i.e., Stage A in Figures 5 and 6(b)) for a 2.0 mm HDPE geomembrane immersed in air, water and leachate at 85 and 55°C. They then used Arrhenius modeling for zero oxidative induction time (see Hsuan and Guan\textsuperscript{(15)} and Hsuan and Koerner\textsuperscript{(10)} for the procedure) at various service temperatures. Table 3 presents their data for air, water and leachate immersion. Note that they also made projected combinations, of which the “air-water” system replicates geomembranes in dam applications. At 20°C, they predict Stage A in Figures 5 and 6(b) to be 180 years.
Table 3 – Estimated Antioxidant Depletion Time (years) for a Primary HDPE Geomembrane (ref. Sangram and Rowe\textsuperscript{14})

<table>
<thead>
<tr>
<th>Temp (\degree C)</th>
<th>Laboratory Tested</th>
<th>Leachate-air</th>
<th>Leachate-water</th>
<th>Air-water</th>
<th>Leachate-unsaturated soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air</td>
<td>Water</td>
<td>Leachate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>390</td>
<td>190</td>
<td>40</td>
<td>210</td>
<td>110</td>
</tr>
<tr>
<td>15</td>
<td>330</td>
<td>160</td>
<td>36</td>
<td>180</td>
<td>100</td>
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<td>230</td>
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<tr>
<td>30</td>
<td>90</td>
<td>44</td>
<td>12</td>
<td>50</td>
<td>28</td>
</tr>
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</table>

This value nicely substantiates earlier work by Hsuan and Koerner\textsuperscript{10} who found times for antioxidant depletion in HDPE geomembranes of 200 years for standard OIT tests and 215 years for high pressure OIT tests at 20\degree C temperature. Furthermore, Hsuan and Koerner have juxtaposed their Stage A data, with retrieved HDPE containers for Stage B and literature values for Stage C, to obtain half-life predictions. Table 4 presents this data which results in a 712-year prediction at 20\degree C temperature. This lifetime prediction value has recently been corroborated by Müller and Jakob\textsuperscript{16}. More important for dam waterproofing, however, is that the predicted half-life exponentially decreases with increasing service temperature. For example, at 40\degree C temperature, the predicted half-life falls to 109-years.

Table 4 – Lifetime Prediction of HDPE at Elevated Field Temperatures

<table>
<thead>
<tr>
<th>Field Temperature</th>
<th>Stage “A” (yrs.)</th>
<th>Stage “B” (years)</th>
<th>Stage “C” (yrs.)</th>
<th>Total Ave. Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (deg)</td>
<td>F (deg)</td>
<td>Std OIT</td>
<td>HP-OIT</td>
<td>Ref. 1</td>
</tr>
<tr>
<td>20</td>
<td>68</td>
<td>200</td>
<td>215</td>
<td>30</td>
</tr>
<tr>
<td>25</td>
<td>77</td>
<td>135</td>
<td>144</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>86</td>
<td>95</td>
<td>98</td>
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<td>35</td>
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</tr>
<tr>
<td>40</td>
<td>104</td>
<td>45</td>
<td>47</td>
<td>10</td>
</tr>
</tbody>
</table>

Notes: Stage “A” measured values from G. Hsuan research
Stage “B” estimated values from field samples
Stage “C” literature values from Martin & Gardner\textsuperscript{17} and Viebke, et al.\textsuperscript{18}

Table 2 listed six possible resin types for use in dam applications. Of these HDPE is probably the least used in dam applications (due to its high expansivity properties), yet it is the material about which most lifetime prediction is known. Quite possibly, HDPE is the most stable of polymers resulting in the longest lifetime, however, this remains to be seen. Clearly, a tremendous amount of research is needed to estimate the half-life of all of the various geomembranes which are used, or being considered for use, in dam applications.
4.2 Exposed Geomembranes

Lifetime prediction of exposed geomembranes have taken two very different pathways; prediction from laboratory weatherometers and anecdotal feedback from field performance.

For an accelerated simulation of direct sunlight 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.

The Xenon Arc Weatherometer (ASTM G151) 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 settlings 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 weatherometer is commonly used method for exposed geosynthetic lifetime prediction.

Fluorescent UV Lamps (ASTM G154) are an alternative type of accelerated laboratory test device which became available in the early 1970’s. They only reproduce the low wave length of the sunlight spectrum. 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 sunlight quite well. This device (as well as the other weatherometers) can handle elevated temperature and programmed moisture on the test specimens.

The literature is abundant with negative comments about the validity of laboratory weatherometer studies. In spite of these comments, owners and designers of facilities using geosynthetics are calling for product certification and guarantees concerning resistance to photo-initiated degradation. For example, all generic geosynthetic specifications require a certain percentage of strength retained after a stipulated duration of exposure in either Xenon Arc or UV-fluorescent weatherometers. Indeed, use of laboratory weatherometers represents a possible way to predict lifetime performance if not from a rigorous quantitative approach at least from a comparison of one material to another.

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 mm thick polyisobutylene bonded directly to the face of the dam. There were numerous problems encountered as described by Scuero\textsuperscript{19}. Similar experiences followed using PVC geomembranes. In 1980, a geocomposite was first used at Lago Nero (recall Table 1) which had a 200 g/m\textsuperscript{2} 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 generally used for these dams is proving to be quite durable. Tests by the dam owners on residual properties show only nominal changes in properties. As indicated in Miller, et al.\(^{12}\) and Hammond, et al.\(^{13}\), however, different PVC materials and formulations can result in different behavior.

Regarding exposed geomembranes in flat roofs, past practice in the USA is almost all with EPDM and CSPE and, more recently, with fPP, recall Table 2. 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\(^5\). 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 dam waterproofing of all of the types mentioned in this paper.

### Summary and Recommendations

There appears to be at least three different applications for geomembranes in dam waterproofing:

<table>
<thead>
<tr>
<th>Dam Application</th>
<th>UV-Exposed</th>
<th>Temperature</th>
<th>Freeze/Thaw Cycle</th>
<th>Wet/Dry Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth or Earth Rock</td>
<td>no</td>
<td>below ambient</td>
<td>varies</td>
<td>yes</td>
</tr>
<tr>
<td>Roller compacted concrete</td>
<td>no</td>
<td>below ambient</td>
<td>nominal</td>
<td>yes</td>
</tr>
<tr>
<td>Masonry or Concrete</td>
<td>yes</td>
<td>ambient</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

As such, the variety of conditions make a universal lifetime prediction extremely different. Thus, this paper has described research on the geomembrane type which has had the majority of effort, that being covered HDPE used in landfill applications. While this material promises service lifetime of hundreds of years, the elevated temperatures of exposed or nearly exposed geomembranes in dam applications greatly reduce such long lifetimes. It was shown that HDPE decreases its predicted half-life from 712-years at 20°C, to 109-years at 40°C. The complicating issue of freeze/thaw cycling does not appear to be a concern, Comer, et al.\(^{20}\). On the other hand, wet/dry cycling has not been researched to our knowledge.

Exposed geomembrane lifetime was addressed from the perspective of using laboratory weatherometers to accelerate the aging process. However, there are many critics of this approach. Alternatively, field performance is very unequivocal. Experience in Europe, mainly with PVC, 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, give 20\(^*\)-years of service. The newest geomembrane type in such applications is fPP which currently carries similar warranties.
To the authors, it is clear that European practice, with its widespread use of geomembranes for dam waterproofing, is quite apart from practice in the USA. In this regard it is recommended to proceed as follows so as to develop the requisite confidence needed for use of geomembranes as dam waterproofing:

(i) Document and analyze geomembrane dam rehabilitation in Europe (and elsewhere) with particular emphasis on durability.
(ii) Document and analyze geomembrane use in flat roofs and other exposed applications, e.g., pond and reservoir liners as well as canal liners.
(iii) Extend HDPE laboratory studies on covered geomembranes to other polymer types such as PVC, LLDPE, fPP, EPDM and CSPE.
(iv) Evaluate, to the extent possible, various additives particularly antioxidants in polyolefins (HDPE, LLDPE and fPP) and plasticizers in PVC.
(v) Initiate a broad research program on lifetime prediction of exposed geomembranes (of all types and formulations) using laboratory weatherometers.

Acknowledgements

The financial assistance of the member organizations of the Geosynthetic Institute and its related institutes for research, information, education, accreditation and certification is sincerely appreciated. Their identification and contact member information is available on the Institute's web site at <<geosynthetic-institute.org>>.

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