Longevity of Geosynthetic Cover Components – 15450

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ABSTRACT

Geosynthetics form many of the key components in modern landfill cell and final cover designs. Models for the long-term performance assessment of systems incorporating these components have traditionally relied on a small number of standard assumptions originally developed to address the needs of the Resource Conservation and Recovery Act (RCRA) Subtitle D solid waste industry. These past estimates demonstrated that, even under a series of highly conservative factors, the longevity of these components far exceeds the requirements for typical solid waste facilities. Traditionally, the interpretation of the geosynthetic degradation research has been deterministic as opposed to probabilistic, often due to the relative scarcity of degradation data for particular formulations and environmental conditions. Long-term studies of the mechanical and chemical properties of geosynthetics subjected to accelerated aging processes have been conducted in an attempt to better quantify their longevity to address applications where performance may be required for 1,000 years or more. Of the many cover system geosynthetic components, geomembranes appear to have the most significant impact on the long-term performance of cover systems. Based on available long-term aging studies, a series of property degradation curves and their corresponding model parameters are available for geomembranes. A strong area of need in the performance assessment of shallow disposal facilities is how to connect these research findings with inputs to probabilistic models. Significantly, factors affecting geomembrane performance, such as geomembrane thickness, anti-oxidant package, molecular weight, oxygen exposure, and drainage, can be adjusted and re-engineered using a proposed approach to meet specific performance targets.

INTRODUCTION

Geosynthetics form many of the key components in modern landfill cell and final cover designs. Typical applications include geosynthetic clay liners (GCL) and geomembranes (GM) that act as barriers to water infiltration, geotextiles (GT) that act as filters and separators, geonets (GN) and geocomposite drains that transmit subsurface water, and geogrids (GG) that are used for veneer stability and differential settlement control [1,2]. Figure 1 presents a cross-section view of the typical components of a composite final cover system incorporating geosynthetics. Common geosynthetic components of a typical final cover include the GM in place of a compacted clay liner, a GT/GN geocomposite drainage layer in place of the granular drainage media, a GCL to augment the geomembrane and/or substitute or supplement the clay barrier, and geopipes (GP) to collect cover drainage water.

Other cover components shown in Figure 1 include the topsoil layer, which resists erosion and facilitates vegetative growth; protective soil, which acts as a further buffer to erosion, animal intrusion, root growth, and frost intrusion; and the barrier clay, which acts together with the geomembrane as a composite barrier to surface water infiltration. Water is introduced to the cover system in the form of atmospheric precipitation onto the cover surface. Some of this water does not enter the soil and is drained as run-off water. Other water is stored in the topsoil, taken up by plants, and returned to the atmosphere via evapotranspiration. The remaining water percolates vertically to the drainage media, where it is intercepted by the composite barrier and diverted to drainage structures. A smaller fraction of the percolated water may enter the barrier clay through holes in the geomembrane or via diffusion through the geomembrane. Water that enters the barrier clay can then percolate through the barrier clay and eventually enter the landfill below.

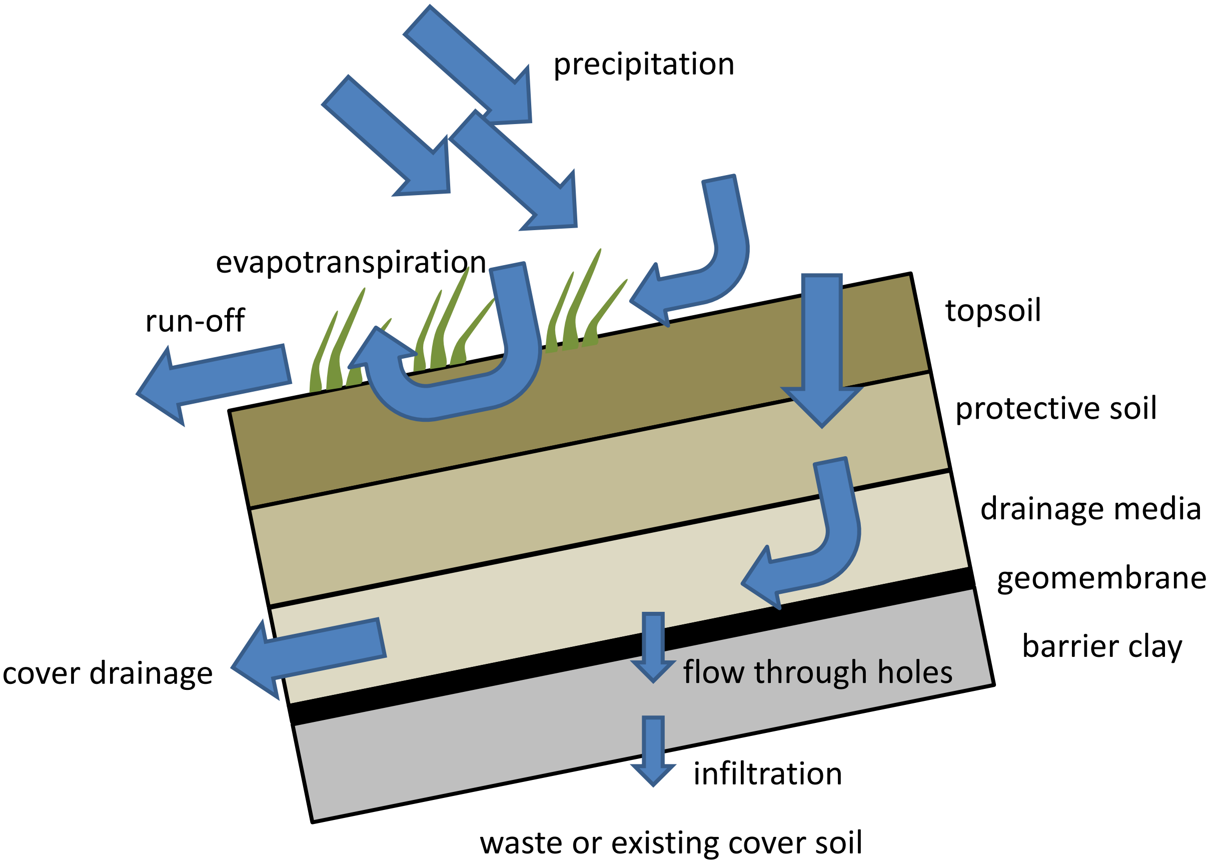

Figure 1. Typical Cover System Configuration Incorporating Geosynthetics

Given the important roles served by the various geosynthetic components of the typical cover system in limiting the infiltration of surface water into landfills, significant attention is given to the ability of these components to maintain adequate performance over the desired life of the cover system. Of the various factors that can affect this long-term performance, the durability of the geosynthetic materials is a key consideration. Accordingly, a number of theoretical, laboratory, and field experimental studies have examined the durability of geosynthetics and produced conceptual and quantitative models to describe changes in material properties with time (e.g., [3,4,5,6,7,8,9,10,11,12]). Table I presents different factors leading to degradation in the performance of the layers of the final cover system.

The risks associated with each of the factors identified in Table I can be addressed through engineering design of final cover systems. Of the factors identified in Table I, polymer degradation has been identified as an issue of particular concern [7,11,13]. Polymer degradation is related to the chemistry of the polymers used in geosynthetic manufacture. In order to quantify the longevity of geosynthetic cover components with respect to polymer degradation, studies examining the chemical processes involved must be reviewed.

TABLE I. Factors Affecting the Long-Term Performance of Cover Systems [1,2]

	Cover System Layer				
Degradation Factor	Topsoil/ Protective soil	Drainage Layer	Geomembrane	Geosynthetic Clay Liner (GCL)	Compacted barrier soil
Erosion	●				
Burrowing Animals	●	●	●	●	
Plant Roots	●	●			
Differential Settlement		●	●	●	●
Clogging		●			
Polymer Degradation		● (if GN/GT)	●	●	
Clay Chemical Interaction				●	●

Models for the long-term performance assessment of cover systems incorporating geosynthetic components have traditionally relied on a small number of standard assumptions originally developed to address the needs of the Resource Conservation and Recovery Act (RCRA) Subtitle D solid waste industry. The performance estimates developed using these standard assumptions have demonstrated for RCRA applications that, even under a series of highly conservative factors, the longevity (for example >200 years [1]) of the geosynthetic component materials far exceeds the requirements for typical solid waste facilities.

Long-term studies of the mechanical and chemical properties of geosynthetics subjected to accelerated aging processes have been conducted in an attempt to better quantify their longevity. This quantification is needed for applications where geosynthetics could be expected to perform for 1,000 years or more. Of particular interest for engineers designing these systems and analysts modeling their performance are parameters describing the continuous (rather than discrete) degradation in their properties and the environmental factors affecting this process. Due to the relatively short service life required in solid waste applications, the set of assumptions supporting RCRA applications necessarily do not need to consider these aspects of the degradation process, which can lead to an unnecessarily pessimistic and overly simplified model for geosynthetic performance in longer-term assessments.

Based on available long-term aging studies, a number of useful data are available that quantify the long-term performance of several important geosynthetic materials. These curves allow a more refined assessment of the longevity of systems incorporating these components, and accordingly, allow a refinement of landfill designs and projections of future risks during these facilities' lifetimes. Importantly, these studies also highlight specific design features of the geosynthetic materials and the design of final cover systems that can be engineered to achieve specific performance targets.

In the following section, a discussion of the mechanism of degradation affecting each type of geosynthetic material is discussed. Afterwards, a discussion of the quantification of these mechanisms is presented. Finally, an example framework for the interpretation of the available data and their incorporation into probabilistic models of long-term performance is proposed. Due to the complexity of the processes involved in geosynthetic material degradation, a number of abstractions of these processes are needed to facilitate performance assessments. Accordingly, a possible approach to incorporate the knowledge gained from available research is presented.

DISCUSSION OF GEOSYNTHETIC DEGRADATION

Table II presents the major types of polymeric materials typically used to construct the geosynthetic components of landfills. These materials are of particular interest to the construction of cover systems. Also shown in Table II are the geosynthetic types typically manufactured using each of these materials. The mechanisms for degradation, the factors affecting degradation, and the typical test measurements used to evaluate degradation are also provided.

TABLE II. Types of Geosynthetics and their Degradation Mechanisms [3]

Polymer Type	Geosynthetic Type (s)	Mechanism for Degradation	Factors Affecting Degradation	Test Measurements of Degradation
High Density Polyethylene (HDPE)	Geomembrane (GM) Geopipe (GP) Geogrid (GG)	Oxidation Photo-Degradation (Photo Oxidation)	Tertiary Hydrogen Atom Crystallinity Orientation Temperature Oxygen Concentration Chemistry of Surrounding Liquid Media	Tensile strength Tensile elongation Melt Index Fourier Transform Infrared (FTIR) Oxidative Induction Time (OIT - GM) Resistance to Oxidation (GT, GG)
Linear Low Density Polyethylene (LLDPE)	GM			
Flexible Polypropylene (fPP)	GM			
Polypropylene (PP)	Geonet (GN) Geopipe (GP) Geotextile (GT)			
Polyvinyl Chloride (PVC)	GM	Migration of Plasticizers Photo-Degradation (zip-elimination of HCl; degradation of plasticizers)	Type/Quantity of Plasticizer	Thickness Cold Bending Plasticizer Content Tensile Strength Tensile elongation
Polyethylene Terephthalate (PET)	GG, GT	Hydrolysis Photo-Degradation (chain scission)	Carboxyl End Group Molecular Weight Morphology	Tensile Strength Tensile elongation Molecular Weight

A more exhaustive treatment of these mechanisms is provided in the literature and review papers summarizing the state of knowledge are available, for example [3,7]. The purpose of this paper is to discuss the available data and model parameters of interest to analysts and engineers considering the longevity of these components for applications with service life values greater than 200 years. Existing studies into performance assessments of cover systems have pointed to the importance of HDPE GM degradation on long term performance of the overall system to control exposure from shallow disposal (e.g., [13,14]). Accordingly, the following discussion focuses on HDPE GM degradation. However, many of the following concepts are applicable to other geosynthetic components according to the degradation mechanisms outlined in Table II.

It is important to understand the chemical process of HDPE GM degradation in order to use consistent terminology when discussing this degradation and to allow the selection of relevant models for performance assessments. One problem with typically-used GM lifetime values is that they are not specific as to what end-of-life definition is used. The following discussion presents the HDPE GM oxidation process in order to introduce the specific terminology to be used in quantifying GM longevity in terms of cover system performance. Figure 2 presents the major stages of HDPE oxidation. The first stage is the antioxidant depletion time. Antioxidants are chemicals added to HDPE during manufacture to delay the oxidation of the HDPE material itself. The length of time to antioxidant depletion depends on a number of environmental factors as well as the type and quantity of antioxidants used in the GM formulation [3,5,8]. Following antioxidant depletion, the induction period begins, wherein the degradation of the mechanical properties of the GM due to oxidation can be detected. The following acceleration and deceleration periods are when most of the mechanical property degradation occurs.

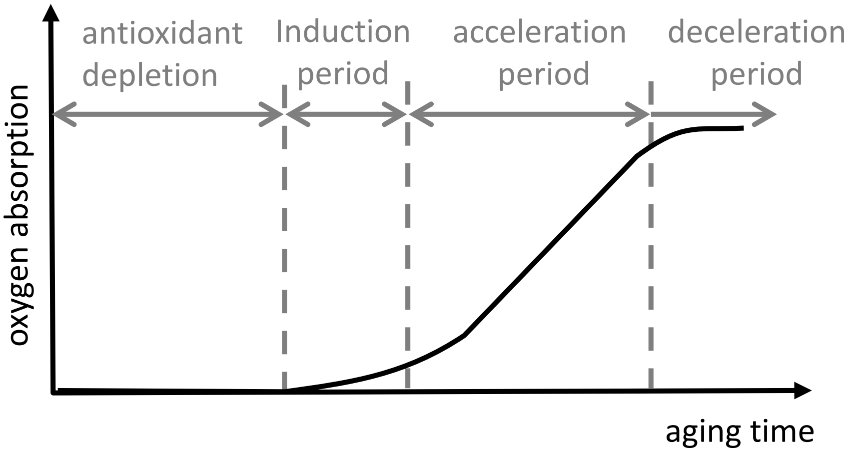

Figure 2. Stages of Oxidation in Polyolefins such as HDPE used in Geomembranes (adapted from [3])

Figure 3 illustrates the effect of the oxidation process presented in Figure 2 on the mechanical properties of HDPE GMs. The GM is considered to be significantly degraded when the mechanical properties, typically tensile strength and tensile elongation, have reached 50% of their original values. This value is often computationally convenient, as will be discussed below, since this value corresponds to the half-life of the first-order reaction equation typically used to quantify this degradation.

Based on the available literature, especially [3,9,12], there appear to be three major phases in the life of a cover system that are relevant to their performance assessment with respect to water infiltration and contaminant transport: 1) initial installation, 2) long-term chemical degradation, 3) long-term physical degradation. In the first phase, the rate of infiltration depends entirely on the quality of installation and the engineered configuration of the cover system. Infiltration of the cover can be minimized through the implementation of a robust construction quality assurance program. The resulting rate of infiltration, accounting for changes in precipitation, can be expected to continue throughout the chemical degradation phase, which for HDPE GMs is understood to be the antioxidant depletion stage of HDPE degradation.

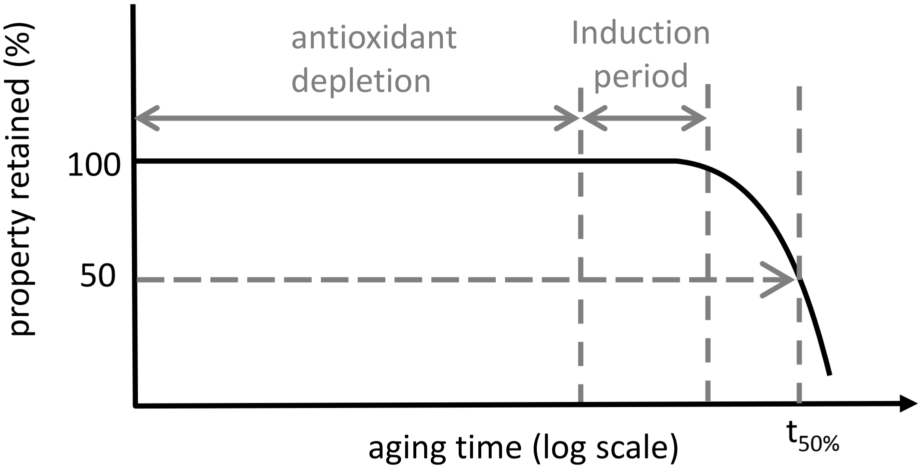

Figure 3. Stages of Oxidation of Polyolefin Geosynthetics in Terms of Engineering Property Value (adapted from [3])

The third stage then corresponds to the eventual reduction in the engineering properties of HDPE GMs in the thermal oxidation stage of HDPE degradation. It is important to note that the reduction in the mechanical properties of HDPE (i.e., tensile strength and elongation at break) does not guarantee the formation of stress cracks [9]. Accordingly, a significant reduction in properties as well as other mechanical factors are required before mechanical distress occurs and the barrier function of the HDPE GM will begin to degrade. Also important is the fact that stress cracks form preferentially at wrinkles, welds, and other defects in response to tensile stress [9,14]. Decreasing these factors can greatly reduce the incidence of stress cracks, even under degraded GM conditions.

QUANTIFICATION OF GEOSYNTHETIC DEGRADATION

A number of long-term studies into the degradation of geosynthetics are available (e.g., [3,4,5,6,7,8,9,10,11,12]). These long-term studies include both experiments where environmental conditions are similar to the design application and accelerated studies where environmental factors are adjusted to increase the rate of degradation. These accelerated tests are needed since the service life of these materials extends into the hundreds of years.

A major consideration in the quantification of geosynthetic longevity is the definition of the useful life of the material. From a performance assessment perspective, this definition is especially important since the risk of exposure is not directly related to the mechanical properties of the geosynthetics. For example, an HDPE geomembrane can be expected to continue functioning as a hydraulic barrier even if the tensile properties of the polyethylene have degraded considerably [9]. The problem of describing the long-term performance of HDPE geomembrane in its barrier role is particularly difficult for the analyst since measurement of HDPE GM impedance to flow is not an industry-standard test [15]. Indeed, the flux that can be measured through intact GM samples is extremely small [16]. Considering the importance of estimated of possible flow through a geomembrane layer in order to model transport mechanisms in a performance assessment, some quantitative guidance is needed.

Several guidance documents related to shallow disposal facility performance, (e.g., [17,18]) identify the need for quantitative, probabilistic models for engineered systems with complex behavior and large uncertainties. The aggregate performance of a composite cover system including an HDPE GM would appear to have large uncertainty since the ability of water from the surface to pass through the composite final cover would appear to vary from nearly zero to potentially measurable quantities. Typically-used deterministic hydraulic models of final cover performance, such as HELP [19], used in the RCRA solid waste industry have addressed this concern by simulating small holes in HDPE GMs that allow water to pass through. Equations for the calculation of flow through defects in the GM have been developed from theoretical and field studies [20,21,22,23]. While one of these models has been incorporated into HELP [19], recent model improvements should be considered in light of the sensitivity of performance models to this aspect of the problem. Significantly, analysts considering the problem have noted that a GM with no leaks can be expected to perform as an effectively impermeable barrier [14] while significant degradation could allow water in direct contact with the underlying clay component as though the GM is not present [13]. The reality is somewhere in between and recent knowledge enables the narrowing of these extreme bounds on the problem.

It is often assumed that geomembranes will cease to function effectively following degradation of its other engineering properties, such as tensile strength and elongation. Since there is not exhaustive data available to address this issue, the conservative position is often taken that the hydraulic barrier function of an HDPE geomembrane becomes seriously impaired following a 50% decrease in mechanical properties. This approach is consistent with previously proposed methodologies for GM lifetime predictions. However this approach is very conservative as it has been documented that it is the development of cracks, not a decrease in mechanical properties that is directly responsible for increased infiltration through GMs and that GMs otherwise function as effective hydraulic barriers regardless of tensile strength [9]. In fact, [14] make the case that no cracking may occur if the GM is not subjected to tension. This issue is discussed further near the end of the following section.

First, a discussion of the approach to quantify the processes in Figures 2 and 3 is in order. Because the degradation processes discussed in the previous section are chemical reactions, rate equations are applicable to modeling degradation. First-order reaction equations have generally been found to be applicable to the problem [3].

The standard measure to determine the amount of anti-oxidants present in an HDPE GM sample is the Oxidative Induction Time (OIT), measured according to standard test method ASTM D 3895 [24]. Antioxidant depletion, corresponding to the antioxidant depletion period from Figures 2 and 3 is expressed quantitatively using

$$OIT_t = OIT_0 \exp\left(-kt\right) \qquad \text{(Eq. 1)}$$

where OIT_t is the OIT at aging time t, OIT_0 is the initial OIT of the GM, and k is the rate of antioxidant depletion (often expressed in units of month^{-1}). For the purpose of quantifying longevity for modeling purposes, the OIT of an un-stabilized HDPE GM is considered to be 0.5 min [10], allowing the computation of the length of time until antioxidant depletion using Eq. 1. Note that Eq. 1 is of the same form as the first-order equation used to describe the degradation in mechanical properties of geosynthetics with time. However, these two mechanisms are distinct and should not be confused.

A number of aging studies have examined the effect of different environmental conditions, antioxidant packages, and GM thickness on rate k. Aside from photo-degradation, which is not applicable to buried applications, the most significant relevant environmental condition to GM degradation appears to be temperature. Higher temperatures result in faster depletion of antioxidants and faster oxidation of HDPE. This effect has facilitated accelerated aging studies.

Due to the need for accelerated tests, significant research effort has been expended to study the effect of temperature on geosynthetic degradation rate constants (k). Specifically, researchers have considered the application of Arrhenius plots and the resulting equations to accelerated tests. The basic form of the Arrhenius equation is given by

$$k = Aexp\left(-\frac{E}{RT}\right) \quad \text{(Eq. 2)}$$

where k is the reaction rate constant, E is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol-K), T is the absolute temperature (K) and A is a material constant. Arrhenius plots of experimental k versus 1/T data allow the evaluation of E/R (the slope of a line on an Arrhenius plot). Different values of activation energy E have been found for various combinations of environmental conditions and GM formulations. From a modeling perspective, these studies allow the selection of k values corresponding to the cover system design under consideration. The engineering implications of the availability of these data are discussed below. The remainder of this section summarizes the major effects that have been investigated.

Since the major chemical process leading to the degradation of HDPE GM mechanical properties is oxidation, the availability of oxygen is a critical parameter. Because oxygen is typically introduced to final covers in the vapor phase, the relevant measure is oxygen pressure (often a partial pressure in practice). As the oxygen pressure increases, the rate of oxidation increases. This effect has allowed the development of accelerated aging experiments in order to allow the development of equations for k including temperature and oxygen pressure. These equations facilitate the modeling of HDPE oxidation at temperatures and pressures encountered in service [3].

Because the availability of oxygen to oxidize HDPE GMs is controlled by diffusion through the GM, thicker HDPE GMs have longer times to reach the induction period [5]. This relationship appears to be highly non-linear as oxidation studies indicate a concentration of oxidation near the surface, with increases in HDPE GM thickness leading to a significant increase in the time for oxygen to diffuse into GMs. Also of potential interest is the diffusion of antioxidants would be similarly slowed by increased GM thickness.

Other effects such as contact with water and metals have been documented. Water in contact with the GM can decrease the availability of oxygen [7]. However, it can also contain dissolved metals with can accelerate GM degradation [3].

The research cited above provides insight into the impact of these factors on values of k governing antioxidant depletion and also first-order equations describing oxidation of HDPE. Of particular interest in these studies is the calculation of factors on k quantifying the impact of each of the above effects on the rate of degradation, allowing a consideration of the combination of effects. Accordingly, engineers and analysts can make informed decisions regarding the central value and uncertainty in k for the specific materials and cover configurations included in their design. The application of this ability to performance assessment is discussed in the following section.

APPLICATION TO FACILITY PERFORMANCE ASSESSMENT

Considerable research effort has been devoted to the topics discussed in the previous sections. A strong area of need in the performance assessment of shallow disposal facilities is how to connect these research findings with inputs to probabilistic models. This need is present because final cover component subject matter experts are not typically conversant in probabilistic modeling techniques and likewise, many modelers are not final cover experts. This section provides an outline of possible interpretations of the available research knowledge that will enhance the accuracy of performance assessment models.

From the research reviewed in the previous section, some inferences about the uncertainty in geosynthetic lifetime predictions are possible, allowing their use in probabilistic performance assessments. Probabilistic performance assessments for surface disposal facilities have typically been performed using Monte Carlo simulation, (e.g., [13,17]). Inputs to Monte Carlo simulation ideally include probability distributions describing the relative likelihood of discrete events or continuous properties, although common Monte Carlo simulation frameworks allow for the introduction of non-parametric information as well. In the case of cover systems, a distribution is needed to describe the relative likelihood of abstracted property values used to model infiltration. While the research discussed in the previous section could be used to develop a probabilistic model of degradation with time, it is anticipated based on existing practice that the most likely use will be to establish distributions representing the relative likelihood of various degraded cover system conditions at a single point in time – a “snapshot” of probabilistic performance after a defined period has elapsed following construction.

Due to the complexity of the chemical processes involved in geosynthetic degradation and the complexity of the interaction of this degradation with changes in the performance of the cover system, significant abstraction is required for performance assessment modeling, even with highly sophisticated models. Following the line of inquiry presented in the previous section, the degradation in tensile properties of geomembrane following the depletion of anti-oxidants does not immediately lead to an increase in cover system infiltration. Rather, the formation of stress cracks enabled by the degradation in tensile properties is required first. The formation of stress cracks is itself a complicated problem [9]. Therefore, the following convention is proposed based on established research methodologies.

Figure 4 summarizes the basic phases of GM degradation and its effect on cover system infiltration according to the proposed abstraction. The initial (as installed) performance depends strongly on the construction quality assurance program and cover system configuration. Studies into the performance of geosynthetics as installed in field trials are available [11] and allow confirmation of the initial installed performance for typical cover configurations and typical HDPE GM products. The quality of the initial installation will control the infiltration rate until other changes to the system occur. Of particular interest to cover performance is the reduction in the ability of the GM/clay composite barrier to resist infiltration. According to the above discussion, this reduction could begin after both the depletion of antioxidants, quantified as an OIT_t of 0.5 min and the degradation of tensile properties to a particular value (often 50%). However, it has been noted [9,14] that the depletion of antioxidants and the oxidation of the HDPE GM does not guarantee a reduction in the ability of the cover system to resist infiltration. One assessment [14] argued that the GM could perform indefinitely as an impermeable barrier provided that the GM is not placed into tension by differential settlement or other localized stresses. Accordingly, the conservative assumption presented here that the appearance of cracks and water infiltration through these cracks will begin between a 50% and 90% reduction in tensile properties (between times $t_{50\%}$ and $t_{10\%}$ from Figure 3) can be considered an upper bound on infiltration rates. The lower bound of no infiltration is potentially interesting, but depends strongly on the mechanical performance of other components of the system. To complete the Figure 4 curve depicting the most likely degradation in the final cover performance, additional information about the mechanical stresses placed on the final cover is needed. An approach to accomplish this task is described below.

The development of tensile stresses in geomembranes is possible as the result of localized sliding and differential settlement. Considering the typical cover system designs for radioactive waste applications are engineered to minimize the risk of sliding and thereby prevent tension in the cover system geosynthetics, the most likely cause of tension is from differential settlement. Figure 5 presents the graphical output from a single realization of a Monte Carlo simulation of differential settlement performed by [25]. Of interest in the figure is the irregular distribution of depressions and concentrated zone of deformation. These depressions are the areas where the greatest tensile stresses will develop as the result of differential settlement. Figure 6 presents a cumulative histogram of flooded area computed for several such realizations. Flooded area is a convenient metric for the severity of differential settlement since engineered cover systems will pool water as the result of significant localized distortions in the cover. Mobilized tensile stress can be calculated from these distortions and compared to criteria for crack formation. The resulting distribution of crack occurrence can be used directly as an input to stochastic infiltration models. Note that this distribution has two major components: 1) the spatial distribution of cracks, which will be abstracted as a number of cracks per unit area (N_c), and 2) a cumulative distribution expressing the relative likelihood of N_c values between realizations. This second distribution of N_c values is anticipated for use in the more general cover system performance models.

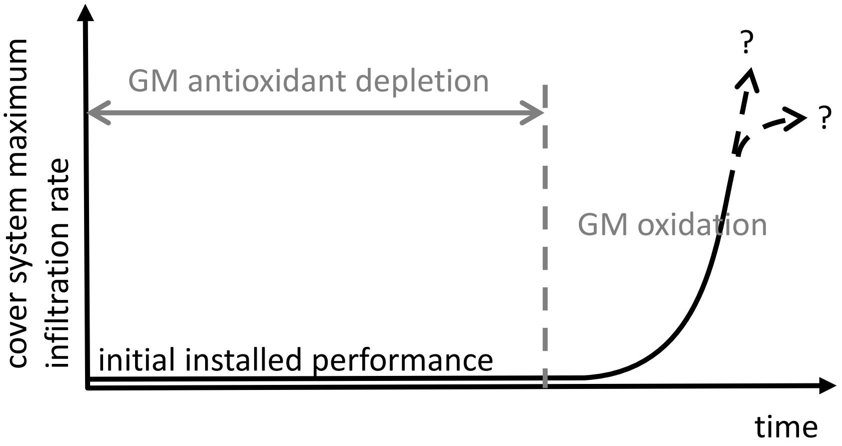

Figure 4. Illustration of Major Abstracted Phases of the Effects of GM Degradation on Cover System Infiltration.

Figure 5. Example Realization of Differential Settlement Model of Final Cover System

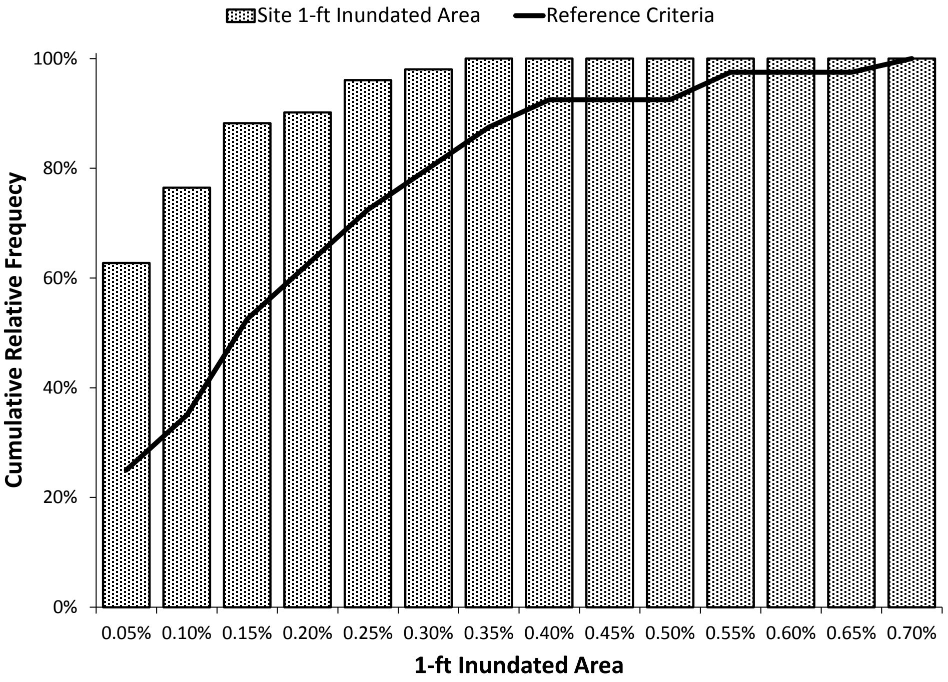

Figure 6. Example Distribution of Flooded (Inundated) Cover Area Corresponding to Differential Settlement

The final functional piece of this process is the interface between performance assessment and engineering. With the above proposed sequence, it is possible to develop a performance assessment model that incorporates material degradation and mechanical site effects into the more general model of system performance. It is anticipated that the point in time *t* (e.g., 1,000 years after cover construction) for which a particular performance target must be met will be established as part of the regulatory review and performance assessment. Accordingly, for a given HDPE GM formulation, the degraded tensile properties at time *t* and the resulting distribution of cracks will result in a simulation that either meets or does not meet the probabilistic performance targets for the cover system. If the design fails to meet the performance targets due to the degraded condition of the GM, the GM formulation can be re-engineered according to the design variables presented earlier (GM thickness, antioxidant package, molecular weight, etc.), the cover can be configured to limit oxygen exposure, and the cover can be improved to limit distortions. The modeling effect of these improvements will be to develop a revised distribution of crack occurrence at time *t* reflecting the degraded condition of the revised cover system. If the revised system meets the performance targets, the revised design becomes one of the engineering recommendations for the cover system. According to this methodology, there is a direct connection between the selection of cover system components and the performance assessment, allowing feedback and design optimization, meeting the intent of the engineering/performance assessment interface articulated by [13].

CONCLUSIONS

Use of geosynthetic degradation data and observations from previous studies has several relevant applications to the design and performance assessment of waste disposal facility cover systems.

For performance assessments, quantitative data about the longevity of geosynthetic cover components under different environmental conditions can be used in models of cover system risk by projecting the degraded performance of the system at time *t* following construction. Robust abstracted distributions of crack occurrence are possible by incorporating available data about degraded GM properties and models of differential settlement.

For cover system engineering, expert analysis of present and future environmental conditions is needed to select geosynthetics, specify polymer and additive formulations, and configure cover system layering to maximize the effective life of the cover system. An overview of these aspects of the engineering problems has been presented.

Traditionally, the interpretation of the geosynthetic degradation research summarized in this paper has been deterministic as opposed to probabilistic. One reason why deterministic analyses are common is the relative scarcity of degradation data for particular formulations and environmental conditions. Therefore, conservative estimates of the effective lifetime of geosynthetics have been applied. This in turn, has led analysts to consider the performance of cover systems at discrete points in time. Due to the complexities involved, it is not currently proposed to introduce a coupled temporal, probabilistic model of cover performance. Rather, it is proposed to consider the time prior to significant GM degradation that will be tolerable for exposure risk given the other aspects of the system. Engineering of HDPE GMs and their installation allows adjustment of this parameter and can be used to optimize the design with respect to performance.

Performance assessments are meant to inform the design process and vice-versa, leading to an interactive process wherein the cover system design can be optimized in order to meet quantitative performance targets. Accordingly, there is a need for analysts to provide feedback to engineers regarding the performance of cover system design and for engineers to provide analysts with quantitative performance data from which to refine analyses. Critically, the factors identified in this paper affecting the long-term performance of cover systems, such as geomembrane thickness, anti-oxidant package, molecular weight, oxygen exposure, and drainage, can be adjusted and re-engineered to meet specific performance targets. Therefore, performance assessments need not rely only on performance data for standard products, as it is possible for engineers to create material specifications, testing programs, and cover cross sections to provide enhanced performance as needed. Considering that GM manufacturing is performed in lots to support incoming orders and projects, the geosynthetics industry is currently positioned to allow enhanced material specifications to support these requirements. It is important for engineers and analysts alike to be aware of this capability as it can reduce long-term risks at modest cost. The geosynthetic engineering consultants, manufacturers, researchers, testing firms, and installers that comprise the geosynthetic industry are knowledgeable in the materials, methods, and testing protocols required to allow this optimization.

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