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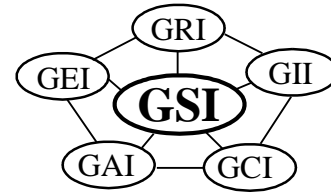
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GRI Guide GS12*

Standard Guide for

Lifetime Prediction of Geosynthetics Using Time-Temperature-Superposition (TTS) and Arrhenius Modeling

This guide was developed by the Geosynthetic Research Institute (GRI), with the cooperation of the member organizations for general use by the public. It is completely optional in this regard and can be superseded by other existing or new standards on the subject matter in whole or in part. Neither GRI, the Geosynthetic Institute, nor any of its related institutes, warrant or indemnifies any projects developed according to this standard either at this time or in the future.

1. Scope

    1.1 This guide focuses on the preferred methodology of lifetime prediction of polymeric related geosynthetics using time-temperature-superposition (TTS) and Arrhenius modeling.

    1.2 The general procedure is based upon laboratory incubation of representative coupons of the geosynthetic material being evaluated. Specimens are then cut from the coupons, tested and the results analyzed according to this guide.

    1.3 Multiple incubations at constant temperatures will always be involved since the basic hypothesis of accelerated degradation of polymeric related geosynthetics is that increasing temperature increases all of the various degradation mechanisms such as oxidation, ultraviolet light, hydrolysis, chemicals, radioactivity and biological agents.

    Note 1: Other actions such as constant stress, elevated pressure, etc. can be imposed as long as such environments are constant to all temperature incubation exposures.

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*This GRI standard is developed by the Geosynthetic Research Institute through consultation and review by the member organizations. This guide will be reviewed on an as-required basis. In this regard it is subject to change at any time. The most recent revision date is the effective version.

1.4   Lifetime predictions are generally based on "halflife" which is considered a 50% change in a physical or mechanical property(s) from the as-manufactured baseline property(s).

Note 2:   The most common properties that are monitored as incubation time progresses are tensile strength and tensile elongation. Other properties that may be used for monitoring over incubation time are density, melt index, thickness, antioxidant depletion, plasticizer content, puncture resistance, burst resistance, tear resistance, cracking, etc.

1.5   The extrapolation process to a specific site-specific (and invariably lower) temperature is plotted on an Arrhenius graph of reaction rate versus temperature as is common to all polymeric materials.

Note 3:   Other polymer technologies using this procedure are gas pipe, cable shielding and related plastics industries; see references in Section 2.2.

1.6   This guide is limited to the product-specific and incubation/testing-specific conditions, and is meant to simulate field conditions as closely as possible and/or as agreed upon by the parties involved.

1.7   This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this guide to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2.   Referenced Documents

2.1   ASTM Standards
   D4355   Test Method for Deterioration of Geotextiles by Exposure to Light, Moisture and Heat in a Xenon Arc Type Apparatus
   D4439   Terminology for Geosynthetics
   D7238   Test Method for Effect of Exposure of Unreinforced Polyolefin Geomembrane Using Fluorescent UV Condensation Apparatus
   E145   Specification for Gravity-Convection and Forced Ventilation Ovens
   E715   Specification for Gravity-Convection and Forced Circulation Water Baths

2.2   Literature References
   Clough, R. L., Billingham, N. C. and Gillen, K. T., Eds. (1996), "Polymer Durability: Degradation Stabilization and Lifetime Production," Advances in Chemistry Series #249, American Chemical Society, 712 pgs.

   Grassie, N. and Scott, G. (1985), "Polymer Degradation and Stabilization," Cambridge University Press, 222 pgs.

Koerner, R. M. (2012), "Designing With Geosynthetics," 6th Edition, Xlibris, 914 pgs.

Martin, J. W., Rijntz, R. A., Chin, J. and Dickie, R. A., Eds. (2009), "Service Life Prediction of Polymeric Materials; Global Perspective, Springer Press, 537 pgs.

Nelson, W. (1990), "Accelerated Testing; Statistical Models, Test Plans and Data Analysis," John Wiley and sons, 601 pgs.

3. Terminology

    3.1 Definitions
        3.1.1 geosynthetic, n – a planar product manufactured from polymeric material used with foundation soil, rock, earth, or any other geotechnical engineering-related material as an integral part of a man-made project, structure, or system.
        3.1.2 sample, n – (1) a portion of material that is taken for testing or for record purposes; (2) a group of specimens used, or of observations made, which provide information that can be used for making statistical inferences about the population(s) from which the specimens are drawn.
        3.1.3 coupon, n – a portion of a material or laboratory sample from which multiple specimens can be taken for testing.
        3.1.4 specimen, n – a specific portion of a material or laboratory sample upon which a test is performed or which is taken for that purpose (Syn. test specimen).

        Note 3: The order of size hierarchy established by ASTM; i.e., lot, roll, sample, coupon and specimen (in order of decreasing size), will be used in this guide. That said, a <u>coupon</u> is incubated while <u>specimens</u> are cut from it for actual testing.

4. Incubation Methods

    The selection of an method to incubate geosynthetic coupons is highly dependent on the targeted degradation mechanism of the particular material and primarily on the type of resin from which it is manufactured. In this regard, Table 1 is offered but the references cited in Section 2.2 contain a wealth of pertinent, and much more specific, information. In Table 1 it should be recognized that thermal degradation in the form of high temperature exacerbates all types of degradation and, as such, is at the heart of time-temperature-superposition which is used herein. In this regard, the tacit assumption is that the higher the temperature, the greater the degradation from all types of mechanisms that may be acting on the material.

        Note 4: There is indeed an upper limit as to the incubation temperature of each resin type. Beyond this upper level the polymer structure no longer behaves as it does at lower temperatures. It is felt that this upper temperature is about 90°C for PE, PP and PET. It could well be lower for PVC and PS and perhaps even higher for EPDM. See references cited for more detailed information.

Table 1 –Commonly Used Geosynthetic Resins and Their Degradation Mechanisms
[P = primary, S = secondary, T = tertiary]

Mechanism	PE	PP	PET	PVC	EPDM	PS
thermal[1]	P	P	P	P	P	P
oxidation[2]	P	P	S	P	S	P
ultraviolet[3]	P	P	P	P	P	P
hydrolysis[4]	S	S	P	S	T	S
chemical[5]	S	S	S	S	S	S
radioactive[6]	T	T	T	T	T	T
biological[7]	T	T	T	S	T	T
stress[8]	?	?	?	?	?	?

Notes: 1 = high temperature has the effect of exacerbating all other acting mechanisms
2 = full oxygen at 21% is more aggressive than buried situations at lower oxygen values
3 = only acts when exposed to the atmosphere
4 = both very high and very low pH-values are important considerations
5 = refers to water and mild leachates, but not hydrocarbons which are more aggressive
6 = refers to low level radioactive waste liquids
7 = refers to bacteria and fungi, but not burrowing animals
8 = compressive, tensile or bending stresses are usually involved and may contribute to other degradation mechanisms… dynamic stresses would be extremely difficult to model for the long incubation times required.

4.1   Thermal Degradation Incubation

Elevated temperature may be a degradation mechanism in and of itself but it certainly has the effect of increasing all other mechanisms that may be involved. As such, it is the key to time-temperature-superposition as utilized in this guide.

4.2   Oxidation Degradation Incubation

The evaluation of geosynthetic coupons so as to assess oxidative degradation is quite straightforward. Forced air ovens (at least three) set at different constant temperatures are used. They are relatively inexpensive, easy to maintain and standardized under ASTM E145; see Figure 1.

Figure 1 – Three constant temperature air ovens.

4.3   Hydrolytic Degradation Incubation

The evaluation of geosynthetic coupons so as to access hydrolytic degradation is quite straightforward. Forced circulation water baths (at least three) set at different constant temperatures are used.   They are relatively inexpensive, easy to maintain, and standardized under ASTM E715; see Figure 2.

Figure 2 – Three constant temperature water baths.

4.4   Ultraviolet Light Degradation Incubation

The evaluation of geosynthetic coupons so as to assess ultraviolet light degradation is quite straightforward and utilizes one of two different laboratory weathering devices; namely,
- Xenon arc apparatus per D4355 and
- Fluorescent ultraviolet apparatus per D7238.

These devices are quite expensive, require regular maintenance, and can consume considerable power and water; see Figure 3a and 3b. At least three devices set at different constant temperatures are used. For long-term incubation, i.e., more than a few months, the Xenon arc apparatus becomes extremely expensive.

Note 5:   Since incubations of properly formulated geosynthetics require years of incubation, all exposed durability studies at GSI have used the fluorescent ultraviolet apparatus as shown in Figure 3b.
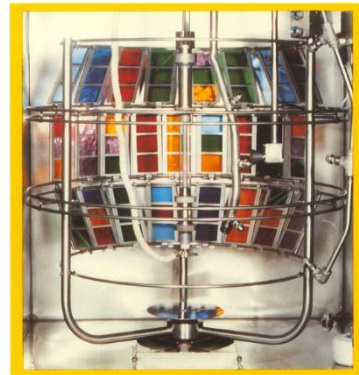
(a) Outside and inside of a Xenon arc device

(b) Outside and inside of a fluorescent ultraviolet device
Figure 3 – Different ultraviolet incubation devices.

4.5 Other Degradation Mechanisms

There are indeed additional degradation mechanisms given in Table 1 which may be appropriate to evaluate. Furthermore, they can be superimposed on coupons being incubated in ovens, baths or UV-devices. In this manner, synergy between multiple mechanisms is being imposed and evaluated accordingly. For example, the incubation of a simulated landfill geomembrane, under constant compressive stress and immersed in leachate (all under constant temperature) has been evaluted and is shown in Figure 4. This ten-year study conducted at 85, 75, 65 and 55°C used 20 such columns; five at each constant temperature. The added complexity of incorporating applied stress of any type makes any type of incubation very difficult, cumbersome and expensive.
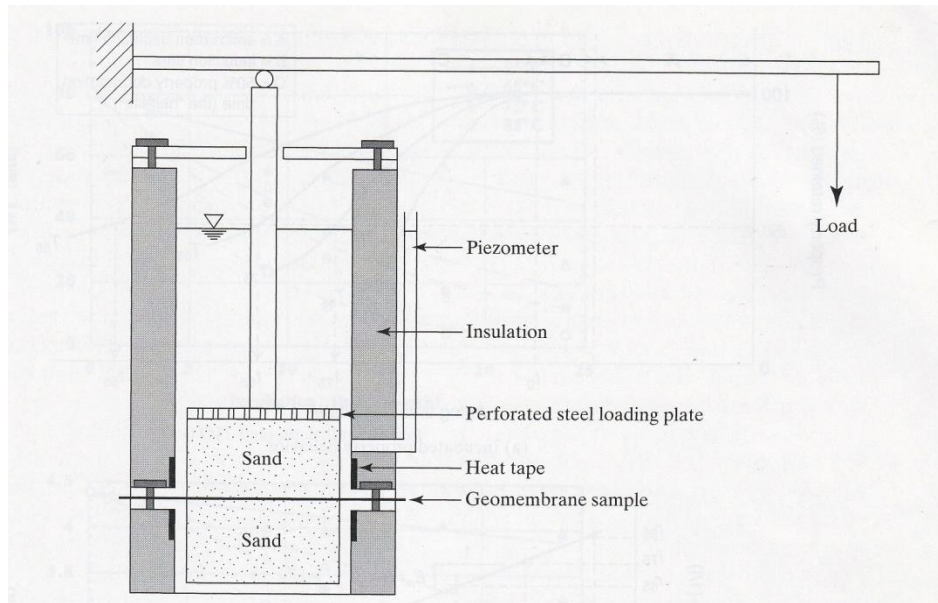

Figure 4 – Devices to incubate coupons under several degradation mechanisms (ref. Koerner, 2012).

4.6 Monitoring (i.e., Data Generation) of Incubated Geosynthetic Coupons

Whatever the method used for incubation, the various coupons must be periodically removed and evaluated directly or have specimens cut from the coupons and have these evaluated according to a specific test method; recall Note 2. In this regard, multiple coupons must be incubated at each temperature so that sufficient material is available for the latter stages of degradation. To illustrate the monitoring procedure, see Figure 5 which shows strength retained and elongation retained of a geosynthetic material at 60, 70 and 80°C over a continuous period of up to 22,000 light hours in a fluorescent ultraviolet device per ASTM D7238. For the settings used in this incubation (20 hours lights-on and 4 hours lights-off with condensation) this amounts to 26,400 total hours, or 3.01 years.
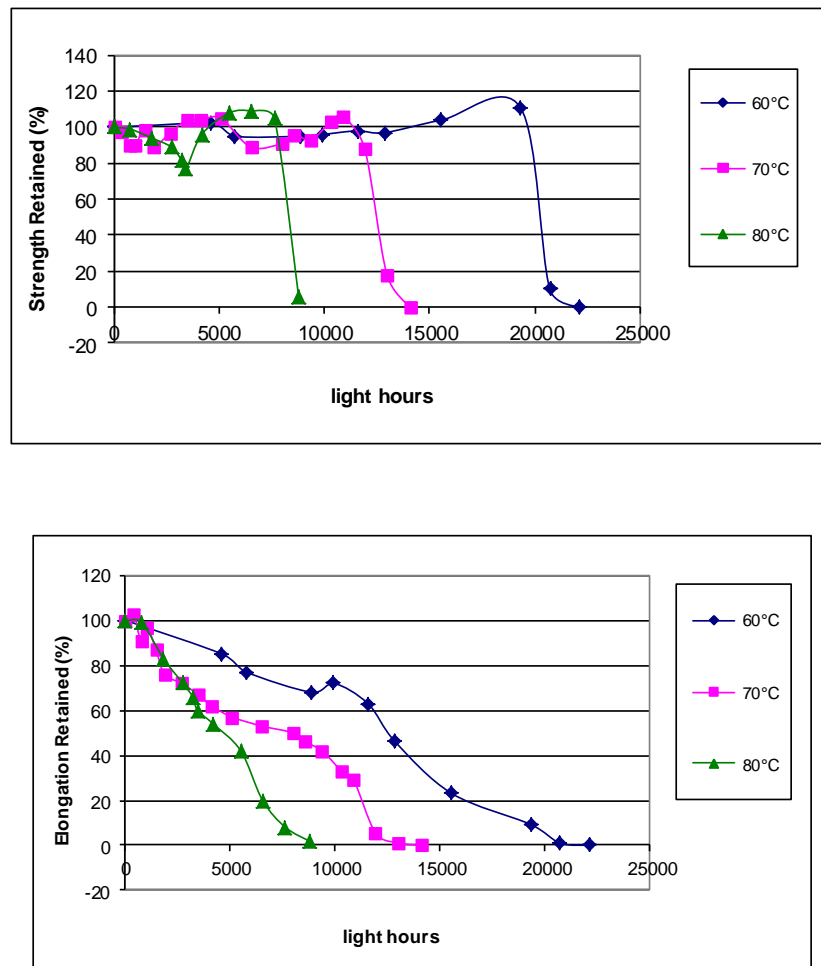

Figure 5 – Changes in strength retained and elongation retained of a geosynthetic material evaluated over a long incubation time.
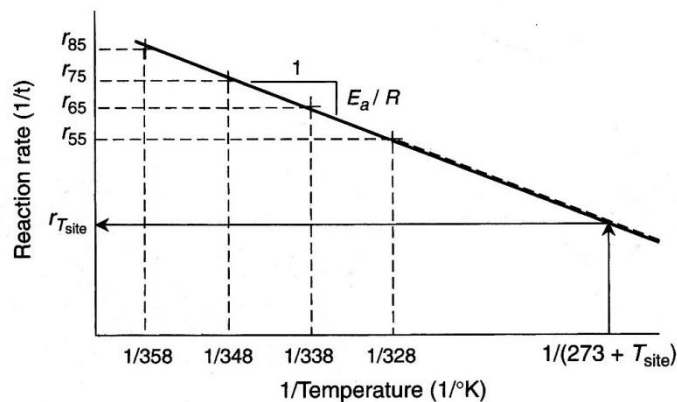
5. Arrhenius Modeling for Lifetime Prediction

In the references cited in Section 2.2 it can be noted that there are several lifetime prediction methods available, however, GSI (and many others) prefer Arrhenius modeling.

> Note 6: Svante Arrhenius (1859-1927) was a Swedish physical chemist and a 1903 Nobel laureate. He is known for a formula for modeling the temperature dependence of reaction rate constants; ref. Wikipedia. (The writer did not know him!)

Arrhenius modeling is used throughout the polymer industry for lifetime predictions. Commonly used for the prediction itself is the property value being monitored at 50% of its original value. This is called the "halflife" and is considered as a conservative value for most prediction purposes. The procedure is graphically illustrated in Figure 6.
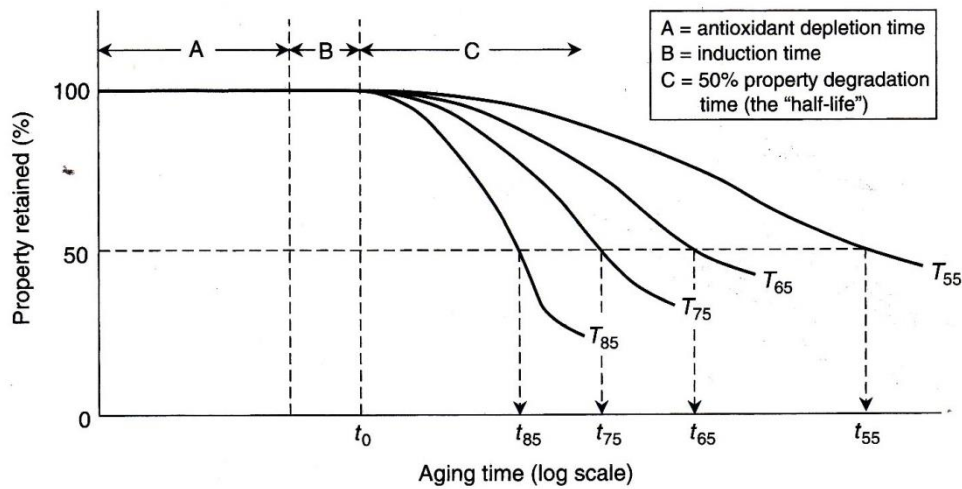
(a) Incubated property behavior

(b) Arrhenius plot for half-life property

Figure 6 –Time-temperature-superposition data at four elevated temperatures and Arrhenius modeling for lifetime prediction (ref. Koerner, 2012).

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Figure 6a shows that the 50% retained value is extended to intersect each of the constant temperature data curves (in degrees Kelvin) and then used to obtain the accompanying aging times on the x-axis. *The inverse of these aging times is the reaction rate at each specific incubation temperature.* Figure 6b continues the process by plotting the inverse reaction rates versus the associated inverse temperatures. This is the Arrhenius curve. Its slope is the activation energy divided by the gas constant and is a fundamental characteristic of the material being evaluated.

> Note 7: It would be excellent if at some point in the distant future the geosynthetics industry would have available the activation energies of the various products in commercial use. That said, this is a daunting task!

By extrapolating this curve to lower (and site-specific) temperatures the lifetime is readily obtained using the following Arrhenius equation for the extrapolation:

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

where

E_{act}/R = slope of Arrhenius plot,
T-test = any of the specific incubated (high) temperatures, and
T-site = site-specific (lower) temperature.

The data of Table 2 was obtained in this manner. It is illustrative of the type of lifetime prediction information obtained by time-temperature-superposition followed by Arrhenius modeling which is the focus of this particular guide.

> Note 8: Extrapolation of any type of experimental data is contentious. Values of one order-of-magnitude (via ASCE) to many orders-of-magnitude (via creep data using shifting and SIM testing) are always weighty considerations. Regarding this guide, however, extrapolation <u>down</u> to site specific temperatures is considered "safer" than <u>up</u> to higher temperatures. Of course, one could always incubate at lower temperatures but times to reach halflife would be measured in decades rather than years.

Table 2 – Halflife Prediction Times of a Geomembrane Beneath a Landfill as a Function of its In-Situ Service Temperature [Koerner, 2012)

In Service Temperature (°C)	Stage "A" (years)			Stage "B" (years)	Stage "C" (years)	Total Prediction* (years)
	Standard OIT	High Press. OIT	Average OIT			
20	200	215	207	30	208	445
25	135	144	140	25	100	265
30	95	98	97	20	49	166
35	65	67	66	15	25	106
40	45	47	46	10	13	69

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

6.   Summary

The most frequently asked question by owners, users and specifiers of geosynthetic materials is, "how long will it last?" The procedures of this guide are meant to provide such information and in so-doing illustrate that the method can generate lifetime data in a quantified manner.