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PORTSMOUTH ON-SITE DISPOSAL CELL (OSDC) HIGH DENSITY POLYETHYLENE (HDPE) GEOMEMBRANE LONGEVITY

Mark A. Phifer

JANUARY 31, 2012

Savannah River National Laboratory
Savannah River Nuclear Solutions
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Prepared for the U.S. Department of Energy Under Contract Number DE-AC09-08SR22470

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REVIEWS AND APPROVALS

M. A. Phifer, Author, Radiological Performance Assessment	Date
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R. S. Aylward, Manager, Environmental Restoration Technology	Date

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CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
D&D	decontamination and decommissioning
GCL	geosynthetic clay layer
GSI	Geosynthetic Institute
HDPE	high density polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
HP-OIT	High Pressure Oxidative Induction Time
LLW	low-level waste
LMDPE	Linear Medium Density Polyethylene
MLLW	mixed low-level waste
NRC	Nuclear Regulatory Commission
OIT	Oxidative Induction Time
OSDC	On-Site Disposal Cell
RCRA	Resource Conservation and Recovery Act
UV	Ultraviolet
WVT	water vapor transmission

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1.0 EXECUTIVE SUMMARY

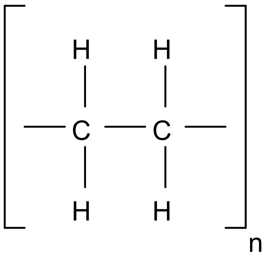
It is anticipated that high density polyethylene (HDPE) geomembranes will be utilized within the liner and closure cap of the proposed On-Site Disposal Cell (OSDC) at the Portsmouth Gaseous Diffusion Plant. The likely longevity (i.e. service life) of HDPE geomembranes in OSDC service is evaluated within the following sections of this report:

- Section 2.0 provides an overview of HDPE geomembranes,
- Section 3.0 outlines potential HDPE geomembranes degradation mechanisms,
- Section 4.0 evaluates the applicability of HDPE geomembrane degradation mechanisms to the Portsmouth OSDC,
- Section 5.0 provides a discussion of the current state of knowledge relative to the longevity (service life) of HDPE geomembranes, including the relation of this knowledge to the Portsmouth OSDC, and
- Section 6.0 provides summary and conclusions relative to the anticipated service life of HDPE geomembranes in OSDC service.

Based upon this evaluation it is anticipated that the service life of HDPE geomembranes in OSDC service would be significantly greater than the 200 year service life assumed for the OSDC closure cap and liner HDPE geomembranes. That is, a 200 year OSDC HDPE geomembrane service life is considered a conservative assumption.

2.0 HDPE GEOMEMBRANE OVERVIEW

Polyethylene is the simplest hydrocarbon polymer, produced from the polymerization of resins consisting of a dominant ethylene monomer, which has unsaturated bonds, and α-olefin copolymers such as butane, hexane, methyl pentane or octane. The repeating unit of polyethylene has the structural form shown below:



$$\left[-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}- \right]_n$$

Polymerization results in a long ‘zigzag’ chain structure of this repeating unit with side branching due to the copolymers. Polyethylene is semi-crystalline, containing both amorphous (0.853 g/cm^3) and crystalline regions (1.004 g/cm^3). The co-polymers, which produce the side branching, result in a lower density and lower crystallinity. Polyethylene is considered a thermoplastic, since it can be repeatedly heated and shaped as desired and will maintain the remolded shape when cooled. (Koerner 1998; Needham et al. 2004)

High density polyethylene (HDPE) is one of the most common polymers utilized in the production of geomembranes (Koerner 1998). HDPE geomembranes consist of 95-98% resin, 2-3% carbon black, and 0.25-1% antioxidants. The crystallinity of HDPE geomembranes ranges between 44 to 67.5%, and they have a minimum sheet density of 0.940 g/cm^3. (GRI 2003; Koerner and Hsuan 2003; Needham et al. 2004) The permeability of water through an intact HDPE geomembrane is not that of a hydraulic conductivity through interconnected pore space, but rather it is a water vapor diffusion process (Rumer and Mitchell 1995). Therefore the water permeability of HDPE geomembranes is not determined by standard hydraulic conductivity tests performed for porous materials but by a water vapor transmission (WVT) test (Koerner 1998). A typical value of water vapor transmission through an intact 100 mil HDPE geomembrane is approximately 0.006 g/m^2-day (Rumer and Mitchell 1995), which equates to a saturated hydraulic conductivity of approximately 1.0E-13 cm/s (Koerner 1998). Schroeder et al. 1994a, for use within the Hydrologic Evaluation of Landfill Performance (HELP) model, takes the saturated hydraulic conductivity of HDPE geomembranes as 2.0E-13 cm/s. Therefore water transport through a HDPE geomembrane is typically dominated by holes through the geomembrane, if present (Schroeder et al. 1994a; Schroeder et al. 1994b). Rowe et al. (1995) and Rowe (2004) report that “HDPE geomembranes act as an excellent diffusion barrier to water and hydrated ions such as chloride with negligible migrations being observed in tests that have been running for over a decade.” Sangam and Rowe (2002), reporting on the work of August et al. (1992), state that metals cannot readily diffuse through HDPE geomembranes. Therefore it is generally assumed that no significant diffusion of non-volatile, dissolved ions occurs through intact HDPE.

3.0 HDPE GEOMEMBRANE DEGRADATION

The following potential HDPE geomembranes degradation mechanisms are discussed in detail in the succeeding sections (Koerner 1998; Needham et al. 2004; Rowe 2004; Phifer et al. 2007):

- Antioxidant Depletion
- Thermal Oxidation
- Tensile Stress Cracking
- Ultraviolet (UV) radiation
- High Energy Irradiation
- Biological (microbial, root penetration, burrowing animals)
- Chemical

3.1 ANTIOXIDANT DEPLETION

Antioxidants are added to HDPE geomembranes primarily to prevent thermal oxidative degradation (see Section 3.2). As long as significant antioxidants are present within a HDPE geomembrane, as measured by Oxidative Induction Time (OIT) tests, thermal oxidative degradation will be prevented and the mechanical properties of the geomembrane will remain essentially unchanged. However after the antioxidants have been depleted, thermal oxidation of the geomembrane can begin. Typical antioxidants packages consist of a phosphite and a hindered phenol at 0.1 to 1.0 weight percent of the geomembrane. Phosphites are most effective at higher temperatures and are used as manufacturing process stabilizers, whereas hindered phenols are effective over a wide temperature range and are used as long-term field stabilizers. (Koerner 1998; Hsuan and Koerner 1998; Sangam and Rowe 2002; Mueller and Jakob 2003; Rowe 2004; Needham 2004)

The OIT time determined from OIT tests is related to the quantity and type of antioxidants in the polymer. OIT tests use a differential scanning calorimeter with a special testing cell capable of sustaining pressure. In the standard OIT test (ASTM 2007) a 5 mg specimen is brought to a temperature of 200°C and a pressure of 35 kPa under a nitrogen atmosphere. Oxygen is then introduced and the test is terminated when an exothermal peak is reached. The OIT time is the time from oxygen introduction to the exothermal peak. The high pressure OIT (HP-OIT) test (ASTM 2006) is conducted similar to the standard test except it is conducted at a temperature of 150°C and a pressure of 3,500 kPa is utilized.

Three major accelerated antioxidant depletion studies have been performed or are currently on-going:

- Drexel University / Geosynthetic Institute (GSI) (Hsuan and Koerner 1998; Koerner et al. 2011)
- German Federal Institute for Material Research & Testing, Landfill Engineering Laboratory (Mueller and Jakob 2003)

- Queen's University, Geo-Engineering Centre, Barrier Systems Project (Sangam and Rowe 2002; Rowe et al. 2008; Rowe and Rimal 2008a; Rowe and Rimal 2008b; Rowe et al. 2009; Rowe et al. 2010a; Rowe et al. 2010b)

The following are the primary conclusions that have been drawn from these major antioxidant depletion studies (Hsuan and Koerner 1998; Mueller and Jakob 2003; Sangam and Rowe 2002; Rowe et al. 2008; Rowe and Rimal 2008a; Rowe and Rimal 2008b; Rowe et al. 2009; Rowe et al. 2010a; Rowe et al. 2010b):

- No significant changes in physical and mechanical properties of the HDPE geomembrane occur until the antioxidants are essentially depleted.
- The antioxidant depletion rate is first and foremost dependent upon the temperature of the HDPE geomembrane. All else being equal lower temperatures result in lower rates and a longer service life.
- The antioxidant depletion rate is dependent upon the solution within which the HDPE geomembrane is immersed. All else being equal the rate increases in order with immersion in air, water, and leachate (organics, surfactants, trace metals, and pH). The surfactant component of the leachate has the greatest effect upon the rate; in general as the surfactant concentration increases the rate increases.
- The antioxidant depletion rate is dependent upon the solid material in contact with the geomembrane. All else being equal the rate increases in order with geosynthetic clay layer (GCL), sand, geotextile in contact with the geomembrane. These solid materials reduce the area of the geomembrane contacted by the air, water, and/or leachate, and thereby serve to reduce the antioxidant depletion rate.
- The antioxidant depletion rate is dependent upon the thickness of the HDPE geomembrane. All else being equal the rate decreases with increasing thickness.
- There is evidence that increased overburden pressure may result in a decreased antioxidant depletion rate, all else being equal.
- Antioxidant depletion occurs over time due to diffusion out of the HDPE geomembrane and oxidative consumption within the geomembrane. Under conditions of low temperature and low oxygen levels, diffusion is the predominant antioxidant depletion mechanism as with typical field conditions. Oxidative consumption is the predominant mechanism, under conditions of high temperature and high oxygen levels.
- Earlier accelerated antioxidant depletion studies which utilized immersion tests (i.e. direct immersion of HDPE geomembrane in solution) under estimate the time required for antioxidant depletion. Realistic estimates of the service life of HDPE geomembranes require the use of accelerated antioxidant depletion tests that simulate the expected field conditions.

The studies utilized different HDPE geomembranes with potentially different antioxidant packages. All three studies assumed that the antioxidant packages of the HDPE geomembranes they tested included phosphites and hindered phenols, however the quantity of each was unknown. The antioxidant packages are typically treated as proprietary information, by the HDPE geomembrane manufacturers, and therefore the information is not generally available to the public. Differences in the makeup of the antioxidant packages could have a significant impact on the on the estimated antioxidant depletion times derived from each study.

3.2 THERMAL OXIDATIVE DEGRADATION

Thermal oxidative degradation is the principal degradation mechanism for HDPE geomembranes in landfills (Rowe 2004). Thermal oxidative degradation of a HDPE geomembrane can begin only after the antioxidants have been depleted (see Section 3.1) and only if oxygen is available (Koerner 1998; Mueller and Jakob 2003; Needham et al. 2004). However thermal oxidative degradation does not begin immediately after antioxidant depletion. An induction period (i.e., the time between antioxidant depletion and onset of thermal oxidation) occurs between antioxidant depletion and the on-set of thermal oxidation. Based upon the examination of exhumed HDPE milk containers at the bottom of landfills the induction period has been estimated at 20 to 30 years (Koerner 1998). Longer induction periods have been estimated based upon accelerated laboratory testing (Rowe et al. 2009)

Thermal oxidative degradation is initiated with the production of free radicals ($R^{\bullet}$) within the polymer structure due to elevated temperatures, high energy irradiation, etc. (Koerner 1998; Needham et al. 2004). If oxygen is available the free radicals rapidly combine with oxygen producing peroxide free radicals ($ROO^{\bullet}$). These peroxide free radicals can then react with intact portions of the polymer to form additional free radicals and hydroperoxides (i.e., oxidized polymer chains (ROOH)). The hydroperoxides can then decompose to produce additional free radicals. This progression leads to accelerated polymer chain reactions, resulting in polymeric main chain scission (i.e., breakage of covalent bonds within the polymer structure) (Koerner 1998; Koerner and Hsuan 2003; Needham et al. 2004). The following are the primary thermal oxidative degradation reactions:

$RH + \text{energy}\ \ R^{\bullet} + H^{\bullet}$
$R^{\bullet} + O_2 \rightarrow ROO^{\bullet}$
$ROO^{\bullet} + RH + \text{energy} \rightarrow ROOH + R^{\bullet}$, where RH = polymer chain, $R^{\bullet}$ = free radical, $ROO^{\bullet}$ = peroxide free radical; ROOH = hydroperoxides (i.e. oxidized polymer chains)

Polymeric main chain scission caused by oxidation results in embrittlement of the HDPE geomembrane and degradation of its mechanical properties (Koerner and Hsuan 2003; Mueller and Jakob 2003: Rowe et al. 2009). However, even after the HDPE geomembrane becomes brittle it remains intact and can withstand high pressure (Mueller and Jakob 2003). Oxidation only occurs in amorphous regions of an HDPE geomembrane, since oxygen cannot enter the crystalline regions. Therefore the overall rate of oxidation is inversely proportional to the degree of crystallinity (Needham et al. 2004). Elevated temperatures and the presence of transition metals (e.g. manganese, copper, aluminum, and iron) increase the rate of oxidation (Needham et al. 2004). However complete oxidation of a HDPE geomembrane will take an extended period of time. It has been estimated by Albertsson and Banhidi (1980) that a 60-mil thick HDPE geomembrane would take 10,000,000 years for complete oxidation based upon a mass loss of 0.00001% per year once oxidation starts (Needham et al. 2004).

However if oxygen is not available, the production of free radicals ($R^{\bullet}$) leads to polymer cross-linking (i.e., combining polymer molecules) rather than polymer chain scission. Polymer cross-linking up to a point in general improves the mechanical properties of the HDPE geomembrane (Kresser 1957; Frados 1976; Schnabel 1981; Sangster 1993; Koerner 1998).

Based upon this information it has been concluded (Koerner 1998; Needham et al. 2004) that HDPE geomembranes in landfill service will slowly degrade by thermal oxidation. Oxidation will generally be limited by the availability of oxygen within the subsurface, and such slow oxidative degradation will not result in the disintegration or disappearance of the geomembrane within a timeframe of interest (i.e., thousands to ten thousands of years). Thermal oxidative degradation is of no concern where oxygen has been removed from the surface of the geomembrane.

3.3 TENSILE STRESS CRACKING DEGRADATION

After the antioxidants in a HDPE geomembrane have been depleted and the induction period has been completed, thermal oxidation of the geomembrane commences if oxygen is present causing embrittlement and degradation of mechanical properties over time. However the geomembrane will remain an effective hydraulic barrier unless it is physically damaged or develops holes or cracks. Holes or cracks can develop from the following two types of tensile stress cracking in a HDPE geomembrane (Needham et al. 2004):

- Ductile tensile failure is a ductile failure where the applied tensile stress exceeds the short-term tensile break strength of the geomembrane.
- Brittle stress cracking is a brittle failure where the applied long-term tensile stress is less than the short-term tensile break strength of the geomembrane.

In general, HDPE geomembrane installations should be designed so that the short-term tensile break strength of the geomembrane is not exceeded. However subgrade settlement and geomembrane downdrag by waste settlement on the side slopes can occur and cause exceedance of the geomembrane's tensile break strength. (Needham et al. 2004)

Brittle stress cracking, on the other hand, can occur as oxidation of the HDPE geomembrane proceeds and causes increased embrittlement and degradation of its mechanical properties over time. As thermal oxidation proceeds brittle stress cracking will occur where the geomembrane is under stress at lower and lower stresses over time. However as cracking occurs stresses are relieved thus reducing the likelihood of further cracking. Brittle stress cracking can be exasperated by elevated temperatures and contact with agents such as detergents, alcohols (e.g., methanol, ethanol, and propanol), acids and chlorinated solvents (i.e., environmental stress cracking).

The extent of brittle stress cracking is dependent upon the geomembrane stress crack resistance (SCR), the local and global stress over the geomembrane, the geomembrane temperature, the fluid in contact with the geomembrane, and the extent of thermal oxidative degradation (Needham et al. 2004; Rowe et al. 2009). However as long as the geomembrane is not subjected to tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact, for practical considerations, indefinitely (Needham et al. 2004).

Of the three major accelerated antioxidant depletion studies, two studies have had some the HDPE geomembrane tests extend through both antioxidant depletion and the induction period into thermal oxidation. However very few of the tests have extended into the thermal oxidation period, due to the extended test times (years to tens of years) required, even at elevated temperatures. Estimates of HDPE service life based upon these accelerated tests are based upon the reduction of the HDPE geomembrane material properties such as tensile break strength, tensile break strain, stress crack resistance, etc. to some arbitrary specified level such as a 50% reduction in the material property. However such service life predictions probably underestimate the actual service life, because HDPE geomembrane service life is really dependent upon the subsequent formation of cracks or holes in the geomembrane that results from the reductions in material properties produced by thermal oxidation rather than on the reductions in material properties themselves.

3.4 ULTRAVIOLET (UV) DEGRADATION

HDPE geomembrane degradation due to short-wavelength ultraviolet (UV) radiation (i.e. sunlight) exposure has been extensively studied both in the laboratory and field (Koerner 1998; Koerner and Hsuan 2003). Exposure to UV radiation and subsequent penetration of UV radiation into the polymer structure causes polymer degradation by chain scission and bond breaking. Additionally, photo-oxidation due to UV radiation and atmospheric exposure causes significantly faster antioxidant depletion than thermal oxidation (Needham et al. 2004).

However current HDPE geomembrane formulations typically contain 2 to 3% carbon black and may contain other ultraviolet chemical stabilizers to minimize ultraviolet degradation. Due to carbon black usage, UV radiation is not considered a significant degradation mechanism for short-term exposures associated with construction, where the geomembrane is covered in a timely manner. Typically exposure of less than several years is not considered a concern for the following reasons:

- Manufacturers’ warranties for up to 20 years are available for exposed HDPE geomembranes (Koerner 1998; Needham et al. 2004).
- On-going laboratory weatherometer predictions of the service life of exposed HDPE geomembranes demonstrate that the exposed service life is at least 36 years in a dry arid environment (Koerner et al. 2011).

Additionally UV degradation is not autocatalytic, that is after burial UV degradation does not continue to occur (Bonaparte et al. 2002).

3.5 HIGH ENERGY IRRADIATION DEGRADATION

HDPE degradation by high energy irradiation can be similar to degradation by UV radiation (Needham et al. 2004). It has often been cited that the basic mechanical properties of a typical polymer start to change due to irradiation degradation by main chain scission at a total dose greater than 1 to 10 Mrad (Phillips 1988; Koerner et al., 1990; Koerner 1998; Nimitz et al. 2001; Needham et al., 2004). However, as discussed below, the impact of irradiation on polymers, and on HDPE in particular, is determined primarily by the total absorbed dose and the presence or absence of oxygen.

The absorption of high energy ionizing radiation such as gamma rays (γ-rays) by polymers primarily results in the production of free cation radicals and the ejection of electrons within the polymer. The ejected electrons can induce additional ionizations or produce electronic excitation in surrounding molecules. Secondary reactions can include the production of ions (both cations and anions) and free anion radicals. These products of radiation absorption are unstable and are reactive toward surrounding intact molecules resulting in both cross-linking (combining polymer molecules) and main-chain scission (breakage of polymer molecules). For polyethylene the extent of irradiation induced cross-linking or main chain scission appears to be independent of the type of radiation within a factor of 2 (i.e., alpha particles, beta particles, gamma-rays, X-rays, protons). Cross-linking predominates in the absence of oxygen and main chain scission predominates in the presence of oxygen. (Schnabel 1981; Sangster 1993; Harper 1996; Kudoh et al. 1996)

Irradiation of polyethylene in the absence of oxygen at relatively low doses (i.e. less than 10 Mrad) primarily results in cross-linking, which improves temperature and chemical resistance, increases the elastic modulus, tensile strength, and hardness, reduces the solubility, and improves the weatherability of the polyethylene (Kresser 1957; Frados 1976; Schnabel 1981; Sangster 1993). However, at high absorbed doses polyethylene becomes very hard and brittle (Kresser 1957; Kane and Widmayer 1989; Sangster 1993). For HDPE the ultimate strength half-dose value in vacuum has been measured at greater than 5,000 Mrad and the ultimate elongation half-dose value in vacuum has been measured at between 10 to 30 Mrad (Brandrup and Immergut 1989). The half-dose value is the absorbed dose required to reduce a particular mechanical property of the polymer by half under a defined environment (Brandrup and Immergut 1989; Schnabel 1981)

However during irradiation in the presence of oxygen (i.e., in the presence of air) polyethylene undergoes predominately main-chain scission, which results in a rapid deterioration and subsequent deleterious impact upon mechanical properties. Main-chain scission can occur during reactions involving peroxyl and oxyl radicals. Since the oxidation of free cation radicals, produced during irradiation, results in peroxyl and oxyl radicals, the presence of oxygen during irradiation results in the occurrence of more main-chain scission. Additionally oxygen can react with lateral macroradicals, which would otherwise cross-link, thus reducing the occurrence of cross-linking. Finally radiation can provide the activation energy necessary for oxidation to occur, if oxygen is available. (Schnabel 1981; Sangster 1993; Sun et al. 1996; Badu-Tweneboah et al. 1999)

In the absence of oxygen the dose rate does not appear to influence the impact of irradiation on polyethylene (Brandrup et al. 1999). However in the presence of oxygen the following are two apparent dose rate effects (Schnabel 1981; Brandrup and Immergut 1989):

- High dose rates can result in the rapid depletion of oxygen within a polymer. This can result in further polymer deterioration, due to the combined effect of irradiation and oxidation which produces main-chain scission, being limited by oxygen diffusion into the polymer. In the case of polyethylene this can actually lead to increased cross-linking due to further irradiation once the interior oxygen has been depleted and an actual improvement in mechanical properties. In this case main-chain scission only occurs at the surface of the polymer where oxygen is available. This, therefore, produces an apparent dose rate effect upon polymer deterioration at high dose rates. (Brandrup et al. 1999). At low dose rates polymer deterioration due to main-chain scission produced by irradiation and oxidation is not limited by oxygen diffusion into the polymer. Therefore at these low dose rates the full impact of combined irradiation and oxidation is realized. Therefore at lower dose rates, dose rate does not appear to impact degradation due to irradiation but it appears to be dependent upon total dose and the presence of oxygen. Polymer thickness also impacts the influence of oxygen on the polymer, since the thicker the polymer the longer the diffusion path for oxygen diffusion into the polymer (Brandrup et al. 1999). Figure 1 and Table 1 provide the impact of dose rate on the half-dose values for ultimate strength and ultimate elongation of HDPE in air (Brandrup and Immergut 1989). From Figure 1 it is seen that dose rates above about 5000 Rad/hr have an apparent dose rate effect while dose rates below 5000 Rad/hr do not.
- High dose rates can also result in an increase in the polymer’s temperature. Many chemical reactions have fairly high activation energies, which can be overcome with the irradiation induced temperature increase and lead to reactions which might not otherwise occur (Brandrup et al. 1999).

Mechanical stress combined with irradiation is also known to accelerate radiation-induced degradation. (Hamilton et al. 1996)

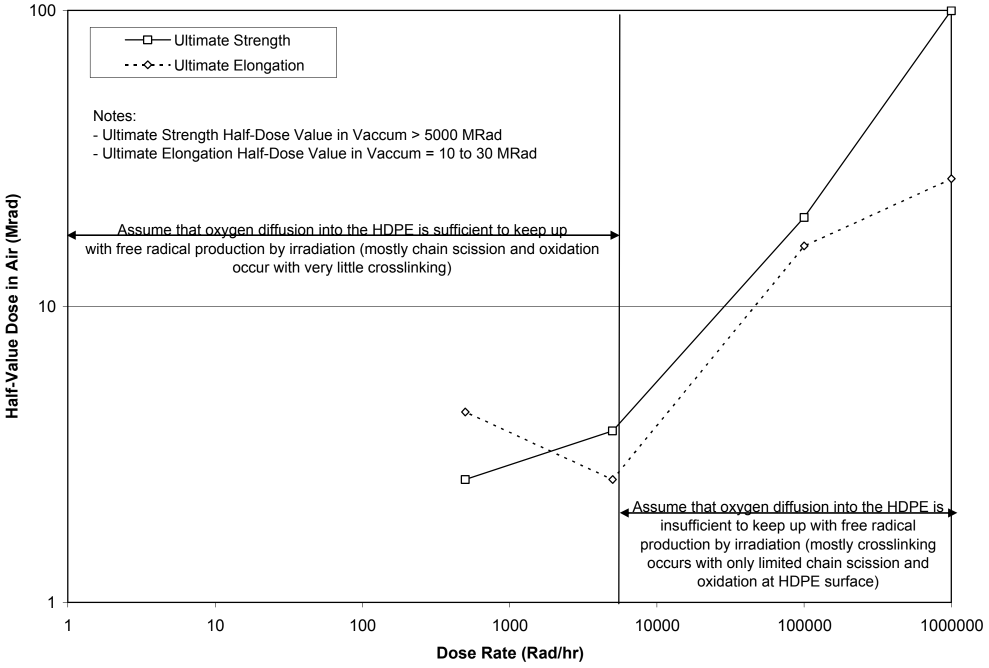


Figure 1. Dose Rate Impact on HDPE Ultimate Strength and Elongation Half-Value Dose in Air (Brandrup and Immergut 1989)

Table 1. Dose Rate Impact on HDPE Ultimate Strength and Elongation Half-Value Dose in Air (Brandrup and Immergut 1989)

Dose Rate (Rad/hr)	Ultimate Strength Half-Value Dose in Air (Mrad)	Ultimate Elongation Half-Value Dose in Air (Mrad)
1000000	100	27
100000	20	16
5000	3.8	2.6
500	2.6	4.4

The impacts of irradiation on HDPE can be mitigated by one or a combination of the following:

- The radiation dose rate can be lowered through the use of shielding to reduce the total dose absorbed by the HDPE over the period of concern,
- The level of oxygen to which the HDPE is exposed over the period of concern can be lowered so that the level and rate of degradation is oxygen dependent,
- Antioxidants (prevents oxidative chain reactions and scavenges free radicals) and carbon black (acts as an energy sink) can be incorporated into the HDPE to lower the

impact of the presence of oxygen and radiation (Schnabel 1981; Brandrup et al. 1999),
- Thicker HDPE, such as 100 mil (2.5 mm) rather than 60 mil (1.5 mm), can be utilized to limit degradation to the surface of the sheet rather than to its interior, and/or
- Tensile stress on the HDPE can be minimized.

Staff from the Nuclear Regulatory Commission (NRC) recommended the following within Kane and Widmayer 1989:

> “To compensate for the uncertainties associated with the long-term performance of geosynthetics, and to provide the level of confidence that is required by federal regulations, the use of geosynthetics alone (e.g., as a low-permeability geomembrane or as a geotextile filter fabric) is not recommended by the NRC staff. However, the use of geosynthetics to complement and improve the performance of natural soils and rocks or other proven construction materials is recommended by the staff.”

The NRC also established a 100 Mrad regulatory guideline to promote selection of polyethylene materials with extremely low risk of degradation under the exposure conditions expected in thigh integrity containers (Badu-Tweneboah et al. 1999).

Several HDPE irradiation examples are provided below particularly those dealing with its use in low-level radioactive waste disposal service:

- Whyatt and Fansworth (1990) evaluated a 60-mil HDPE geomembrane in simulated short-term (up to 120 days) chemical compatible tests with a high pH (~14) inorganic solution at 90°C and subjected them to radiation doses ranging from 0.6 to 38.9 Mrad. The solution consisted predominately of the following in descending order: sodium, nitrite, nitrate, aluminum, potassium, and sulfate. With immersion in the solution and an applied radiation dose, the break strength and elongation decreased (i.e. properties degraded), while yield and puncture strengths and their associated elongations all increased (i.e., properties improved). The 38.9 dose was slightly greater than the break elongation half-dose value of the HDPE geomembrane under the conditions tested. No other properties tested were near the half-dose value.
- Badu-Tweneboah et al. 1999 performed an evaluation that demonstrated that the polyethylene components of a low-level radioactive waste disposal landfill in Barnwell South Carolina would perform their intended function of containment during at least the 500-year design period. The two polyethylene components were a 60 mil HDPE geomembrane in the cover system and 3/8 inch thick Linear Medium Density Polyethylene (LMDPE) inner liners within concrete high integrity containers for the disposal of low-level radioactive waste.
- Compatibility testing was performed on the 60-mil smooth HDPE geomembrane planned for the Hanford Grout facility. HDPE samples were exposed to a dose rate of 740,000 rads per hour until a total radiation dose of 16 Mrad or 37 Mrad was reached. The total dose of 37 Mrad resulted in a greater than 25% decrease in geomembrane strength and elasticity. Then the HDPE was immersed in a 194°F solution with a pH

of 9.2 and a concentration of inorganics of 368,336 mg/L. It was stated that under these conditions the HDPE showed no unacceptable effects. (INEEL 2004)
- Traditional radiation sterilization of polymers for medical implants is performed to a dose of 2.5 Mrad (Deng et al. 1996).

In summary, in relationship to low-level disposal and the use of a HDPE geomembrane, a total dose of 2.6 Mrad appears to be a reasonable limit for total dose to the HDPE geomembrane below which no significant degradation should occur. The HDPE ultimate strength half-value dose in air at a dose rate of 500 Rad/hr was 2.6 Mrad (Brandrup and Immergut 1989). The basic mechanical properties of a typical polymer start to change due to irradiation degradation at a total dose greater than 1 to 10 Mrad (Phillips 1988; Koerner et al., 1990; Koerner 1998; Nimitz et al. 2001; Needham et al., 2004), with levels as high as 100 Mrad being listed as acceptable (Badu-Tweneboah et al. 1999).

3.6 BIOLOGICAL DEGRADATION (MICROBIAL, ROOT PENETRATION, BURROWING ANIMALS)

Biological degradation of HDPE geomembranes could potentially be caused by microbial biodegradation, root penetration, or burrowing animals. Limited investigations have been performed relative to the microbial degradation of HDPE geomembranes. Koerner (1998) stated that the high-molecular-weight polymers used for geomembranes are judged insensitive to microbial (i.e., fungi or bacteria) biodegradation.

Information regarding root penetration of HDPE geomembranes is present in the literature. Available references, including field experience at the Savannah River Site (SRS), indicate HDPE geomembranes of the thickness used for landfill liners typically preclude root penetration and cause roots to follow laterally atop the geomembrane surface. Landreth (1991) describes a USEPA test using four membranes “that might be used in waste management facilities for landfill cover systems”, including polyethylene. The results were that although root mass achieved maximum density atop the membranes, “there was no evidence of root penetration”. Badu-Tweneboah et al. (1999) confirm this with their statement that roots are not likely to penetrate an intact geomembrane, they are likely to develop laterally above the geomembrane, and they are not known to enlarge existing geomembrane defects. Additionally Carson (2001) indicated that roots do not penetrate geomembranes. An investigation conducted by Serrato (2004) at SRS showed that roots from overlying pine trees turned horizontally and followed along the top of the geomembrane upon reaching a HDPE geomembrane without damaging or penetrating it. Newman et al. (2004) describe the thirty-year durability of a 20-mil thick polyvinylchloride (PVC) geomembrane used as an aquaculture pond liner. They interpreted the lack of holes to indicate resistance to both microorganisms and root penetration from the dense stand of cattails, trees, and other vegetation. In general, polymer sheets such as polyethylene, polypropylene, and PVC are impervious to roots, and are commercially marketed as root barriers. For example, the Henry Company markets various polypropylene root barrier sheets for “green roofs” and other horticultural applications. “Root Stop HD (Heavy Duty)” is a commercially available 27-mil thick HDPE root barrier distributed by Hydrotech, Inc., also designed for rooftop gardens.

In summary roots reaching intact portions of HDPE geomembranes are unable to penetrate it. Such roots upon reaching intact portions of HDPE geomembranes instead turn and continue growth laterally along the top of the geomembrane in a down slope direction. Roots that reach HDPE geomembranes are only potentially able to penetrate it in locations where holes in the geomembrane have already formed due to HDPE degradation; however the probability of such penetration is very low (Phifer et al. 2007).

Very little information is available relative to the potential for geomembrane damage due to burrowing animals. A geomembrane would have to be harder than the burrowing animals' teeth or claws to avoid the potential for damage. Therefore geomembranes are potentially vulnerable to burrowing animals. Logically it is assumed that stronger, harder, and thicker geomembranes are more resistant to burrowing animals. (Koerner 1998) While unprotected HDPE geomembranes are potentially vulnerable to burrowing animals, increased depth and the use of an overlying rock biointrusion barrier can preclude this degradation mechanism.

3.7 CHEMICAL DEGRADATION

A significant number of studies have been conducted in the laboratory on leachate effects on HDPE geomembranes and in general no significant deterioration in physical or mechanical properties has been recorded in any of them (Needham et al. 2004). Because these tests have generally shown that municipal solid waste landfill leachate is relatively benign towards HDPE geomembranes, such leachate resistance tests are now rarely required in the United States (Needham et al. 2004). HDPE manufacturers have compiled chemical resistance charts for saturated solutions or pure chemical which are generally reliable (Koerner 1998; GSE 2012). However the following chemical degradation mechanisms have been reported:

- HDPE geomembrane contact with some organic compounds, either as a concentrated solution or as pure liquids, can cause absorption of the organic into HDPE causing subsequent swelling and softening of the geomembrane. In general this condition is reversible and the geomembrane returns to its original condition once the organic is no longer present at the geomembrane surface. (Needham et al. 2004)
- The oxidation rate of HDPE geomembranes in contact with solutions containing transition metals such as copper, manganese, and iron may be increased at the surface of the geomembrane, since the dissolved metals may break down hydroperoxides in the geomembrane and create additional free radicals. (Sangam and Rowe 2002; Needham et al. 2004; Rowe et al. 2008).

4.0 HDPE GEOMEMBRANE DEGRADATION APPLICABILITY TO PORTSMOUTH ON-SITE DISPOSAL CELL (OSDC)

Construction of an On-Site Disposal Cell (OSDC) at the Portsmouth Gaseous Diffusion Plant is under consideration for disposal of decontamination and decommissioning (D&D) waste (FBP 2011; Chiou 2011). Table 2 provides a list of the waste form under consideration for disposal in the potential Portsmouth OSDC. Of the waste listed in Table 2, approximately 1.8 million cubic yards (Myd^3) is low-level waste (LLW) or mixed low-level waste (MLLW) (i.e. radioactively contaminated), which includes each of the waste forms and all of the D&D process gas equipment and Resource Conservation and Recovery Act/ Comprehensive Environmental Response, Compensation, and Liability Act (RCRA/CERCLA) soil and debris. The primary radionuclides associated with this material include U-234, U-235, U-238, Tc-99, Np-237, and Pu-239 (Table 3 provides the half-lives and modes of decay associated with these radionuclides). Approximately 0.3 Myd^3 of the Table 2 waste is non-contaminated (i.e. no radioactive or hazardous contaminants) solid waste. (FBP 2011) It is anticipated that approximately 1.7 Myd^3 will be disposed within the proposed OSDC and that 0.4 Myd^3 will be disposed off-site. The waste assumed to be disposed off-site includes all of the non-contaminated solid waste (~0.3 Myd^3) and 0.1 Myd^3 of the radioactively contaminated D&D process gas equipment. (FBP 2011; Chiou 2011) It is further anticipated that much of the radioactively contaminated RCRA/CERCLA soil and debris will also be contaminated with trichloroethylene (Chiou 2011).

Table 2. Potential OSDC Waste Types (FBP 2011)

Waste Form	Volume (cubic yards)
D&D Asbestos (transite siding, building pipe, floor tile, cable insulation)	51,000
D&D Concrete (concrete pads, floors, pillars, basements, and concrete building construction materials)	420,000
D&D Debris (wood, rubber, concrete not separable from debris, metal other than Process Gas Equipment, siding, gypsum, roofing material, flooring, and brick)	534,000
D&D Process Gas Equipment (compressors, converters, motors, process piping, and values directly used for uranium enrichment; all of which is radioactively contaminated)	280,000
D&D Soil (residual soil adhering to slabs and soil requiring removal as an integral part of D&D activities)	266,000
RCRA/CERCLA Soil & Debris (soil and landfill debris generated during RCRA corrective actions; most of which is expected to be LLW or MLLW)	603,000
Total	2,154,000

Table 3. Radionuclide Half-life and Mode of Decay

Radionuclide	Half Life [1] (years)	Decay / Radiation [1, 2]
U234	2.46E+05	α, γ
U235	7.04E+08	α, γ
U238	4.47E+09	α, γ
Tc99	2.11E+05	β, γ
Np237	2.14E+06	α, γ
Pu239	2.41E+04	α, γ

[1] Tuli 2005 and Baum et al. 2009

[2] Mode of decay in order of predominance; α = alpha particle; β = beta particle; γ = gamma ray

Figure 2 provides a cross-section of the proposed OSDC and Table 4 provides the associated thicknesses of each of the layers. The closure cap HDPE geomembrane will be located beneath a three foot thick biointrusion barrier, it will be approximately ten feet deep, and it will be approximately six feet above the waste. Two HDPE geomembranes will be located within the liner system, which will be approximately 50 feet deep. The upper liner system HDPE geomembrane will have two feet of material between it and the waste and the lower one will have approximately three feet of material between it and the waste.

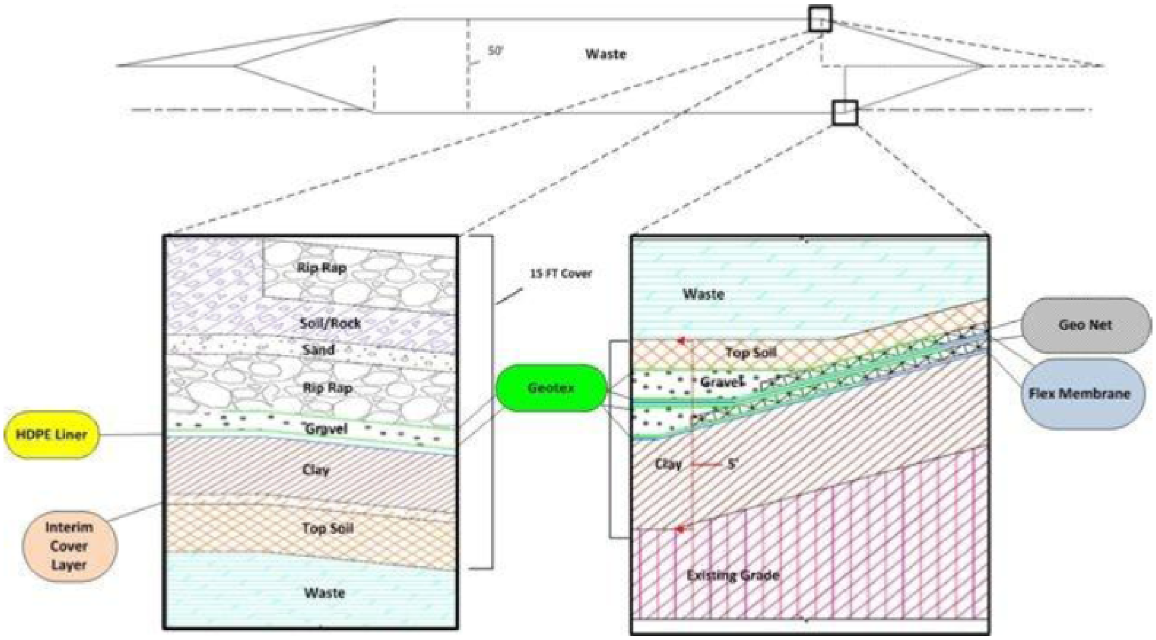


Figure 2. Proposed OSDC Cross-Section

Table 4. Proposed OSDC Layer Thickness

OSDC Layer	Thickness (inches [1])
Soil/Rock	60
Sand Filter Layer	12
Rock Biointrusion Layer	36
Gravel Lateral Drainage Layer	12
HDPE Geomembrane	80-mil
Geosynthetic Clay Layer	~0.2
Compacted Clay Layer	36
Soil	36
Waste	600
Soil	12
Gravel Leachate Collection Layer	12
HDPE Geomembrane	80-mil
Geosynthetic Clay Layer	~0.2
Gravel Leak Detection Layer	12
HDPE Geomembrane	80-mil
Geosynthetic Clay Layer	~0.2
Compacted Clay Layer	36

[1] Units of inches unless otherwise indicated

The applicability of the potential HDPE geomembrane degradation mechanisms outlined in Section 3.0 to the HDPE geomembrane to be used within the proposed OSDC closure cap and liner system has been addressed within Table 5 and Table 6, respectively. Based upon this evaluation the following degradation mechanisms/stages are applicable to both the OSDC closure cap and liner HDPE geomembranes:

- Antioxidant depletion
- Induction period
- Thermal oxidation
- Tensile stress cracking

The likely longevity (i.e. service life) of HDPE geomembrane utilized within the OSDC will be addressed in Section 5.0 based upon the above degradation mechanisms/stages.

Table 5. Applicability of HDPE Geomembrane Degradation Mechanisms to OSDC Closure Cap HDPE Geomembrane

Potential HDPE Geomembrane Degradation Mechanisms	Applicability to HDPE Geomembrane within OSDC Closure Cap
Antioxidant depletion	**Applicable**: While present antioxidants prevent thermal oxidation. Antioxidant depletion occurs due to diffusion (primary) and oxidative consumption (secondary). The rate is primarily dependent upon temperature, pore fluid, and the surrounding porous media. Antioxidant depletion of the OSDC closure cap HDPE geomembrane will occur.
Thermal oxidation	**Applicable**: If oxygen is present, thermal oxidation will begin after antioxidants are depleted and the induction period is over. It causes polymer main-chain scission (bond breaking) and over time results in mechanical property degradation and embrittlement. It is likely that sufficient oxygen will be present for thermal oxidation of the OSDC closure cap HDPE geomembrane to occur.
Tensile stress cracking	**Applicable**: As thermal oxidation proceeds tensile stress cracking can occur as a ductile tensile failure based upon the geomembrane tensile break strength or brittle stress cracking based upon geomembrane stress crack resistance (SCR) due to the applied tensile stress on the geomembrane. As long as the geomembrane is not subjected to significant tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact. Differential settlement and any slippage between layers on the side slopes are the most likely phenomenon to produce stresses that result in tensile stress cracking of the OSDC closure cap HDPE geomembrane at some point in time.
Ultraviolet (UV) radiation	**Not Applicable**: UV radiation is not a significant degradation mechanism requiring consideration, since the OSDC closure cap HDPE geomembrane will only be exposed to sunlight for a short duration and because its contains carbon black.
High energy ionizing radiation	**Not Applicable**: The primary radionuclides of concern within the low-level radioactive waste to be disposed within the OSDC include U-234, U-235, U-238, Tc-99, Np-237, and Pu-239. All of these are long-lived radionuclides that decay predominately by alpha particle emission (see Table 3). The HDPE geomembrane within the closure cap will have six feet of compacted clay and soil between it and the waste zone (see Table 4). Additionally the radionuclides will be dispersed throughout the 50-foot waste zone (see Table 4), which consists predominately of soil, concrete, and metal. The six feet of material between the HDPE geomembrane and the waste zone and the composition of the waste zone will effective shield the OSDC closure cap HDPE geomembrane from the radiation emanating from the waste zone (predominately alpha radiation). Therefore the total absorbed dose should be substantially less than 2.5Mrad, below which no significant mechanical property degradation will occur due to high energy ionizing radiation.
Microbial	**Not Applicable:** Evidence to date indicates HDPE geomembranes are insensitive to microbial degradation, due their high-molecular-weight and density.
Root penetration	**Not Applicable:** Ten feet of material will exist between the OSDC closure cap surface and the underlying HDPE geomembrane, including the three foot rock biointrusion layer, both of which should severely limit the ability of roots to reach the HDPE geomembrane. Additionally Intact HDPE geomembranes are impervious to roots. Roots can only penetrate HDPE geomembranes in locations where holes in the geomembrane have already formed due to other modes of HDPE degradation.
Burrowing animals	**Not Applicable:** Ten feet of material will exist between the OSDC closure cap surface and the underlying HDPE geomembrane, including the three foot rock biointrusion layer, both of which should preclude the ability of burrowing animals to reach the HDPE geomembrane.
Chemical	**Not Applicable:** OSDC closure cap HDPE geomembrane will be located above the waste and will not contact leachate.

Table 6. Applicability of HDPE Geomembrane Degradation Mechanisms to OSDC Liner HDPE Geomembrane

Potential HDPE Geomembrane Degradation Mechanisms	Applicability to HDPE Geomembrane within OSDC Liner
Antioxidant depletion	**Applicable**: While present antioxidants prevent thermal oxidation. Antioxidant depletion occurs due to diffusion (primary) and oxidative consumption (secondary). The rate is primarily dependent upon temperature, pore fluid, and the surrounding porous media. Antioxidant depletion of the OSDC liner HDPE geomembrane will occur.
Thermal oxidation	**Applicable**: If oxygen is present, thermal oxidation will begin after antioxidants are depleted and the induction period is over. It causes polymer main-chain scission (bond breaking) and over time results in mechanical property degradation and embrittlement. It is likely that sufficient oxygen will be present for thermal oxidation of the OSDC liner HDPE geomembrane to occur.
Tensile stress cracking	**Applicable**: As thermal oxidation proceeds tensile stress cracking can occur as a ductile tensile failure based upon the geomembrane tensile break strength or brittle stress cracking based upon geomembrane stress crack resistance (SCR) due to the applied tensile stress on the geomembrane. As long as the geomembrane is not subjected to significant tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact. Geomembrane downdrag by waste settlement on the side slopes is the most likely phenomenon to produce stresses that result in tensile stress cracking of the OSDC liner HDPE geomembrane at some point in time.
Ultraviolet (UV) radiation	**Not Applicable**: UV radiation is not a significant degradation mechanism requiring consideration, since the OSDC liner HDPE geomembrane will only be exposed to sunlight for a short duration and because its contains carbon black.
High energy ionizing radiation	**Not Applicable**: The primary radionuclides of concern within the low-level radioactive waste to be disposed within the OSDC include U-234, U-235, U-238, Tc-99, Np-237, and Pu-239. All of these are long-lived radionuclides that decay predominately by alpha particle emission (see Table 3). The HDPE geomembrane within the liner will have a minimum of two feet of soil and gravel between it and the waste zone (see Table 4). Additionally the radionuclides will be dispersed throughout the 50-foot waste zone (see Table 4), which consists predominately of soil, concrete, and metal. The two feet of material between the HDPE geomembrane and the waste zone and the composition of the waste zone will effective shield the OSDC liner HDPE geomembrane from the radiation emanating from the waste zone (predominately alpha radiation). Therefore the total absorbed dose should be substantially less than 2.5Mrad, below which no significant mechanical property degradation will occur due to high energy ionizing radiation.
Microbial	**Not Applicable:** Evidence to date indicates HDPE geomembranes are insensitive to microbial degradation, due their high-molecular-weight and density.
Root penetration	**Not Applicable:** Greater than fifty feet of material will exist between the OSDC closure cap surface and the underlying liner HDPE geomembrane, including the three foot rock biointrusion layer, both of which will preclude the ability of roots to reach the HDPE geomembrane.
Burrowing animals	**Not Applicable:** Greater than fifty feet of material will exist between the OSDC closure cap surface and the underlying liner HDPE geomembrane, including the three foot rock biointrusion layer, both of which will preclude the ability of burrowing animals to reach the HDPE geomembrane.
Chemical	**Not Applicable:** The OSDC waste will consist predominately of soil, concrete, and metal, therefore any leachate produced should be basic and have elevated calcium. This type of leachate is not aggressive toward HDPE (see Section 3.7).

5.0 HDPE GEOMEMBRANE LONGEVITY

Various service life (i.e. longevity) predictions for HDPE geomembranes not exposed to sunlight (i.e. non-exposed) are presented within the following subsections. In general these service life predictions are based upon following degradation mechanisms/stages (i.e. the same that were found to be applicable to both the OSDC closure cap and liner HDPE geomembranes within Section 4.0):

- Antioxidant depletion
- Induction period
- Thermal oxidation

All of these degradation mechanisms/stages are temperature dependent as will be seen within the following subsections. In general near surface subsurface temperatures can be taken as the annual average temperature of the area in question. The average temperature at the Portsmouth OSDC location is 53.3°F (12°C), which is taken as the annual average near surface subsurface temperature there. These data are taken from the weather station closest to the Portsmouth Gaseous Diffusion Plant that records temperature data, which is located in Waverly, Ohio approximately 10 miles north (NOAA 2010). Because the waste within the OSDC will be largely inert waste (i.e. soil, concrete, metal, asbestos (see Table 4)) with no putrescible waste, an increase in temperature due to biodegradation will not occur within the OSDC.

5.1 DREXEL UNIVERSITY / GEOSYNTHETIC INSTITUTE (GSI) LONGEVITY PROJECTIONS

Hsuan and Koerner (1998) reported on HDPE geomembrane antioxidant depletion testing of a commercially available 60 mil thick HDPE geomembrane. Four sets of five columns for a total of twenty were maintained at elevated temperatures of 85, 75, 65, and 55°C and under a static normal load of 260 kPa and a 300 mm head of tap water. The top surface of the HDPE was saturated sand and the bottom surface was dry sand vented to the atmosphere. Samples were retrieved at various time intervals and analyzed for numerous physical, mechanical, and chemical properties including OIT.

Koerner et al. 2011 produced the Table 7 lifetime prediction for non-exposed HDPE geomembranes, based upon the testing described above and an evaluation of testing by others. As seen within Table 7, a 446 year total predicted service life is predicted at a temperature of 20°C. Projecting the data to the anticipated OSDC temperature of 12°C results in an estimated total predicted service life of approximately 900 years.

Table 7. Koerner et al. 2011 Lifetime prediction for Non-exposed HDPE Geomembranes

Temperature (^oC)	Antioxidant Depletion Period (years)	Induction Period (years)	Thermal Oxidation Period [1] (years)	Total Predicted Service Life (years)
20	208	30	208	446
25	140	25	100	265
30	97	20	49	166
35	66	15	25	106
40	46	10	13	69

[1] The thermal oxidation period is defined as the time it takes for the tensile properties of the HDPE to be reduced by 50%. Even at this point the material still exists and functions; however its functionality may have decreased from that of initial placement.

5.2 GERMAN FEDERAL INSTITUTE FOR MATERIAL RESEARCH & TESTING, LANDFILL ENGINEERING LABORATORY LONGEVITY PROJECTIONS

Mueller and Jakob (2003) report on HDPE geomembrane antioxidant depletion testing of nine commercially available 100-mil thick HDPE geomembranes made by five different manufacturers from seven different resins. HDPE samples were immersed in air and de-ionized water (i.e., exposed on both sides) at 80°C. At various times samples were removed and tested for OIT, tensile strength, and elongation. Based upon this testing Mueller and Jakob (2003) conservatively estimated that under normal ambient conditions (20^oC) with submersion in water that the service life of HDPE geomembranes would be at least 300 years and up to 1000 years.

5.3 QUEEN'S UNIVERSITY, GEO-ENGINEERING CENTRE, BARRIER SYSTEMS PROJECT HDPE LONGEVITY PROJECTIONS

Sangam and Rowe (2002) and Rowe et al. 2009 reported on HDPE geomembrane antioxidant depletion testing of a GSE Lining Technology, Inc. 80-mil thick smooth HDPE manufactured from a copolymer resin. HDPE coupons were immersed in air, tap water, and synthetic landfill leachate (i.e., exposed on both sides), each at temperatures of 22 ± 2, 40, 55, 70, and 85^oC. Samples were retrieved at various time intervals and analyzed for OIT, stress crack resistance, and tensile properties.

Rowe et al. 2009 produced the Table 8 lifetime prediction for non-exposed HDPE geomembranes immersed in landfill leachate, based upon the testing described above. As seen within Table 8, the total predicted service life at a temperature of 20^oC is estimated to be between 685 to 1905 years. Projecting the data to the anticipated OSDC temperature of 12^oC results in an estimated total predicted service life of between 1,400 to 4,100 years.

Table 8. Rowe et al. 2009 Lifetime Prediction for Non-exposed HDPE Geomembranes Immersed in Landfill Leachate

Temperature (^oC)	Minimum Total Predicted Service Life (years)	Maximum Total Predicted Service Life (years)
20	685	1905
35	150	380
50	40	90

[1] The thermal oxidation period is defined as the time it takes for the tensile properties or stress crack resistance of the HDPE to be reduced by 50%. Even at this point the material still exists and functions; however its functionality may have decreased from that of initial placement.

5.4 OTHER HDPE GEOMEMBRANE LONGEVITY PROJECTIONS

Peggs 2003 conducted a review of HDPE geomembrane durability literature and concluded that once a HDPE geomembrane is installed with proper Quality Assurance (QA), its resistance to leakage is a function of its stress crack resistance, its oxidation resistance, its imposed stresses, and its stress relaxation rate. Therefore to increase service life a HDPE geomembrane should be selected with a high stress crack resistance and good thermal ageing properties and should be installed with good QA oversight and testing. Under these conditions Peggs 2003 would expect that a municipal solid waste landfill HDPE geomembrane should last for about 400 years.

Needham et al. 2004 and Needham et al. 2006 conducted a review of HDPE geomembrane durability literature and concluded that HDPE geomembrane service life is dependent upon its material degradation and the subsequent formation of holes by tensile stress cracking. Based upon this review Needham et al. 2004 and Needham et al. 2006 developed a methodology for combining HDPE degradation mechanisms (antioxidant depletion, thermal oxidation, and tensile stress cracking) into an estimate of generation of holes over time. Also based upon their review they developed the Table 9 estimate of the antioxidant depletion period.

Table 9. Needham et al. 2004 and Needham et al. 2006 Antioxidant Depletion Period Prediction

Temperature (^oC)	Antioxidant Depletion Period (years)
20	450 to 1,300
30	140 to 530

6.0 SUMMARY AND CONCLUSIONS

It is anticipated that degradation of the OSDC closure cap and liner 80-mil HDPE geomembranes will occur through antioxidant depletion, induction (i.e. time to initiate thermal oxidation once antioxidant depleted), thermal oxidation, and tensile stress cracking. HDPE geomembrane service life projections based upon these degradation mechanisms at 20°C range from 300 to 1,900 years (see Section 5.0). The HDPE geomembrane service life would be even greater at the anticipated OSDC temperature of 12°C. Based upon existing data the 200 year service life assumed for the OSDC closure cap and liner HDPE geomembranes is considered a conservative assumption. Additionally based upon existing data, the service life of the OSDC 80-mil HDPE geomembrane will be longer than that of a 60-mil HDPE geomembrane, which is typical for landfill applications. While it is anticipated that the service life of a 100-mil HDPE geomembrane would be longer than that of the OSDC 80-mil HDPE geomembrane, 100-mil HDPE geomembranes present significant workability issues during construction due to their inherent increased stiffness.

Of the waste forms under consideration for disposal in the potential Portsmouth OSDC (see Table 2), the D&D process gas equipment includes five different sizes of converters. It is anticipated that the most highly contaminated converters will be disposed off-site. Two modes of disposal are under consideration for the converters being evaluated for disposal within the potential OSDC. The modes of converter disposal under consideration include: 1) cut, place, and compact; and 2) intact placement. (Chiou 2011) Use of the cut, place, and compact mode of converter disposal will result in no significant subsidence potential associated with the OSDC, therefore subsidence would not be applicable as a degradation mechanism to the OSDC HDPE geomembrane. However use of the intact placement mode of converter disposal could result in subsidence resulting in differential settlement at the surface of the OSDC closure cap. This degradation mechanism is not applicable to the OSDC liner HDPE geomembrane, but it is potentially applicable to the OSDC closure cap HDPE geomembrane, if the converters are disposed intact. It is only applicable to the OSDC closure cap HDPE geomembrane if the following are true:

- Intact converters disposed within the OSDC have large internal void spaces,
- It is anticipated that the converters will degrade to the point of collapse within a time frame of concern, and
- Such collapse will result in substantial differential settlement at the surface of the OSDC closure cap.

Otherwise subsidence as a degradation mechanism is not applicable at all.

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