SERVICE LIFE OF A LANDFILL LINER SYSTEM SUBJECTED TO ELEVATED TEMPERATURES

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ABSTRACT: Subtitle D landfills may experience elevated temperatures for a variety of reasons such as hydration of combustion ash, waste biodegradation with and without leachate recirculation, aluminum waste and combustion ash reactions, and wastes received with elevated temperature. Elevated temperatures can reduce service life and/or effectiveness of composite liner system components by accelerating antioxidant depletion of geomembranes and desiccation of low hydraulic conductivity compacted soil liners and geosynthetic clay liners. This paper uses a case history to illustrate the potential effect(s) of elevated temperatures on a composite liner system and the associated reduction in service life and/or effectiveness. This paper also discusses possible criteria for assessing the service life of liner system components, such as, applicable engineering properties, locations for service life assessments, and definitions for liner failure.

Keywords: Aluminum, dross, exothermic chemical reaction, landfill fire, landfill gas, elevated temperature, geomembranes, geosynthetics, durability, waste disposal

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INTRODUCTION

Municipal solid waste (MSW) placement facilities are required to have a barrier system to control the escape of contaminants from the waste to groundwater or surface water bodies to negligible levels. Landfill temperature is important because it can affect performance of various barrier system components, such as the geomembrane, low hydraulic conductivity compacted soil liner (LHCSL), geotextiles, and geosynthetic clay liner (GCL). Elevated temperatures can reduce the service life of geomembranes, LHCSL, and GCL (Rowe 2005) in both single and double composite liner systems (Southen and Rowe 2004; Rowe 2005; Southen and Rowe 2005a,b; Rowe et al. 2008, 2009, 2010; Rowe and Hoor 2009; Southen and Rowe 2011; Azad et al. 2011; Rowe 2011).

Landfill monitoring shows that heat generated by MSW, hydration of combustion ash, and aluminum waste and combustion ash reactions can significantly increase the temperature at the underlying liner system. Liner system temperatures of 30–40°C can be expected (Klein et al. 2001; Yoshida and Rowe 2003; Rowe et al. 2004; Rowe 2005; Koerner and Koerner 2006; Koerner et al. 2008; Yesiller et al. 2005; Hanson et al. 2005, 2008, 2010; Rowe and Islam 2009; Rowe 2011) and in some cases temperatures up to 60°C have been measured (Calder and Stark 2010; Stark et al. 2011; Rowe 2011). The heat generated by a waste containment facility is a function of waste accepted, management practice, e.g., leachate recirculation and gas system operation, and nature of the waste degradation process. Brune et al. (1991) report an increased rate of waste placement correlates with an increased rate of temperature increase of 10^0C/ton increase. Available moisture can accelerate the rate of temperature increase and temperature in the landfill by increasing the rate of waste degradation (Rowe 2005).

More recently, aluminum production waste (APW) and combustion ash related reactions can generate temperatures up to 150ºC (300ºF) (Calder and Stark 2010; Stark et al. 2011) which become problematic for landfill operations. The U.S. Department of Energy (1999) estimates that at least one million metric tonnes (approximately 1.1 million short tons) of APW are placed annually in RCRA Subtitle D landfills. These waste materials contain variable amounts of aluminum metal and aluminum compounds, such as aluminum carbide, aluminum nitride, aluminum sulfide, and aluminum oxides, mixed with sodium and potassium salts and other substances (Manfredi et al. 1997; Shinzato et al. 2005; Szczygielski 2007) that can react with available moisture. The most likely reactions of APWs in a Subtitle D landfill or non-hazardous industrial landfill involve the amphoteric reaction of aluminum metal with water (Calder and Stark 2010) as shown below:

$$Al_{(Metal)} + 3\,H_2O_{(Liquid)} \rightarrow Al(OH)_3 + 3/2\,H_{2\,(Gas)} + Heat \qquad (1a)$$

$$2\,Al_{(Metal)} + 3\,H_2O_{(Liquid)} \rightarrow Al_2O_3 + 3\,H_{2\,(Gas)} + Heat \qquad (1b)$$

$$Al_2O_3 + (OH)^{-1} + H_2O_{(Liquid)} \rightarrow Al(OH)_3 + 3/2\,H_{2\,(Gas)} + Heat \qquad (2)$$

These reactions can release large amounts of heat and possibly flammable hydrogen gas in the waste. Internal temperatures of waste masses experiencing this reaction have been observed between 88^o C (170^{o}F) and 110^o C (230^{o}F), at which desirable microbial activity is terminated and corresponding methane production is severely curtailed. These exothermic reactions and associated changes in gas composition and increased gas pressure also usually cause intense nuisance odors (for example ammonia) and possible combustion of surrounding MSW.

APW reactions can involve pure Al (metal) as shown in Reactions (1a and 1b) above, however, the percentage of pure Al (metal) metal in APW depends on several factors, e.g., the amount of reprocessing to remove Al (metal) that has been performed and the amount of Al (metal) trapped between aluminum oxides (Al_2O_3) and a surficial salt flux layer. As a result, APW usually contains mostly aluminum oxide as well as aluminum nitride (AlN), aluminum carbide (Al_4C_3), and/or aluminum sulfide (Al_2S_3), all of which can combine with water, see Reactions below, and result in ammonia (NH_3), methane (CH_4), and hydrogen sulfide (H_2S) gas being produced, respectively:

$$2AlN + 3\,H_2O_{(Liquid)} \rightarrow Al_2O_3 + 2\,NH_3 \qquad (3)$$

$$Al_4C_3 + 6\,H_2O_{(Liquid)} \rightarrow 2\,Al_2O_3 + 3\,CH_4 \qquad (4)$$

$$Al_2S_3 + 3\,H_2O_{(Liquid)} \rightarrow Al_2O_3 + 3\,H_2S \qquad (5)$$

EFEECT OF ELEVATED TEMPERATURES ON ENGINEERED COMPONENTS

This section describes the potential impact of elevated temperatures on geomembranes, LHCSLs, and GCLs that may be used in a composite liner system. For example, elevated temperatures can reduce service life by accelerating antioxidant depletion and desiccation of geomembranes and LHCSLs, respectively, in composite liner systems. Potential for desiccation depends on the temperature gradient, the water retention behavior of the subgrade soil below the LHCSL or GCL, and location of the groundwater surface (Rowe 2005).

Effect of Temperature on HDPE Geomembranes

This section focuses on the effect of elevated temperatures on the performance of High Density Polyethylene (HDPE) geomembranes. The focus is on HDPE geomembranes, instead of some other geomembrane type, because they are frequently used for the geomembrane component of a composite liner system in Subtitle C (hazardous waste) and D (MSW) landfills.

With the interest in waste to energy, e.g., methane generation, disposal of APW, combustion of MSW for energy and to reduce waste volume, bio-reactors, and acceleration of decomposition via leachate recirculation, temperatures in landfills are increasing and causing increased temperatures at the liner system (Rowe et al. 2010; Rowe 2011). For example, thermistors installed on top of the liner system geomembrane in a facility undergoing an aluminum reaction measured sustained temperatures of 86ºC (140ºF) (Stark et al. 2011). HDPE geomembrane manufacturers do not recommend sustained temperatures greater than 57ºC (160ºF) for HDPE and 46ºC (140ºF) for linear low density polyethylene (LLDPE) which are primarily used for final cover systems and not composite liner systems (Yazdani, personal communication, 2005). Elevated temperatures can accelerate the depletion of the antioxidants added during the geomembrane manufacturing process and accelerate subsequent oxidation of the polymer leading to a loss in stress crack resistance and a decrease in geomembrane service life (Rowe et al. 2009, 2010).

HDPE geomembranes consist of, by weight percentage, 96 to 97% polyethylene resin, 2 to 3% carbon black, and approximately 0.5 to 1% antioxidants (Hsuan and Koerner 1998). Antioxidants are added to HDPE geomembrane formulations to reduce polymer degradation during processing and oxidation reactions during the initial stage of geomembrane service life (Hsuan and Koerner 1998). The degradation of HDPE geomembranes has been examined by a number of researchers (Hsuan and Koerner 1998; Sangam and Rowe 2002; Muller and Jacob 2003; Tarnowski et al. 2005; Needham et al. 2006; Jeon 2008; Rowe 2005; Rowe and Rimal 2008a, 2008b; Rowe et al. 2008, 2009, 2010; Rimal and Rowe 2009) and consists of the following three stages: (Stage A) depletion of antioxidants; (Stage B) induction or start of polymer degradation; and (Stage C) polymer degradation and decrease in key physical properties (Hsuan and Koerner 1998).

The duration of each of the three stages is referred to as depletion time (Stage A), induction time (Stage B), and degradation time (Stage C), respectively. During Stage A, antioxidants present in the geomembrane are progressively volatized, diffused, and/or oxidized (Koerner 1998). The duration of Stage A is important because the active antioxidants protect the geomembrane from degradation. During Stage B, polymer degradation commences but there is no measurable change in geomembrane engineering properties even though the antioxidants have been significantly reduced or removed (Koerner 1998). Induction of polymer degradation continues in Stage B until the effects of the oxidation-induced scission of polyethylene chains becomes measurable (Koerner 1998). During Stage C, measurable changes in the engineering properties of the geomembrane occur (Koerner 1998) until the service life of the geomembrane is reached. The service life of a geomembrane is the sum of the duration of these three stages. Table 1 provides the service life of HDPE geomembranes subject to temperatures of 20ºC to 60ºC in a laboratory simulated liner system (Rowe 2005) using 50% reduction in the tensile strength at break as the end of service life.

Table 1. Estimated HDPE geomembrane service life based on 50% reduction in tensile strength at break for different temperatures (based on Rowe, 2005)

Fig. 1: Duration of degradation stages A, B, and C and total service life based on 50% reduction in tensile strength at break (data from Rowe 2005)

Fig. 1 shows the decrease in service life with increasing temperature. Only the results for Stage A, or antioxidant depletion, are based on laboratory testing that simulates landfill disposal conditions. Stage B and C degradation are based on polyethylene pipe test results presented by Viebke et al. (1994). Although the estimated service life values assume a constant temperature, even a short duration of elevated temperature can significantly reduce HDPE geomembrane service life to several decades (see Fig. 1) and, by extrapolation, to as little as a few years at higher temperatures (Rowe and Islam 2009).

Typically service life is defined as the time required for a 50% reduction in some geomembrane property such as tensile stress at break or stress crack resistance (Rowe 2005, Rowe et al., 2009; Rowe 2012). Rowe et al. (2009) and Rowe (2012) indicate that stress crack resistance is likely the critical physical parameter with respect to predicting the service life of HDPE geomembranes because studies using geosynthetic landfill liner simulators (Rowe 2012) has shown that when GMs reach the end of their service life they experience extensive stress-cracking and the number of holes goes from a few holes/ha to 30 to 100 holes/m^2. At this point the liner can no longer be considered a composite liner and leakage will be controlled by the clay liner component.

Effect of Temperature on LHCSL

Landfill elevated temperatures can adversely impact the performance of the LHLHCSLCSL by inducing moisture migration via thermal gradients across the LHCSL. These gradients induce thermal movement of moisture from the LPCSL to the underlying cooler subgrade or groundwater. This moisture movement is caused by the expansion of liquid water and the increase in water vapor pressure as temperature increases. The resulting water vapor recondenses when it reaches the cooler subgrade. Doll (1997) modeled moisture migration from a heat-source in landfill barriers and found that significant drying can occur unless downward vapor diffusion due to temperature gradients can be balanced by capillary rise from underlying strata.

The primary concern for LHCSLs is the low hydraulic conductivity compacted soil (LPCS) can lose some moisture (desiccate) due to thermal flow and subsequently shrink. This shrinkage increases the potential for LPCS cracking and development of preferential pathways for leachate and landfill gas flow through the LHCSL and into the underlying groundwater system (Rowe 2011). The potential for shrinkage of a LHCSL, however, decreases as overburden stress increases (Southen and Rowe 2005b). The horizontal compressive stresses in the soil developed due to overburden stresses, e.g., overlying waste, as well as the tensile strength of the soil act to resist the formation of shrinkage cracks (Zhou and Rowe 2005). Zhou and Rowe (2005) suggest that a horizontal stress of greater than 38 kPa is sufficient to resist shrinkage cracking for a liner with properties similar to the one they examined. Using a horizontal earth pressure coefficient of 0.5, a horizontal stress greater than 38 kPa corresponds to a vertical stress of greater than 76 kPa. Using a waste unit weight of 11.8 kN/m^3, a waste thickness above the LHCSL of greater than about 6.5 m would be sufficient to resist shrinkage cracking according to Zhou and Rowe (2005) for a liner with properties similar to the one they examined.

Effect of Temperature on GCLs

The behavior of alternate wet and dry cycles on GCL hydraulic conductivity is important particularly when the duration and intensity of the dry cycle is sufficient to cause desiccation of the bentonite component of the GCL (Shan and Daniel 1991). Boardman and Daniel (1996) evaluated a single, but severe, wet-dry cycle on a number of GCLs and found essentially no change in GCL hydraulic conductivity.

Zhou and Rowe (2005) also evaluated the effect of thermal gradients on drying and cracking of a GCL. The profile analyzed consists of a 1 cm thick GCL overlying a 4 m thick soil layer. The initial temperature of the profile was assumed to be 10ºC and a temperature increase of 16°C was applied. Zhou and Rowe (2005) conclude that for the GCL they considered, desiccation cracking is unlikely if the horizontal compressive stress on the GCL is greater than 43 kPa or a waste thickness of 3.6 m. Experimental studies also suggest that GCLs in a bottom liner systems can self-heal and regain their hydraulic conductivity when rehydrated with water (Shan and Daniel 1991; Boardman and Daniel 1996; Lin and Benson 2000; Southen and Rowe 2005a, Azad et al. 2011). The re-healing may be less effective if permeated with leachate containing significant cations (Rowe 2011). Also Southen and Rowe (2005a) and Azad et al. (2011) demonstrate that the potential for desiccation GCL depends on the type of GCL (they are not all the same) and the (a) thermal gradient, (b) vertical stress, and (c) nature of material (i.e. its grain size distribution and hence water retention curve and its initial moisture content) below the GCL.

ELEVATED TEMPERATURE CASE HISOTRY

The effects of elevated temperatures on a Subtitle D compliant composite liner system are illustrated using a case history and some of the liner system issues that can develop when a facility experiences elevated temperatures. This case is described in detail by Stark et al. (2011) so only briefly reviewed herein. The facility operated normally from 1991 until July 2001, at which time the original 35.7 hectares (Cells 1-6) started exhibiting changes in behavior. The facility accepted between 544,200 metric tonnes (600,000 short tons) and 1,033,206 metric tonnes (562,000 short tons) of aluminum production waste from 1991 through 2004. According to the March 2007 Findings and Orders issued by the Ohio EPA, from 1993 to 2006 the facility placed approximately 544,311 metric tonnes (600,000 tons) of aluminum production wastes (mostly black dross or salt cake) in Cells 1, 3, 4A, 4B, 6, and 7 (see Fig. 2). Around 2005, it became obvious that the facility was experiencing an abnormal reaction because of the extremely bad odors, elevated temperatures, increased gas and liquid pressures, and rapid settlement of the waste. Changes in leachate composition and quantity are important to determine whether or not an APW reaction is occurring. If significant amounts of sodium and potassium chlorides (salt fluxes) are leached from APW, the quality of the leachate will change dramatically (as will likely occur if leachate recirculation is performed). The salt fluxes are added to aluminum recycling process to protect the molten metal from oxidation, help remove superficial aluminum oxide layer, promote coalescence of aluminum drops, and maintain the oxides in suspension (Totten and MacKenzie 2003). Based on observations and gas and leachate compositions, it was concluded that an exothermic aluminum reaction was occurring and generating considerable heat. The reaction was magnified and increased by the liquid introduced into the facility via leachate recirculation reacting with the previously disposed APW. The leachate recirculation began in 1996 and ended in 2006. During this ten year time period approximately 103 million liters (27.2 million gallons) of leachate was recirculated.

The aluminum production waste lay dormant from 1991 until about July 2001 when small changes in leachate and gas constituents started being observed. Minimal APW was reacting during this dormant period. This suggests that leachate recirculation was the trigger for the reaction shown in the equations (1a, 1b, and 2) above, although with more time for water to infiltrate and dissolve the salt fluxes covering the APW some reactions and temperature increase may have developed subsequently even without leachate recirculation.

At this site, the composite liner system consists of a single composite liner system with the following components in Cells 1 through 4 (see Fig. 4):

- 0.3 m (1 ft) leachate collection system washed sand (Cell 1) or pea gravel (Cells 2,3, and 4),
- 400 g/m^2 (12 oz/yd^2) to 540 g/m^2 (16 oz/yd^2) Protective nonwoven geotextile, 1.5 mm (60-mil) HDPE geomembrane,
- and 1.5 m (5 ft) low hydraulic conductivity compacted soil (LPCS).

In Cells 5A through 5D and 6, the composite liner systems consist of the following components:

- 0.3 m (1 ft) leachate collection system pea gravel (Cell 5D, 6) or 0.45 m (1.5 ft) shredded tires (5A, 5B, 5C) ,
- 270 g/m^2 (12 oz/yd^2) to 540 g/m^2 (16 oz/yd^2) Protective nonwoven geotextile,
- 1.5 mm (60-mil) HDPE geomembrane,
- Needle-punched reinforced geosynthetic clay liner (GCL), and
- 0.9 m (3 ft) low hydraulic conductivity compacted soil (LPCS).

Measurement of leachate collection system temperatures in the vicinity of Cell 6 (see red box in Fig. 2) was performed to primarily evaluate temperature conditions at or near the geomembrane in the single composite liner system and the measured sustained temperatures exceeded 85^{o}C (185^{o}F). Given the sustained elevated temperatures, the integrity of the composite liner system was investigated. Extrapolating the data in Fig. 1, the service life of the 1.5 mm (60 mil) thick HDPE geomembrane used in the single composite liner system would have reached the end of its service-life after only three–four years at 85^{o}C if the GM was similar to that upon which the data in Fig. 1 is based. The next paragraphs investigate possible indicators of the integrity of the composite liner system.

Fig. 2: Site Overview and Cell Layout

One possible indication of the loss of integrity of the composite liner system is reflected in the increased leachate volume pumped from Cells 1-6 (see Fig. 3). From 1999 until 2005, most of the leachate generated was recirculated so the volume of leachate transported off-site during this period was minimal. Leachate recirculation ended in 2006 when the landfill was exhibiting abnormal characteristics.

From 1991 through 2004, the 35.7 hectares comprising the initial facility generated between 3,776 m^3 (997,615 gallons) to a maximum of 23,005 m^3 (6,077,840 gallons) as shown in Fig. 3. In 2004, the leachate volume was 11,808 m^3 (3,119,622 gallons). In 2005, the leachate volume increased to 45,688 m^3 (12,070,732 gallons) and continued to increase in subsequent years with 108,954 m^3 (28,785,700 gallons) in 2006, 129,786 m^3 (34,289,500 gallons) in 2007, 127,184 m^3

(33,602,100 gallons) in 2008, 93,151 m^3 (24,610,600 gallons) in 2009, and 76,837 m^3 (20,300, 450 gallons) in 2010.

The total 103,102 m^3 (27,239,715 gallons) of leachate that were recirculated at the facility over approximately 10 years is assumed to be the primary source of the leachate volume increase. However, waste solidification activities in the vicinity of Cells 1 and 4B (see Fig. 2) contributed some moisture to the waste mass, but probably less than the recirculation activities. The amount of leachate generated by the effects of the reaction and subsequent combustion significantly exceeds the total amount of leachate recirculated. For example, from 2006 through 2008 the annual volume of leachate generated (~120,000 m^3 or 31,700,000 gallons) exceeds the total amount of leachate recirculated from 1996 to 2006 (103,102 m^3 or 27,239,715 gallons). In addition, the total volume of leachate generated from only 2006 through 2008 (363,215 m^3 or 95,961,653 gallons) far exceeds the total amount of leachate recirculated from 1996 to 2006 (103,102 m^3 or 27,239,715 gallons). Thus, there is a significant amount of unexplained leachate being collected.

Infiltration of precipitation is not thought to have contributed significantly to the increased leachate volume because a significant portion of the 35.7 hectares (Cells 1 through 6 in Fig. 2) was covered with a 2.0 mm (80 mil) thick HDPE geomembrane to control odors after 2006. However, prior to placement of this cover geomembrane, surface water ponding occurred within a large bowl-shaped area at the top of the landfill created by rapid settlement of the underlying waste which may have contributed some moisture to the leachate quantity.

Other potential sources of the excess leachate include: (1) water generated by the heating and/or combustion of organic wastes (i.e., initial waste moisture content); (2) non-combustion chemical or biochemical reactions; and (3) possible groundwater inflow due to an inward gradient (as discussed below with respect to Fig. 4) through a heat or slope movement damaged liner system.

A possible source of leachate is the initial moisture content of the MSW which was estimated to be about 20% because of the leachate recirculation prior to the reaction. Using a reaction area of about 16 hectares (40 acres) and half of the moisture is removed by the gas extraction system, a total increase in leachate of 426,698 m^3 (112,733,911 gallons) may have been generated from the waste. The leachate volume was estimated using a waste volume of cubic meters (50 m deep x 360 m wide x 450 m long) and multiplying it by 20% and a waste unit weight of 11.8 kN/m^3. However, this additional volume does not completely explain the increase in leachate volume.

Fig. 4 shows a shallow excavation in the ubiquitous mine spoil (located east of Cell 8) that naturally filled with water. In addition, hydrogeologic drawings for the Permit Application (Eagon & Associates 2002) show a zone of saturation in the mine spoil which is present along the landfill liner sideslope.

The sidewall liner on the south side of the landfill in the vicinity of Cell 6 (dashed box in Fig. 2) may have been damaged due to high temperatures, gas pressures, leachate chemical composition, and/or the 2006 slope failure. If the liner system was compromised, groundwater from the adjacent (see Fig 4.) mine spoil and underlying shale and siltstone bedrock could have migrated into the waste mass and contributed to the excessive leachate volume because the liner system is below the zone of saturation in the mine spoil. Based on the earlier discussion a sustained temperature of 85^oC for three to four years (and even less at higher temperature) may have been sufficient to cause failure of the geomembrane. Thus some of the excess leachate could be the result of water ingress through the liner system if the geomembrane failed. In this context, the service-life of composite liner components is discussed below.

Fig. 3: Leachate volume and handling as a function of time

Fig. 4: Water filled excavation east of Cell 8 (see Fig. 2)

SERVICE LIFE OF COMPOSITE LINER SYSTEM COMPONENTS

The presence of elevated temperatures at or near a liner system in the case history described above, as well as others, raises the question of how should service life of the liner system and in particular the geomembrane, LHCSL, and/or GCL be evaluated. This question is usually raised after elevated temperatures have been detected and leads to many questions, such as, what criteria should be used to assess service life, how should the criteria be investigated, and what remedial measures should be implemented for the liner system.

Examples of Possible Service Life Criteria

This issue is complicated in the United States because there is no regulation on the required service life of a composite liner system. In contrast, Ontario (Canada) Regulation 232/98 requires a service of 150 years for the primary liner system and 350 years for the secondary liner system in the double composite liner system required for a Subtitle D compliant landfill (OMoE 1998). Based on the data presented in Fig. 1, the geomembranes in the case history described above would not meet Ontario Regulation 232/98 because the service life of the 1.5 mm thick HDPE geomembrane is significantly less than 150 years based on the measured temperatures.

Because the Subtitle D in the United States does not specify a service life as Ontario Regulation 232/98 does, some possible service life durations in decreasing duration are listed below:

- 150 years as required by Ontario Regulation 232/98;
- End of 30 year post-closure period;
- Installation of final cover system;
- End of active filling and installation of interim soil cover over the entire facility;
- End of active filling and installation of interim soil cover in placement area.

The Ontario Regulation 232/98 is clear about the required service life, and suggests that this might be achieved for a geomembrane used in a normal MSW landfill where liner temperatures are 30-40^{o}C (it was not written for bio-reactor landfills and did not envisage co-disposal with aluminum dross) provided the following requirements are met:

(1) the oxidation induction time of the geomembrane exceeds 100 minutes as determined by ASTM D3895 or 250 minutes as determined by ASTM D5885;

(2) the oxidation induction time of the geomembrane after oven aging at 85°C for 90 days as described in ASTM D5721 must exceed (a) 80% of the value for the original geomembrane as determined by ASTM D3895 or (b) 80% of the value for the original geomembrane as determined by ASTM D5885

Of course, a sample of the impacted geomembrane must be obtained from the facility to assess the oxidation induction time which may be difficult because of the presence of waste and elevated temperatures.

Hsuan and Koerner (1995) selected the the criterion for geomembrane service life as when a specific design property has been reduced by 50% of its initial value. This is referred to as the half-life of the geomembrane. Although the design property, e.g., tensile strength or strain at break, may be reduced by 50% and the geomembrane becomes brittle, the geomembrane may still function as a hydraulic barrier. Thus, this half-life concept may not be appropriate for estimating the service life of a geomembrane for containment purposes (Rowe 2012).

HDPE Geomembrane Service Life Criteria

The function of a geomembrane is to be an effective barrier to: leachate migration, convection of landfill gas, and diffusion of both leachate and landfill gas. Therefore, it is appropriate to consider degradation of the advective and diffusive properties of a geomembrane as a means for evaluating geomembrane service life. Advective flow through a geomembrane liner can only occur significantly through holes or defects in the geomembrane. Defects in the geomembrane arising after certification can take the form of fully penetrating holes, such as, tears, rips, pinholes, holes, and cuts during soil or waste placement. In addition, geomembrane imperfections, e.g., wrinkles, creases, large tensile stresses, may subsequently develop into or cause fully penetrating holes. Holes also may develop throughout the service life of the geomembrane at partially penetrating defects and areas of weakness or stress, or may be the result of new damage, e.g., slope movement. Numerous factors can lead to development of geomembrane holes, including:

- waste disposal activities;
- articles of waste penetrating the geomembrane;

- pressures arising from the waste load causing puncturing by overlying gravel or protruding stones from underneath the geomembrane;
- long-term degradation of overlying protection geotextiles with a reduction in the protection afforded against gravel puncture;
- tensile stresses in the geomembrane, e.g., at wrinkles or poor quality seams, leading to stress cracks or opening of partially penetrating defects;
- excessive tensile stresses resulting from down-drag caused by waste settlement, subgrade settlement, or stresses in the vicinity of the base of leachate wells;
- catastrophic events including slope instability and landfill fires (Adams et al., 1997);
- leachate-geomembrane incompatibility in hazardous waste landfills; and
- long-term degradation of the geomembrane polymer with a loss of physical properties.

Many of the causes of defects, damage, and stresses in a geomembrane can be prevented with adequate design, proper liner construction, and waste disposal practices.

Geomembrane Advective and Diffusive Flow

Advective flow through a geomembrane can also occur due to tearing of the geomembrane under tensile stresses. In evaluating landfill slope stability, stresses across the liner system are typically designed to be transmitted in shear such that no tensile stresses are applied to the geomembrane or other geosynthetic liner component (e.g. GCL). Factors of safety in slope stability analyses are used to ensure stability and minimal deformation of landfill slopes which can result in tensile stresses being applied to the geomembrane or even geomembrane tearing (Stark et al. 1998). In addition, the upper surface of the geomembrane is frequently overlain by a geotextile cushion, intended to protect against stress concentrations on the geomembrane surface. However, while the cushion geotextile may be adequate for minimizing short-term puncture, many are not sufficient to control the tensile strains induced by the overlying drainage material and wrinkles in the geomembrane to acceptable levels because they are based on short-term tests at room temperature (Brachman and Gudina 2008a,b; Dickinson and Brachman, 2008). Elevated temperatures because of accelerated creep, degradation, or melting of the nonwoven geotextile filaments can result in an increase in these tensile strains/stresses. In this case, stress cracking may become widespread, depending upon the size and angularity of the overlying drainage material (Rowe 2012).

HDPE geomembranes are described as excellent diffusion barriers to inorganic constituents (Rowe, 2005); however, organic constituents can migrate through HDPE geomembranes by molecular diffusion (Rowe et al. 2004; Rowe 2005). Diffusion rates are generally estimated using Fick's law as a function of constituent concentration gradient and the diffusion coefficient. Islam and Rowe (2009) report tests on the effect of aging on diffusion through HDPE geomembranes. They conclude that HDPE geomembrane aging results in an increase in crystallinity, which results in a reduction in the diffusion coefficient and thus diffusive transport although the improvement still does not make the HDPE geomembrane an effective diffusion barrier for volatile organic compounds.

HDPE Geomembrane Service Life

Rowe (2005) also uses a 50% reduction in the tensile strength at break to define geomembrane service life or failure. However, Fig. 5 shows that the tensile strength at break decreases significantly with increasing temperature whereas the tensile strength at yield does not. Thus, selecting the right engineering property to define failure in the presence of elevated temperatures is important. However, once an engineering property is selected, another issue is whether the 50% reduction is determined using the manufactured or specified value. It seems prudent to use the specified value because this is the property that the project engineer determined was relevant even though it is likely lower than the manufactured value (Rowe 2011).

Alternatively, service life could be related to geomembrane performance instead of an engineering property. For example, geomembrane failure only occurs if the geomembrane leaks because there is limited correlation between tensile strength at break and geomembrane leakage. If the elevated temperatures are sufficient to melt the geomembrane as observed by Adams et al. (1997), this service life criteria would be fairly easy to implement because leakage would probably be detected. However, if complete melting does not occur there may be a time lag between elevated temperatures and leakage. The length of this lag will depend on the level of temperature. Rowe (2011) indicates that failure as a hydraulic barrier will be associated with the formation of stress cracks in the geomembrane although in a composite liner the LHCSL liner (if still intact) will continue to provide some resistance to leakage (or inflow of water if an inward gradient is present). Thus, a significant increase in leachate as discussed in the case history earlier indicates possible geomembrane and/or LHCSL or GCL failure. There will also be a time lag between the loss of the hydraulic effectiveness of the geomembrane and leakage being detected; the length of this time lag will depend on site hydrogeology and the type and location of the monitors, e.g., groundwater monitoring wells, being used to detect the leakage. These time lags may cause a change in economic viability of the facility before leakage is detected resulting in insufficient funds being available for an expensive cleanup. If this is deemed the case, advective and diffusive flow should be considered when evaluating leakage of the geomembrane and the potential for future leakage. If future leakage is deemed possible, additional financial resources should be allocated by the facility.

Location of Service Life Assessment

It is implicit in Ontario Regulation 232/98 (although not clearly stated) that the location where geomembrane service life should be assessed is the most critical location (i.e. that which would allow an escape of contaminant to the environment that might exceed the maximum allowable concentrations as defined in §10 of OMoE 1998). One such critical location is the sump where sustained liquid and gas pressures may be present that could facilitate advective and diffusive flow. Of course, this assumes there is no clogging of the leachate collection system that could result in sustained liquid and gas pressures accumulating at other places above the liner system besides the sump. For example, most geomembranes are placed with some wrinkles (Chappel et al., 2011; Rowe 2011). These wrinkles can results in local ponding of leachate, especially on a relatively flat landfill base, until the leachate level is high enough to flow over the wrinkle. Thus the service life would need to be met everywhere.

Another area where service life could be evaluated is landfill side slopes because the liner system, in particular the geosynthetics and the LHCSL, are subjected to tensile stress imposed by the waste especially if it is settling due to overburden stresses, waste degradation, or waste reaction or combustion. In the case described by Adams et al. (1997) liner system damage occurred along the side slope of the hazardous waste landfill due to elevated temperatures.

Fig. 5: Engineering property retained as a function of time for an incubation temperature of 115^0C (239^0F) (after Hsuan and Guan 1998)

LHCSL Service Life Criteria

In the case history described above, the temperature measured in the leachate collection system above the geomembrane exceeded 85^oC (185^oF). The LHCSL is directly below the geomembrane so it can be assumed that at least the upper surface of the LHCSL also experienced a temperature of 85^oC (185^oF). This is significant because the ASTM Test Method for measuring moisture content of soils (ASTM D2216) requires placing the soil in an oven at 110^oC (230^oF) for only twenty-four hours. In the case history described above, the LHCSL was subjected to elevated temperatures for years not just twenty-four hours as required by ASTM D2216. Thus, it can be assumed that some of the moisture was removed from at least the upper portion of the LHCSL resulting in a decrease in moisture content. A decrease in moisture content can result in desiccation and subsequent cracking of the LHCSL which can facilitate leachate and gas migration. Desiccation of the LHCSL was observed by Adams et al. (1997) after excavation of the waste mass in the vicinity of elevated temperatures.

During construction and service life of a LHCSL, the two main moisture migration mechanisms are:

1. equilibration of soil moisture potential between LHCSL and subgrade;
2. moisture migration due to the thermal gradient produced by high temperatures generated during waste decomposition, aluminum reactions, or ash hydration.

For LHCSLs, mechanism (1) is of short duration and occurs during construction; mechanism (2) occurs throughout the life of the landfill; and mechanism (3) is initiated during waste disposal and is the focus of the recommendations presented below.

Wrinkling of the overlying geomembrane allows development of air-pockets above the LHCSL which can collect moisture driven from the LHCSL generated by elevated temperatures above the geomembrane. The air in the wrinkles can be heated and transmitted resulting in a large portion of the LHCSL being subjected to elevated temperatures. The LHCSL moisture can collect in the wrinkles and then condense when the temperature reduces, e.g., night-time or end of the reaction or combustion, or the humidity reaches 100%. On horizontal surfaces, recondensing moisture may be reabsorbed by the LHCSL, (although absorption to the original level may not occur without significant bentonite being present) with little loss in moisture content (although the LHCSL may still be damaged).

On landfill side slopes or a sloping landfill base the condensing moisture will flow via gravity downslope away from the source causing the LHCSL to desiccate and crack resulting in greater hydraulic conductivity. Thus, sloped areas of a landfill are extremely susceptible to LHCSL desiccation in the presence of elevated temperatures. The presence of overlying waste can reduce the potential for LHCSL cracking (Zhou and Rowe, 2005) but this is less effective on a side slope because the full overburden stress is not applied normal to the sideslope as it is on the base of the landfill. In addition, Soong and Koerner (1999) found that overlying waste does not remove geomembrane wrinkles created during installation.

GCL Service Life Criteria

The discussion above for the LHCSL also applies to the GCL. However, the GCL may be better suited to accommodating elevated temperatures because the underlying bentonite may be able to re-absorb the condensed liquid available in geomembrane wrinkles. On landfill side slopes or a sloping base condensing moisture will also flow away from the source reducing the amount of water available for re-hydration by the GCL. Moisture and bentonite migration in GCLs along landfill sideslopes has been observed in the field (Stark et al. 2004) which can also reduce the potential for re-absorption.

POSSIBILE REMEDIAL MEASURES

Some of the possible remedial measures that could be implemented after sustained elevated temperatures are measured on or near the liner system include:

- Excavate the waste so the liner system can be repaired as illustrated by a hazardous waste landfill, containing industrial waste sludges and other chemical manufacturing by-products that experienced temperatures near the liner system of about 800ºC (Adams et al. 1997). Adams et al. (1997) describe the damage to the geosynthetic components of the liner system in the immediate vicinity of the combustion as complete disintegration, melting, and/or fusing of the various components together near the center of the heated area. Rippling and stretching of the materials along the perimeter of the visibly damaged area also occurred. In several areas, melted geosynthetic materials were observed in desiccation cracks in the secondary LHCSL (Adams et al. 1997).
- Install additional ground water monitoring wells down gradient of the area subjected to elevated temperature to facilitate detection of leakage. If leakage is detected, the closer

spaced monitoring wells should trigger a quicker remedial action. One of the drawbacks of this approach is that if leakage is detected, the contaminants, i.e., leachate and gas, have already entered the subsurface which can substantially increase remediation costs.

- Stop active filling in the portion of the landfill experiencing elevated temperatures and apply a suitable low hydraulic conductivity cover to prevent infiltration.
- In addition to installing additional ground water monitoring wells down gradient of the elevated temperature area, increase the required post-closure bonding to compensate for possibly higher remediation costs.

CONCLUSIONS AND RECOMENDATIONS

Subtitle C and D landfills may experience elevated temperatures for a variety of reasons, such as hydration of combustion ash, waste biodegradation with and without leachate recirculation, aluminum waste and combustion ash reactions, and wastes received with elevated temperature. Sustained elevated temperatures can reduce the service life of composite liner system components by accelerating antioxidant depletion and polymer degradation (e.g. loss of stress crack resistance) of the geomembrane(s) and desiccation of low hydraulic conductivity compacted soil liners and/or geosynthetic clay liners. This paper highlights some of the questions that can arise when assessing the integrity of a composite liner system in the presence of sustained elevated temperatures. Based on experiences with landfills with elevated temperatures, the following recommendations are presented for ensuring an effective landfill barrier in the presence of elevated temperatures:

- Perform a leak location survey after placement of the leachate collection system layer to eliminate defects in the geomembrane prior to waste placement so if elevated temperatures develop it is recognized that the geomembrane initially did not have any defects. Thus, unless the elevated temperatures melt the HDPE geomembranes or, weaken the geomembrane such that stress cracking occurs, which may occur along side slopes where tensile stresses are imposed or on the base if the protection layer is not adequate, the geomembrane may be still performing as a barrier. Additional analysis of side slopes and the application of tensile stresses to the geosynthetics should be further investigated.
- Aluminum waste should not be mixed with tire shreds or fly ash because of possible alkalinity, moisture, and heat that can facilitate other reactions.
- Leachate recirculation should not occur if aluminum production waste or combustion ash has been placed in the landfill.
- Leachate recirculation should not be undertaken at any landfill unless appropriate measures have been taken to ensure the additional liquid will not cause an unexpected reaction or leakage from the facility. In addition, the facility should demonstrate that the liner temperature will be kept at a temperature less than 40^{o}C and the liner temperature will be monitored before, during, and after leachate recirculation so changes in the waste temperature can be quickly identified.
- If temperatures greater than 40^{o}C are anticipated (e.g. landfills with leachate recirculation until demonstrated otherwise), then the barrier system should include design features to minimize the temperature reaching the liner. This will involve a number of elements but will likely require active measures to control the liner temperature (e.g., Rowe et al.

2010). In landfills with a double composite liner system, considerations should also be given to the effect of temperature on the secondary (as well as the primary) liner (Rowe and Hoor, 2009; Hoor and Rowe 2011). Other measures to reduce temperature on the primary liner might include ensuring a sufficiently thick leachate collection layer to act as a thermal barrier or buffer between the waste and the liner system as has been recently done for a Subtitle D landfill and an APW monofill in the United States. This layer should consist of open gravel with sufficient air space to help dissipate heat from the overlying waste before it reaches the liner system and ensure effective and rapid leachate collection. Low hydraulic conductivity material should not be used for this layer because it will not convey leachate quickly to the sump and will not quickly dissipate heat. Shredded tires are also not recommended for the leachate collection layer because tire shreds can melt and result in a large decrease in hydraulic conductivity and/or contribute to other reactions. Coal combustion ashes are also not recommended because they may facilitate other reactions within the landfill.

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List of Tables

Table 1. **Estimated HDPE geomembrane service life based on 50% reduction in tensile strength at break for different temperatures (based on Rowe, 2005)**

Temperature (°C)	Service Life (years)
20	565-900
30	205-315
35	130-190
40	80-120
50	35-50
60	15-20

List of Figures

Figure 1
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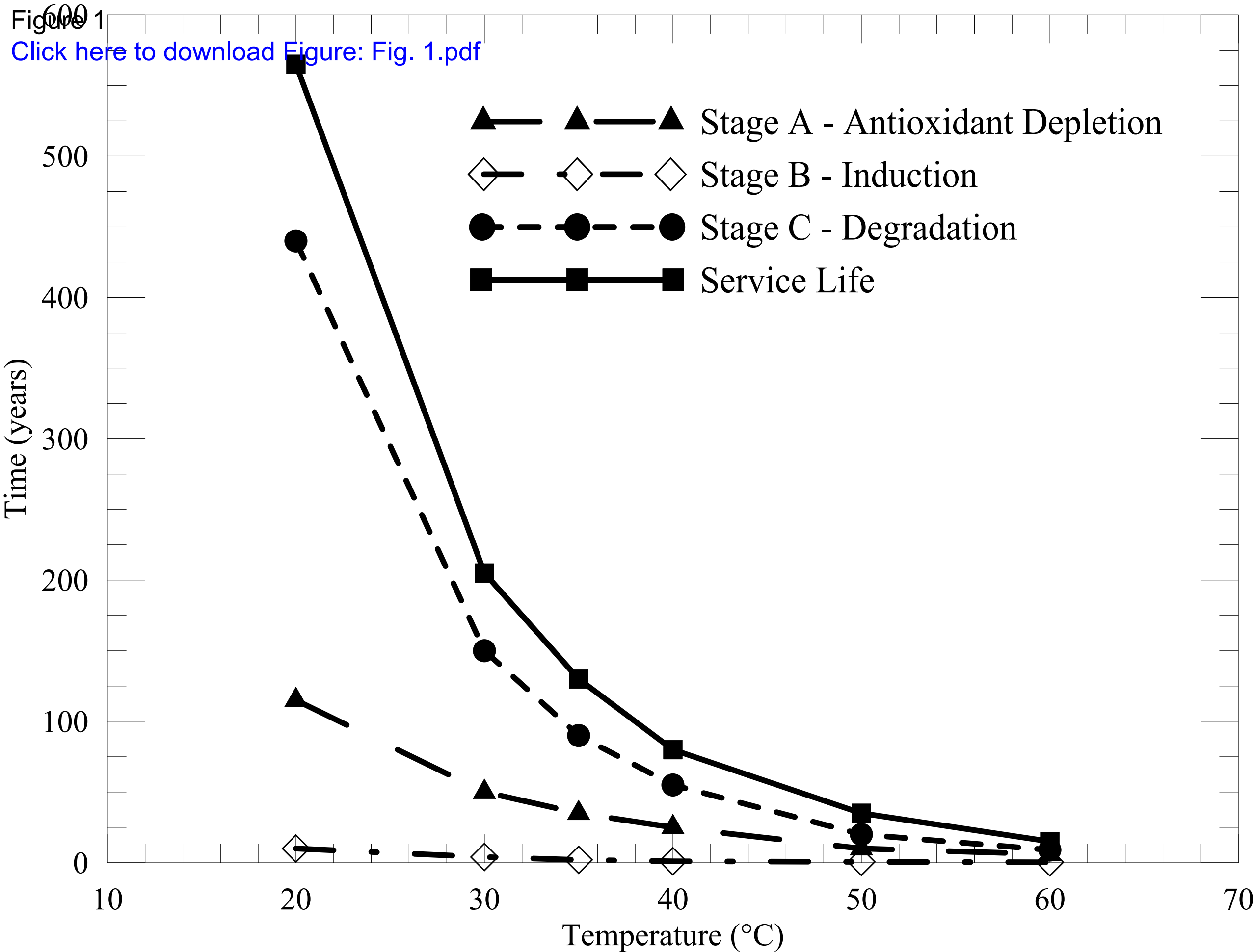

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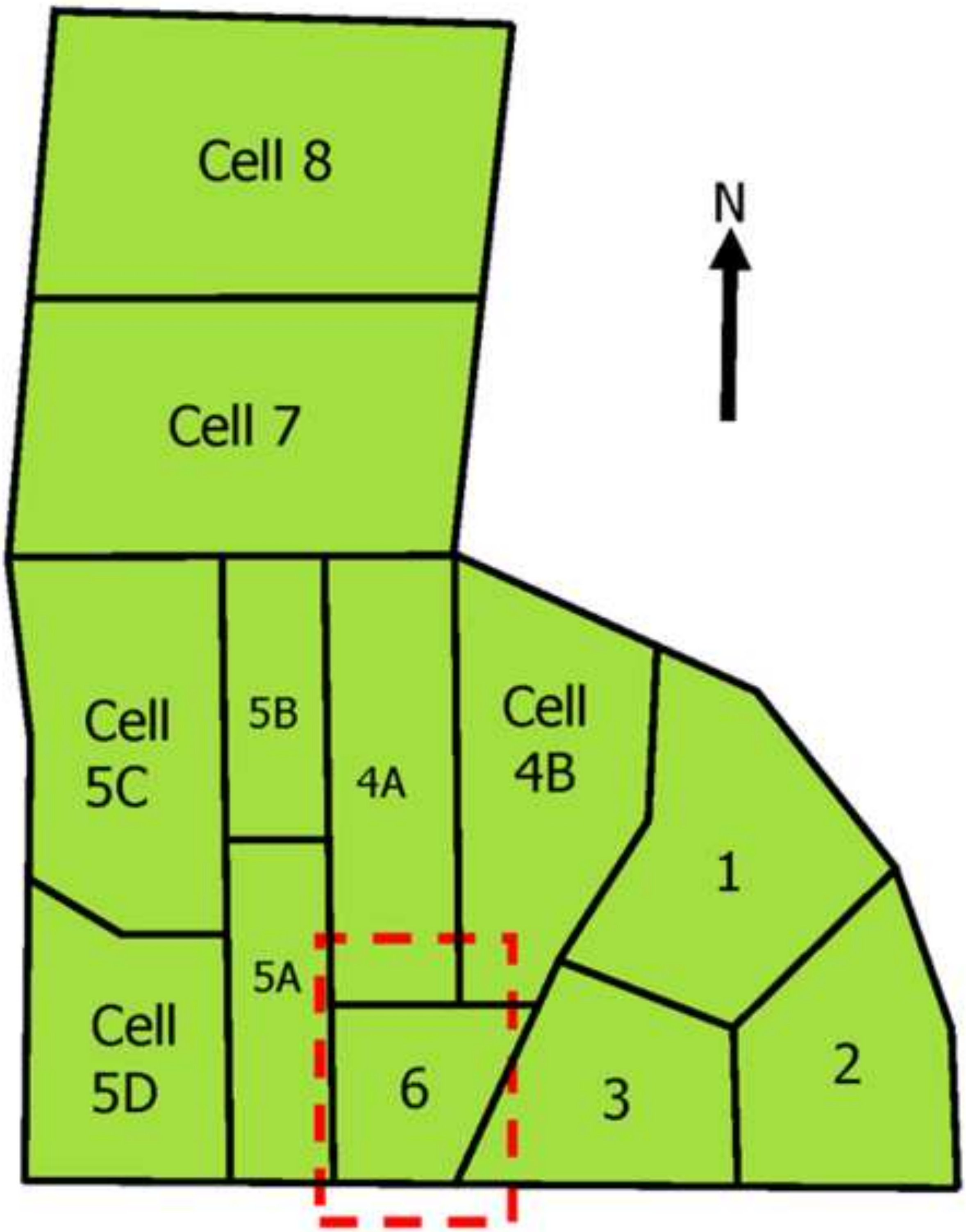

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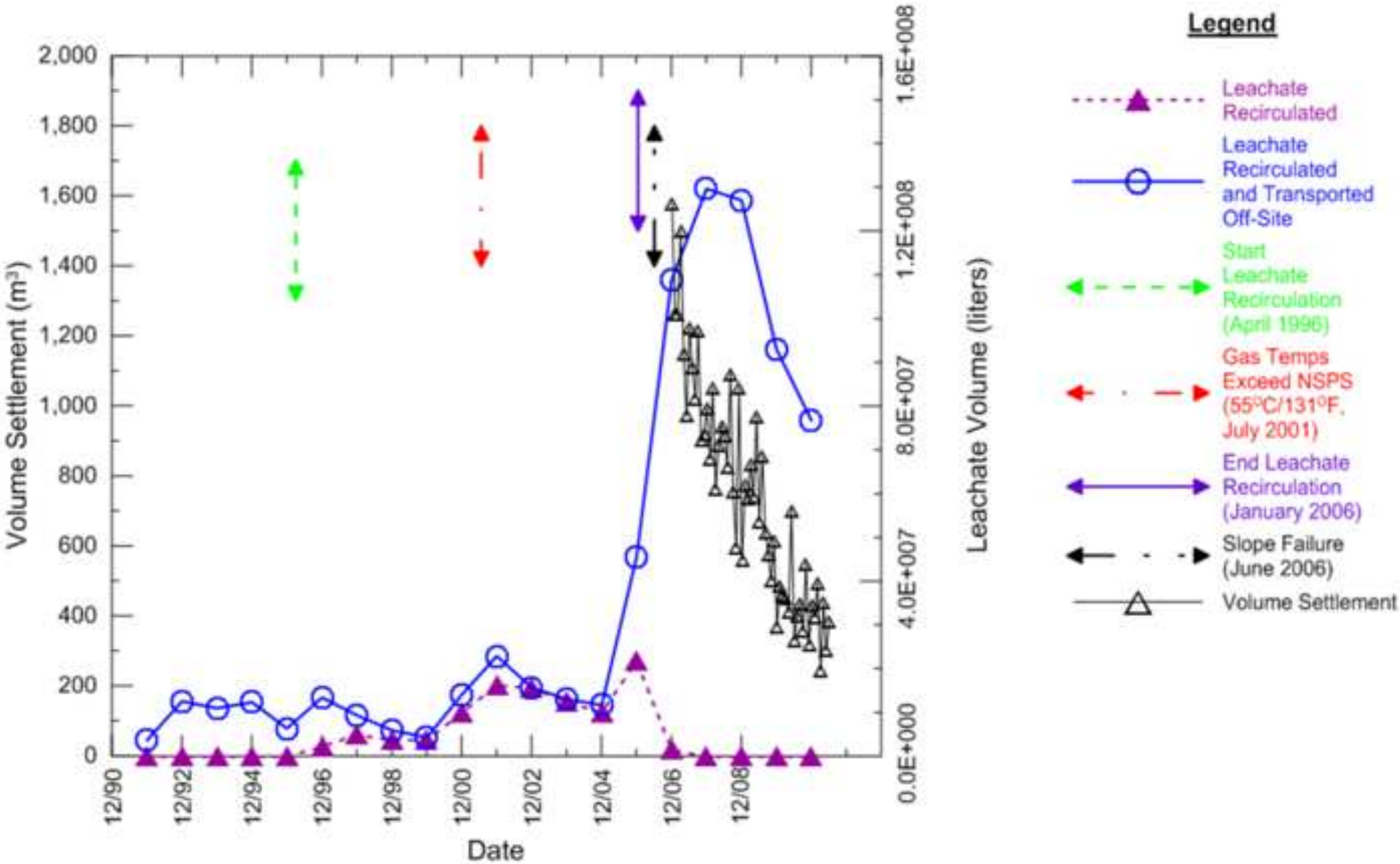

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