A GCL EQUIVALENCY ASSESSMENT FOR A PROPOSED MUNICIPAL SOLID WASTE LANDFILL

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ABSTRACT
The present paper examines a bottom liner design proposed for a “second generation” landfill in Nova Scotia in which an existing clay till material present near the landfill will act as a borrow source for the primary compacted clay liner (CCL). Preliminary laboratory testing and field experience with the clay have shown it to have a variable hydraulic conductivity (10^{-10} m/s to 10^{-8} m/s). Since the higher range of hydraulic conductivity values will not meet the province’s 10^{-9} m/s CCL requirement, two “alternative technologies” are being considered to utilize on-site clay for the primary liner system (geosynthetic clay liner (GCL) and sand-bentonite liner (SBL)). To meet provincial guidelines, the “alternate technologies” must at least be “equivalent” to the regulatory liner system with respect to contaminant migration. Modelling performed for two contaminants (chloride and dichloromethane), shows that both the GCL and SBL based designs are capable of providing “equivalent” performance to the regulated Nova Scotia liner system.

RÉSUMÉ
Cet article examine le design d’une couche de base proposé pour un site d’enfouissement de “deuxième génération” en Nouvelle-Écosse, dans lequel un till d’argile présent à proximité du site sera utilisé comme matériel source pour la couche d’argile compactée primaire (CCL). Des essais de laboratoire préliminaires ainsi que l'expérience de terrain avec l'argile ont montré une conductivité hydraulique variable (10^{-10} m/s à 10^{-8} m/s). Puisque les hautes valeurs de conductivité hydraulique ne rencontreront pas les exigences de la province de 10^{-9} m/s, deux “technologies alternatives” sont considérées en utilisant l'argile présente sur place, pour le système primaire (une couche d'argile géosynthétique (GCL) et une couche de sable-bentonite (SBL)). Pour rencontrer les règlements provinciaux, les “technologies alternatives” doivent être au moins “'équivalentes” au système de réglementation quant à la migration de contaminants. La modélisation effectuée pour deux contaminants (chlorure et dichlorométhane) a démontré que les designs proposés, soit avec le GCL ou le SBL, sont capables d’atteindre une performance au moins “équivalente” à celle du système de réglementation de la Nouvelle-Écosse.

1. INTRODUCTION

Modern municipal solid waste landfills rely on engineered leachate collection systems and base liner systems to mitigate contaminant migration from the landfill into the underlying hydrogeological environment. Traditionally, base liner systems such as natural clayey deposits, compacted clay liners (CCLs) and geomembranes (GM) have been utilized to minimize contaminant transport through the barrier system. In some areas, economic use of low hydraulic conductivity clay is not possible and hence geosynthetic clay liners (GCLs) or sand-bentonite liners (SBL) are used in place of, or, in combination with clayey barriers to provide the low hydraulic conductivity component of the liner system required by various regulatory authorities. In many regulations in which there is the “flexibility” to use alternate GCLs or SBLs based systems, it is the duty of the designer to demonstrate that the proposed alternate system is “equivalent” to the low hydraulic conductivity (1×10^{-9} m/s) CCL it is replacing. “Equivalency” with respect to GCLs is a topic that has been discussed from several different viewpoints in the technical literature (Koerner and Daniel, 1993; Rowe et al., 1997, Rowe, 1998; Foose et al. 1999). However, since the primary function of a bottom liner system is to mitigate contaminant migration from the landfill, equivalency comparisons should, as a minimum, include a contaminant migration assessment. As discussed by Rowe et al (1997) and Rowe (1998) a proper equivalency assessment of a bottom liner system should include all relevant factors influencing contaminant migration through the barrier system such as diffusion, advection (including leakage between the geomembrane and liner contact), sorption (if present), biodegradation (if present), and finite service lives of engineered components. When each of these factors are considered in conjunction with the landfill characteristics (i.e. size and leachate characteristics) and the hydrogeological setting, a proper comparison of equivalency between a CCL and GCL barrier system can be made.

The purpose of this paper is to demonstrate the type of "equivalency" assessment discussed above, applied to a proposed landfill project in Nova Scotia. Three potentially different designs of the clayey component of the primary composite liner are assessed for "equivalency" using the methods described in this paper.

2. BACKGROUND

2.1 Provincial Municipal Solid Waste Guidelines

In recent years, the province of Nova Scotia has taken an aggressive stance in implementing progressive waste management strategies. Currently the province diverts approximately half of its municipal solid waste from landfills by waste reduction, recycling and composting programs (NSDEL, 2003). Even with the success of this waste diversion program, there is still a requirement for municipal solid waste landfills for disposal of surplus waste products. As late as the 1970s, Nova Scotia had approximately 100 "dumps" accepting garbage in the province. By 2005, the province of Nova Scotia will require all existing landfills to conform to new standards (NSDEL, 2003) which are based on existing guidelines set forth by the province (NSDEL, 1997). These new requirements will result in as few as 7 municipal disposal sites in the province by 2005 (NSDEL, 2003).

Existing municipal solid waste landfill guidelines in Nova Scotia require the base of landfills to be lined with a double liner system. Figure 1 shows a simplified schematic of the regulated base liner system required for use in Nova Scotia.

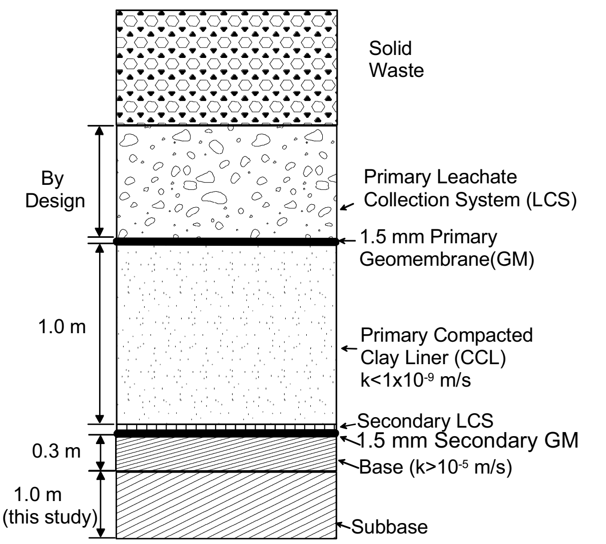


Figure 1. Schematic of Regulated Municipal Solid Waste Landfill Liner Systemfor Nova Scotia (modified from NSDEL, 1997) (*some layers have been left outofschematic for clarity).

*Regulations require minimum 1m separation between groundwater elevation and secondary LCS

Generally speaking, the double liner system consists of a primary leachate collection system overlying a primary GM/CCL composite system, a secondary leachate collection system and secondary geomembrane. Geotextiles are to be used as required for protection of the geomembranes placed in the landfill. As stated in the regulations, "all of the components of the landfill should be designed to function over the lifespan of the facility" (NSDEL, 1997). Lifespan is defined in the guidelines as "the period of time in which a facility will produce contaminants at levels which could have an adverse effect if discharged to the surrounding environment". This design philosophy is similar to the contaminating lifespan concept discussed by Rowe et al (2004) and Ontario provincial municipal solid waste guidelines (MOE, 1998).

In the Nova Scotia guidelines, the CCL used as part of the primary composite liner system must be a minimum of 1 m thick with a hydraulic conductivity of less than $1x10^{-9}$ m/s. In many parts of the province, there may be difficulty achieving this hydraulic conductivity specification during construction and hence "alternate technologies", such as low hydraulic conductivity geosynthetic clay liners (GCLs) and sand-bentonite liners (SBLs) can be proposed within the framework of the guidelines to achieve an "equivalent" barrier system to that specified.

2.2 Proposed Municipal Solid Waste Landfill

This paper examines an example of proposed municipal solid waste landfill in Nova Scotia in which hydraulic conductivity of the primary CCL will most likely not meet provincial guidelines without some form of amendment to the liner system. The landfill is an extension of an existing municipal solid waste landfill that is currently not a "second generation" landfill. According to data summarized by JWA (2004), the new landfill will be situated next to the existing landfill. Under the proposed landfill, bedrock consists of Upper Carboniferous to Early Devonian granite with an approximate bulk hydraulic conductivity of 10^{-6} m/s in the upper portion (10 m) of the rock. Groundwater levels in the upper portion of the rock are within approximately 0.5 m of the rock's surface, with an average linear groundwater velocity of 1 m/a to 16 m/a. Fracture migration is the primary hydraulic transport mechanism.

The overburden in the area of the landfill footprint consists of approximately 0 m to 2 m of clayey sand glacial till material. Grain size analyses indicate approximately 10 percent gravel, 50 percent sand, 30 percent silt and 10 percent clay sized particles. Occasional boulders and cobbles are also present within the glacial till material. Plasticity indexes of the clay tills are approximately 7 percent to 10 percent. Excess clayey till material of similar composition is also present within economic transportation distance of the proposed landfill. Preliminary laboratory testing of the remoulded clayey till material suggests a hydraulic conductivity of slightly less than 1 x 10^{-9} m/s, although previous experience with this material suggests field measured hydraulic conductivities could be as high as 1 x 10^{-8} m/s. Nova Scotia guidelines require field air-entry infiltrometer testing on the constructed CCL. As discussed by Rowe et al (2004), field-based infiltrometer hydraulic conductivity testing is performed with no overburden effective stress present on the liner. Application of an effective stress similar to that expected under waste loading conditions will most likely result in lower hydraulic conductivity results than that measured in infiltrometer testing due to subsequent consolidation of the clay liner (Gordon et al., 1989 and King et al., 1993).

Economically, the most cost–effective material to use as part of the primary compacted clay liner system is the clayey till present near the site (there is no viable source of acceptable clay near the landfill). It is being proposed that the clayey till be screened to a 50 mm minus material and be used to construct the majority of the primary CCL. By using this material, significant cost savings will be realized. To provide an allowance for potentially high field hydraulic conductivities of the clayey CCL, two "alternate technologies" have been proposed for the landfill to improve the hydraulic conductivity of the primary CCL.

2.2.1 Proposed "Alternate Technology A"

Alternate technology A employs a GCL for use as an "amendment" to the primary compacted clay liner (CCL) system, as shown in Figure 2 (i.e. GCL over 1 m of recompacted clayey till material. For design purposes, a conservative value of "exceeded" hydraulic conductivity of 5 x10^{-8} m/s was chosen for design. This design value of hydraulic conductivity was chosen to account for potential larger values of hydraulic conductivity from that measured in the laboratory. The purpose of the GCL is to provide the low hydraulic conductivity to the primary barrier system. GCLs have shown in the literature to exhibit hydraulic conductivities of less than 1x10^{-10} m/s, even when exposed to various municipal solid waste leachates (Petrov and Rowe, 1997). The proposed amendment maintains the primary barrier thickness at 1m, although readily available site material will be used for construction.

2.2.2 Proposed "Alternate Technology B"

Alternate technology B employs a 0.15 m SBL as an "amendment" to the primary CCL, as shown in Figure 3 (i.e. 0.85 m of CCL of "exceeded" hydraulic conductivity of 5x10^{-8} m/s over 0.15 m of SBL). SBLs have shown in the literature to achieve hydraulic conductivities lower than 1x10^{-10} m/s and hence also provide low hydraulic conductivity to the barrier system. As with alternate technology A, the proposed amendment maintains the full primary barrier thickness at 1m, while allowing readily available site material to be used for construction. However, based on preliminary cost comparisons of alternate technologies A and B, the GCL based liner system may be cheaper that the SBL based system. Sand-bentonite liners are currently utilized at Halifax Regional Municipality's Otter Lake Landfill in a similar capacity for the primary barrier system.

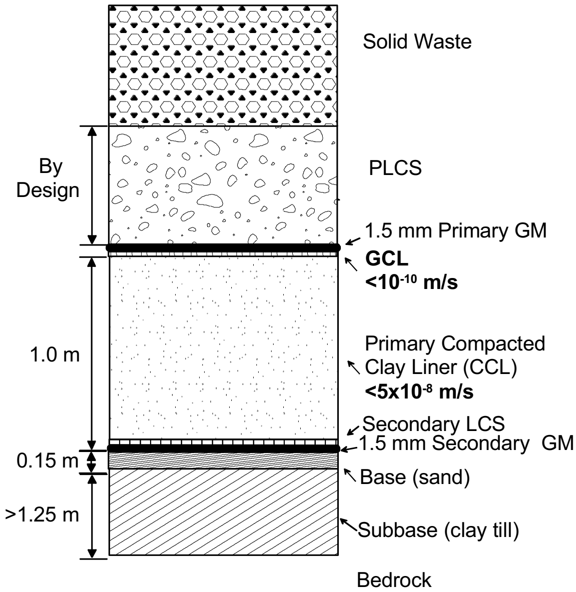


Figure 2. Schematic of alternate technology A for proposed landfill.

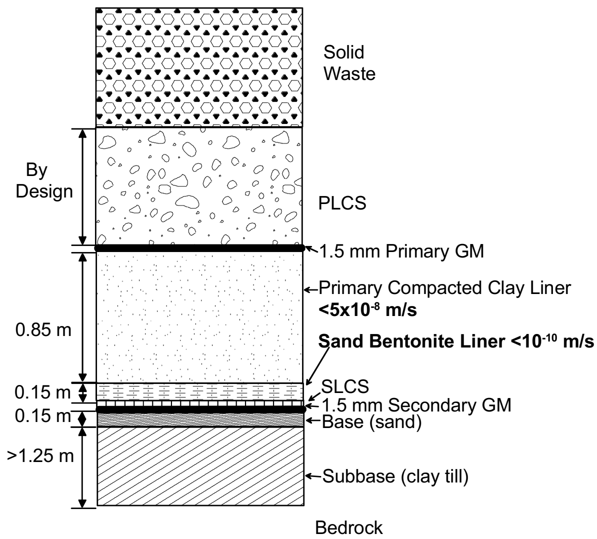


Figure 3. Schematic of alternate technology B for proposed landfill

It should be noted that both alternate technologies "A" and "B" examined will be situated directly on the "base", underlain by the "subbase" as shown in Figures 2 and

3. The “base” will consist of a sand (to act as a cushion to the secondary GM) while the “subbase” will consist of the clay till material present on the site.

Selection of the most appropriate barrier design involved performing contaminant transport assessments, a summary of which is described below.

3. METHODOLOGY

3.1 Proposed Liner Systems

To assess the “performance” of these two proposed alternate technologies, contaminant transport analyses were performed with the computer program, POLLUTE (Rowe and Booker, 1999). This program is specified for use when assessing “alternate technologies” for landfill liner barrier systems as requested in section 3.3(e), subsection 2 of the Nova Scotia Municipal Solid Waste Guidelines (1997). As stated, this contaminant transport analysis will be used to “demonstrate” that the materials in question meet or exceed the liner system specified by section 3.3(d) of the Nova Scotia Municipal Solid Waste Guidelines (1997). To facilitate the comparison, the two proposed alternate technologies were compared to the landfill liner standard specified by section 3.3(d) of the Nova Scotia Municipal Solid Waste Guidelines (1997) as shown in Figure 1. The Nova Scotia guidelines do not provide any specific parameters or methodologies to be utilized for the contaminant transport analyses and hence to perform a rationale assessment, general recommendations set forth by the Ministry of Environment of Ontario (1998) were used in this contaminant transport assessment. Other parameters necessary for modelling were obtained from the noted literature sources.

3.2 Landfill Modelling

The contaminant transport assessment utilized assumptions regarding the proposed landfill that were known at the time of preparation of this paper. As shown in Table 1, the landfill was assumed to have a plan area of 1000m by 300 m, which would encompass the entire proposed lifespan of the facility. If this landfill is to be expanded beyond this proposed size, similar, additional contaminant transport analyses will have to be performed.

Two different contaminants were examined in the assessment; chloride and dichloromethane (DCM). Chloride is a relatively conservative contaminant while DCM is an organic contaminant that has been found in low concentrations in MSW leachate (Rowe, 1995). These two contaminants are also suggested critical contaminants to examine for barrier assessments, as specified by the Ministry of Environment of Ontario (MOE, 1998). As shown in Table 1, the DCM half-life in the leachate was assumed to be 10 years. A conservative DCM half-life of 50 years was assumed for the soil based on the results of Rowe et al (1997a). No sorption of DCM to the soil layers was considered in the analysis (a conservative assumption for DCM). Other pertinent parameters for the GMs, CCLs, GCL, base and subbase layers are provided in Table 2.

Table 1. Hypothetical Landfill Characteristics.

Landfill Properties	
Length (m)	1000
Width (m)	300
Mass of Waste/unit area (t/m^2)	15
Proportion of chloride in waste (mg/kg)	1800
Proportion of DCM in waste (mg/kg)	2.3
Initial concentration in leachate	
Chloride, c_o (mg/L)	2500
DCM, c_o, (mg/L)	3.3
Percolation through waste (m/a)	0.15
Chloride, $t_{1/2}$ (a)	∞
DCM in landfill, $t_{1/2}$ (a)	10
DCM below primary GM, $t_{1/2}$ (a)	50
Aquifer Properties	
Thickness Modelled, (m)	3
Porosity (-)	0.1
Base Darcy Flux (horizontal), v_b (m/a)	1

As discussed in the Ontario MOE guidelines, finite service lives must be considered in the contaminant transport modelling to reflect both certain and uncertain failure of engineered components of the landfill barrier system (see Table 3). It was assumed that the primary leachate collection system was functioning as designed (design leachate level of 0.3 m) and removing leachate for a period of 60 years. At this time, the primary leachate collection system underwent a gradual “failure”; a leachate mound instantaneously developed above the primary liner system to 50% of its maximum height (5 m). At 70 years, it reached its maximum height of 10 m. At 150 years, the primary geomembrane was assumed to instantaneously fail, causing the leachate mound height to decrease to the point where all infiltration coming into the landfill was migrating through the primary liner system. At 350 years, the secondary geomembrane and secondary leachate collection system was assumed to undergo instantaneous “failure” and all infiltration coming into the landfill (0.15 m/a) was being transferred into the underlying hydrogeological system. A summary of the leakage rates (calculated using the methods outlined by Rowe, 1998) for the three cases considered is shown in Table 3.

4. RESULTS AND DISCUSSION

4.1 Chloride Modelling

Figure 4 shows modelling results of the proposed barrier systems for chloride. It is interesting to note that the results of each of the three cases considered for chloride are essentially indistinguishable from each other (i.e. the graphs of the NSDEL regulated case and

Table 2. Barrier parameters used in contaminant migration assessment.

	Prim. Sec.GM	CCL (NSDEL Spec.)	CCL (“exceeded” clay)	GCL	Sand-Bentonite	Subbase	Base
Thickness (m)	0.0015	1.0	See Figure2	0.01	See Figure3	See Figures 1 to 3	
Diffusion Coefficient Chloride (m^2/s)	$1x10^{-13}$	$6x10^{-10}$	$7x10^{-10}$	$2x10^{-10}$	$5x10^{-10}$	$6x10^{-10}$	$8x10^{-10}$
Diffusion Coefficient DCM (m^2/s)	$1x10^{-12}$	$6x10^{-10}$	$7 x10^{-10}$	$2x10^{-10}$	$5x10^{-10}$	$6x10^{-10}$	$8x10^{-10}$
Henry’s Coefficient Chloride, S_{gf}, (-)	$8 x10^{-4}$	-	-	-	-	-	-
Henry’s Coefficient DCM S_{gf} (-)	2.3	-	-	-	-	-	-
No of holes/ha	2.5	-	-	-	-	-	-
Hole radius (mm)	0.005	-	-	-	-	-	-
Service life (a)	See Table 3	∞	∞	∞	∞	∞	∞
Primary GM	150	-	-	-	-	-	-
Secondary GM	350	-	-	-	-	-	-
Hydraulic Conductivity (m/s)	-	$1x10^{-9}$	$5x10^{-8}$	$1x10^{-10}$	$1x10^{-10}$	$1x10^{-8}$	$1x10^{-5}$
Geomembrane-Clay Transmissivity (m^2/s)	-	$1.6x10^{-8}$	$7.3x10^{-8}$	$2x10^{-10}$	$7.3x10^{-8}$	-	$2x10^{-5}$
Sorption, $\rho_d K_d$ (-)	-	0	0	0	0	0	0
Porosity	-	0.35	0.35	0.70	0.50	0.3	0.4

Notes: References: Rowe (1998), Lake and Rowe (2000), Lake and Rowe (2004), Ontario Ministry of Environment (1998)

Table 3. Leakage rates for systems considered.

Time Period	Description	Leakage Through Primary Liner (m/a)			Leakage Through Secondary Liner (m/a)		
		NSDEL Reg.	Alt. A	Alt. B	NSDEL Reg.	Alt. A	Alt. B
0-60 years	Operating PLCS & SLCS	$4.7x10^{-5}$	$7.0x10^{-5}$	$1.8x10^{-4}$	$4.7x10^{-5}$	$7.0x10^{-5}$	$1.8x10^{-4}$
60-70 years	Failure of PLCS, Leachate Mound Height to 5m	$6.4x10^{-4}$	$9.3x10^{-4}$	$2.5x10^{-3}$	$6.4x10^{-4}$	$9.3x10^{-4}$	$1.7x10^{-3}$
70-150 years	Leachate Mound at Max. Height of 10m	$1.2x10^{-3}$	$1.8x10^{-3}$	$4.9x10^{-3}$	$1.2x10^{-3}$	$1.7x10^{-3}$	$1.7x10^{-3}$
150-350 years	Failure of Primary GM	0.15	0.15	0.15	$1.8x10^{-3}$	$1.7x10^{-3}$	$1.7x10^{-3}$
> 350 years	Failure of Secondary GM and Geonet	0.15	0.15	0.15	0.15	0.15	0.15

Notes:
PLCS: Primary Leachate Collection System; SLCS: Secondary Leachate Collection System
Design leachate level 0-50 years for PLCS=0.3m; Design leachate level on SLCS from 0-350 years – 0.01 m

the two alternatives plot on top of each other). Chloride is a conservative inorganic contaminant, since it is assumed that it undergoes no sorption/degradation in the landfill or the soil during its migration through the landfill barrier system. For all three of the barrier systems examined, aquifer chloride concentrations are well below the typical chloride drinking water objective of 250 mg/L for the size of the landfill considered. This is not surprising for a high density polyethylene (HDPE) geomembrane double-lined barrier system. HDPE geomembranes have been shown to be excellent diffusive barriers to ionic compounds such as chloride (Rowe et al., 1995) and as discussed by Lake and Rowe (1999), mass transport of inorganic contaminants such as chloride across HDPE geomembranes will be governed by leakage through a few small holes in the geomembrane. This concept is illustrated by the results shown in Figure 4, where even for a 10 m high leachate mound above the barrier systems examined, the chloride impact in the aquifer prior to 350 years (secondary geomembrane failure) was approximately zero for each of the three cases. After secondary geomembrane “failure”, flushing of leachate from the landfill occurs, causing a maximum chloride aquifer concentration of approximately 17 mg/L for each of the three cases to occur at approximately 360 years. An analysis of each of the three cases indicated that after approximately 180 years, chloride concentrations in the landfill will decrease to concentrations below 250 mg/L, suggesting a contaminating lifespan with respect to chloride of 180 years.

Based on the results shown for chloride, it appears as if for the conditions examined herein, alternate technologies A and B are “equivalent” with respect to chloride contaminant transport relative to the regulatory specified liner system.

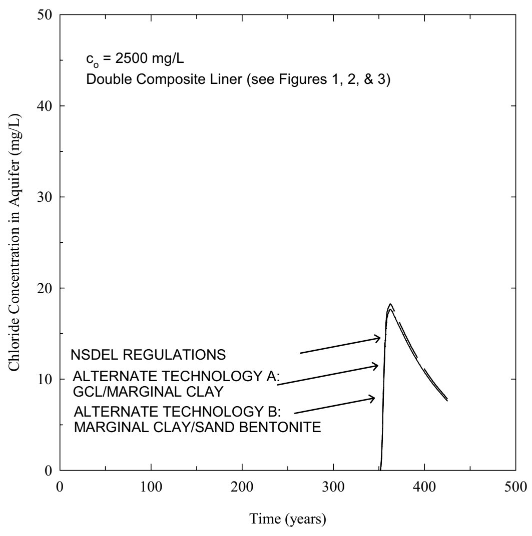


Figure 4. Chloride modelling results, alternate technologyA and B compared to Nova Scotia regulatory liner system.

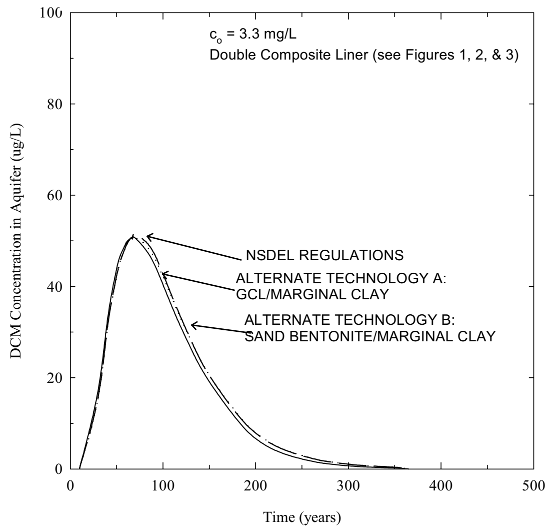
4.2 Dichloromethane (DCM) Modelling

Volatile organic compounds such as DCM are often present at low levels in municipal solid waste leachate (Rowe, 1995). Small VOC molecules such as DCM will migrate more readily through HDPE GMs than chloride (Sangam & Rowe, 2001) and hence are important to consider for design of HDPE geomembrane lined systems. Contaminant migration of DCM through the double lined systems of the cases considered in Figures 1 to 3 will not be controlled by leakage through GMs, as for chloride, but by diffusion and degradation of the compound as it migrates through the barrier system (Lake and Rowe, 1999).

Figure 5 shows results for the three cases examined for DCM. Relative to the chloride results in Figure 4, it can be seen that peak DCM impact in the aquifer occurs relatively quickly (approximately 60 years) for all three cases examined. The regulated barrier system limits DCM peak concentrations to the Maximum Acceptable Concentration (MAC) of 50 ug/L specified by many drinking water guidelines. Figure 5 also shows that alternate technologies A and B essentially plot on top of the regulated case, indicating that for all practical purposes, the alternative GCL lined barrier system is equivalent to that of the regulated case for DCM (and chloride).

An analysis of each of the three cases indicated that in less than 50 years, DCM concentrations in the landfill will decrease to concentrations below 50 μg/L, suggesting a contaminating lifespan with respect to DCM of less than 50 years.

Figure 5. DCM modelling results, alternate technologyA and B compared to NovaScotiaregulatorylinersystem.



The main reason for similar DCM aquifer concentrations for all three liner systems is that the total thickness of the double lined system is the same. Although there are minor variations in the three liner contaminant transport properties, the diffusion and degradation of DCM by the total soil thickness is essentially controlling the contaminant migration through the liner system. To demonstrate the importance of total thickness of the double lined system, a similar analysis was performed for Alternate Technology A (GCL system) except it was assumed that the total thickness of the primary liner was reduced to 0.7 m thick (GCL thickness the same). As shown in Figure 6, DCM aquifer results for this thinner barrier system were slightly higher than 50 μg/L compared to previous results (also shown on Figure 6 for comparison). As stated above, the majority of its migration is controlled by the soil thickness separating the landfill from the aquifer. By reducing the thickness of the primary CCL to 0.7 m, there is more diffusive flux through the liner and less biodegradation in the soil. Practically speaking, even though chloride results would suggest a thinner barrier system (lower cost) would be adequate at preventing chloride impacts, the same hypothesis will not hold true for DCM. It should be noted that a similar outcome was found if the CCL was reduced to 0.7 m thick for the NSDEL regulated case and the SBL system.

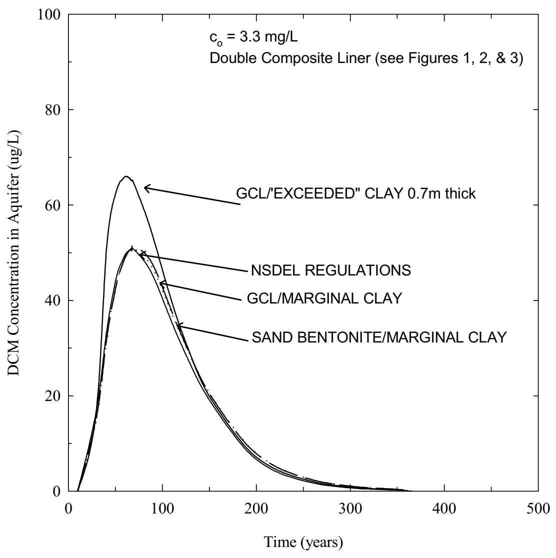


Figure 6. Comparison of DCM modelling results; effect of reducing primary CCL thickness to 0.7 m.

It is important to recognise that the theoretical aquifer concentrations shown in Figures 4, 5 and 6 represent concentrations at the down-gradient edge of the landfill. Since the down-gradient edge of the landfill must be 100 m away from the property boundary, further attenuation of concentration levels in the aquifer due to other physical, chemical and biological processes will most likely occur. A sensitivity analysis of the effect of horizontal aquifer velocity showed that upgradient base velocities of as low as 0.1 m/a will still produce acceptable impacts in the aquifer, for the conditions modelled. Higher velocities produced lower impacts in the aquifer.

5. SUMMARY AND CONCLUSIONS

Based on the assumptions adopted for this comparison, it appears as if both Alternate Technologies A and B will provide similar protection to that specified by the NSDEL regulated liner system. Concentrations of chloride and DCM at the downgradient edge of the aquifer were below typical drinking water guidelines throughout the contaminating lifespan of the proposed landfill. For practical purposes, it could be said that the three liner systems examined are “equivalent” with respect to contaminant transport. Additional analyses performed using the methods described in this paper can also assess other alternative liner systems provided sufficient information is available for modelling the systems.

The results presented herein assume that the landfill barrier components will be constructed to acceptable industry standards. Any modifications to the proposed barrier systems should be checked using methodologies similar to those adopted in this paper.

Although the majority of the information presented in this paper was taken from an on-going project, differences may exist from actual conditions and that presented herein. It should also be noted that the third author was not involved in any aspects of the landfill design for the project.

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