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Oral presentation

Written submission from Kerry Rowe

Exposé oral

Mémoire de Kerry Rowe

In the Matter of the

Canadian Nuclear Laboratories (CNL)

Application from the CNL to amend its Chalk River Laboratories site licence to authorize the construction of a near surface disposal facility

À l'égard des

Laboratoires Nucléaires Canadiens (LNC)

Demande des LNC visant à modifier le permis du site des Laboratoires de Chalk River pour autoriser la construction d'une installation de gestion des déchets près de la surface

Commission Public Hearing
Part 2

Audience publique de la Commission
Partie 2

May and June 2022

Mai et juin 2022

2022 04 09

The Canadian Nuclear Safety Commission (CNSC)

Dear Commissioners,

RE: Submission regarding “Canadian Nuclear Laboratories’ application to amend its Chalk River Laboratories site licence to authorize the construction of a near surface disposal facility” - **Long-term safety/design theme**

I would like to provide this written input to, and provide an oral intervention at Part 2 of the hearing on the theme of long-term safety/design. Specifically, in this intervention I will cover the following :

1. Safe long-term containment is much better than remediation.
2. Base barrier system design
   2.1 Comparisons of ECM design with two common standard design
   2.2 Comparisons of ECM design with Port Granby and Port Hope designs
3. Cover barrier system design
4. Comparison of the NSDF ECM cover barrier system with those in 5 US LLW facilities
5. Geomembrane selection and design for a long service life
   5.1 Geomembrane (GMB) basics
   5.2 The Queen’s study and geomembrane performance assessment
   5.3 Geomembrane service life assessment
   5.4 Conditions to be met to achieve the predicted geomembrane service lives
6 Construction quality assurance (CQA)
   6.1 CQA testing before the commencement of barrier system construction
   6.2 On-site CQA before construction of the barrier system
   6.3 On-site CQA during construction of the barrier system
   6.4 Expectations of the CQA consultant
7 Geomembrane versus concrete
8 Period of operations
9 Long institutional control
10 Monitoring and groundwater protection

The Intervenor

I hold Canada Research Chair in Geotechnical and Geoenvironmental Engineering at Queen’s University and have special expertise in the design of barrier systems and hydrogeology related to waste containment of various forms including municipal, hazardous, low level and high-level radioactive waste as well as mine waste and oil and gas production waste. I have provided expert services to IAEA, CNSC, regulatory bodies such as the Ontario Ministry of Environment and Climate change, and similar bodies in Canada, the US, Australia, and South Africa. A brief biographical sketch is given in Appendix A. My experience of relevance to the subject matter of this hearing includes having served as:

- expert advisor concerning
    - remediation of contaminant escapes due to inadequate containment or temporary storage (e.g., numerous hydrocarbon spills),

  - landfill leachate and gas escape from Cranbourne (Stevenson Rd) landfill where hundreds of residents had to leave their homes,
  - the containment of the residue of the 1990 Hagersville tyre fire,
- an expert reviewer on behalf of CNSC of the design of the Port Hope low-level waste facility,
- co-author of the technical elements of Ontario's regulation 232/98 for disposal of municipal solid waste in landfills,
- co-author of the Federal guidelines on disposal of hazardous waste in landfills published by the Canadian Council of Ministers of the Environment (CCME),
- Canada's technical representative on an International Atomic Energy Agency committee looking at near surface disposal of long-lived low-level radioactive waste,
- as an expert reviewer of the study of the relative performance and longevity of the candidate geomembranes considered for use in the NSDF ECM conducted under the direction of Dr. Fady Abdelaal at Queen's University and wrote a report for CNL based on the data provided in the Queen's report, and
- a third-party expert independent reviewer of the proposed Near Surface Disposal Facility Engineering Containment Mound cover and liner design during its various stages of development.

I listened to Part 1 of the Hearing and would like to comment on several issues and questions that were raised in Part 1 as well as several other issues I consider relevant to the Commission's consideration of the proposal.

1 Safe long-term containment is much better than remediation.

History has shown that it is a mistake to rely on historic inadequate containment of buried waste and temporary storage of waste. In none of the cases where I have been called in had anyone responsible for the facility expected a problem. But then a major occurred. The potential escape of contaminated water passing through buried or temporarily stored low-level waste may not be as dramatic as the Hagersville tyre fire but should be avoided. It can be avoided by placing it in a state-of-art facility that incorporates the lessons learnt from 40 years of research and monitoring of modern landfill facilities – especially those with a double composite liner where the performance of the primary liner can be reliably monitored.

It is my understanding that low-level waste (LLW) is currently stored using old methods that could present a risk to people and the environment over time. The longer it takes to excavate and safely dispose of this waste, the further will be the escape of contaminants and the longer it will take to remediate existing low-level radioactive contamination.

Interim storage of the waste not only presents more risk to workers' health and safety as indicated by CNL but also presents a problem if an unexpected event occurs (e.g., a fire). The proposed NSDF ECM will allow for the environmental remediation and local, long-term, safe disposal of low-level radioactive waste currently in temporary storage on-site.

Some have described the NSDF ECM facility as a "dump". Let me be very clear: the proposed NSDF ECM facility is not a dump. Dumps are typically characterized, and many exist, as man-made depressions (often from the extraction of aggregates or mining), or natural depressions, or valleys, that have been filled with waste without any serious consideration of the site hydrogeology, waste restrictions, leachate control and collection, or barrier system. These dumps have justifiably caused concern and many have been problematic in terms of environmental impact because of an absence of appropriate waste management and engineering design. As I will discuss in more detail in the following sections, the NSDF ECM barrier system has been carefully designed to contain both waste and leachate with six independent lines of defence. In my professional opinion, it offers a safe technological solution that takes advantage of 40 years of research and monitoring of landfills to build modern barrier systems using proven technology.

2 Base barrier system design

2.1 Comparisons of ECM design with two common standard designs

2.1.1 Configuration

The proposed NSDF ECM bottom barrier system is shown in detail in Figure 1 and more generically in Figure 2a to allow direct comparison with the barrier system required for the large municipal solid waste landfill as per Ontario Regulation 232 generic design published in 1998 (Figure 2b) and the Canadian Council of Ministers of the Environment (CCME) hazardous waste landfill generic design requirements for a hazardous waste facility published in 2005 (Figure 2c). All three systems shown in Figure 2 have the same basic system:

(a) a primary leachate collection system with a layer of gravel as its essential component.
(b) a primary composite liner.
(c) a leak detection and secondary leachate collection system with the gravel layer as its essential component.
(d) a secondary composite liner.

However, when one examines the details there are some differences that represent the evolution of knowledge 15 to 25 years. Three obvious differences are evident – (1) thicknesses, (2) replacement of a compacted clay liner (CCL) in the primary liner by a geosynthetic clay liner (GCL) in the ECM and (3) the thickness of the geomembrane in the primary liner was increased from 1.5 mm to 2mm. What is not apparent from the figures are important details such as the resistance to vertical flow (hydraulic conductivity, *k*) of the clay liners and the resistance to horizontal flow at the interface (interface transmissivity, θ) between the geomembrane and clay liners. Without getting into the technical details the differences can be illustrated by a comparison of the relative leakage through the various liner systems (a) if there was no geomembrane (Table 1) and (b) with the geomembrane (Table 2).

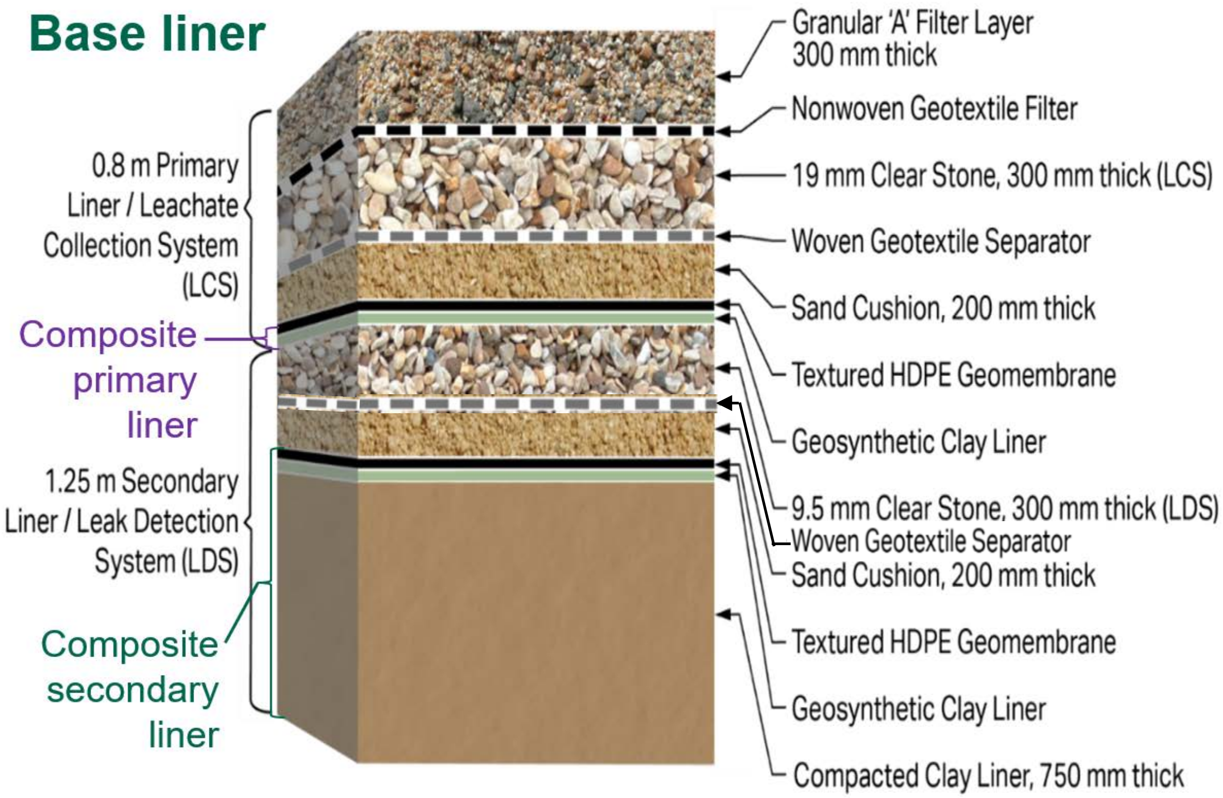

Figure 1: Proposed NSDF ECM bottom liner

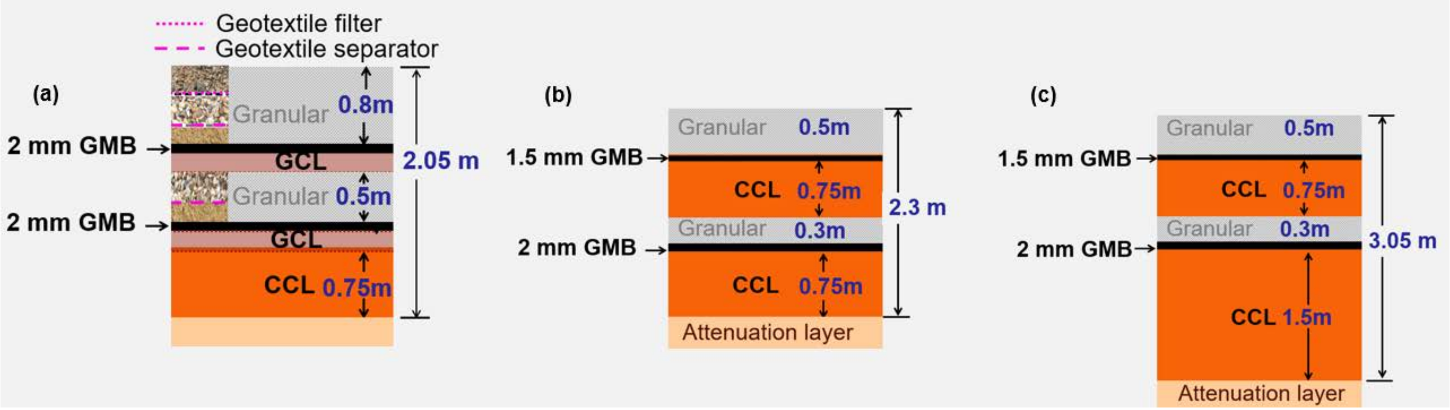

Figure 2: (a) NSDF ECM, (b) Ontario Reg. 232/98 Generic Design, (c) CCME Hazardous Waste landfill guidelines

2.1.2 Comparison of potential leakage for the different designs

2.1.2.1 No geomembrane – clay liners only

Taking the leakage through a 0.007 m thick geosynthetic clay liner (GCL) subject to the design head of 0.2 m [1] above the GCL (Figure 2a without the geomembrane) as the reference leakage, it is found that despite the greater thickness of the compacted clay (CCL) in O.Reg. 232/98 (Figure 2b without the geomembrane) and the CCME designs (Figure 2c without the geomembrane) the leakage through the CCL was 30% higher (Table 1) than through the GCL to be used for the ECM. This is because of the substantially lower hydraulic conductivity[2] of a GCL compared to the CCL.

Similar results were obtained for the secondary liner in the absence of a geomembrane with the 0.75 m-thick O.Reg. 232/98 and the 1.5 m CCME designs giving leakages similar to the ECM GCL alone (Table 1).

This explains the reason for the relatively thin GCL in the primary liner as an alternative to a substantially thicker compacted clay liner even if there was no geomembrane. However, the difference becomes even clearer when the geomembrane and clay liners are used together to form a composite liner.

Table 1: Comparison of relative leakage through primary and secondary clay liner (assuming NO geomembrane) taking leakage through ECM primary GCL under design head as 1.

		No Geomembrane		
Liner	Head on clay liner (m)	ECM (Fig.2a)	O.Reg 232 (Fig.2b)	CCME (Fig.2b)
Primary clay liner	0.2	1.0	1.3	1.3
Secondary clay liner	0.2	0.4	0.43	0.38

Expected k_{GCL}= 1x10^{-11} m/s (based on tests at Queen's[3]) ; k_{PCCL}=3x10^{-10} m/s & k_{SCCL}=1x10^{-10} m/s under 250 kPa[4] [5] (k_{CCL}=3x10^{-10} m/s specified and average k_{CCL}=3x10^{-10} m/s achieved in field construction at the Halton Landfill); Design head = 0.2 m

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[1] AECOM "Base Liner and Final Cover Evaluation and Optimization" Report 232-508600-TN-002 2 CNL dated 7 December 2018, Appendix D, pD17. Conservatively assumes protection layer is saturated. No head buildup in drainage layer as per calculations in Appendix D

[2] The calculations in Tables 1 and 2 are based on my experience with what can reasonably be expected with good construction quality assurance as discussed in §6 below.

[3] Testing at Queen's of a GCL meeting the specifications for the NSDF ECM and prehydrated with simulated NSDF leachate and permeated at 250 kP gives hydraulic conductivity, k_{GCL} , of a 0.007 m-thick GCL at 250 kPa of $k_{GCL} \leq$ 0.7x10^{-11} m/s and so I used a value of 1x10^{-11} m/s as a conservative but reasonable estimate.

[4] Based on an airspace of 1.43x10^{6} m^{3} in 12 ha (Section 3.2.1 of 232-03610-SAR-001*) the average waste and daily/intermediate cover thickness is 11.9 m with another minimum of 2.05 m of cover to give a total thickness of approximately 14 m and using a unit weight of 18 kN/ m^{3} (Section 3.2.1.11 of 232-03610-SAR-001 *) the estimated stress on the liner = 14 x 18= 252 kPa. * CNLs Near Surface Disposal Facility Safety Case 232-03610-SAR-001 dated 2021/01/08

[5] The hydraulic conductivity of the primary CCL was assumed to be 3 times higher (3x10^{-10} m/s - the value specified for the primary liner at the Halton landfill which is constructed over a gravel drainage layer) than the secondary CCL (1x10^{-10} m/s the average value that we actually achieve with a well constructed CCL) because more caution will be required and potentially less compacted effort applied to the lower lifts of the primary liner given the need

2.1.2.2 Composite geomembrane clay liners

If there were no holes in the geomembrane there would be zero leakage. Actions will be taken to minimize holes and especially holes in wrinkles in the geomembrane as discussed later in §6. However, to illustrate the beneficial role of the geomembrane working with the clay liner as proposed for the ECM (Figures 1 and 2a), it will be assumed that (a) there is a slit in the geomembrane 0.1 m long and 0.001 m wide (area 100 mm²), (b) a wrinkle 10 m long and 0.1 m wide with a hole having an area of 100 mm². Table 2 summarizes the normalized leakage through the double-lined designs shown in Figure 2 divided by the calculated leakage for the reference case of a design head on the GCL alone.

Table 3 gives the calculated leakage for the entire 12 ha ECM in litres per day assuming one such defect per hectare.

Table 2: Comparison of relative leakage through primary and secondary composite liners by diving the calculated leakage by the leakage through ECM primary GCL (no geomembrane) at the design head (thus greater the number is less than 1 the greater is the benefit provided by the geomembrane): (a) 0.1 m long and 0.001m wide slit (area 100 mm^2) and (b) a hole in a 0.10 m long and 0.1 m wide wrinkle with a hole.

	Head on composite liner (m)	A GMB and clay composite liner with a hole in the GMB			A GMB and clay composite liner with a hole in a wrinkle in the GMB		
		0.1x 0.001 m slit (Area=100 mm^2)/ha			10 m x 0.1 m wrinkle with hole/ha		
Composite liner		ECM (Fig.2a)	O.Reg 232 (Fig.2b)	CCME (Fig.2b)	ECM (Fig.2a)	O.Reg 232 (Fig.2b)	CCME (Fig.2b)
Primary	0.2	0.000 002	0.000 18	0.000 18	0.0022	0.019	0.019
Secondary	0.2	0.000 003	0.000 10	0.000 13	0.0012	0.011	0.012

Expected k_{GCL}= 1x10^{-11} m/s; k_{PCCL}=3x10^{-10} m/s & k_{SCCL}=1x10^{-10} m/s under 250 kPa; k_{GCL}= 2x10^{-10} m/s; k_{CCL}=1x10^{-9} m/s below wrinkle under 0 kPa[6]; θ_{GCL} = 2x10^{-11} m^2/s; θ_{CCL} = 2x10^{-8} m^2/s; Design head = 0.2 m

Table 3: Calculated leakage (litres per day) through primary and secondary composite liners for 12 ha facility under design head as 1 (a) 0.1 m long and 0.001m wide slit (area 100 mm^2) and (b)a hole in a 0.10 m long and 0.1 m wide wrinkle with a hole

Geomembrane = GMB	A GMB and clay composite liner with a hole in the GMB			A GMB and clay composite liner with a hole in a wrinkle in the GMB		
Head on liner	0.1x 0.001 m slit (Area=100 mm^2)/ha			10 m x 0.1 m wrinkle with hole$^{\#}$/ha		
Composite liner	ECM (Fig.2a)	O.Reg 232 (Fig.2b)	CCME (Fig.2b)	ECM (Fig.2a)	O.Reg 232 (Fig.2b)	CCME (Fig.2b)
Primary clay liner	0.006	0.55	0.55	6.8	57	57
Secondary clay liner	0.0096	0.32	0.41	3.6	33	41

Expected k_{GCL}= 1x10^{-11} m/s; k_{CCL}=3x10^{-10} m/s under 250 kPa; k_{GCL}= 2x10^{-10} m/s; k_{CCL}=1x10^{-9} m/s below wrinkle under 0 kPa; θ = 2x10^{-11} m^2/s; Design head = 0.2 m ; $^{\#}$hole radius = 5.6mm Area = 100 mm^2

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to minimize damage to the underlying layers. The secondary CCL has no such restrictions. Both values are below specified value at 50 kPa due to the application of 5 times higher stress.

[6] For the compacted clay liner, the specification requires 1x10^{-9} m/s at 50 kPa less than or equal to 1x10^{-9} m/s.

With the slit in the geomembrane, the proposed ECM design had a leakage almost 500,000 times smaller than if there were no geomembrane or 0.0002% of that though the GCL alone as the primary liner. In absolute terms leakage collected per day from the entire site after closure is estimated as 0.006 L/d. The leakage through the proposed ECM design is also 90-fold smaller than with the 0.75 m-thick O.Reg. 232/98 and the 1.5 m CCME designs (which would give a still small absolute leakage of 0.55 L/d). A similar conclusion of far better performance for the proposed ECM design than either the 0.75 m-thick O.Reg. 232/98 and the 1.5 m CCME designs is reached for the secondary liner (Tables 2 & 3).

A 10 m long wrinkle with a hole will increase leakage to 1000 times higher than that with the slit. The leakage through the primary liner from the 12 ha site is still low at 6.8 L/d however this example does illustrate why it is important to limit the presence of wrinkles at the time the liner system is covered. Wrinkles are a result of the thermal expansion of the geomembrane when it gets hot due to solar exposure. A white geomembrane reduces the wrinkling at a given time of day after sunrise but does not eliminate wrinkles. However, thermal-induced wrinkles can be kept to a negligible value by controlling the time of day at which it is covered to either (i) before significant heating by the sun or (ii) after the sun has set and the geomembrane has cooled sufficiently to contract to its original state. Limiting the time of day at which geomembrane can be covered will be an important responsibility of the CQA team (see §6)

Comparing the leakages with a wrinkle for the ECM and to regulatory designs simply confirms the previous conclusion that the proposed ECM design is also substantially better at minimizing leakage compared to either the 0.75 m-thick CCL of O.Reg. 232/98 generic design or the 1.5 m-thick CCL of the CCME generic design.

In summary, the proposed ECM barrier system is substantially (by a factor of 10 to 100) better than the generic design provided in either O. Reg 232 for a large municipal solid waste landfill or in the CCME document for hazardous waste landfills. Also, the proposed ECM design has a much longer service life both because of the nature of the design and the choice of the geomembrane as discussed below.

2.1.3 Geomembrane differences

Ontario Reg. 232/98 (Schedule 3) establishes a service life of 150 years for a 1.5 mm-thick HDPE primary geomembrane and 350 years of a 2 mm-thick HDPE secondary geomembrane subject to several requirements including most importantly an oxidative induction time of the geomembrane exceeding 100 minutes, as determined by ASTM D3895[7], and 250 minutes as determined by ASTM D5885[8].

To put the Ontario Reg. 232 (Schedule 3) numbers in context, a 2 mm-thick HDPE geomembrane produced in 1997 with an oxidative induction time of 133 minutes (ASTM D3895), and 380 minutes (ASTM D5885) was tested in simulated municipal solid waste landfill leachate for 17 years[9] and resulted in the projected service life of over 2000 years at the ECM liner operating temperature.

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[7] ASTM D3895 American Society for Testing and Materials Standard Test Method for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry

[8] ASTM D5885 American Society for Testing and Materials Standard Test Method for Oxidative-Induction Time of Polyolefin Geosynthetics by High-Pressure Differential Scanning Calorimetry

[9] Ewais, A.M.R., Rowe, R.K., Rimal, S. and Sangam, H.P. (2018) "17-year elevated temperature study of HDPE geomembrane longevity in air, water and leachate", Geosynth. Int., 25(5):525-544.

The proposed ECM design will require the use of a 2 mm-thick geomembrane tested at Queen's with an oxidative induction time of the geomembrane exceeding 170 minutes (ASTM D3895) and 750 minutes (ASTM D5885) with a projected service life at operating temperature for the ECM liner far exceeding 2000 years.

2.2 Comparisons of ECM design with Port Granby and Port Hope designs

CNL has constructed bottom liners for Port Granby and Port Hope low-level waste facilities (Figure 3a & 3b) and these are compared with the proposed NSDF ECM barrier system (Figure 3c).

In terms of the basic functional units the Port Granby barrier system of Figure 3a has:

- a rather unique primary leachate collection system comprised of a geocomposite drain sandwiched between two granular layers, and
    - a single composite liner comprised of a 2 mm-thick HDPE geomembrane and a 0.75 m thick compacted clay liner.

Port Hope (Figure 3b) has:

- a more conventional 0.3 m gravel primary leachate collection system,
- geotextile protection layer,
- a primary composite liner comprised a 2 mm-thick HDPE geomembrane and GCL,
- a 0.3 m thick gravel leak detection and secondary leachate collection drainage layer sandwich between a geotextile filter above and a geotextile protection layer below, and
- a secondary composite liner comprised of a 2 mm-thick HDPE geomembrane and 0.75 m-thick compacted clay liner.

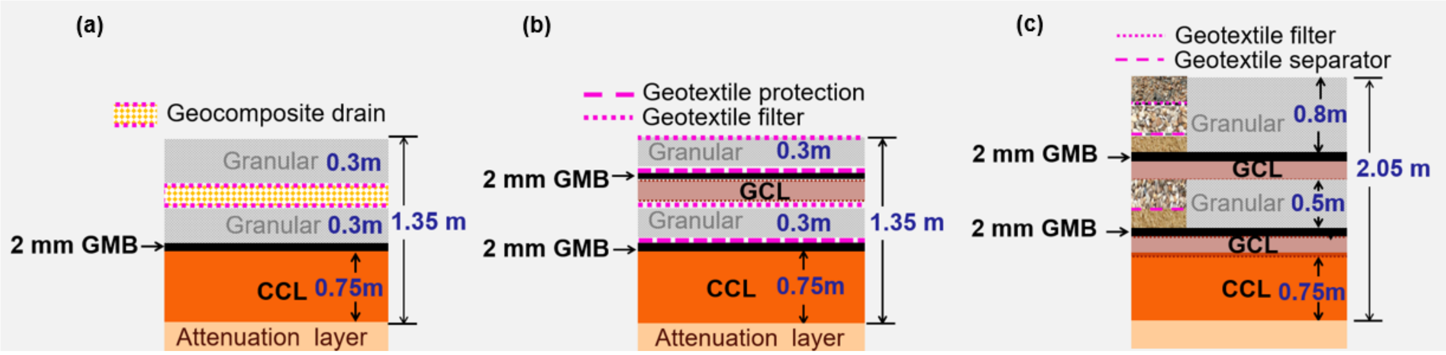

Figure 3: Three CNL LLW bottom barrier systems: (a) Port Granby, (b) Port Hope, and (c) NSDF ECM

The NSDF ECM (Figure 3c) has

- a leachate collection system consisting of a 0.3 m granular (19 mm gravel) layer as the primary component (leachate collection pipes are also provided in the granular layer for use before closure but are not needed in the long-term) and is as good as, or better than, those for Port Granby and Port Hope.

  - overlain by a nonwoven geotextile filter[10]/separator and a 300 mm layer of granular A filter (Figure 1). While this geotextile will function as a filter, it is primarily present for construction reasons and is not relied upon in the long term. The granular A filter serves the same function as the geotextile filter in the Port Hope design and the 300 mm concrete sand layer above the geocomposite drain in the Port Granby design. The ECM filter is more robust than either of the approaches used in Port Granby or Port Hope filters and has an indefinite service life (i.e., > 2000 years).
  - It is underlain by a woven geotextile separator (for construction purposes and not required long-term) and a 200 mm thick layer of sand that serves the same role as the geotextile in the Port Hope design (Port Granby has no such protection layer). After the design of Port Hope, research has shown that a sand protection layer is substantially better at minimizing indentations and tensile strains in the geomembrane caused by the gravel drainage layer than a geotextile. Protection (which is itself substantially better than no protection layer). The sand protection layer will not only minimize strains but also is likely to slow the degradation of the geomembrane more effectively than the geotextile. The sand protection layer has the additional advantage of an indefinite service life (i.e., > 2000 years).
- a primary composite liner similar to that of Port Hope except that it has a 2 mm-thick geomembrane that was selected based on detailed studies (see §4). As illustrated in §2.1.2, this composite liner is substantially better than the Port Hope or O.Reg 232/98 liner system comprised of a 2 mm geomembrane and a 750 mm-thick CCL.
- a secondary leachate collection system comprised of the 300 mm-thick 9.5 mm gravel drainage layer as the primary component. This is comparable to both Port Granby and Port Hope.
  - This is underlain by a 200 mm-thick layer of sand that serves the same role as the geotextile in the Port Hope design and the sand above the primary geomembrane in the Port Granby design.
- a secondary liner comprised of a 2 mm-thick HDPE geomembrane, a GCL and a 750 mm-thick compacted clay liner (CCL). As illustrated in §2.1.2, this composite liner is substantially (by a factor of 10 to 100 times or 1 to 2 orders of magnitude) better than Port Hope or O.Reg 232/98 secondary liner system comprised of a 2 mm geomembrane and 750 mm CCL. Port Granby has no secondary liner.

In summary, the proposed ECM barrier system is substantially better than either the Port Granby or Port Hope designs in terms of minimizing leakage and has a longer service life.

3 Cover barrier system design

Cover systems represent the first line of defence intended to prevent contaminant migration from a waste containment facility. For a LLW facility, it will also act as a barrier to radiation while serving its typical primary function in any waste facility of controlling, and for an LLW facility minimizing, infiltration into the waste facility and hence minimizing leachate generation. The design of a cover will depend on the local environmental conditions. A cover system in a humid environment, such as in Ontario, can be quite different from a cover system in an arid environment. Thus, caution is required in comparing cover systems for different LLW facilities to consider the different requirements dictated by the climatic

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[10] A geotextile or granular filter is intended to allow the passage of fluid while minimizing the migration of solid particles into the underlying drainage layer.

conditions at the site. In particular, a difference in precipitation, the severity of wet-dry cycles and the depth to which they penetrate, and the severity of freeze-thaw cycles and the depth to which they penetrate must be considered in any comparison.

Figure 4 provides a visual comparison of the cover systems at CNLs Port Granby, Port Hope, and the proposed NSDF ECM. All three have the same basic features to minimize infiltration and maximize the longevity of the cover system. General fill or sandy loam primarily acts as a spacer to increase the thickness of the cover and in some cases to allow contouring of the cover (e.g., Figure 5) to encourage most of the flow to particular locations. The topsoil is to support plant growth. The plants serve to minimize erosion.

The only notable differences between the designs are the (a) more complex three layers of granular material below the composite liner for Port Granby compared to Port Hope and the ECM, (b) the use of a geotextile the filter layer at Port Granby compared to a granular filter layer at Port Hope and the ECM, and (c) the overall thickness of the cover material. Each will be briefly discussed below.

The more complex granular system below the composite liner at Port Granby seeks to encourage drainage of any leakage through the cover to a collection point. This is quite an unusual design for a humid environment and, in my opinion, is not necessary. The Port Hope and ECM sandy foundation layers are more typical.

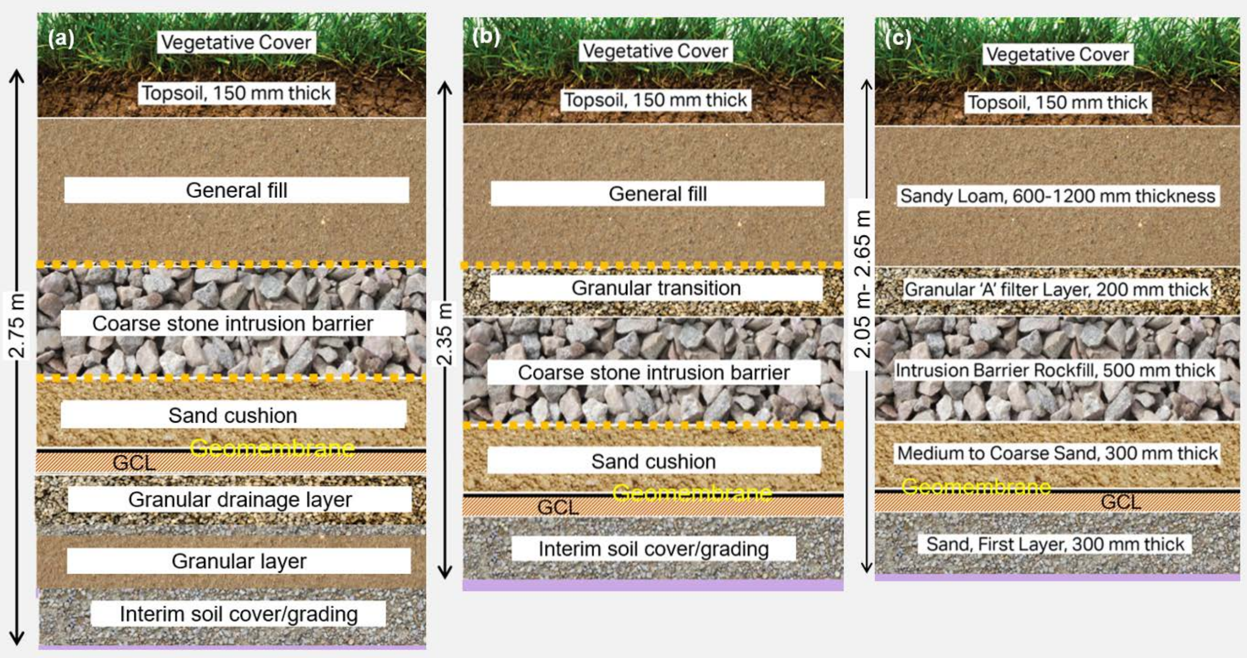

Figure 4: Three CNL LLW cover systems: (a) Port Granby, (b) Port Hope, (c) NSDF ECM

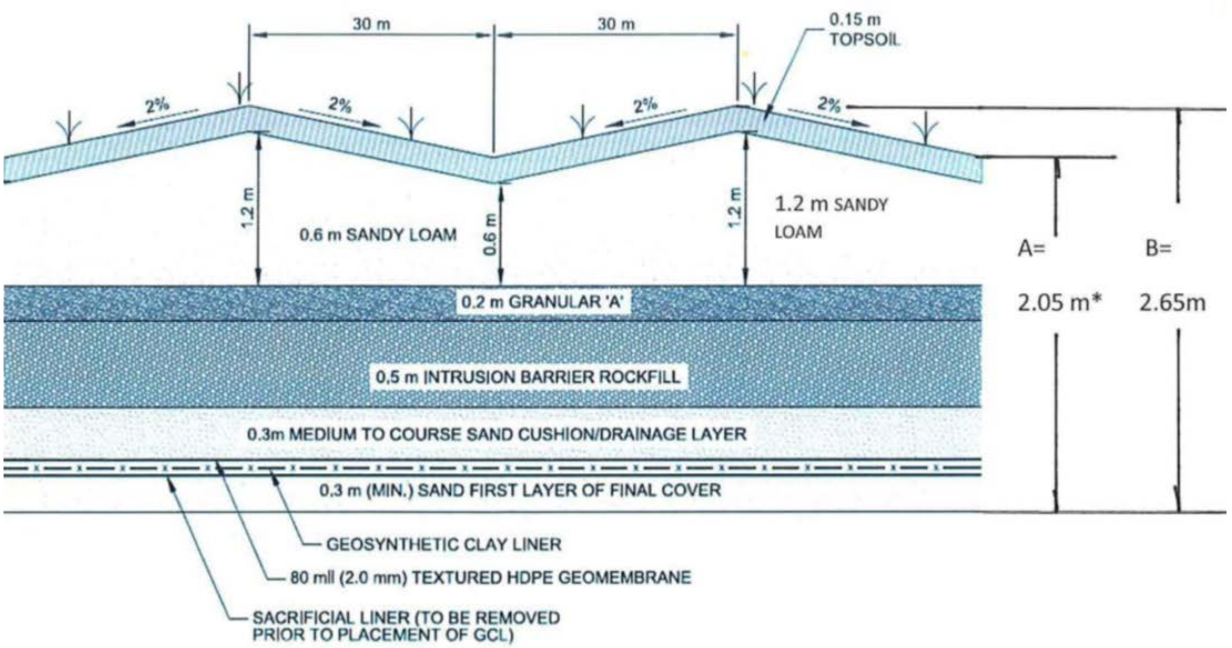

Figure 5: Details cross-section showing the variation in cover thickness to allow contouring of the surface to encourage the flow of precipitation to controlled locations.

The geotextile filter used at Port Granby is only likely to be effective for the service life of the geotextile which is likely to be of the order of 30 to 50 years. The granular filter layer at Port Hope and the ECM serves the same function but with an indefinite service life (i.e., thousands of years).

The thickness of the general fill or sandy loam layer is primarily to protect the GCL from significant and frequent freeze-thaw cycles. The thickness will vary with location depending on the depth of frost penetration. The thickness is considered to be adequate at all three locations. The thickness is usually varied to allow contouring of the surface to control surface water flow (e.g., see Figure 5 showing the shaping of the surface proposed for the ECM responsible for the variability and thickness of this layer in the ECM).

A question that may well be asked is why use a GCL instead of a compacted clay liner? The answer is that a composite bottom liner with a GCL is 10 to 100 times more effective at minimizing leakage than a composite liner with compacted clay (CCL). This was illustrated by the numerical example in Tables 2 and 3. It is confirmed by field studies. For example, using observed leakage through primary liners reported by Bonaparte et al. (2002)[11], Rowe (2005)[12] demonstrated that after landfill closure the average monthly flow through composite liners with a GCL was 0.6 litres per hectare per day (lphd) compared with 50 lphd for a composite liner with a CCL; an 83-fold difference. To put these numbers in context, both are

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[11] Bonaparte, R. & Gross, B. A. (1993). LDCRS flow from double lined landfills and surface impoundments, EPA/600/R-93/070. Springfield, VA: NTIS Publication PB93-179885.

[12] Rowe, R.K. (2005). “Long-term performance of contaminant barrier systems”, 45th Rankine Lecture, *Geotechnique*, 55(9):631-678.

extremely low. Leakage of 0.6 lphd corresponds to percolation of only 0.02 mm per year per square meter of the cover while 50 lphd corresponds to 1.8 mm/year/m^2.

The numbers quoted above are for bottom liners. The difference will be even more notable for covers. This is because an appropriately selected GCL has self-healing capacity and can accommodate the effects of differential settlement which can be expected due to consolidation of the underlying waste much more readily than a compacted clay liner. Furthermore, a CCL is much more susceptible to cracking as a result of wet-dry and freeze-thaw cycles. In Ontario, the leakage through a CCL at a typical municipal solid waste landfill is expected to be 150-250 mm/year/m^2. In a composite liner with an adequate thickness of soil above the CCL, leakage will be less but can be expected to exceed 50 lphd and could easily be up to twice that amount. For example, at the Fernald Preserve facility[13] in Cincinnati, Ohio, the precipitation is about 580 mm/year/m^2 and the leachate collected is about 59 lphd (assuming 100% collection) which implies that the cover is quite effective at deflecting all but a very small proportion (0.37%) of the infiltration in the year for which data is given (2009).

4 Comparison of the NSDF ECM cover barrier system with those in 5 US LLW facilities

CNL's Safety Assessment Report[14] provides detailed documentation of compliance with national and international requirements. Appendix B of the same document provides a concordance showing where each specific regulation or recommendation is addressed in CNL's documentation. To supplement that documentation and the discussion in the previous two sections, I thought it might be useful for the Commission to see a high-level comparison of the NSDF ECM proposed cover and barrier systems with the cover and barrier systems of five LLW disposal facilities in the US as shown in Table 4. The listing of the elements within the cover system in the base barrier system has been organized to put similar components in the same colour and at the same level for ease of comparison.

The first column shows the components of the proposed NSDF ECM. The second column shows the components of the Oakridge Environmental Management Waste Facility (EMWF). This facility was the subject of an external technical review by Dr. CH Benson, Dr, WH Albright, DP Ray and J. Smegel Drs. Benson and Albright are well-known US experts on cover systems and Dr. Benson is a well-known expert on barrier systems more generally. Their report[15] states at this low-level radioactive waste facility "*all of the cells are lined with a state-of-the-art double liner system*". No issues or problems were reported with either the cover or the barrier system design. Thus, it represents a good starting point for the comparison with the NSDF ECM.

Comparing the columns for the NSDF ECM and the Oakridge MWWF, both systems have the same long-term functional elements with the only difference being the geotextile separator layers above the biointrusion barrier layer and below the drainage layer. These two geotextile layers are not needed for the NSDF ECM. The primary difference between the covers is the use of a GCL in the ECM and a CCL at

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[13] Powell, J. Abitz, R.J., Broberg, K.A., Hertel, W.A. and Johnston, F. (2011) "Status and Performance of the On-Site Disposal Facility Fernald Preserve, Cincinnati, Ohio—11137", WM 2011 Conference, February 27–March 3, 2011, Phoenix, AZ

[14] "Safety Assessment Report -Near Surface Disposal Facility Safety Case", Report 232-03610-SAR-001 Revision 2, dated 2021/01/08

[15] Benson,CH, Albright, WH, Ray, DP, and Smegel , J (2009) "Independent technical review report: oak ridge reservation review of the environmental management waste management facility at Oak Ridge" ETR Report ETR-11 Date: February 2008 http://www.em.doe.gov/Pages/ExternalTechReviews.aspx

Oakridge. Other things being equal, the ECM composite liner can be expected to give a leakage that is 10 and 100-fold smaller than that with the compacted clay liner because of the much lower transmissivity at the interface between the geomembrane and clay liner for the case with a GCL.

Comparing the ECM and Oakridge base barrier systems, both have a geotextile and soil filter layer above the leachate collection system (LCS). The Oakridge facility relies on a geotextile to protect the geomembrane whereas the NSTF ECM has a bore robust sand protection layer. The primary liner is a single geomembrane for the Oakridge facility and is likely to leak substantially (by a factor of 10 or an order of magnitude) more than the composite liner in the ECM for any given hole in the geomembrane. In terms of minimizing leakage to the underlying leak detection and leachate collection system, the ECM design is much more conservative (i.e., safe) and will provide far more effective control of leakage than the primary liner of the Oakridge facility as a composite liner with compacted clay.

The ECM has a secondary composite liner with a GCL and compacted clay and once again the ECM is likely to result in 1 to 2 orders of magnitude (i.e., 10 to 100 times) less leakage to the presence of the GCL than the composite liner in the Oakridge system. Thus, the ECM base barrier system goes above and beyond the “state-of-the-art double liner system” at Oakridge EMWF.

Table 4: Comparison of the NSDF ECM cover and barrier system with those of five US LLW facilities

	Proposed NSDF ECM	**Oak Ridge EMWF, TN**	**Hanford ERDF, WA**	**Fernald OSDF, OH**	**CERCLA DF, ID**	**Clive, UT***
Cover	Top soil Soil layer Granular filter Biointrusion layer Drainage/protection layer GMB/GCL Granular layer	Top soil Soil layer Granular filter layer Geotextile Biointrusion layer Drainage layer Geotextile GMB/CCL Geotextile Granular layer	Soil/rock layer General fill layer Geocomposite drainage layer GMB/CCL liner	Soil/rock layer Soil layer Granular filter Biointrusion layer Drainage layer Geotextile GMB/GCL/CCL	Top soil Earthfill layer Granular filter layers Biointrusion layer Granular layers GMB/CCL liner	Crushed rock layer Granular filter layer Soil layer Granular filter layer Geotextile GMB/CCL
Base	Granular filter layer Geotextile LCS Geotextile Sand protection layer GMB/GCL liner LDS/LCS Geotextile Sand protection layer GMB/GCL/CCL liner	Soil layer Geotextile LCS Geotextile GMB LDS/LCS GMB/CCL liner	Soil layer LCS Geotextile GMB LDS/LCS Geotextile GMB/CCL liner	LCS GMB/GCL liner LDS/LCS Geotextile GMB/GCL liner	LCS GMB/GCL liner LDS/LCS GMB/CCL	Crushed rock Granular filter layer Soil layer Geotextile GMB/CCL

GMB = HDPE geomembrane liner
CCL = Compacted clay liner
GCL = Geosynthetic clay liner
LCS =Leachate collection system layer
LDS/LCS = Leak detection/leachate collection layer

NSDF ECM = Near Surface Disposal Facility Engineered Containment Mound
EMWF = Environmental Management Waste Facility
CERCLA -DF = Comprehensive Environmental Response, Compensation and Liability Act Facility
* EnergySolutions (Formerly Envirocare of Utah, Inc.)
ERDF = Environmental Restoration Disposal Facility
OSDF = On-Site Disposal Facility

The cover at the Hanford ERDF does not have a biointrusion layer and relies on a geocomposite drainage layer with a very limited service life relative to the granular drainage layer at the ECM. Also, the composite liner at the Hanford ERD involves a CCL compared to a GCL and hence can be expected to have a leakage 10 to 100 times that of the cover for the ECM and otherwise similar conditions. The double-lined barrier system in Hanford ERDF has the same basic structure as that of the Oakridge EMWF and the same comments apply in the same comments apply. Thus, the ECM base barrier system goes well above and beyond the "state-of-the-art double liner system" at the Hanford ERDF.

The cover at Fernald OSDF is like that for the ECM except that it has a composite GMBs/GCL/CCL composite liner compared to the GMB/GCL composite at the ECM. Considering the susceptibility of CCLs in covers to cracking due to differential settlement the system at the ECM is considered comparable to, if not better than, that at the Fernand OSDF. The baseliner systems have a very similar structure except that the secondary liner is simply a GMB/GCL without the CCL component present in the ECM. In reality, the difference is small.

The most notable difference between the ECM cover and the CERCLA DF cover (Table 4) is the use of a GMB/GCL at the former and a GMB/CCL liner at the latter. As previously noted, under otherwise similar conditions leakage through the GMB/CCL liner is expected to be 10 to 100 times higher than that through the GMB/GCL liner and a base system and likely even higher still in a cover where the CCL is susceptible to cracking.

Finally, comparing ECM and Clive covers, the ECM has a biointrusion layer and drainage layer that are not present in the Clive facility; to important differences in terms of long-term performance in favour of the ECM. Like the Oak Ridge and CERCLA facilities discussed above, and for the same reasons, the composite liner with a CCL in the Clive facility can be expected to give a leakage 10 to 100 times higher than one would predict for the ECM facility under the same conditions. Referring to the barrier system, the ECM has a more functional drainage layer and a sand protection layer that are not present at Clive. Furthermore, the ECM has two composite liners compared to one at Clive and the use of a GCL instead of a CCL as the clay component of the upper composite liner. In short, the ECM base barrier system is far superior to that of Clive.

Thus, the cover and base barrier system for ECM is considered to range between similar (at best) to better and far better than the five US facilities examined, with the leakage through the cover under identical conditions expected to be substantially lower for the NSDF ECM. Similarly, for the bottom barrier system. However, particularly concerning covers, it should be noted that the climatic conditions are notably different at the various facilities and since leakage through a cover will be substantially affected by climatic conditions, the leakage through the cover may vary less than implied in the discussion above, relative to the ECM, particularly in climates with low precipitation.

5 Geomembrane selection and design for a long service life

5.1 Geomembrane (GMB) basics

There is an extensive body of research into the longevity of HDPE geomembranes with a large proportion of it being for municipal solid waste (MSW) landfills and a smaller proportion related to low-level waste. The chemistry of MSW leachate is aggressive with respect to the aging of geomembranes and the MSW liner temperature will remain in the range of 30 to 40°C (or higher) for decades. Predictions of service life based on data for MSW leachate will be conservative (i.e., will err on the side of underestimating the geomembrane service life) for LLW leachate. The data that has been obtained for MSW leachate can therefore be used as a benchmark for assessing performance in LLW leachate.

An HDPE geomembrane is about 97% polyethylene resin, about 2-3% carbon black, and up to about 1% additives which predominately consist of a group of chemical compounds called antioxidants and stabilizers. The resin provides the physical properties of the geomembrane and the hydraulic containment. The most important of these properties is one referred to as stress crack resistance (SCR). The carbon black is to protect the geomembrane from ultraviolet light when it is left in the sun (e.g., during construction before it is covered). The antioxidants protect the geomembrane against thermo-oxidative degradation.

The service life of an HDPE geomembrane has three stages. During Stage I the protective antioxidants deplete until, eventually, the effective chemical is no longer present. Stage II is a lag period after the antioxidants are depleted and before there is a measurable degradation in the polymer. During Stage III the geomembrane physical properties begin to degrade due to thermo-oxidative degradation. The service life of the geomembrane is reached when the key physical property, the stress crack resistance, decreases to below a threshold at which it can no longer sustain the tensile stresses/strains to which it is subjected. Thus, the service life of the geomembrane can be increased in three ways:

(i) using a resin with a relatively high representative stress crack resistance (denoted by SCR_m),
(ii) using a better antioxidant package that delays the depletion of antioxidants in a given chemical and thermal environment, and
(iii) designing to minimize tensile stresses/strains that must be sustained by the geomembrane.

All three approaches were adopted in the ECM barrier system design.

The length of each of the stages of the service life can be predictably related to temperature (in K) by and well-established Arrhenius relationship. Thus, one can take advantage of a time-temperature shift to accelerate each of the stages by testing at higher temperatures and then extrapolating the results to lower temperatures.

5.2 The Queen's (2018[16]) study and Rowe (2019)[17] geomembrane performance assessment

CNL commissioned a 16-month study of five 2 mm-thick textured candidate geomembranes (GMBs) from three manufacturers. The study was conducted at Queen's University (Contract starting on 28 February 2017) under the direction of Prof. F.B Abdelaal Ph.D. The geomembranes were immersed in a simulated municipal solid waste (MSW) leachate (denoted L3) and two simulated Near Surface Disposal Facility (NSDF) leachates (denoted L7 and L9) at a range of temperatures and tested periodically (Queen's 2018). All candidate GMBs had a white side (upper) and two of the GMBs (xTD and yTA) had a conductive layer

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[16] Queen's. 2018. "HDPE Geomembranes-Long-Term Performance Measurement Testing Near Surface Disposal Facility Project", Report #5, November, prepared by Zafari, M. and Abdelaal, F.B. and submitted to Canadian Nuclear Laboratories Ltd. (CNL), dated 18 November 2018, 349p.

[17] Rowe, R.K. (2019) "Geomembrane Relative Performance Report- Final- Canadian Nuclear Laboratories Near Surface Disposal Facility", Technical Report issued to Canadian Nuclear Laboratories; dated February 2019. CNL 197p.

on the underside. I performed an expert review of the work and prepared a *Geomembrane Relative Performance Report* (Rowe 2019).

Also, it is been found that predictions made on the early time data for antioxidant depletion overpredict the rate of depletion which slows down with time and gives a conservative (i.e., errs by underestimating) the time to antioxidant depletion. Thus, predictions based on the 16 months of testing reported in Queen's (2018) will underestimate the time to depletion. This is known for a fact because those tests have now been running for 50 months and a few examples will be given below of the difference in prediction resulting from the extra data.

Based on experimental data generated by Queen's University, three of the five candidate GMBs (denoted as xTB, yTA and xTD) were considered to have an acceptable stress crack resistance for use in the liners of the NSDF ECM. Thus, 2 of the 5 geomembranes were excluded from further consideration for use in the ECM although they may well be suitable for other applications with shorter service life.

5.3 Geomembrane service life assessment

According to Environment Canada, the annual average temperature at Chalk River is 5.6°C (1981-2010) and, since the waste does not generate any significant heat, the sustained temperature of the liner after waste placements and closure is expected to be relatively close to the annual average temperate (i.e., around 6°C at present. Allowing for a few degrees increase in temperature due to climate change over the design life of the ECM, the bottom liner temperature is still expected to be below 10°C. Based on 9-16 months of antioxidant depletion data in simulated MSW leachate, Queen's (2018) predicted the time to antioxidant depletion (Stage I) immersed in MSW L3 to be greater than 2000 years for xTB, 890 years for yTA, and 125 years for xTD. It is these numbers that I used to estimate the service life of the three geomembranes in Rowe (2019). Based on 43 to 50 months of data, the corresponding numbers are now > 2000 years for xTB, > 2000 years for yTA, and 300 years for xTD. These times can be multiplied by 3.4 to obtain the time to depletion in the field in a composite liner.

The antioxidant depletion trends in NSDF leachates L7 and L9 were very similar to but slower than in leachate L3. None of the GMBs had reached a clear depleted (residual) value even at 85°C in 9-16 months of testing in leachates L7 and L9 (compared to 5-7 months in L3). Assuming that they would eventually deplete to the same residual values as in leachate L3, the predicted time to Std-OIT depletion immersed in NSDF leachate L9 at 10°C was greater than 2000 years for xTB and yTA, and 350 years for xTD. Queen's (2018) also gave a more conservative worst-case estimate of the time to OIT depletion in L9 conservatively assuming that they had already reached residual at 85°C. Notwithstanding this (overly) conservative assumption, the predicted time to depletion immersed in NSDF L9 at 10°C was 1300 years for yTA, 290 years for xTB and 37 years for xTD. Immersion testing is extreme exposure and studies have shown (Rowe 2019) that the depletion time in a composite liner is about 3.4-times longer. With 43 to 50 months of data, these numbers can be revised at 10°C was >2000 years for yTA, >2000 years for xTB, and 1750 years for xTD, and about 3.4-times longer for each in a composite liner.

Based on input from CNL (2019) regarding the level of radioactivity in the NSDF leachate and a review of key literature it is concluded that (i) the level of radioactivity expected in the NSDF leachate is no more than 0.001% of that needed to affect the service life of the GMBs, and (ii) the effect of radioactivity in the NSDF leachate on the NSDF GMBs would be negligible.

Based on available data and the interpretation presented by Rowe (2019), two GMBs (denoted as xTD and yTA) were considered suitable for the NSDF ECM. They both have service lives estimated to be more than 2000 years and hence well above the required 550-year design life. Thus, there is a very high probability that when it is in the NSDF composite liner at <10°C, this GMB will be in Stage I (OIT depletion) for the entire 550-year design life even under the "worst-case" interpretation of the OIT data in Queen's (2018). As illustrated by the examples given above of the change in prediction with 43 to 50 months of data the predictions in Queen's (2018) and Rowe (2019) are quite conservative. No oxidative degradation of the selected geomembranes is expected during the ECMs design life although there will be some depletion of antioxidants and a reduction in SCR to SCR_m.

5.4 Conditions to be met to achieve the predicted geomembrane (GMB) service lives

The predicted service lives assume that (i) the tensile strains do not exceed the maximum allowable strains as defined by Rowe (2018)[18], and (ii) there will be quality construction and an independent construction quality assurance (CQA) consultant with excellent up-to-date knowledge of GMBs, GCLs, CCLs, and the design who has extensive field CQA experience and the resources to ensure that all construction activity related to the barrier system, or that could affect the barrier system, is visually monitored by trained and experienced inspectors reporting to the CQA consultant. About six months will be needed to conduct all the CQA testing required to confirm that the selected GMB is manufactured to meet all expected performance requirements. Thus, the GMB needs to be manufactured and stored well in advance of the proposed construction.

The ECM design discussed earlier (Figure 1) can be expected to ensure minimum tensile strains in the geomembrane and satisfy condition (i), subject to condition (ii) being satisfied and the approved geomembrane manufactured consistently with the geomembrane tested by Queen's (2018). Condition (ii) is discussed below. Rowe (2019)[19] concluded with 14 recommendations to CNL[20].

6 Construction quality assurance (CQA)

The NSDF ECM bottom barrier system design and material specifications have been developed to provide excellent long-term containment of the waste and any liquid that comes in contact with the waste while the cover will minimize the amount of water that comes in contact with the waste once it is placed. However, the design is a series of drawings and words in the specifications. These are realized by construction and it is essential that there be third-party knowledgeable construction quality assurance. When it comes to construction, you get what you inspect, not what you expect.

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[18] Rowe, R.K. 2018. Recommend Maximum Allowable Strain (MAS) and design considerations for HDPE geomembranes to be used in the NSDF, Technical Memorandum to Canadian Nuclear Laboratories (CNL) dated 20 August, 27p.

[19] Rowe, R.K. (2019) "Geomembrane Relative Performance Report- Final- Canadian Nuclear Laboratories Near Surface Disposal Facility", Technical Report issued to Canadian Nuclear Laboratories; dated February 2019. CNL 197p.

[20] The geomembrane specification states that the pre-approved products are the "Solmax nonconductive textured premium HD 2.00 White Reflective RT" and the GSE conductive "HDT-080ME-WBC-B-W0" geomembranes. Although both geomembrane products are pre-approved, the preference is for the Solmax noncondictive product.

The CQA firm needs to be very knowledgeable regarding the design and the design intent as well as geomembranes and GCLs and compacted clay liners.

6.1 CQA testing before the commencement of barrier system construction

The two most viable candidate geomembranes for the NSDF ECM (nonconductive xTB and conductive yTA) were selected based on careful testing and consideration of five products that have nominally the same base resin but different antioxidant packages, different outer layers, and were from different production plants. All these factors can affect GMB performance. Thus, the geomembrane supplied must be the same resin, antioxidant package, and carbon black in the core as well as the resin and additives in the outer two co-extruded, textured, layers as those tested by Queen's (2018). However, even with this condition satisfied, there will be some variability in the manufactured product. Construction quality assurance testing will be required to confirm that the antioxidant package and resin are consistent with tests conducted by Queens. This can best be achieved by immersing specimens taken from the manufactured rolls for the project and testing for 90 days immersed in simulated MSW leachate L3 at 85°C and 55°C checking the depletion rate and stress crack resistance after 90 days of immersion is similar to the results obtained by Queen's.

While manufacturers generally have good processes, things can go wrong in the manufacture of GMBs. One of the purposes of the NSDF CQA testing is to identify if any such problems have occurred in the manufacture of the material to be used for the ECM. The CQA tests need to be performed on material specifically to be used in the NSDF ECM and not material said to be equivalent. To allow time to conduct the required CQA testing and obtain results to confirm the suitability material sufficiently in advance of it being installed, tests on off-roll unaged GMB should be initiated immediately after the material is manufactured and the results provided promptly to the CQA consultant. The testing on 90 day-aged geomembranes will take a minimum of five months elapsed time between when the laboratory receives the geomembrane and the issuing of a report.

In addition to the CQA testing alluded to above, testing also is required (i) to confirm that the interface friction angles assumed by the designers are met, and (ii) to verify the suitability of the proposed protection layer. These performance tests need to be conducted using the materials that will be used in construction. They should be undertaken as soon as possible after approval to verify the suitability of the materials being considered for use in these two respects, and if necessary, make alterations well before construction is to commence. These tests are likely to take several months. The GMB used in the interface shear tests (especially if CNL chooses to use the conductive yTA) should be carefully inspected for any sign of damage and, in particular, delamination after the tests. I do not expect any delamination will be observed however it is important to verify that it does not occur.

6.2 On-site CQA before construction of the barrier system

Experience has shown that problems with construction can be minimized by verification of the contractor's proposed equipment and procedures by the construction of a verification barrier system to meet the specifications. This goes above and beyond the test pad envisaged for the compacted clay liner in the specifications. I recommend verification test construction of the entire system bottom barrier system conducted before full-scale construction.

The CQA consultant will need to carefully monitor the construction of the verification test pad to identify any problems with equipment or procedures and to ensure that any such problems are rectified before full-scale construction. Following the construction of the verification test pad, it should then be carefully exhumed to identify any "hidden" problems (e.g., damage that may have occurred as the soil was placed over a liner system) due to how the equipment was operated or the nature of the equipment. This should be carefully documented and any changes to make equipment, materials, or procedures need to be made before the beginning of the actual barrier system construction. This also provides an opportunity for the contractor and workers to become familiar with the level of scrutiny to which they will be subjected during construction.

In addition to improving equipment and methods, the verification test also has a significant psychological benefit on construction workers. Workers tend to be more conscientious when they know they going to be checked. For example, leak location surveys have found a notable difference in the number of defects they find between surveys done when workers did not know that there would be a leak location survey compared to projects where the workers knew a survey would be conducted and that their workmanship would be checked by a leak location survey.

6.3 On-site CQA during construction of the barrier system

The CQA consultant will need to have adequate staff to monitor and ensure that the installation is consistent with the drawings and specifications. To do the latter, sufficient qualified individuals need to be available to be continuously watching all facts of work related to the barrier system or that could impact the barrier system. Their task is to not only monitor but most importantly identify any deficiencies at the time they occur and then ensure they are rectified promptly.

Even the best CQA has the potential to miss a small hole or another potential source of leakage. Thus, an electrical leak location survey is required (i) after placement of the geomembrane and before it is covered, and (ii) after the geomembrane is covered by a layer of granular material. This will be required for both the secondary and primary liners as well as the cover when it is eventually placed. There is clear evidence that an appropriate leak location survey will substantially reduce the number of holes in a liner when it goes into service and hence very substantially reduce leakage. However, while a good leak location survey can be expected to detect all large holes it cannot be guaranteed to detect very small holes. This is why the GCL is required to minimize any leakage through any such holes.

The CQA is not limited to minimizing holes in the short term. It is also intended to minimize the potential for the formation of holes in the future. This involves ensuring that construction is such as to limit the strains to below a maximum allowable strain (Rowe 2018). Also, the geomembrane must be covered at a time when there are minimal wrinkles (< 8% of the site at the time the GMB is covered; a maximum wrinkle height of 50 mm; no wrinkle longer than 5 m and preferably no more than 3 m). Also, the welds are a very important aspect of CQA. Particular care is required to (i) avoid welds in critical locations (see Rowe 2018), (ii) minimize the number of destructive dual-track wedge weld samples that will need to be repaired with extrusion welds, and (iii) control the weld thickness reduction.

6.4 Expectations of the CQA consultant

CQA consultant will be expected to:

1. Develop a CQA plan

2. Conduct CQA on the materials that are to be used and immediately after they are manufactured.
3. Provide the personnel and expertise required to:
    a. conduct detailed CQA of the verification test construction.
    b. carefully document the subsequent exhumation of the verification test section to identify any problems,
    c. prepare a report documenting the verification test construction and exhumation,
    d. recommend revisions to the construction methods, equipment, personnel, and fine-tuning of design details and/or specifications, to address any problems identified in the verification tests
4. Provide expertise and personnel required to implement and perform the necessary CQA through the placement and covering to the point that no damage could be done to the liner during construction of the barrier system (generally speaking, until after the placement of 0.6 m soil over the liner system). There should be sufficient personnel such that:
    a. appropriately qualified personnel will visually watch and photographically document all construction activity involving, or in the vicinity of, the liner at all times that there is any such activity.
    b. the CQA inspector can intervene promptly when any inappropriate action or material is observed,
    c. at no time shall any construction activity that could impact the liner's long-term performance be unobserved,
    d. appropriately document the CQA.
5. Inspect and accept or reject each element of the liner system.

7 Geomembrane versus concrete

A comparison of the relative leakage in Table 1 and Table 2 shows that, with appropriate construction quality assurance (CQA as discussed above), the combination of a modern HDPE geomembrane with a compacted clay liner (CCL) would reduce leakage by about 7000-fold and with a geosynthetic clay liner (GCL) by about 500,000-fold compared to the clay liner alone. In a bottom liner on a firm base the bentonite in the GCL and the clay and the CCL have an indefinite service life (>> 2000 years). Geomembranes have finite service life but with the appropriate combination of materials, design, and construction quality assurance they can also be expected to have a service life of millennia (>2000 years) at a liner temperature of 10° C or less. All three liner components can tolerate any differential settlement that can be expected with the proposed design and any earthquake event considered in the CNL proposal.

In Part 1 of the Hearing, a Commissioner asked the question (page 127 of the transcript) "*I wanted to understand how the seismic events are accounted for in this multi-layer bottom liner concept and why geomembranes were chosen rather than concrete or something more -- intuitively not permeable*."). Both a geomembrane and concrete are man-made materials. Both will have a finite service life and will eventually crack. However, concrete is a rigid and brittle material from the outset whereas a geomembrane is a plastic and flexible material until near the end of its service life when it eventually becomes brittle. Brittle materials will crack when subjected to conditions that induce sufficient tension. "*Concrete cracks when the tensile strain, exceeds 0.010 to 0.012 percent. This limiting tensile strain is* *essentially independent of concrete strength*"[21]. Modern HDPE geomembranes fail when the sustained tensile strain exceeds about 5 to 6%. Thus, they can sustain about 500-fold greater strain before cracking than concrete. "*Concrete cracking can develop during the first days after placing and before any loads are applied*"[21]. While this can be mitigated to some extent by inserting reinforcing steel, reinforcing steel is also prone to degrade and concrete and reinforced concrete have a history of degrading at a much faster rate than modern geomembranes. As a consequence of its ductility, a geomembrane is far more resilient and able to resist differential settlement and earthquakes than a rigid concrete structural slab which would be the alternative to on geomembrane. Thus, a geomembrane represents a far more effective "impermeable" liner than concrete. If the geomembrane is placed without any holes it is, to all practical purposes, impermeable. The possibility of holes is recognized and addressed by (a) construction quality assurance, and (b) the use of the geomembrane as part of a composite liner with the clay component (especially a GCL) to minimize leakage to an essentially negligible value for any hole that could reasonably escape detection by CQA (i.e., estimated leakage through the primary liner after closure with excellent CQA and leak detection surveys that misses a 0.1m x 0.001 slit; see Table 3).

8 Period of operations

The proposed period of operations of the NSDF ECM before final closure is approximately 50 years. This is not an unusual period of operations. Many waste disposal facilities are operated over periods of many decades. From my files of recent projects, I can give two examples of Ontario landfills with comparable operating periods.

- The Ridge Landfill in Blenheim Ontario began operations in 1966. It was expanded in 1999 with an expected closure date of 2021. Thus, it had been operating for 54 years when in 2020 an environmental assessment approved a 21,000,000 m^3 expansion over another 20 years to about 2041 which will extend its operating life to 75 years.
- The Halton landfill was approved with 5 cells and began taking waste in 1991. It has now been operating for over 30 years and at present Cell 1 is full, Cell 2 is mostly full, and Cell 3 has several more years of capacity remaining and is currently accepting most of the waste. I am currently engaged to work on the detailed hydrogeology and final design of Cell 4 for construction in around 2024 with expected construction of Cell 5 in around 2032 and closure of the current facility around 2041 (unless an expansion is approved) with an operating period of 50 years.

9 Long institutional control

The NSDF ECM will require institutional control for centuries. It is not alone. Large MSW landfills can be expected to require institutional control for at least as long and in some cases even longer. Implicit in the design life of 350 years for large MSW landfill secondary liners (O.Reg 232/98) is a need to monitor until the contaminating lifespan is reached and to maintain the cover system until that time. There is also growing recognition that mine waste will need institutional control in perpetuity. In many respects, these are much greater challenges than institutional control of the NSDF ECM.

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[21] Leonhardt, F, (1988) "Cracks and Crack Control in Concrete Structures", Special report: arevised and updated version of an article originally published in the Proceedings of the International Association for Bridge and Structural Engineering (1ABSE), Zurich, Switzerland, 1987, p.109

Long-term maintenance of structures is not new to humankind. Many structures around the world have survived for centuries and some even for millennia to today. Examples are listed in Table 5.

The level of maintenance and intervention required for any of the structures far exceeds that likely to be required for the NSDF ECM. Post closure, the primary requirements for monitoring will be monitoring of leachate generated in the primary and secondary collection systems and removal as necessary (volumes are expected to be very small; see Table 3), monitoring the cover for erosion, and minor maintenance as required.

Table 5: Examples of structures surviving for centuries to millennia (with maintenance)

Sanchi Stupa, India (c. 300 BC)	Maison Carrée, Nimes, France (16 BC–4AD)
Chapel of St. Peter on the Wall, Bradwell-on-Sea, England (7th century)	
Aachen Cathedral (796AD)	Westminster Abbey, London, England (1245)
Maison Puiseaux, Quebec City, QU (1637)	St Paul's Cathedral, London, England (1697)
Buckingham Palace, London, England (1703)	Sinclair Inn, Annapolis Royal, NS (1708)
Basilique-cathédrale de Notre-Dame-de-Québec, Quebec City (1743)	
Fort George, Niagara-on-the-Lake, ON (1802)	Government House, Halifax, NS (1805)

10 Monitoring and groundwater protection

Leachate collection will be required before closure. To the extent that there will be leakage through the primary liner system, it can be expected, based on experience, to be a maximum before closure.

Monitoring will be required during the period of institutional control

Once the final cover system has been built, it becomes the first line of defence and will minimize the generation of any fluids that come into contact with the waste. If at any time during the monitoring period, a defect in the cover system allows an unsatisfactory level of leakage, the cover system can be repaired and the leakage stopped throughout institutional control. Should this ever be required, an additional drainage layer and liner system could readily be added to the cover system.

The primary leachate collection and liner system represent the second line of defence. It is expected that more than 99% of any leakage through the cover will be collected by the primary leachate collection system and less than 1% is likely to escape through the primary liner provided that it is correctly constructed (see §6 above).

The leakage through the primary liner is expected to be very small (see §2) and will need periodic monitoring and leachate collected, if necessary.

The leak detection (leachate collection) and liner system represent the third line of defence. The leak detection system will need to be monitored and leachate collected, if necessary. No measurable leakage is expected through the secondary liner. However, the level of any fluids in the sump should be kept low. If there were to be any leakage through the secondary liner, its most likely location is at the sump. Recognizing the sump is the most vulnerable location for leakage, the design incorporates a third composite liner below the sump (Figure 6).

In the event of unexpected leakage through the primary liner, the secondary drainage system can be pumped to ensure negligible escape through the secondary liner. Post closure, the only way they could be unexpected leakage through the primary liner is if there is unexpected leakage through the cover and hence a cover repair would also be required.

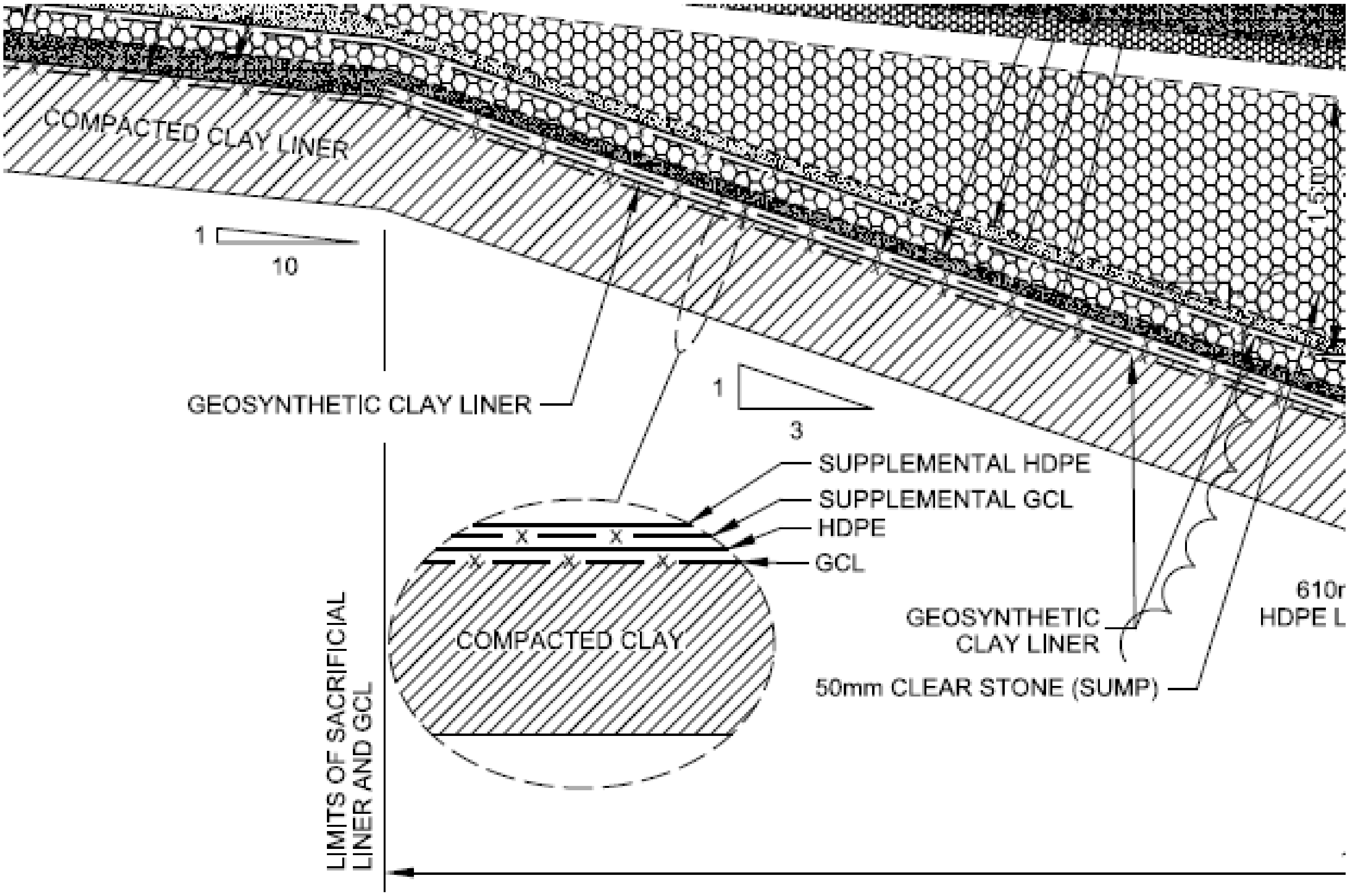

Figure 6: Detail showing the third composite liner ("Supplemental HDPE" over "Supplemental GCL") located above the HDPE/GCL/compacted clay of the secondary liner). Detail extracted "the air surface disposal facility engineering containment mound civil-leachate sump plan and section" drawing B1550-106120-501-01-DD-D

Monitoring wells outside the ECM represent the fourth line of defence. A primary location for external monitoring is downgradient from sumps in the secondary liner system.

The contingency plan represents the fifth line of defence.

The long travel time required to reach any receptor is the sixth line of defence.

Closing comments

In summary, based on quantitative comparisons with other systems in Ontario (i.e., with similar climates) the proposed cover and barrier system for the NSDF ECM is considered to be better to far better than is required by Ontario's landfill regulations and the CCME hazardous waste landfill guidelines as well as the LLW facilities at Port Granby and Port Hope. Based on a qualitative comparison of the components of the cover and liner systems with 5 US LLW facilities located in a range of climates and hydrogeologic environments, the cover and barrier system proposed for the NSDF ECM, is considered to range between better and far better than the five US facilities examined

Yours sincerely.

Kerry Rowe

R.Kerry Rowe OC

Appendix A: Brief Bio of **R. Kerry ROWE**, OC, B.Sc., B.E., Ph.D., D.Eng, DSc(hc), FRS, FREng, NAE, FRSC, FCAE, Dist.M.ASCE, FEIC, FIE(Aust), FCSCE, P.Eng, CP.Eng.

Professor R. Kerry Rowe was educated at the University of Sydney in Australia. He was awarded a BSc (Computer Science) in 1973, B.E. (Hons I, Civil Engineering) and the University Medal in 1975, a Ph.D. in 1979, and D.Eng in 1993. He was awarded a DSc(hc) by Western University in 2016 to recognize his contribution to both the advancement of science and the engineering practice in environmental protection. From 1971 to 1974 he was a cadet engineer and from 1975 to 1978 a geotechnical engineer with the Commonwealth of Australia Department of Construction. Dr. Rowe then spent 21 years as a professor, including 8 years as **Chair** of the Department of Civil and Environmental Engineering, at the University of Western Ontario, Canada (1979-2000). From 2000-2010 he served as **Vice-Principal (Research)** at Queen's University in Kingston, Canada. He is presently the **Distinguished University Professor** (2019-) and the **Canada Research Chair in Geotechnical and Geoenvironmental Engineering** (2010-) in the Department of Civil Engineering at Queen's University.

Professor Rowe’s research and consulting have been in contaminant migration through soil and rock, landfill design, containment of contaminated sites, geosynthetics (including geotextiles, geomembranes, geogrids, geonets, etc.), tailings storage facilities, heap leach pads, dams, reinforced embankments and walls, tunnels in soft ground, and failure of slopes and excavations. Rowe is a pioneer of the relatively young yet broad field of geoenvironmental engineering. He has conducted pioneering research on the long-term performance of leachate collection systems, HDPE geomembranes, geosynthetic clay liners and in particular the interactions between the various components of barrier systems. His team was the first to quantify wrinkling in landfill liners and demonstrate that leakages observed in lined landfills — inexplicable by traditional calculation methods — can be explained and predicted by considering typical wrinkle distributions. This is changing construction practice and moving the industry towards reducing leakage to negligible levels. He was the first to show that PFAS in landfills will require a more elaborate design than is commonly adopted to prevent an unacceptable impact.

He has consulted on over 180 waste disposal, remediation, hydrology, dam, and tunnelling projects worldwide including over 85 landfill or containment sites worldwide and provided innovative solutions to cleaning up the environment in geographic locations ranging from the **Arctic** to the **Antarctic**. He was the key advisor in developing technical aspects of Ontario's current landfill regulations. He co-wrote Canada’s current *Federal guidelines for landfilling hazardous waste*. He was appointed by the Ontario Minister of the Environment to the *Expert Panel to Review the Design and Operations of the Taro Landfill*. Following a significant incident where landfill gas caused the evacuation of hundreds of residents around a landfill in Melbourne, Australia (2008) he was called by the Victorian EPA to provide advice on mitigating the immediate problem. He then co-wrote the key liner components of *new landfill standards for the State of Victoria*, now used as a model for much of the country. His work has also greatly influenced the current national landfill standards and state of practice in South Africa. He has served on an International Dam Construction and/or Remediation Panel for 13 dams and has been a senior advisor for 5 other dams. He has been an expert witness in numerous legal cases involving forensic analysis as well as in environmental assessment and protection hearings.

He has more than **425** refereed journal papers, **3** books, **19** book chapters, and over **360** full conference papers. His *h*-index (77, Google; 50, Web of Science) is **one of the highest in geotechnical engineering worldwide**. His work on leachate collection systems won the **Ontario Ministry of the Environment’s**

Award of Excellence for Research and Development. Rowe's papers have won **32 Best Paper awards** and been runner-up on 35 occasions. Different aspects of his work have won the **International Geosynthetics Societies Gold Medal** (1996, 2004, 2014, 2018). In 2015, he won the **Thomas Telford Gold Medal** (for the best paper in the 34 journals published by the Institution of Civil Engineers U.K. in 2014) and the **Miroslaw Romanowski Medal** (for exceptional scientific work relating to environmental problems) from the Royal Society of Canada.

He has presented 80 Keynote, 28 Distinguished, and 484 invited lectures in 38 countries, including the Giroud Lecture (2002), **Rankine Lecture** (2005), Manuel Rocha Lecture (2006), Zeng Guo-Xi Lecture (2009), Casagrande Lecture (2011), **Karl Terzaghi Lecture** (2017), and Mercer lecture (2019). In 2013, the *International Society for Soil Mechanics and Geotechnical Engineering* created the **R. Kerry Rowe Lecture** to honour his seminal contributions to the development of geoenvironmental engineering. In 2021, the *International Geosynthetics Society* created the **Kerry Rowe Lecture** to honour his seminal contributions to the development of geosynthetic engineering.

In 2013, he was elected to the world's oldest and most prestigious scientific society recognizing fundamental contributions to science, the **Royal Society (U.K.)**. He was also elected as a **Foreign Member of the U.S. National Academy of Engineering** (2016), a fellow **UK Royal Academy of Engineering** (2010), and both the **Royal Society of Canada** (2001) and the **Canadian Academy of Engineering** (2001). In 2020, he was elected a **Distinguished Member American Society of Civil Engineers**, the *highest award* and recognition of the world's largest civil engineering society.

Over the past 40 years, Rowe was a winner of the **Excellence in Teaching Awards** and **Excellence in Graduate Student Supervision** Awards. He has supervised **125 research students,** including 41 research Masters and 84 Ph.D. students, both Canadian and international. He was the Editor of the highly regarded International Journal ***Geotextiles and Geomembranes*** from 1997 to 2021, and presently serves as subject Editor of Royal Society Open Science, Associate Editor of the ***Canadian Geotechnical Journal***, on the Editorial Board of 11 other journals, and over the past has served 10 years on the editorial board of ***ASCE Journal Geotechnical and Geoenvironmental Engineering*** and 4 years on the Board of ***Geotechnique***. He was appointed an **Officer of the Order of Canada** in 2018 "For his seminal contributions to the field of geoenvironmental engineering, notably for his pioneering research in waste barrier systems.".