A geocomposite barrier for hydrocarbon containment in the Arctic

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ABSTRACT*: The paper describes the background and remediation steps that were taken to contain migration of a subsurface hydrocarbon contaminant plume at a site in the Canadian Arctic. A composite liner consisting of a novel fluorine surface-treated high-density polyethylene geomembrane and a geosynthetic clay liner was selected as the short-term (several years) barrier solution. The paper describes the design details, the selection criteria, and the challenges that were overcome to install the barrier system. A complimentary program of site monitoring is underway together with a parallel program of laboratory testing investigating the long-term effects of freeze-thaw, low temperatures, and contact with jet fuel on specimens of the barrier components. Results from site monitoring show that the barrier system is performing as planned three years after installation. Laboratory tests completed to date show that the geosynthetic barrier materials can be expected to maintain acceptably low rates of hydrocarbon diffusion and advection well beyond the original 3-year design life of the barrier system.*

KEYWORDS: Geosynthetics, barrier, hydrocarbon containment, Arctic, geomembrane, Geosynthetic Clay Liner

INTRODUCTION

The Canadian Department of National Defence is currently undertaking a $625 million (Cdn) program focused on the cleanup of Canadian Distant Early Warning Line (DEW Line) sites located on the Canadian Arctic coastline from the Yukon Territory in the west to Baffin Island in the east. Other sites, which are located from Baffin Island southwards along the Labrador coast, have also been subjected to environmental site assessments as part of National Defence's environmental stewardship program. The paper describes the background and remediation steps that were taken as a rapid response to contain migration of a subsurface hydrocarbon contaminant plume at one radar site in the eastern Canadian Arctic. The focus of the paper is on the design of a composite liner system comprised of a novel fluorine surface-treated high-density polyethylene (f-HDPE) geomembrane (GM) and a geosynthetic clay liner (GCL). In addition, the paper summarizes some results from a laboratory program for post-construction assessment of the durability of the geosynthetic barrier materials. This paper is an expanded and updated version of previous conference papers that have focused on different aspects of this project (Li et al. 2002a,b; Bathurst et al. 2005; Rowe et al. 2005).

Project Background

The project site is a North Warning System long-range radar installation located at 63°20′23″N, 64°08′45″W on Brevoort Island, approximately 225 km east of Iqaluit, the capital of Nunavut Territory (Figure 1). The site was re-built in 1987 and is now called BAF-3. Brevoort Island is roughly 40 km long and 10 km wide and is located east of Baffin Island in a zone of continuous permafrost. The annual average precipitation at BAF-3 is 600 mm, with snowfall 335 mm per year and rainfall 265 mm per year. Annual average frost occurrence is 322 days and fog averages 150 days in the year. The construction season is limited to 4 to 6 weeks per year.

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Figure 1. Location of BAF-3 site.

Initial Site Assessment

In 1998, during the initial site assessment of BAF-3, visual inspection of the beach area confirmed the presence of two large petroleum, oil and lubricants (POL) tanks situated within a lined berm area approximately 75 m north of the ocean (Figures 2 and 3). Given that the existing POL tanks had replaced older tanks dating back from the original Brevoort Relay Station (RES-X-1; a DEW Line Rearward Communications Site), the potential for fuel leaked from corroded tanks or spilled during deconstruction activities was investigated. At that time, the collection and analyses of limited soil samples revealed the presence of Arctic diesel (jet fuel) in the sloped area between the tanks and the ocean at levels up to 14,000 ppm total petroleum hydrocarbons (TPH).

In 2000, additional sampling was undertaken to fully delineate the area contaminated with TPH between the existing POL tanks and the ocean (Environmental Sciences Group, 2001). The goal was to collect sufficient samples to determine the lateral and vertical extent of hydrocarbon (HC) contamination, and to determine whether jet fuel was migrating towards the ocean. This necessitated collection of samples (in a grid pattern) south of the tanks, north of the ocean, and west and east to find the 'clean' line. The extent of the grid was estimated according to the results of the 1998 program, and the topography of the area, which included a boulder field immediately adjacent to the ocean. Taking into account the approximate surface area (>2500 m^2), a 12 m x 12 m grid was considered to be appropriate and given sufficient coverage to the entire area.

Complications were imposed by the predominance of large boulders; hence an opportunistic sampling strategy was adopted whereby samples were collected wherever conditions allowed given the available equipment. A small backhoe was used to dig test pits to a maximum depth of 1.8 m (depth dependent upon reaching permafrost or bedrock). Ultimately, a total of 21 test pits (providing 74 samples) were excavated, with coverage extending to within ~20 m of the ocean (i.e. to the beginning of the boulder field). Laboratory analysis indicated that although many surface soil samples were uncontaminated, most of those collected at depth had TPH levels exceeding acceptable criteria. It became apparent that fuel spilled or leaked at the tank source had migrated down-slope towards the ocean. Whether contamination had reached the bay was questionable, as the difficulty of sampling beneath the boulder field immediately adjacent to the water was impossible to overcome. The area extent of the HC-contaminated zone below and down-slope of the existing POL tank farm is illustrated in Figure 3.

It should be emphasized that the site assessment described here was carried out by scientists focused on identifying the subsurface contamination type, its depth, and delineating the area extent of the contaminant plume. Geotechnical information was limited to aerial photographs of the site and soil samples which had been retrieved from one test pit. Information on the depth to permafrost, depth to bedrock, and the size and area extent of boulders observed in site photographs was also not available for design.

The results of the site assessment were communicated to Environment Canada and other related government departments, and a collective decision was made to deal with the problem. The stakeholders agreed that a short-term containment solution was required by the end of the summer of 2001 to contain the contaminant plume until the contaminated ground could be excavated or otherwise cleaned up at a later date. The short-term solution had to be one that could be implemented at a remote site within a short construction season.

Figure 2. View looking toward ocean showing existing fuel tanks.

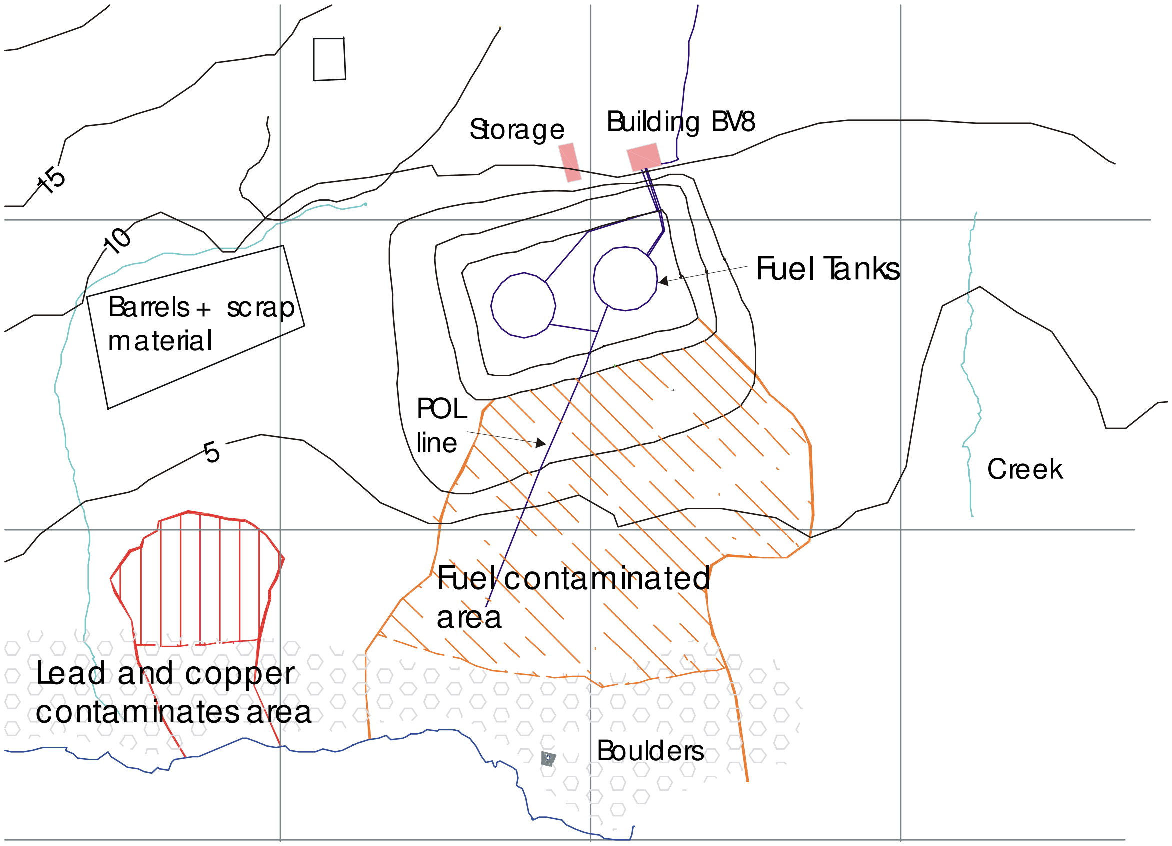

Figure 3. Plan view of fuel contaminated area.

BARRIER SYSTEM

Design and Installation

The final barrier design was influenced by the lack of geotechnical data for the site and the need for a flexible design to adjust to unforeseen site conditions (e.g. buried boulders, variable location, and depth of bedrock and permafrost). The design approach was also influenced by difficult site access. The volume of materials that could be shipped to the site was limited to a sea lift (towed barge) staging out of Montreal once a year during the ice-free summer months and light aircraft during good weather. Construction equipment was restricted to equipment currently on-site. Existing technologies such as compacted clay liners (CCLs) and slurry cut-off walls that require specialized construction equipment and contractors were eliminated during the initial feasibility study by the writers. Both technologies were ruled impractical due to lack of suitable site materials, lack of geotechnical data on subsurface conditions, and poor site access. Furthermore, there were questions regarding the durability of clay materials under extreme cold, freeze-thaw conditions and possible degradation when in contact with fuel and synergistic effects from all these factors.

Based on the factors noted above, the subsurface barrier design was selected as a geosynthetic composite liner system comprised of a geomembrane (GM) and an underlying geosynthetic clay liner (GCL) (Li et al. 2002a,b). A fluorine surface-treated high-density polyethylene (f-HDPE) geomembrane (GM) was selected for the primary barrier. This chemical treatment makes the HDPE liner material more resistant to hydrocarbon diffusion than currently untreated HDPE liners (Sangam et al. 2001). With proper design and good quality control practices, HDPE liners can provide continuous containment without degradation in low-temperature northern environments (Richards and Foster 1991). However, due to the difficult working conditions related to wet and cold weather at this site, it was recognized that seaming of the geomembrane panels could be problematic. Furthermore, the availability of a suitable bedding material for a geomembrane liner was unknown at the time of design. Consequently, a combination of geomembrane and geosynthetic clay liner was thought to be the best option for containment of the spill and that the properties of each would be complimentary. In the event of minor cracking or perforation of the geomembrane or poor seams, the geosynthetic clay liner would act as a back up containment layer. At the time of the design, the literature suggested that GCLs could withstand freeze-thaw cycles without significant changes in hydraulic conductivity (Hewitt and Daniel 1997, Kraus et al. 1997, Quiroz and Zimmie 1998, Chapuis 2000). Installation of GCLs is also relatively easy. The primary concern regarding GCLs in this project was the potential chemical impact of hydrocarbon on the constituent materials and the potential for damage after freeze-thaw in such an extreme climate and in a situation where there was also low confining stress to aid self-healing. These issues are addressed through a complimentary laboratory investigation described later in the paper.

The containment system concept involved the excavation of a continuous trench to a depth of 0.3 m into the existing permafrost (or to bedrock) immediately down-slope of the existing tank farm and then placing the composite liner in the excavation. The barrier would intercept the flow of groundwater (transport mechanism for the contaminant plume) in the down-slope direction and thereby reduce further migration of HC contamination. Since the contaminant liquid of interest is less dense than water (a light non-aqueous phase liquid - LNAPL) the free product was expected to predominantly migrate at the water table.

The barrier system was designed to be placed on the down-slope side of the excavated trench. The decision for a sloped installation was largely dictated by factors such as available manpower and ease of construction. It was recognized that this approach would require more geosynthetic barrier material and excavation than an alternative vertical wall system. However, a vertical trench was not possible because of the presence of large boulders and the possibility of intercepting the groundwater table that could lead to trench wall instability. Photographs of trench excavation illustrating ground conditions at the site are shown in Figures 4 and 5. The groundwater table was not observed during excavation of the trench nor was there visual evidence of free product LNAPL. The ponded water on the permafrost layer in Figure 5 was the result of rainfall runoff.

Figure 4. Photograph illustrating large boulders encountered at east end of trench excavation.

Figure 5. Photograph of trench excavation illustrating bedrock encountered at trench bottom.

The trench excavation geometry of the sloped barrier method is illustrated in Figures 6 and 7. The two trench cross-sections are the same with the exception of the anchorage detail at the bottom of the trench (i.e. anchorage in soil or attachment to bedrock). The trench was excavated with the downstream side at about 1:2 (vertical: horizontal) slope prior to installation of the geosynthetic barrier.

Figure 6 shows the geosynthetic barrier system for the case where the bottom of the barrier is anchored in permafrost soil (Case 1) to a depth of 0.3 m. The primary barrier is an HDPE geomembrane sheet with fluorination pre-treatment supplied by Fluoro-Seal Inc. (Sangam et al. 2001; Sangam and Rowe 2005).

The fluorinated HDPE geomembrane was first produced as a conventional geomembrane and then fluorinated by exposing the geomembrane to elemental fluorine gas on both sides. The fluorine atoms substitute the hydrogen atoms in the carbon-hydrogen (C-H) polyethylene chain, creating carbon-fluorine (C-F) covalent bonds on the outermost surface of the untreated geomembrane. This creates a thin carbon-fluorine layer (0.31-0.37 microns as measured by Scanning Electron Microscope/Energy Dispersive X-Ray).

The untreated HDPE geomembrane was manufactured by GSE Lining Technology Inc., Houston, Texas, USA. This black 1.5 mm-thick (60 mils), smooth-surfaced HDPE geomembrane is produced from specially formulated virgin polyethylene resin. The average density of the geomembrane is 0.94 g/cm^3. The manufacturer's technical data sheet describes the product as having approximately 97.5% polyethylene and the remaining 2.5% consists of carbon black, trace amounts of antioxidants, and heat stabilizers. The measured crystallinity is about 51%. The standard Oxidation Induction Time (OIT) value for the geomembrane is 135 minutes. This OIT value is greater than the minimum value of 100 minutes required by the Ontario Regulation 232/98 - Environmental Protection Act, 1998.

The surface modification treatment also allows an adhesive bond to be used with the HDPE geomembrane instead of traditional heat seaming (Cadwallader and Kastelic 2000). The seam between HDPE liner panels was overlapped by 150 mm and glued together using a two-part adhesive recommended by Fluoro-Seal Inc. It was estimated to take up to 10 to 12 days to reach the full strength of the adhesive at 5 or 6 °C. However, due to the shallow depth of the geomembrane layer, seam integrity with respect to leaks rather than tensile strength was the principal concern. Duct tape and sandbags were used to apply pressure to the seams during adhesive curing.

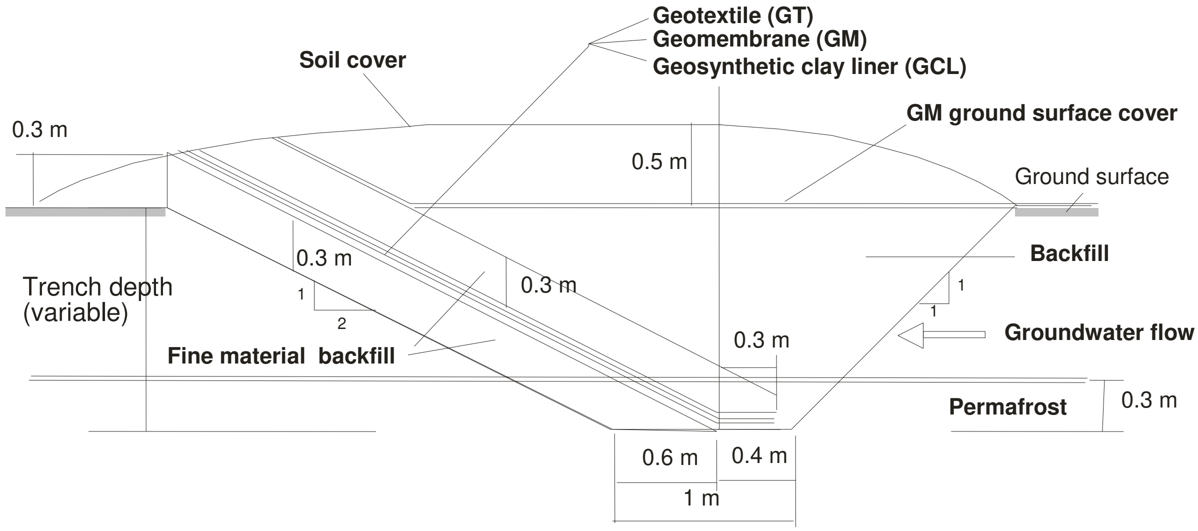

Figure 6. Installation of geosynthetic barrier system anchored in permafrost (Case 1).

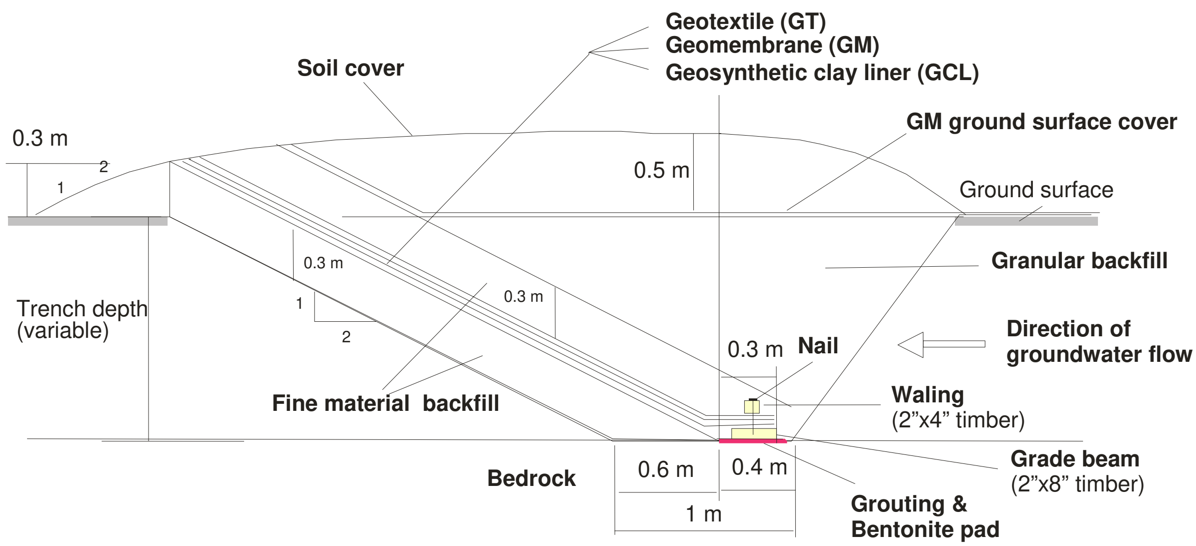

Figure 7. Installation of geosynthetic barrier system anchored to bedrock (Case 2).

The upstream side of the HDPE is protected from the granular backfill by a needle-punched nonwoven geotextile (550 g/m^2) cushion. The down-stream side of the barrier is a needle-punched nonwoven geosynthetic clay liner (GCL). The GCL product (Bentofix Thermal Lock "NWL") has a bentonite mass of 3.66 kg/m^2, hydraulic conductivity of 5×10^{-11} m/sec, and internal shear strength of 24 kPa (typical peak value for specimen hydrated for 24 hours and sheared under 10 kPa normal stress in accordance with ASTM D6243). The swell index of bentonite is 24 ml/2g minimum following ASTM D5890. Loose granular bentonite was placed between panels at a rate of about 400 g per linear m of seam and overlapped by 150 mm. The HDPE and GCL panels were placed using a spreader frame (Figure 8).

The composite system was extended below the permafrost table where practicable. At locations where the excavation trench is located on bedrock, the installation scheme identified as Case 2 was used (Figure 7). The bedrock was cleaned by power washing before using bentonite powder and grout (Sika Arctic Grout) to fill rock surface voids or cracks and to seat a timber grade beam at the bedrock surface. The installation of the geocomposite liner was similar to that shown in Figure 6. Once the two liners were in place, the construction method called for a timber waling to be placed over the geocomposite liner and nailed through to the timber grade beam to secure the bottom end of the barrier. Once buried, water take-up by the GCL membrane and the bentonite powder below the timber grade beam would create the water seal at the bottom of the barrier.

After the geosynthetic barrier was in place, the liner system was then covered with a 0.3 m-thick layer of minus 50 mm gravel. This construction stage is illustrated in the photograph in Figure 8. Next, the trench was backfilled using the excavated materials and the ground surface graded and covered by a low weight pre-seamed scrim-reinforced polyethylene geomembrane (Layfield RPE 25) with a thickness of 0.51 mm and a tensile strength of 1,510 N. The boundaries of the cover sheet were anchored into a 1 to 1.5 m-deep trench and ballasted using on-site backfill and sand bags to prevent wind uplift (Figure 9). The cover sheet extended to the downstream side beyond the excavation and below the backfill mound covering the barrier installation. The cover sheet was intended to minimize infiltration from rainfall and snowmelt into the contaminated zone upgradient of the barrier system.

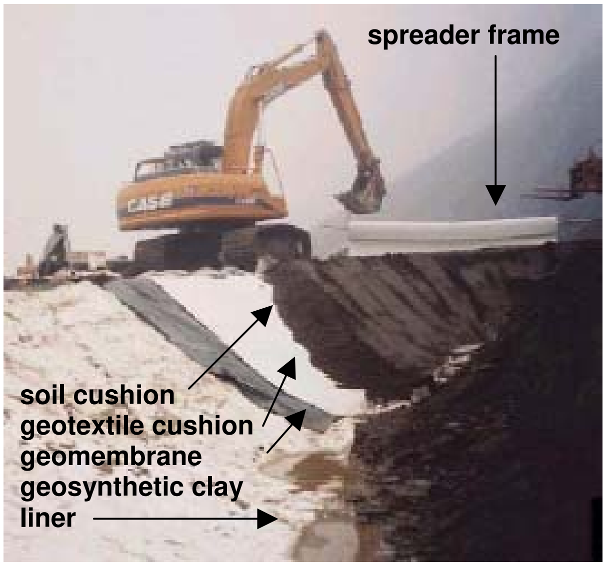

Figure 8. Photograph showing installation and arrangement of liner system components.

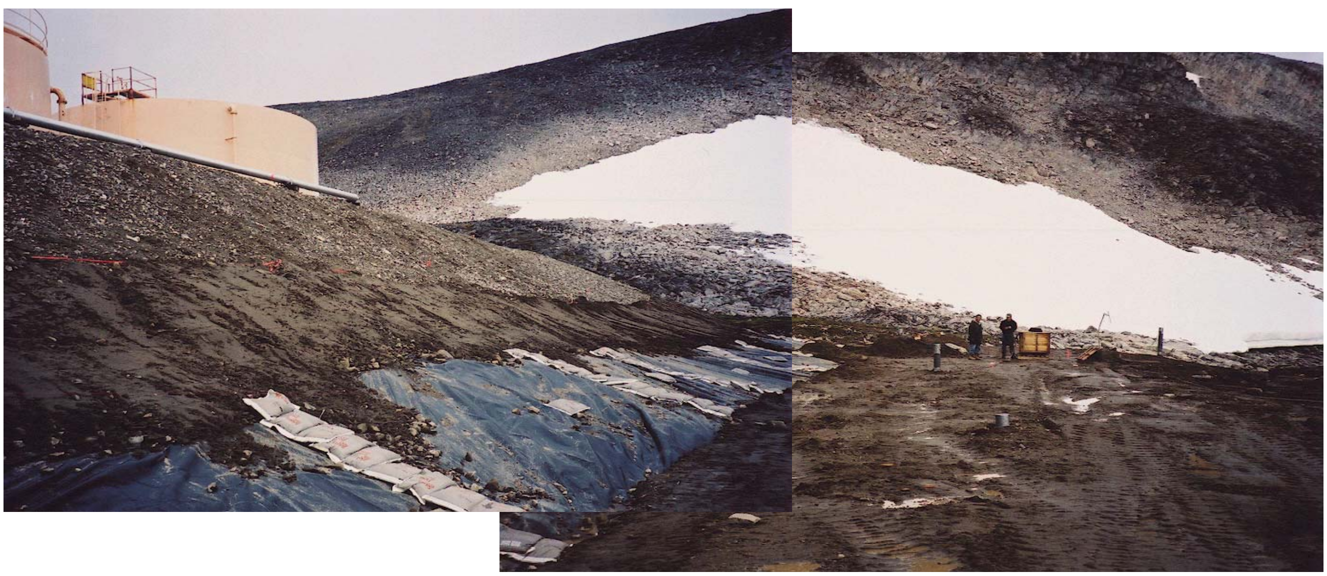

Figure 9. Photograph showing geomembrane cover sheet placed over and upstream of the geocomposite barrier.

The backfill was placed to a height of 0.5 m above ground surface as additional thermal insulation to minimize thawing of the permafrost table and to encourage freeze-back of the permafrost above the bottom of the barrier. At the lowest elevation point on the upstream edge of the trench mound, a buried 150 mm-diameter PVC pipe was placed through the backfill mound to allow surface water collected on top of the ground cover sheet to drain away.

The final trench was excavated in a single straight length about 67 m long with shorter curved sections at each end to bring the barrier trench into contact with the tank farm berms. The location of the trench was dictated by ground conditions that prevented the barrier system from being placed in the boulder field identified in Figure 3. The final alignment is shown in Figure 10. The consequences of the lack of geotechnical data available at the design stage of this project became apparent at the beginning of construction. The depth to permafrost was discovered to be up to 2.6 m deep, significantly greater than the average 1.5 m assumed at the time of the design. The increased depth is believed to be due to the proximity of the trench to the ocean and the large depth of fill that had been placed at the site during site leveling to accommodate the new tank farm. The deeper excavation led to a 73% increase in the amount of the geosynthetic materials required. The demand for minus 50 mm gravel (cushion) was also greatly increased. Shortening of the original trench length and careful management of the quantity of construction materials was required to ensure that there were sufficient geosynthetic materials to build the barrier system.

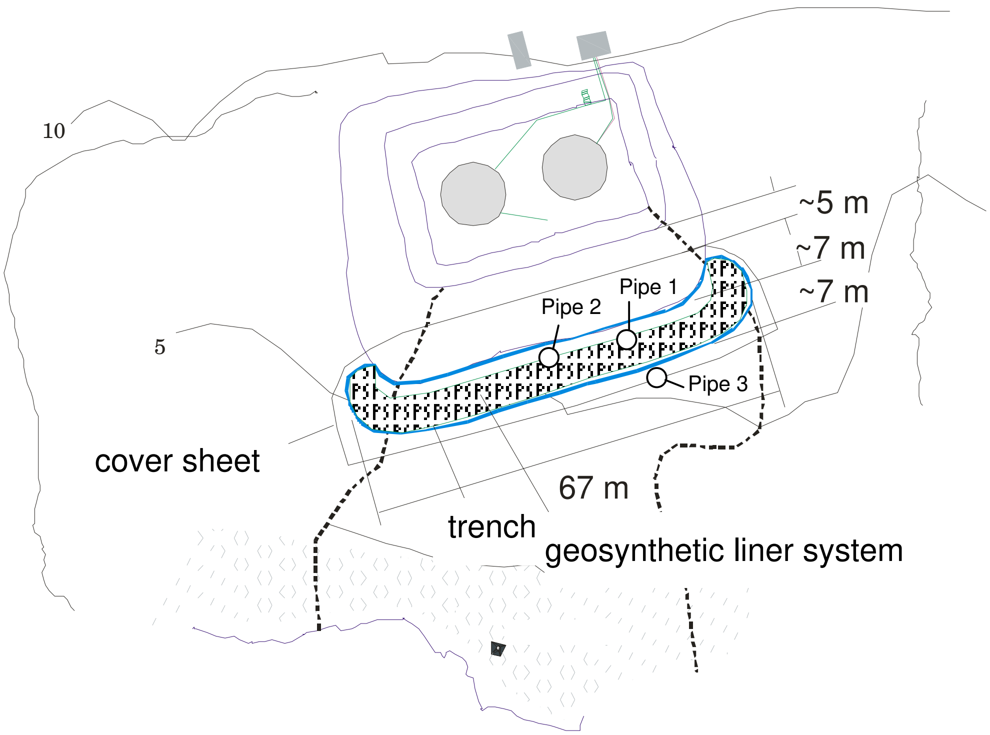

Figure 10. Plan view of containment barrier system location and instrumentation pipe locations.

The entire construction project took 21 days and employed 2 laborers and 2 equipment operators. In addition, a native Inuit "bear monitor" was employed to prevent personnel from being eaten by Polar bears that are indigenous to the area. The main construction equipment was a backhoe excavator. Other equipment including a haul truck, a loader, and a tracked dozer was used to remove and transport fill materials.

Instrumentation

In order to assess the thermal and groundwater regimes at the site, 16 thermocouples and 6 piezometers were installed in three 150 mm-diameter PVC pipes extending to the bottom of the trench excavation. Two pipes were installed immediately upstream of the barrier system and one immediately downstream. The pipes were placed while the excavation was open. An example installation is illustrated in Figure 11. The data acquisition system (Campbell Scientific) was specially designed for harsh environments and consists of a memory module that can be swapped out at intervals and the data downloaded. The module can store up to one year of data. A battery supply connected to a solar panel is used to power the system.

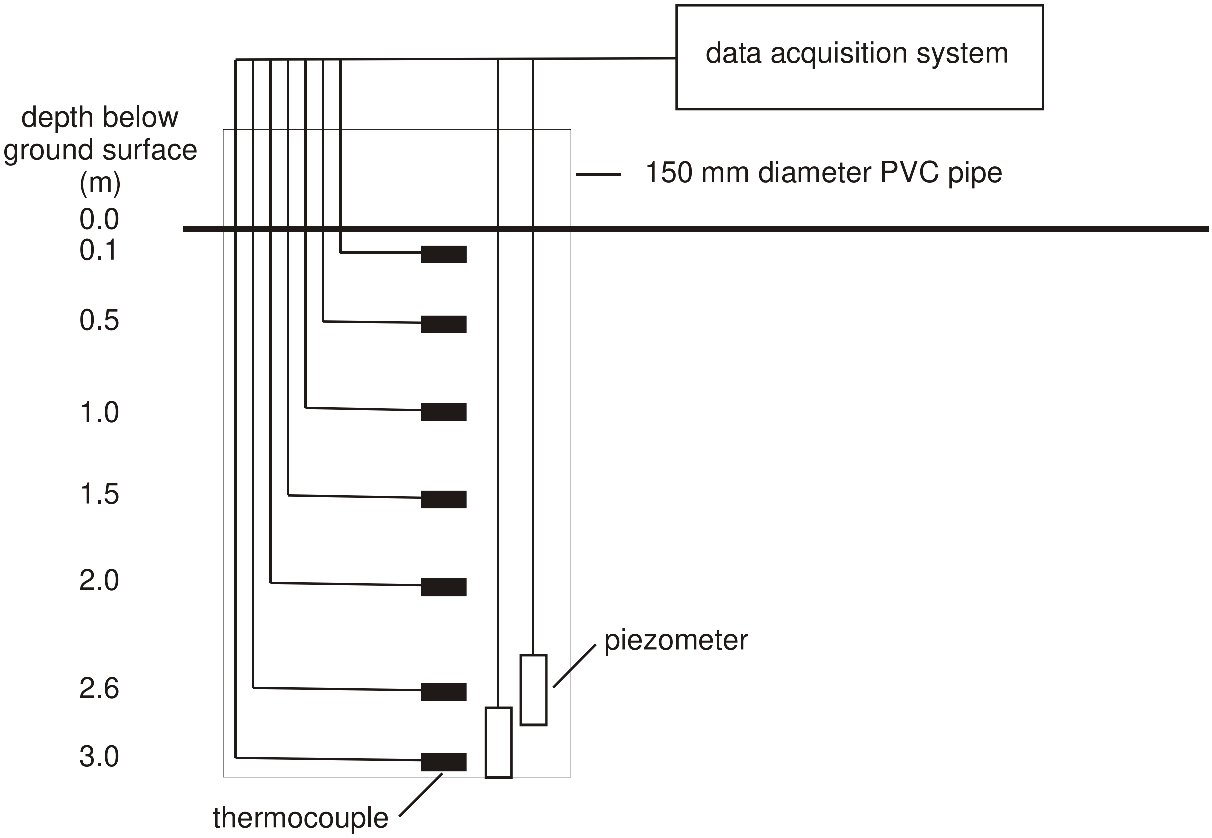

Figure 11. Example thermocouple and piezometer installation (Pipe 1 – upstream of geocomposite barrier).

FIELD PERFORMANCE

Temperature-time records from thermocouples placed in one of the instrumentation pipes immediately upstream of the barrier are shown in Figure 12. The gap in the records is due to severing of the cables by wildlife at the site in early 2002. The cables were repaired the following summer. Based on the data available, the ground temperatures at a given depth are lower in the winter of 2004-05 than the preceding winters. For monitoring points below a 2 m depth, temperatures are persistently below freezing based on the data available. This point is explored further by plotting temperature profiles from the same installation corresponding to the time of barrier installation and at selected times during the summers of 2003, 2004, and 2005 (Figure 13). The data show that freeze-back has occurred to an elevation well above the base of the original trench. The piezometers located close to the base of the barrier were frozen and hence measurement of the groundwater table behind the barrier was not recorded.

Data from the year 2000 TPH sampling program described earlier in the paper are plotted in Figure 14 together with data gathered in the summer of 2004. The data points are for samples recovered downstream of the barrier system only. As in the initial program, the test pits used to retrieve soil samples in the summer of 2004 were put down at opportunistic locations dictated by the distribution of large boulders at and below the ground surface. The data, although subject to the expected variability, shows that the highest TPH concentrations are at a depth that likely corresponds to the location of the undisturbed permafrost level. This supports the notion that subsurface hydrocarbon migration was bounded by the permafrost table at the site. It appears that the general trend of increasing mean TPH levels with depth is preserved for both data sets. However, statistical analysis of the mean TPH concentrations indicates that the levels in 2004 are about 50% of the values determined prior to the installation of the barrier system. This decrease is probably due to a combination of volatilization, natural attenuation, and dispersal; it does, however, indicate that at least in the short term, the source has been effectively isolated.

Taken together, measured TPH values, temperature profiles, and observations made during excavation of sample coupons upstream of the barrier system suggest that the geocomposite liner system is functioning as a barrier to downstream hydrocarbon migration as originally intended.

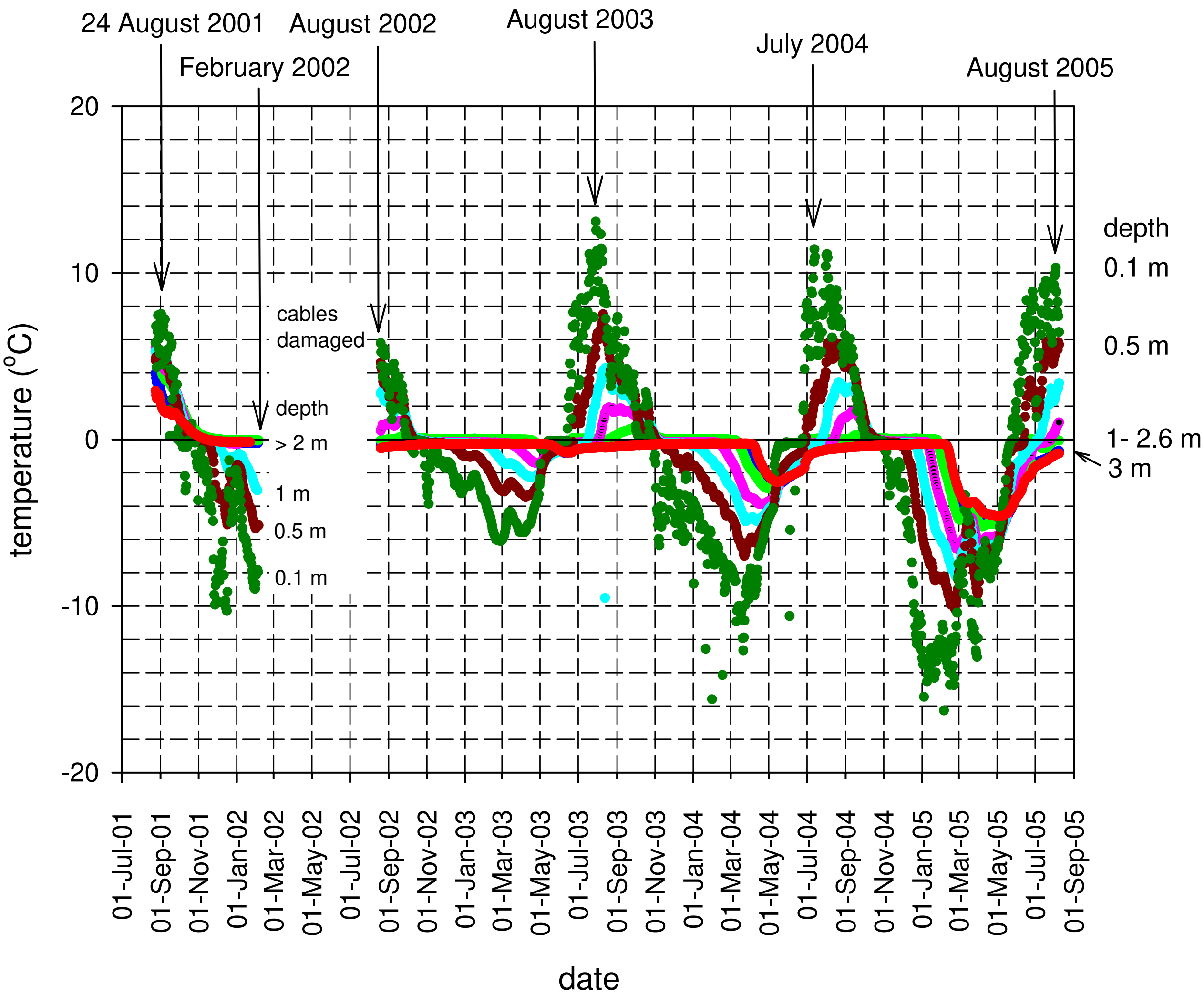

Figure 12. Example temperature-time histories from thermocouples located in Pipe 1 (upstream of barrier).

DURABILITY OF LINER MATERIALS

General

In order to assess how long the "temporary" liner might provide an adequate barrier in the extreme conditions of Brevoort Island, a program of laboratory studies combined with periodic retrieval and examination of samples of liner materials from the field was initiated. This part of the project study is currently ongoing with particular attention directed at the effects of:

(a) interaction of jet fuel with both the geomembrane and GCL;
(b) freeze-thaw on the long-term performance of the GCL; and
(c) influence of frozen and unfrozen conditions on the permeation of unsaturated GCL by jet fuel (Rowe et al. 2005).

Since jet fuel is an organic immiscible liquid, the laboratory program to quantify GCL performance was designed to investigate the effect of:

1) the water-jet fuel interface in the soil pores;
2) the interaction between jet fuel and the bentonite double layer; and
3) changes in pore structure of bentonite due to freeze-thaw and permeation by jet fuel. These objectives influence the choice of test method adopted.

Finally, two different HDPE geomembranes (a typical untreated and a specially fluorinated geomembrane) were exposed to jet fuel and the effect on both the tensile properties and the Oxidation Induction Time (OIT) were assessed with respect to immersion time.

At the time of barrier construction a series of wooden frames supporting coupons (samples) of geosynthetic barrier materials were buried in the backfill immediately upstream of the barrier system (Li et al. 2002a,b). Coupons have been retrieved one year and three years after construction and returned to the laboratory to quantify any changes in mechanical or chemical properties with respect to a matching set of archival specimens. These tests are ongoing and only preliminary results are presented below.

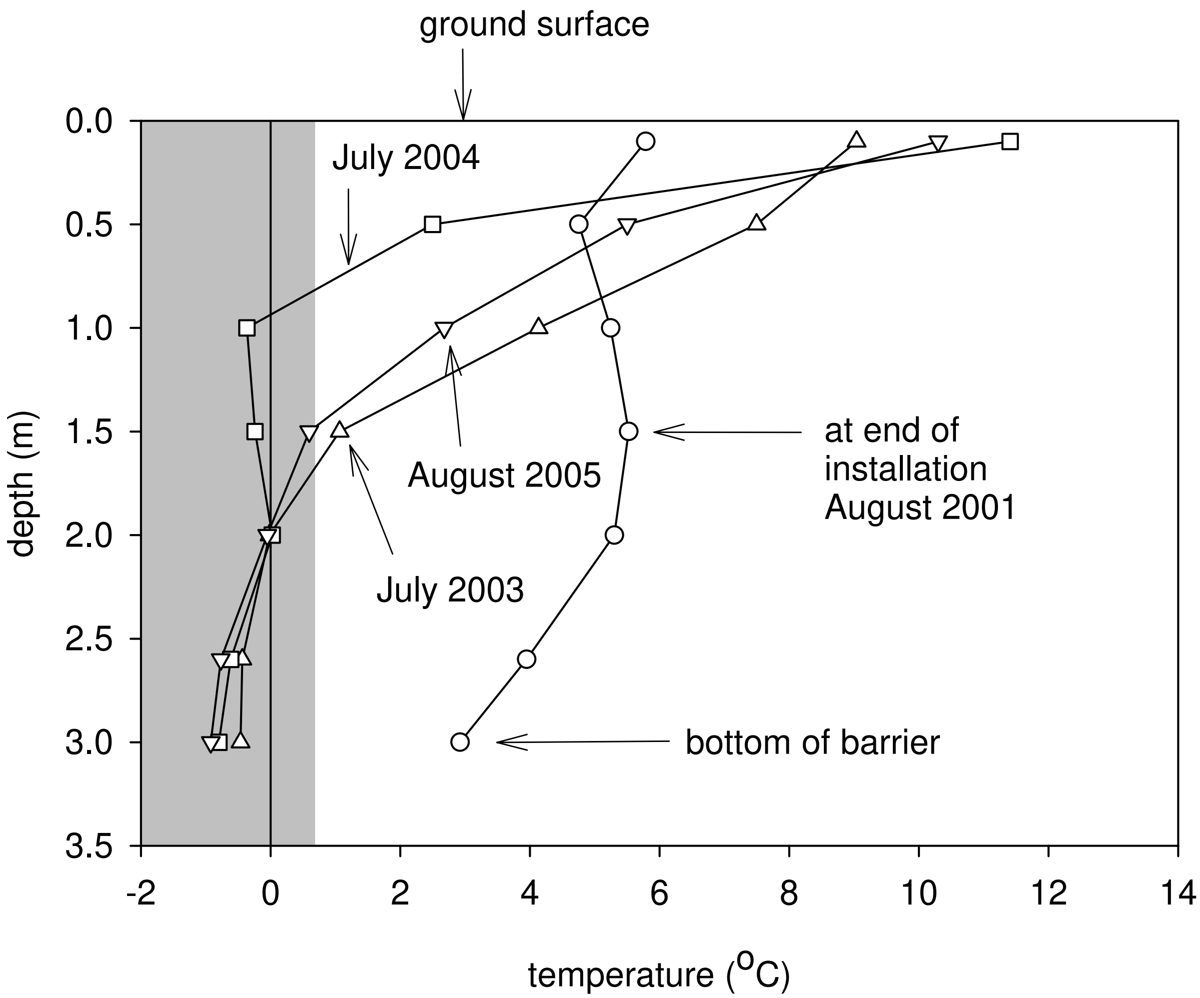

Figure 13. Temperature profiles at location of barrier system corresponding to times of maximum recorded surface temperature.

Results from Laboratory Testing of Retrieved Specimens

Geosynthetic clay liner material

Rigid wall permeameter (RWP) and flexible wall permeameter (FWP) tests have been carried out on buried specimens of the same GCL used in the subsurface barrier at the Brevoort site, one and three years after installation. There was no evidence of uptake by jet fuel from the field-retrieved specimens. The experimental methodology has been described by Rowe et al. (2005). The specimens were initially hydrated (from the bottom) for 5 days under a confining pressure of about 14 kPa at an hydraulic gradient of 20. Following hydration, the specimens were permeated with de-aired water and then jet fuel. These reference tests were carried out at a temperature of 20°C.

- At the end of water permeation, the retrieved GCL specimens had an average mass per unit area of 4460 g/m^2, 4770 g/m^2 and 4720 g/m^2 after 0, 1 and 3 years of field exposure, respectively. It appears that water saturation capacity of the buried specimens has stabilized after 1 year of exposure.

- The hydraulic conductivity, with respect to water for archival specimens, was 2.0 x 10^{-11} m/s and 3.3 x 10^{-11} m/s using RWP and FWP methods of test, respectively. Both RWP and FWP tests gave reduced values of hydraulic conductivity with respect to water of 0.7 x 10-11 m/s (RWP) and 2.0 x 10-11 m/s (FWP) for specimens retrieved from the site after 3 years. Hence, the influence of site exposure after 3 years on hydraulic conductivity of the GCL using a common reference test is detectable, but negligible from a performance point of view.

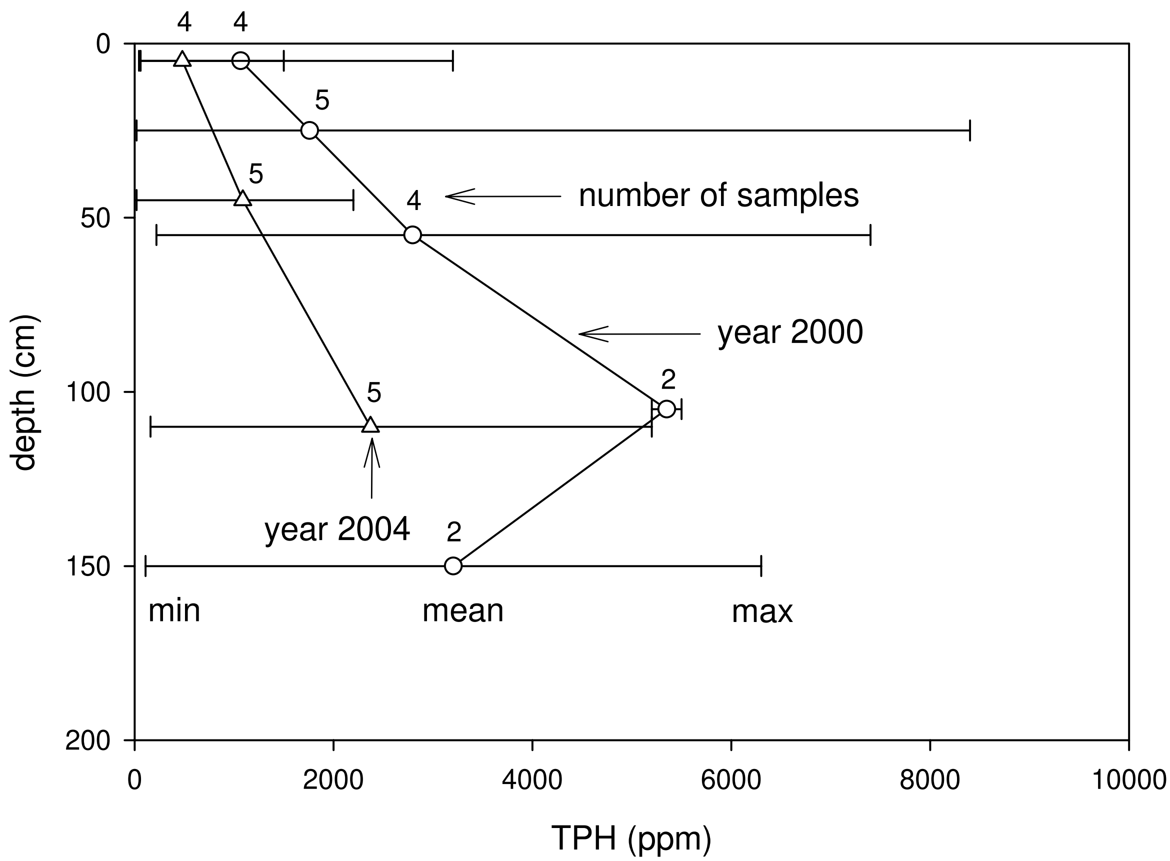

Figure 14. TPH measurements taken downstream of the barrier system before and after installation

Geomembrane materials

Conventional tensile tests carried out in accordance with ASTM D6693 and a displacement rate of 50 mm/min have been performed on archived and exhumed specimens of the 1.5 mm-thick fluorinated geomembrane material used at the Brevoort site. Tensile strengths at break and yield together with corresponding strain values are reproduced in Figure 15. Based on the data available there is no indication of a systematic and significant change in the index tensile properties of the f-HDPE geomembrane since installation.

Oxidation Induction Time (OIT) tests were carried out on specimens as a good indicator of the amount of antioxidant present in the geomembrane. This test is useful for comparing the relative oxidative resistance of geomembranes and extremely useful for monitoring the depletion of antioxidants in the geomembrane. Standard OIT tests were conducted using a differential scanning calorimeter (DSC) (ASTM D3895).

Percent crystallinity for specimens of f-HDPE geomembrane was also obtained in the laboratory. A decrease in polymer crystallinity is typically associated with decreasing mechanical stiffness and chemical resistance. No significant changes were noted in measurements made for multi-year specimens.

Based on the observations noted above, it appears that the mechanical and chemical properties of buried fluorinated HDPE geomembrane materials have not changed significantly since installation. The stable performance of f-HDPE samples exhumed 3 years after burial at the BAF-3 site is in sharp contrast to the results of accelerated testing described below. This highlights the need for accelerated testing in order to estimate life-time performance of the geosynthetics materials used at the Brevoort site.

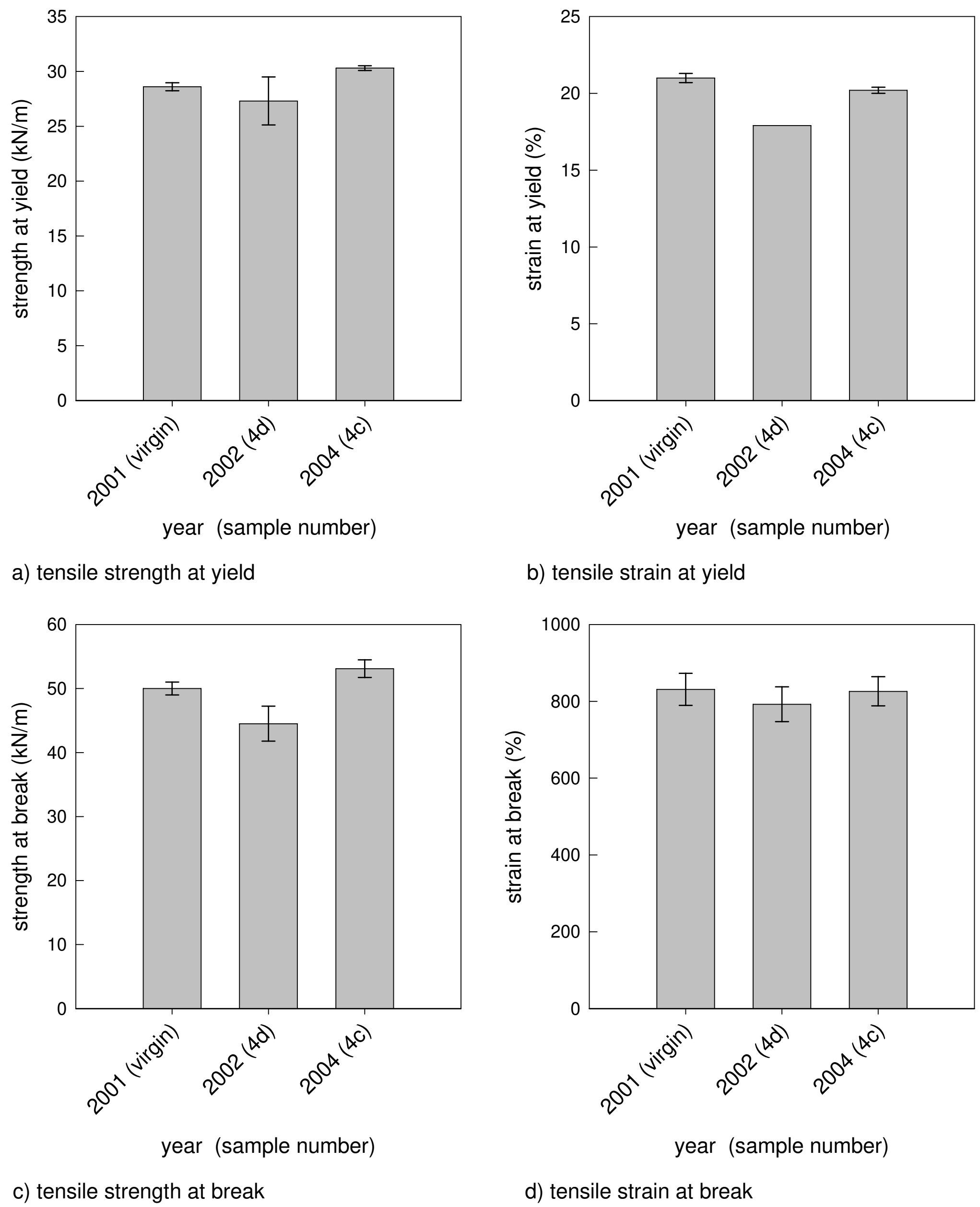

Figure 15. Mechanical load-strain properties of virgin and exhumed 1.5 mm-thick fluorinated HDPE geomembrane samples. Notes: 5 specimens per sample; error bars represent ±1 standard deviation.

Results from Accelerated Laboratory Testing

Geosynthetic clay liner material

The results of accelerated freeze and thaw tests using rigid wall permeameter (RWP) and flexible wall permeameter (FWP) tests have also been carried out on specimens of the GCL used at the Brevoort site. These test results have been reported by Rowe et al. (2005). For both laboratory test procedures, the samples were hydrated under low confining pressure as described for the field specimens, subjected to 0, 5 or 12 freeze and thaw cycles and then permeated with de-aired water and then jet fuel. To provide insight into the behavior of unsaturated GCLs permeated with jet fuel, GCLs hydrated to different water contents were permeated with jet fuel at four temperatures: 20, 5, -5 and -20°C. Additional tests were run where the specimens were first permeated with jet fuel at +5°C, after which the temperature was reduced to -5°C and permeated again with jet fuel.

The following conclusions for the tests completed to date on the GCL specimens (Rowe et al. 2005) are:

- The hydraulic conductivity with respect to water was between 2.0×10^{-11} (RWP) and 3.3×10^{-11} m/s (FWP) at 14 kPa before freeze-thaw, and 2.0×10^{-11} (RWP) and 3.0×10^{-11} m/s (FWP) at 14 kPa after freeze-thaw. Hence, in the presence of water only, freeze-thaw cycles did not influence the hydraulic conductivity of the GCL.

- The long-term hydraulic conductivity of the GCL after the freeze-thaw cycles, with respect to jet fuel, was about 4 times greater than that for water, but was still very low. The intrinsic permeability of specimens permeated with water and then jet fuel was 6.9×10^{-18} m^2 and 2.8×10^{-17} m^2 for the water and jet fuel stages (RWP), respectively. Here, intrinsic permeability is calculated as $k=\eta/\gamma$ where k is the hydraulic conductivity of the permeant, η is dynamic viscosity at 20°C, and γ is unit weight.

- GCLs with a low saturation degree did not perform as well as a hydraulic barrier against jet fuel as specimens with higher degrees of saturation either above or below 0^{o}C (see Table 1).

- At sub-zero temperatures, the intrinsic permeability of the unsaturated GCLs dropped, with a greater effect at -20^{o}C than at -5^{o}C, suggesting that there is some difference in the effect of temperature even for sub-zero temperatures (Rowe et al. 2005). However, if the GCL was permeated with jet fuel prior to freezing, freezing had very little effect on the intrinsic permeability.

Table 1: Hydraulic conductivity of GCLs permeated with Jet Fuel A-1 (adapted from Rowe et al. 2005)

Unfrozen			Frozen		
Degree of saturation	Gravimetric water content, w_c (%)	Hydraulic conductivity, k (m/s)	Degree of saturation	Gravimetric water content, w_c (%)	Hydraulic conductivity, k (m/s)
$S_r \cong 0$	$\cong 8$	2×10^{-6}	$S_r \cong 0$	$\cong 8$	2×10^{-6} (constant head apparatus)
$S_r \leq 0.70$	60-80	$> 10^{-8}$	$S_r \leq 0.60$	60	Samples experienced sidewall leakage
$S_r \geq 0.77$	80	$\leq 3 \times 10^{-10}$	$0.70 < S_r < 0.85$	90	1.8×10^{-11} to 2.5×10^{-10}
$S_r \cong 1$	120	3.4×10^{-11}	$S_r \geq 0.85$	$\geq 110\%$	$\leq 10^{-12}$

Note: w_c = mass of water/mass of dry solids

Geomembrane materials

Untreated and fluorinated geomembrane specimens were immersed in jet fuel and the tensile load-extension curves examined at intervals using conventional tensile tests in accordance with ASTM D6693 and a displacement rate of 50 mm/min. Oxidation Induction Time (OIT) tests were also carried out on specimens of untreated and fluorinated HDPE specimens.

The following conclusions for the tests completed to date on the untreated and fluorinated geomembrane specimens (Rowe et al. 2005) are:

- The tensile test results indicated that within the first ten weeks of immersion in jet fuel, there is a statistically significant effect on the yield stress and strain of the HDPE geomembranes. The amount of stress required to cause yield decreased, and the yield strain increased corresponding to a general decrease in the axial stiffness of both fluorinated and untreated geomembranes. Both samples lost about 20% of their strength during the ten weeks of exposure. In the field case study that is the focus of this paper, the geomembrane is not under tensile load and consequently a loss in mechanical tensile stiffness or strength of 20% would not be a concern.

- Immersion in jet fuel accelerates the antioxidant depletion rate relative to that observed in water or municipal solid waste (MSW) leachate by Sangam and Rowe (2002). Fluorination of the HDPE geomembrane provided a significant beneficial effect and the antioxidants depleted at a much higher rate (2.6 times faster) for the untreated geomembrane than for the fluorinated geomembrane. The total antioxidant depletion time was estimated to be 2.3 and 6.1 years for untreated and fluorinated geomembranes, respectively, at 23^{o}C and is expected to be much longer at field temperatures in the Arctic.

However, it must be noted that immersion of geomembrane specimens in pure jet fuel is a much more aggressive environment than the field condition where the presence of neat jet fuel was not encountered during any of the field season subsurface investigations. The reader is directed to the paper by Rowe et al. (2005) for a detailed description of the experimental program and results described here.

Implications of preliminary laboratory test results

Based on the results of laboratory tests on the barrier materials completed to date, it appears that the GCL used in the geocomposite liner at Brevoort Island can be expected to perform well as a hydraulic barrier in the short to medium term (at least up to 4 years and potentially much longer) with respect to the effect of both freeze-thaw and permeation with jet fuel. The results also demonstrate the beneficial effect of fluorination of HDPE geomembrane used at the site. The service life of the geomembrane is expected to be considerably greater than 6 years.

CONCLUSIONS

A composite geosynthetic containment barrier wall to control migration of a hydrocarbon contaminant plume at a sub-Arctic site has been successfully constructed despite a very short lead time, a lack of geotechnical data and difficult site conditions.

Field data for subsurface temperature and groundwater conditions and downstream TPH measurements taken three years after the original installation indicate that the barrier system is performing as intended.

A monitoring and sample retrieval program has also been described that is integrated with a long-term laboratory investigation of the in-isolation and synergistic effects of fuel oil hydrocarbons, low-temperature, and freeze-thaw cycles on GCL and geomembrane materials. Preliminary laboratory results suggest that both the geomembrane and geosynthetic clay liner used as the dual liner system at the site can be expected to prevent migration of hydrocarbons due to advection and diffusion mechanisms for many years beyond the original 3-year design life of the original installation.

The techniques and lessons learned to date suggest that the barrier system technology employed at the BAF-3 site can be used to minimize subsurface hydrocarbon contaminant migration in the Arctic. Furthermore, many of the lessons learned in this project can be used to assist in making future decisions regarding the use of composite liner systems for containment of hydrocarbon plumes and at more southerly sites.

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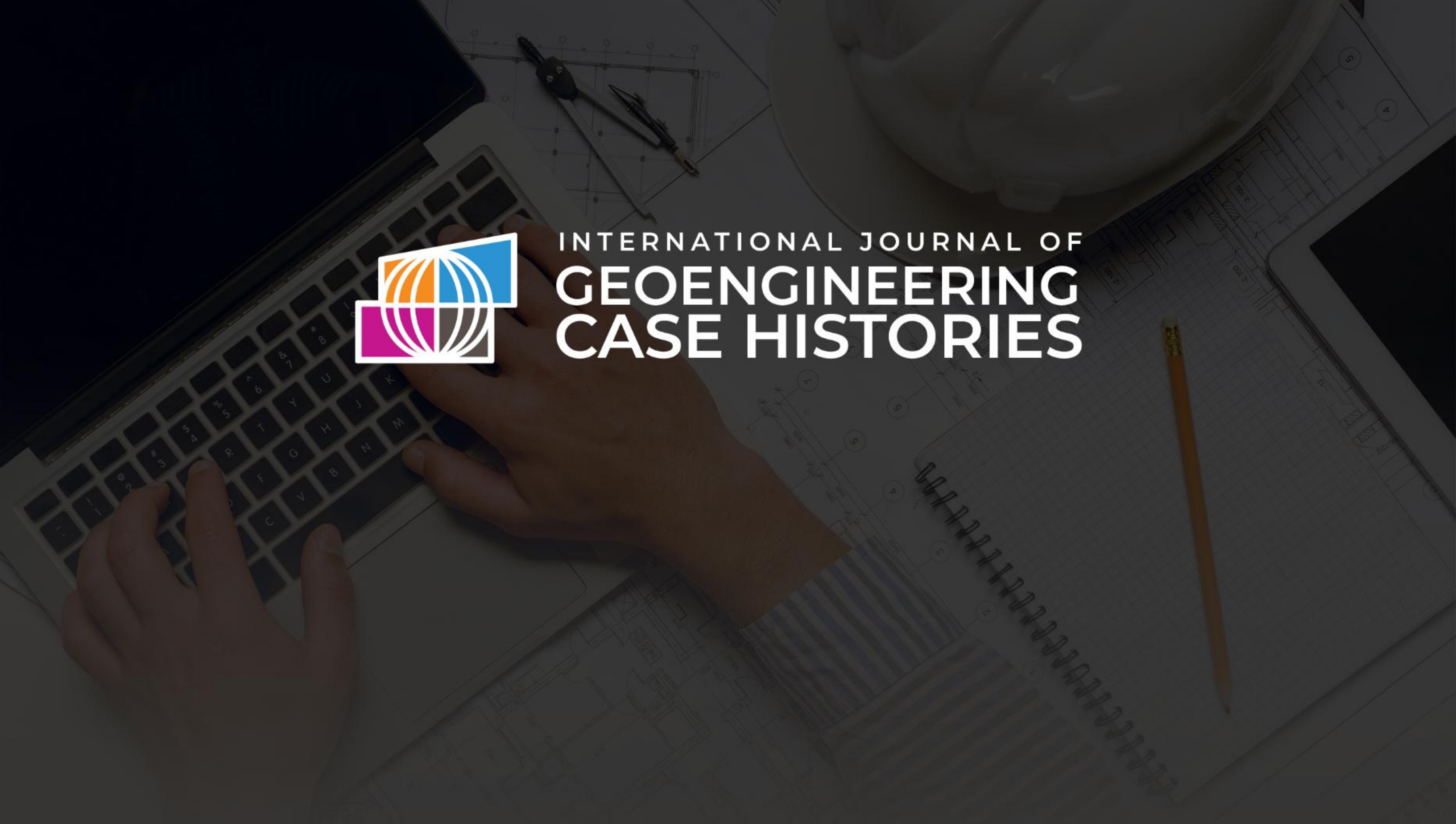
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