Exhibit 101

Jerry
Please note that there
are several pages
within this page
that are illegible
- original is too
light
#23-42 shown

BURLINGTON LANDFILL EXPANSION
REVIEW OF HYDROGEOLOGICAL STUDY

Prepared For
Environmental Assessment Board

1984-05-30

Monenco Ontario Ltd.

MONENCO ONTARIO LIMITED

COLONIA PLACE
2 St. Clair Avenue E., Toronto, Ontario M4T 2T5
Tel.: (416) 961-459[illegible]
Telex: 06-22613
Cables: Monencon

1984-05-30

Environmental Assessment Board
1 St. Clair Ave. W.
5th Floor
Toronto, Ontario
M4V 1K7

Attention: Mr. H. Browne, P.Eng.
Chief Executive Officer

Dear Sir:

Re: Burlington Landfill Expansion
Review of Hydrogeological Study

We are pleased to present Mr. Ridley's review of the hydrogeological aspects of the Burlington Landfill Expansion. The review has designated areas of concern and demonstrated, using illustrative calculations, the potential impact of the proposed expansion on the ground and surface water. Pertinent terms and conditions concerning the proposed expansion were also discussed. It is felt that the proposal can be carried out without creating unreasonable environmental risks provided that certain conditions are fully addressed.

The writer will appear as a witness at the Hearing before the Environmental Assessment Board on the basis of this review.

Yours truly,

Kevin J. D. Ridley

Kevin J.D. Ridley
Hydrogeologist

KJDR/lmm

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

how is the next section, S.13, related to your concerns expressed in SS.3 to 12 ?

1.0 INTRODUCTION

On May 2, 1984 a Monenco hydrogeologist, Mr. Kevin J.D. Ridley, was appointed by the Environmental Assessment Board for Ontario as its "expert witness in hydrogeology and related fields pursuant to Section 18 (9) of the Environmental Assessment Act in respect to the Hearing concerning the Burlington Landfill Expansion". Details describing the duties associated with this appointment are outlined in Appendix A. Briefly, Mr. Ridley is directed by the Board "to investigate the hydrogeology and related matters involved for the proposed Burlington Landfill Expansion", the bulk of which is contained in Volume 2 of the M.M. Dillon Ltd. report entitled "Burlington Landfill Site: Application for Continued Use" as prepared by Gartner Lee Associates Limited (GLAL). A written report of Mr. Ridley's findings and conclusions will be submitted to the Board. Mr. Ridley, in his capacity as a Board witness is also expected "to render guidance and advice to the Canadian Environmental Law Association which represents West Burlington Citizens' group".

The main review focussed on Volume 2. However, Volumes 1 and 3 of the above report as well as previous reports concerning the hydrogeologic aspects of the Burlington Landfill Site, the Bayview Landfill Site and the National Sewer Pipe property were also reviewed.

2.0 GEOLOGIC SETTING

Mr. Ridley concedes the interpretation of the regional and site geology as presented by GLAL in Volume 2 (1984).

what is your concern with the

3.0 HYDROGEOLOGIC SETTING ?

Mr. Ridley is in general agreement with the definition and flow directions of the "water table" and "bedrock" groundwater regimes as they are presented. However, it is felt that there is probably a more pronounced flow component toward the Indian Creek Watershed in the water table regime (Figure 0.13) and a definite flow component toward the Indian Creek Watershed beneath the East Ditch where none is depicted by GLAL in Figure 0.16. Both of these flow components are important because at present there is no toe drain system in this area. It is also felt that although the main flow component is southeasterly, more emphasis should be directed towards the "lesser" flow components toward Falcon Creek and Indian Creek.

There is also general agreement that the area is a groundwater recharge zone as indicated by the vertically downward gradients. However, there is no mention of a groundwater discharge zone on or off the site as indicated by other workers at the adjacent Bayview site. Mr. Ridley feels that after reading the GLAL report (1984) they are assuming that all groundwater discharge from the Burlington site occurs in Lake Ontario.

No quantitative estimation of groundwater flow in the shale in the vicinity of the site was presented in the GLAL report (1984). The quantity of groundwater movement is defined by $Q = KiA$

where Q = groundwater discharge, L^3/T
K = hydraulic conductivity, L/T
i = hydraulic gradient, L/L
A = cross sectional area of flow, L^2

For illustrative purposes a simple calculation can be made to quantify groundwater movement in the vicinity of the site using the following assumptions:

- The average hydraulic conductivity for the shale is 5×10^{-8} m/s (pg. 0-149, GLAL, 1984)

- The average lateral hydraulic gradient is 0.045 (pg. 0-150, GLAL, 1984)

- The reach at the downgradient toe of the landfill is about 350 m (Fig. 0-1, GLAL, 1984)

- The gradients are downward in the shallow regions of the continued use area but "gradually flatten to become more lateral at depths of possibly 20 to 30 m" (pg. 0-32, GLAL, 1984). If it is assumed that the till averages about 10 m thick in this area (pg. 0-119, Fig. 0.8, GLAL, 1984) then the lateral transition occurs between a depth of 10 to 20 m in the shale. Assume a transition depth of 10 m into the shale that is uniform over the whole site and that the saturated thickness of active lateral groundwater flow in the shale is 20 m, (ie. 30 m below the top of the shale). This is verified by GLAL work at Bayview for M.M. Dillon (1982) where the hydraulic conductivity of the shale at a depth of around 30 m was about 1×10^{-9} m/s (pg. 57, Acres, 1982).

Therefore,

$$Q = 5 \times 10^{-8} \text{ m/s} \times 0.045 \frac{\text{m}}{\text{m}} \times 350 \text{ m} \times 20 \text{ m} \times 86400 \frac{\text{s}}{\text{d}} \times 365 \frac{\text{d}}{\text{a}}$$

$$= 496.7 \text{ m}^3/\text{a}$$

$$= 500{,}000 \text{ L/a}$$

Given the above assumptions, about 500,000 L of groundwater per annum flows laterally in a southeasterly direction through an assumed cross sectional area in the shale about 10 m below the top of the shale.

To conclude the general discussion on the hydrogeologic setting, the velocity of groundwater movement in the shale and the breakthrough time of leachate through a 1.5 m thick till layer can be re-analyzed using acceptable alternative methods. These analyses demonstrate the potential for different impact scenarios on the hydrogeologic regime at and off the site that were not discussed by GLAL in Volume 2. They will be discussed in detail later.

your next area of concern is with 4.0 LEACHATE CHEMISTRY, what is your concern?

It has been agreed by all parties that the leachate that was collected from the toe drain collection system is dilute. However, quantification of the amount of dilution cannot be determined and estimates of the amount of dilution cannot be agreed upon. The reasons that the leachate is dilute are:

why do you say the leachate collected from the toe drain is dilute?

- (1) sampling was performed during periods of potential water surplus — why ~~did~~ does this make for a dilute leachate?
- (2) unknown volumes of groundwater have infiltrated into the collection system from outside the fill area
- (3) it is suspected that the retro-fitted toe drain is only collecting leachate from a small portion of the original site and that the underdrain system from the 1980 expansion is collecting 90% of a diluted leachate due to the relative youth of the expansion.

i.e. toe drain

why?

Monitors 8A and 11A both have a standpipe in the refuse and a piezometer beneath the refuse in the shale. It has been indicated on page 0-42 that "extensive chemical analysis has been carried out on samples of the leachate collected from these monitors", i.e., 11 analyses total from all 4 instruments installed in these 2 monitors.

Pages 0-164 to 0-167 inclusive show the analyses for these monitors. It is felt that these samples of "leachate" have also been diluted and never achieved equilibrium over the very short duration that they were sampled (8A - Oct. 1980 to April 1981; 11A - Oct. 1980 to Nov. 1981). These holes were augered open hole through the refuse and then triconed with City water through the augers. Drilling water has leaked from the auger stand, infiltrated the refuse and the shale and caused dilution of the leachate. Judging from the range of dates all recorded sampling of these monitors were performed prior to GLAL field personnel improving their bailing and sampling techniques. However, dilution with drilling water and poor bailing practice would only account for dilute readings in the initial stages since the refuse is possibly more permeable than the upper shale. In the longer term of these monitors' very short chemical sampling program the leachate in three of them appears to be improving in quality (8A-II, 11A-I, 11A-II). This implies that the seals emplaced to isolate each sampling zone were defective permitting surface water to seep into each hole and dilute the leachate sample. The sample program for piezometer 8A-I appears to have been prematurely cut short as the chemical data implies an apparent increasing concentration trend with time.

why?

Table 4.1 shows ranges of variations in leachate concentrations (Pohland, 1980).

what is range for chlorides?

Mr. Leech gave evidence that he felt the leachate concentration was low and that if he had to assume a Cl concentration given no chemical data at all, he would choose a value in the range of 1500 to 2000 mg/L. This value falls at the low end of the range given in Table 4.1. However, leachate chemistry varies from site to site as well as temporally and spatially within each site.

TABLE 4.1 RANGES OF VARIATION IN LEACHATE CHARACTERISTICS

Leachate Parameter	Reported Range of Analysis
pH	<5 - >8
Total Alkalinity, mg/l as $CaCO_3$	0 - >10,000
Chemical Oxygen Demand (C)D), mg/l	<100 - >100,000
Biochemical Oxygen Demand (BOD_5), mg/l	<10 - >100,000
Total Organic Carbon (TOC), mg/l	<100 - >25,000
Total Volatile Acids (TVA), mg/l as Ch_3COOH	<10 - >10,000
Organic Nitrogen, mg/l N	<1 - >1,000
Ammonia Nitrogen, mg/l N	<1 - >1,000
Nitrite-Nitrate Nitrogen, mg/l N	<1 - >100
Total Phosphorus, mg/l P	<1 - >100
O-Phosphate, mg/l P	<1 - >50
Specific Conductance, µmho/cm	<1,000 - >15,000
Oxidation Reduction Potential (ORP), mv	<-200 - >+100
Total Solids, mg/l	<1,000 - >50,000
Total Dissolved Solids, mg/l	<1,000 - >50,000
Total Hardness, mg/l as $CaCO_3$	<50 - >20,000
Chloride, mg/l	<100 - >10,000
Sulfate, mg/l	<10 - >1,000
Calcium, mg/l	<100 - >5,000
Magnesium, mg/l	<20 - >15,000
Sodium, mg/l	<50 - >5,000
Potassium, mg/l	<50 - >3,000
Iron, mg/l	<1 - >2,000
Zinc, mg/l	<1 - >300
Copper, mg/l	<1 - >10
Cadmium, mg/l	<1 - >10
Lead, mg/l	<1 - >2
Nickel, mg/l	<1 - >2
Chromium, mg/l	<1 - >2

Source: Pohland, 1980

Monitoring station 8 was drilled on January 24, 1979 and equipped with one piezometer and one standpipe. Figure 4.1 shows the GLAL log for this hole. These instruments were destroyed or buried on February 6, 1980. In the interim both of these instruments were sampled for chemical analysis. Tables 4.2 and 4.3, both compiled by GLAL, respectively show the results of the analyses for the standpipe and the piezometer. The standpipe which is located in the refuse shows a Cl concentration on May 2, 1979 of 1,190 mg/L. Just over one month later on June 4, 1979 the Cl concentration had increased to 13,000 mg/L. This instrument was destroyed or buried about 8 months later but there is no record of any more sampling for chemical analysis. Both the standpipe and the piezometer in monitor 8 show increasing Cl concentration trends implying that concentrations may have increased even more. Moreover, both of these Cl concentrations exceed the present leachate Cl concentrations reported by GLAL in Volume 2 and Mr. Leech's assumed Cl concentrations. For unknown reasons monitor 8 was never again sampled for chemistry purposes over the 8 months prior to its destruction.

Another interesting observation about monitor 8 was that the June 4, 1979 sampling date occurred during a period of "potential water deficit". This is the only sampling event for chemical analysis of leachate that has occurred during a potential water deficit period.

Can you estimate how much the leachate from the toe drain may have been diluted?

A very rough estimate of the dilution of the leachate as sampled from the toe drain collection system can be determined. This is achieved by using the concentrations of Cl and BOD in monitor 8 and comparing them to their April and November, 1983 concentration counterparts (pg. 0-195, GLAL, 1984). Table 4.4 displays these data. The leachate concentrations of Cl and BOD range from 17 to 120 and 12 to 44 times respectively more concentrated than in the toe drain samples. Moreover, the Cl ratios are conservative because if the increasing concentration trend continued in monitor 8 the ratios would be even greater.

FIGURE 4.1

SOURCE: M.M. DILLON, 1979

BOREHOLE NO. 8

PROJECT NAME BURLINGTON LANDFILL SITE — PROJECT NO. 78-92

CLIENT M.M. DILLON LIMITED — DATE JANUARY 24, 1979

BOREHOLE TYPE BOMBADIER, 0.1 m I.D. HOLLOW STEM AUGERS NX ROCK CORE — GEOLOGIST A.B.

ELEVATION 152.8 m — TECHNOLOGIST

DEPTH (m)	STRATIGRAPHY	DESCRIPTION	SAMPLE TYPE	SAMPLE BLOW/0.3 m	SAMPLE M/C	SAMPLE % RECOVERY	GROUND WATER	REMARKS
0.0		GARBAGE: Alternate layers of garbage and earth fill, moist						
12.5		SHALE: Red, with green beds and green mottling, cryptocrystalline, medium bedded shale, soft, gypsum filled nodules throughout weathered to 13.7 m	NX			100	▲	
			NX			100		
		- 8 -	NX			100		
18.3		Borehole terminated at 18.3 m in shale					⊙	

TABLE 4.2 # WATER ANALYSIS RESULTS

SOURCE: M.M. DILLON, 1979

LOCATION BOREHOLE 8, STANDPIPE 11 REMARKS

PROPERTY \ DATE		May 2, 1979	June 4, 1979									
CONDUCTIVITY μMHOS/CM.		13,850	15,600									
pH		5.5	5.7									
HARDNESS (Ca CO_3)		8,000	10,100									
ALKALINITY (Ca CO_3)		6,890										
CHLORIDES (Cl)		1,190	~~13,000~~ 1,300									
SULPHATES (SO_4)			750									
PHOSPHOROUS AS P	Total											
	Soluble											
NITROGEN (N)	Total Kjeldahl		720									
	Free Ammonia											
	Nitrite											
	Nitrate											
METALS	Potassium (K)		570									
	Magnesium (Mg)											
	Calcium (Ca)											
	Sodium (Na)		930									
	Iron (Fe)	800	970									
B.O.D.			26,000									

NOTE: concentrations in p.p.m. unless otherwise noted.

Gartner Lee Associates Limited

PROJECT 78-92

TABLE 4.3 WATER ANALYSIS RESULTS

TABLE 2 SHEET 2

SOURCE: M.M. DILLON, 1979

LOCATION BOREHOLE 8, PIEZOMETER 1

REMARKS

PROPERTY \ DATE		Apr. 4, 1979	June 4, 1979							
CONDUCTIVITY μMHOS/CM.		5,600	20,000							
pH		6.8	7.0							
HARDNESS ($CaCO_3$)		1,450	3,866							
ALKALINITY ($CaCO_3$)		597								
CHLORIDES (Cl)		2,070	7,760							
SULPHATES (SO_4)		360	420							
PHOSPHOROUS AS P	Total									
	Soluble									
NITROGEN (N)	Total Kjeldahl	70	30							
	Free Ammonia									
	Nitrite									
	Nitrate									
METALS	Potassium (K)		720							
	Magnesium (Mg)									
	Calcium (Ca)									
	Sodium (Na)	740	3,200							
	Iron (Fe)	19								
PHENOLS (ppb)		730								
B.O.D.		560	480							

NOTE: concentrations in p.p.m. unless otherwise noted.

NOTE: concentrations in p.p.m. unless otherwise noted.

Gartner Lee Associates Limited

Gartner Lee Associates Limited

TABLE 4.4

Estimated Dilution Ratios

	Monitor 8-II	Toe Drain				
	June 1979	April 1983		Nov. 1983		Range of *Dilution Ratios
		Cl	BOD	Cl	BOD	
Cl	13000	108	-	762	-	17 to 120
BOD	26000	-	2260	-	594	12 to 44

All concentrations in mg/L.

*Dilution Ratio is a relative indication of a constituent's concentration in leachate from 8-II as compared to leachate from the toe drain collection system.

If the leachate from the toe drain collection system is as dilute as indicated by the above then organics that were found in various monitors downgradient of the landfill would not be detected in the toe drain samples because of the extent of dilution, i.e., the leachate in the toe drain was so dilute that the concentration of these organics were below the detection limit of the analytical equipment used.

It is imperative that leachate from the refuse be sampled for analysis from instruments located within the refuse.

Mr. Leech also stated in evidence that GLAL has sampled leachate springs from other sites. If this is common practice then why has it not been conducted at this site?

To briefly summarize this section, it is felt that the composition of the leachate is an extremely important parameter and it must be accurately determined. Mr. Ridley is not convinced that this has been achieved. It is his concern and to the benefit of all parties that the leachate chemistry be accurately determined in order to evaluate the present impact of the landfill site and the potential future impact of the proposed expansion on the hydrogeologic regime.

now, Mr. Ridley, turning to

5.0 GROUNDWATER CHEMISTRY, what is your concern here?

Accurate determination of the background groundwater chemistry at the site, as is the case for the leachate, is paramount and necessary for the delineation of the existing plume and the extent to which the area groundwater is contaminated. It is felt that the background groundwater chemistry in the shale at the site is not known. It is also felt by all parties that groundwater quality

deteriorates with depth. However, the extent of the deterioration is not known and cannot be quantified until the background groundwater chemistry has been determined.

have you reviewed the comments?

Upon observation of the "Groundwater Analysis Results" contained in Appendix O-3, (GLAL, 1984), it is evident that there is substantial variation in the data base within individual instruments (for example COD and Fe, Nov. 1983, 14-II, pg. O-177 and 17-II, pg. O-185). These variations could be a result of:

- seasonal fluctuations
- poor bailing and sampling practice
- surface water contamination

A condition of electroneutrality must exist for electrolyte solutions. Groundwater is an electrolyte solution. Electroneutrality means that the sum of the positive ionic charges is equal to the sum of the negative ionic charges. The charge-balance equation is expressed as:

$$\sum ZM_c = \sum ZM_a$$

where

Z = ionic valence
M_c = molality of the positive ion species
M_a = molality of the negative ion species

what is a charge-balance eqn used for?

The charge-balance equation can be used to indicate the accuracy of a water analysis. Significant deviation from equality indicates that:

- there are analytical errors in concentrations or

- analysis of certain ionic species present at high concentration levels was omitted.

Deviation from equality is commonly expressed as:

$$E = \frac{\sum ZM_c - \sum ZM_a}{\sum ZM_c + \sum ZM_a} \times 100\%$$

where

E = charge-balance error

A charge-balance error of ±5% is normally considered acceptable.

The charge-balance error was determined for all groundwater analysis data contained in Appendix 0-3 where all major common ionic species were listed. Table 5.1 lists these results. Milliequivalents per liter were used for the analysis of the charge-balance error. The major ionic species used to compute the charge-balance error were Ca, Mg, K, Na, Fe (when present in sufficient quantities), Cl, SO_4 and alkalinity. The alkalinity because of the pH range was assumed to be mainly HCO_3 and it was converted to milliequivalents of HCO_3.

Of the 74 analyses listed in Table 5.1, 47 (or 63.5%) exceeded the acceptable ±5% charge-balance error. This implies that there are either analytical errors in the concentrations or that an ionic species present at high concentrations levels was not included in the analysis. The anionic species, PO_4 and NO_3/NO_2, were generally included in the analyses in Appendix 0-3 but their relative concentrations were low compared to the other anions present. Refer to Table 4.1 for a list of common constituents that are normally

TABLE 5.1

Charge-Balance Error, %

Borehole	No.	DATE Nov. 1981	July 1982	Nov. 1983
1	I	-5.65	-10.98	-0.87
	II	+11.77	+12.77	+8.54
	III	no analysis	no analysis	-10.97
2	I	+8.13	+0.06	no analysis
	II	+11.21	+8.37	no analysis
7	I	no analysis	-3.08	+5.26
	II	no analysis	+19.57	+28.17
	III	no analysis	+62.31	+12.83
8A	I	no analysis	no analysis	no analysis
	II	no analysis	no analysis	no analysis
11A	I	+18.97	no analysis	no analysis
	II	+28.15	no analysis	no analysis
12	I	+1.13	+21.40	+3.12
	II	+2.09	+2.16	+3.39
	III	+50.03	insufficient data	no analysis
13	I	+0.11	-2.54	-0.45
	II	+14.30	+7.98	+9.92
14	I	+4.05	+1.09	-1.93
	II	-0.15	+5.97	+20.62
15	I	+7.21	+1.94	-1.48
	II	+19.40	+8.50	+9.89
16	I	+18.04	+1.24	-2.46
	II	-1.89	-0.91	-2.68
	III	-5.16	-2.50	-1.60
	IV	+13.11	+7.90	+11.95
17	I	+5.64	-10.64	-12.83
	II	+7.37	+3.19	+2.77
	III	+9.27	+5.50	+9.10
	IV	+10.99	+17.01	+34.20
18	I	-	-	-2.12
	II	-	-	+20.56
	III	-	-	+23.55
22	I	-	-	+17.18
	II	-	-	+20.94
	III	-	-	+22.48

found in leachate. Assuming the leachate parameters from this table represent a complete list of all commonly dissolved constituents normally found in leachate and that the most common of the dissolved ionic species in groundwater have been taken into account in the analyses, i.e., Ca, Mg, K, Na, Fe, Cl SO_4, HCO_3/CO_3, NO_3/NO_2 and PO_4; it would appear that greater than 60% of the groundwater chemical analyses are not acceptable. It is surprising that this simple and routine analytical check had not been previously conducted.

It is agreed that the groundwater chemistry of the Queenston shale is sufficiently concentrated in certain species to possibly render it not potable. However, because reliable background groundwater chemistry is not available at the site other sources of chemical data for the Queenston shale are needed. Funk (1979) has determined the groundwater quality in the Queenston shale in the vicinity of the East and Middle Oakville Creeks. Table 5.2 summarizes his data. He concluded that "samples collected from the Queenston Formation reflect a high variability in chemical composition being higher in total dissolved solids, sulfate, chloride and sodium content than samples collected from other hydrogeologic units" and that "some of the water samples collected from the Queenston Formation" are not "suitable for domestic and irrigation uses". Upon closer observation of these data it appears that the groundwater quality is no where near as poor as in the Queenston shale downgradient of the Burlington Landfill site (BH-12, BH-13, BH-14, BH-15, BH-16 and BH-17).

Until the discrepancy in leachate chemistry is resolved and reliable background groundwater chemistry has been determined, it is not possible at this time to conclusively state what proportion of the dissolved species at the above six monitoring stations is contributed by leachate from the landfill site and what is naturally present in the groundwater.

TABLE 5.2

Groundwater Quality of Groundwater from the Queenston Shale (Funk, 1979)*

Dissolved Constituent	Concentration, mg/L Maximum	Minimum	Mean **
pH	7.60	6.70	7.06
Ca	248.0	24.0	113.4
Mg	194.0	1.0	60.3
Na	392.0	2.0	123.7
K	19.0	1.0	10.8
HCO_3	460.0	56.0	245.0
SO_4	1000.0	35.0	342.0
Cl	495.0	6.0	149.2
NO_2 as N	6.9	<0.2	0.9
Total Fe	12.0	<0.05	0.75
TDS	2670.6	445.9	1119.0
Total Hardness as C_aCO_3	1418.0	92.9	545.8

* based on 14 samples

** does not include samples which have ion imbalances greater than 7.5%

6.0 LATERAL GROUNDWATER FLOW VELOCITY IN THE SHALE

The lateral velocity of groundwater movement is defined by

$$V = \frac{Ki}{n}$$

where

V = velocity, L/T
K = hydraulic conductivity, L/T
i = hydraulic gradient, L/L
n = effective porosity, L^3/L^3

GLAL (1984) report a range of K values based on field testing performed by them which is consistent with results of others. They use an average value of 5×10^{-8} m/s for their calculations (pg. 0-149). They measure the lateral hydraulic gradient from Figure 0-16, quote a range of values and use an average value of 0.045. They state that "the fracture porosity of the shale is estimated at 0.05 (5%)". They then proceed to calculate maximum, minimum and average values of groundwater flow velocities in the shale. Ranges were given for K and i where these values have been test-derived or based on testing results. Mr. Leech gave evidence that the porosity of 5% for fractured shales was based on his experience. However, no range was given.

Freeze and Cherry (1979) give a range of values for the porosity of shale of 0 to 10% (pg. 37). Hewetson and Cherry (1983) state that the "porosity of fractured rock is generally 2 or 3 orders of magnitude smaller than in granular deposits and it is considerably more difficult to accurately measure". They go on to say that "there are no fracture porosity values for shale cited in the literature, however for the purpose of illustrative calculations at the Bayview site, a porosity of 1×10^{-3} (0.1%) will be used ....". Since the geologic and hydrogeologic setting of the shale at the Bayview site is

very similar to that at the Burlington site, the same calculation using porosities of 0.1% and 1% can be performed using GLAL data. Table 6.1 lists these data for the lateral groundwater flow velocities in the shale. The maximum lateral velocities increase to 75.7 m/a for a porosity of 0.01 (1%) and 756.9 m/a for a porosity of 0.001 (0.1%).

7.0 DELINEATION OF PLUME AND BH-17

Mr. Leech has given evidence based on information from the GLAL report that he can positively conclude that the plume has not yet reached BH-17. However, it is Mr. Ridley's opinion based on the information discussed in the preceding three sections

- Leachate Chemistry
- Groundwater Chemistry
- Lateral Groundwater Flow Velocity in the Shale

that he (Mr. Ridley) cannot positively conclude that "the plume has not yet reached BH-17". Possible dilution of the leachate, a reliable background groundwater chemistry and discussions of a range of porosities in fractured shale were not fully addressed in the GLAL report. It is Mr. Ridley's opinion that these matters need to be fully addressed especially when attempting to delineate the plume and evaluate the impact it presently has and will have on the hydrogeologic regime.

BH-17 is a critical monitor and has been a topic of much discussion and concern especially when attempting to delineate the extent of plume migration. It is felt that certain important historical facts concerning this monitor were omitted from the GLAL

TABLE 6.1

Lateral Groundwater Flow Velocities in the Shale at Various Assumed Porosities

Velocities, m/a	Porosities		
	0.05 (5%)(pg. 0-150)	0.01 (1%)	0.001 (0.1%)
Maximum	15	75.7	756.9
Minimum	0.0006	0.0029	0.029
Average	1.4	-	-

report. Fortunately knowledge of these facts was obtained from reading earlier reports, from discussions with GLAL personnel and from attending the Hearing. These historical facts are:

- poor bailing and sampling practice
- the holes were triconed with water and not drilled dry
- BH-17 was damaged during construction of the sedimentation pond; however, there are two nests that contain the piezometers and standpipe and it is not known which nest was damaged, how extensive the damage was, if it has been repaired and how the damage may have affected the reported chemical analyses
- the land in front of the landfill is used as a snow storage area and there was no discussion of the possible effects snow storage may have on the reported chemical analyses especially in BH-16 and BH-17.

Ms. Pawlowski (MOE) presented in her witness statement a cross-sectional figure (Figure 1) showing the differential movement of contaminants in a plume. Cl is a conservative contaminant and advances faster than the other contaminants addressed in Pawlowski's Figure 1. Cl also has the ability to advance through a medium that contains clay minerals faster than water. Thus, given that the leachate may contain Cl in excess of 13000 mg/L and that Cl may be transported at velocities greater than the groundwater (>15 m/a), it is not possible at this time to positively conclude that the plume has not yet reached BH-17 and beyond. The issue is farther obscured by uncertainties regarding the fracture porosity of the shale and the absence of reliable analysis of background groundwater chemistry and leachate chemistry.

8.0 ANALYSIS OF LEACHATE ADVANCE AND BREAKTHROUGH FROM THE TILL

On page 0-151, GLAL (1984) has predicted that it would take 75 years for the concentrated leachate front to advance through a 1.5 m till layer using average vertical flow velocities (pg. 0-149). The above velocity term is commonly called the advection term and assumes plug flow. However, when dealing with mass transport of contaminants, especially in a medium that contains a substantial amount of clay, another transport term also applies. This is known as disperson and is the sum of a mechanical velocity component and a molecular diffusion component. Thus, both advection and dispersion are active processes of mass transport. At low velocities the advection term can be neglected and the diffusion component of the disperson term becomes dominant. This has been verified by Quigley et al. (1984) and GLAL (1983). However, Mr. Leech gave evidence that he felt diffusion, although acknowledging it as a component of mass transport, was not that significant.

Information from the paper by Quigley et al. (1984) (Appendix B) is used to reanalyse the advance and breakthrough of leachate using Cl as a contaminant ion. About 10% of the leachate from Phases B and D will not be collected by the underdrain system and will exfiltrate through a minimum 1.5 m thickness of till, i.e., an annual leakage of about 795 m^3 or 795,000 L (pg. 0-152, GLAL, 1984). This amounts to an annual chloride loading ultimately leaving Phases B and D of about 1,200 kg if the leachate is assumed to contain 1,500 mg/L of Cl or about 10,000 kg if the leachate is assumed to contain 13,000 mg/L of Cl. Cl is conservative and will probably not be attenuated to any substantial degree through a 1.5 m thickness of till.

Quigley et al. (1984) use a "one-dimensional diffusion (without advection) from a constant source" relationship. This is defined by the equation $C(x,t) = \text{erfc}\left[\frac{x}{2\sqrt{D^* t}}\right] C_o$

where

C = concentration of solute at some time and distance from the leachate - till interface, M/L^3

C_o = initial concentration of solute in the leachate, M/L^3

erfc = complimentary error function

x = distance, L

D^* = coefficient of molecular diffusion, L^2/T

t = time, T

For illustrative, purposes, the analysis will be conducted using Cl at

C_o = 1,500 mg/L; 13,000 mg/L

x = 1.5 m

$D^* = 4.32 \times 10^{-5}$ m^2/d

It is also assumed that there is no physical or chemical reaction between the leachate and the till. Table 8.1 summarizes the results of the analysis. Depending on the concentration of Cl in the leachate it would take just over 10 to just under 40 years to exceed for example, the criterion for Cl of 250 mg/L in water supplies. Thus, breakthrough of Cl can occur in much less than 75 years. The results in Table 8.1 did not consider advection, anion exclusion, any

TABLE 8.1

Cl Concentration in Leachate Exfiltrating from the Base of the Till at Selected Times

Time, years	C_o 1500 mg/L	13000 mg/L
10	11	94
20	85	739
30	180	1557
40	269	2328

Therefore, V_s ranges from 29 m/a to 579 m/a in a downward direction.

The velocity vector for leachate down into the shale is greater than the velocity vector in the refuse towards the front of the landfill and the RTD. However, this does not give any indication of the potential quantity of leachate movement towards the RTD or into the shale. The quantity of leachate movement is defined by Q = KiA. For illustrative purposes, two cross sectional areas of leachate flow in the refuse will be considered:

- a leachate front 2 m high and 350 m wide moving in a southeasterly direction and

- a leachate front 2 m high and about 1500 m long around the periphyry of the original site moving towards the peripheral edge of the site and the RTD.

The surface area of the original landfill is 22.3 ha. The potential quantity of leachate movement towards the RTD ranges from 900 m^3/a to 3900 m^3/a (900,000 L/a to 3,900,000 L/a). Similarly, the potential quantity of leachate movement into the shale is 323,000 m^3/a (323,000,000 L/a). Of course these quantities are only potential values. If the volumes of leachate are not present in sufficient quantities the shale cannot accept something that is not present. Using Mr. Leech's infiltration value of 180 mm/a after closure, about 40,000 m^3/a (40,000,000 L/a) of leachate will be produced at the original site. Mr. Ridley suspects that most of the potential leachate produced will infiltrate and report into the shale with very little being collected by the RTD.

physical and/or chemical reaction of the leachate with the till or the flux of other ions from the leachate. Advection, anion exclusion and any adverse leachate-till reaction would decrease the time of increasing Cl concentration breakthrough.

Quigley et al. (1984) when discussing domestic waste landfills that are lined with about 1.2 m of soil show from their field data "that a chemical flux of Na and Cl will exit most liners within 10 to 15 years ....". Thus, there is a concern about the exfiltration of leachate from the proposed continued use area from the base of the till layer. It will contribute to the present plume migrating to the southeast as well as create a new plume that will move to the northwest towards the upper reaches of Falcon Creek and to the southeast towards Indian Creek.

9.0 EFFECTIVENESS OF THE TOE DRAIN

9.1 Retro-fitted Toe Drain (RTD)

To date there is no quantification of the effectiveness of the retro-fitted toe drain for collecting leachate from the original site. Mr. Leech has given evidence that the number of leachate springs have been reduced near the periphery of the landfill. This is a qualitative indication that the RTD is working but it gives no indication as to the extent of its "trough" of influence into the landfill or the volume of leachate that is being collected relative to what is escaping vertically downwards into the shale. Recall that the refuse in this area is placed directly on the shale and that the dominant gradient in the shale is vertically downwards.

Exhibit 65 is a map of the location of leachate springs for April-May, 1984. There are about 18 leachate springs that have been mapped near the edge of the landfill and at least one in the valley of

Falcon Creek. Some of these are very close to the RTD. Thus, how effective is the RTD?

For illustrative purposes, the velocity of leachate movement in the refuse is defined by $V_r = \frac{Ki}{n}$

where

$K = 10^{-6}$ m/s (pg. 0-31)

n = 0.25 (pg. 0-31)

i = 0.034 as measured from BH-8A and BH-11A from Fig. 0-13 assuming the main component of flow is towards the southeast

i = 0.041 using the slope of the land between BH-8A and BH-11A

Therefore, V_r ranges from 4.29 m/a to 5.17 m/a in a southeasterly direction.

Similarly, the velocity of the leachate movement vertically downwards into the shale is defined by $V_s = \frac{Ki}{n}$

where

K ranges from 1.05×10^{-5} m/s near the surface at Bayview to 1×10^{-9} m/s at 30 m depth at the same site (GLAL in Dillon, 1982 taken from pg. 57 Acres). However, GLAL has used an "average" value of 5×10^{-8} m/s at Burlington although for the upper 10 m of shale Mr. Ridley suspects that K is greater - assume $K = 5 \times 10^{-8}$ m/s; 1×10^{-6} m/s

n = 0.05 (pg. 0-150)

i = 0.918 vertically downwards as measured from BH-8A-I and BH-8A-II using mean values of water levels pg. 0-131 and 0-133 and tip elevations pg. 0-126.

9.2 Toe Drain for Proposed Expansion Into The Continued Use Area

The toe drain for the proposed expansion is conceptual and has not yet been designed. If it is decided to proceed with the expansion it is suggested that a rigorous hydraulic analysis of its effectiveness be undertaken. One of the prime considerations is to place it deep enough in order to intercept any leachate that will move northwesterly towards Falcon Creek and southeasterly towards Indian Creek from the proposed continued use area. Recall that "the continued use area is in a groundwater recharge zone" and "the gradients are downward" (pg. 6-32). Thus, the projected 795,000 L/a of leachate that exfiltrates and is not collected by the toe drain collection system will recharge downwards. It would be desirable if the toe drain could intercept a major component of this annual quantity.

10.0 POTENTIAL IMPACT OF LEACHATE ON THE HYDROGEOLOGIC REGIME

10.1 Continued Use Area

The loading rate of a dissolved constituent in the leachate is defined by $LR = Q_1C_1$

where Q_1 = the quantity of leachate that exfiltrates, L^3/T

C_1 = concentration of a dissolved constituent in the leachate, M/L^3

LR = loading rate, M/T

This concept can also be applied to the amount of a dissolved constituent that is naturally present in the native groundwater. For illustrative purposes, a mixing equation can be used to predict the

potential impact that the exfiltration of leachate may have on the native groundwater by

$$C_{gw} (Q_s + Q_l) = Q_s C_s + Q_l C_l$$

where C_{gw} = final concentration of ion in groundwater, M/L^3

C_s = original concentration of dissolved constituent in the shale, M/L^3

Q_s = quantity of groundwater movement through the shale, L^3/T

It is assumed that no reaction occurs between the leachate and the groundwater in the shale. The following parameters will be used:

Q_l = 795,000 L/a (pg. 0-152)

C_l : Cl = 1,500 mg/L ; 13,000 mg/L

: BOD = 26,000 mg/L

Q_s = 500,000 L/a (as calculated in Section 3)

C_s : Cl = 200 mg/L BH-1-I

: BOD = 50 mg/L BH-1-I

The final concentration of Cl in the groundwater in the shallow shales ranges from about 1,000 mg/L to about 8,000 mg/L and for BOD it is about 16,000 mg/L. It is suspected that there will be little attenuation of either of these parameters between the proposed use area and discharge to the Falcon and Indian Creeks. There are no known domestic users of groundwater in this area, therefore surface water quality is the main concern. Since there is not any reliable data on the actual chemistry of the leachate or the background quality of the groundwater greater than 6 m into the shale this calculation was only to demonstrate a potential impact.

10.2 Original Landfill Site

A potential impact scenario cannot even be attempted for this area because of the lack of quantitative information on the background chemistry of both the shallow and deep groundwater. However, for illustrative purposes potential loading rates for Cl and BOD can be estimated. Assume that 80% of the 40,000 m^3/a of leachate generated at the original site exfiltrates to the shale. Annual loading rates for Cl would range from 48,000 kg to 416,000 kg (48t to 416t) and could be as high as 832,000 kg (832t) for BOD.

tonne

11.0 THE PHYSICAL AND CHEMICAL INTEGRITY OF THE TILL IN A LEACHATE ENVIRONMENT

All calculations involving the hydraulic conductivity of the till in the GLAL report and up to now in this report have assumed that the till and leachate do not react, i.e., they are compatible. However, this is not always the case. Fine grained soils that are considered suitable as containment barriers typically have a high fraction of clay minerals. These soils display different hydraulic conductivities with different fluids. Work conducted by Mesri and Olson (1971), Anderson (1982) and Brown and Anderson (1983) have verified this phenomena.

It is recommended in "Lining of Waste Impoundment and Disposal Facilities" (Matrecon, Inc., 1980) that determination of the hydraulic conductivity be conducted using fluids that are representative of those that must be contained. Olson and Daniel (1981) have detailed the methods for measuring the hydraulic conductivity of fine grained soils and Daniel (1981) has outlined the problems in predicting the hydraulic conductivity of compacted fine

Table 11.1 Summary of Sources of Error in Estimating Field Permeability of Compacted Clay Liners from Laboratory Tests

Potential Sources of Error	Laboratory k Too Low or High?	Possible Number of Orders of Magnitude of Error*
Compaction at a Higher Water Content in Laboratory than in Field	Low	1 to 3
Maximum Size of Clay Chunks Smaller in Laboratory than in Field	Low	1 to 2
Deleterious Substances, e.g., Plant Roots, Present in the Field but Not in Laboratory Samples	Low	1 to 3
Use of Static or Impact Compaction Rather than Kneading Compaction to Prepare Laboratory Specimens	High	0 to 1
Use of More Corrective Effort in the Laboratory than in the Field, Resulting in Optimum Water Content being Higher in Field than in Laboratory	Low	1 to 3
Air in Laboratory Samples	Low	0 to 1
Use of Excessive Hydraulic Gradient Causing Particle Migration	Low	0 to 1
Lack of Steady-State Seepage due to Stress Change	High	0 to 1
Sample Size too Small in Laboratory Test	Low	0 to 3
Desiccation Cracks in Field	Low	No Data

* A rough estimate based on available data.

Source: Daniel, 1981

grained soils in the laboratory. Table 11.1 is a summary of the sources of error in estimating field hydraulic conductivity of fine grained soils from laboratory testing.

Very briefly, physical and/or chemical breakdown of a fine grained soil can occur if the leachate and till react. Physically the flocculation/dispersion equilibrium may be disrupted and chemically the soil could dissolve or breakdown. Both of these phenomena would result in the failure of the till as an inhibitor to leachate flow causing exfiltration volumes to exceed 10% in the proposed engineered expansion.

Mr. Al Ridegrin of Golder Associates supervised the [illegible] permeability tests (pg. 0-116). He stated that distilled water was used and that the tests were conducted over a short period of time. Distilled water is not going to be stored at Darlington and those fluids at the site will be there for a long time. Distilled water [illegible] having a different chemistry, viscosity and weight density than leachate, dilutes the concentration of ions naturally in the soil causing the double layer of the clays to expand. Expansion of the double layer causes the clay particles to repel one another and go into a dispersed state. As a consequence the hydraulic conductivity will be falsely low. If a representative field fluid, i.e., leachate is used, flocculation rather than dispersion may occur. This could cause an increased hydraulic conductivity that is more representative of field conditions. If leachate cannot be used it is common practice to use a 0.01 N $CaSO_4$ solution. Longer duration of testing is also recommended.

On page 0-146 it is stated that "For calculation purposes, a conservative value of 1 x 10^{-9} m/s is adopted for the unfractured till". If the actual field hydraulic conductivity using leachate was one or two orders of magnitude greater, i.e., 10^{-8} or 10^{-7} m/s then all the calculations concerning breakthrough time and volumes of leachate leakage would be incorrect. Thus 1 x 10-9 m/s is no longer

conservative. Mr. Ridley has observed such increases in hydraulic conductivity by 10,000 times relative to the same soil tested with water. Elsewhere in the literature increases have been observed by as much as 1,000,000 times.

To conclude this section it is interesting to note that on page 0-57 of the GLAL report they recommend that "the collector pipes be wrapped with a geotextile filter provided a manufacturer's guarantee of the materials integrity to leachate can be obtained". Mr. Ridley has similar feelings about the integrity of till to leachate.

12.0 MONITORING AND FIELD RECONNAISSANCE PROGRAM

At a meeting of all hydrogeologic technical personnel at GLAL offices on May 9, 1984 a tentative, future, phased monitoring program was discussed. The following was generally agreed upon:

- all future monitors will be constructed of 2" I.D. stainless steel or threaded PVC, no glue will be used, they will be suitable for sampling for organic analysis

- each hole will contain a single instrument and be 6.25" I.D.

- all holes will be drilled dry

- sand will be installed around collector zone and then the annulus around the pipe will be backfilled (tremied) with a bentonite grout to surface

- all installations will be bailed and sampled as per accepted practice, i.e., test to get reproduceable chemistry over the period of about one month and/or get three agreeable readings of chemistry

- a committee of technical representatives for the MOE, Halton and the City of Burlington will be established to supply input for the new monitoring program

- a deep monitor upgradient of the present site to determine background groundwater chemistry as well as a monitor in the vicinity of BH-12, BH-13 and BH-16 will be installed first

- phased installation of another monitor further downgradient of the landfill but on the property will follow.

Mr. Ridley made the following suggestions at the meeting:

- Mr. Ridley wanted to install monitoring off the site at a distance far enough downgradient where all parties could agree that the plume had not yet advanced

- Mr. Ridley wanted to set up a surface water monitoring program off the site within the Aldershot community.

It is felt that monitoring offsite is good practice. Afterall, contaminants moving in the plume migrate offsite. They do not stop at the site border.

A field reconnaissance program along the incised valleys of the Falcon Creek where it traverses through the Aldershot community should be conducted. Any outcrops of the Queenston shale should be mapped. The area had been mapped by Karrow in the late 1950's but because the scale of Karrow's map is too small (1:50000) (Exhibit 49) representation of any small shale outcrops on the map would be limited

by the scale. To Mr. Ridley's knowledge there has been no offsite field reconnaissance. If there has been offsite reconnaissance it should be documented in the GLAL report.

Morrison Beatty Limited (1980, 1981) report upward and downward gradients southeast of the Bayview Site. Hewetson and Cherry (1983) confirms this observation. Morrison Beatty Limited also report a shallow discharge zone on the other side of Highway 403. Offsite investigations and monitoring should be instigated to determine if this is the case southeast of the Burlington site as well as in the Aldershot community. If the plume is migrating at depth and eventually discharging into Burlington Bay or Lake Ontario, classical hydrogeology dictates that the seepage front will not discharge fully at the Bay or Lake Ontario. Instead, the seepage front will discharge gradationally into the lacustrine sediments as well as into the Bay or Lake Ontario. Moreover, any aberrations in surface topography could promote local discharge zones. This is a major concern as there are many private domestic wells within the Aldershot community (as displayed on page 0-138 (Fig. 0-19) and listed in the GLAL report (pg. 0-139).

13.0 ENVIRONMENTAL RISK ASSESSMENT OF THE BURLINGTON LANDFILL EXPANSION

13.1 Introduction

The crux of the present investigation is appropriately summarized by the second paragraph of the Boards' letter to Mr. Ridley:

> "You are directed to investigate the hydrogeology and related matters involved in the proposal and to report to the Board and to the Hearing your findings as to the hydrogeological impact of the proposed expansion, its possible effects on the environment as defined by

the Environmental Protection Act and whether, in your opinion, the proposal can be carried out without creating unreasonable environmental risks and, if so, under what terms and conditions".

It is felt that the environmental risks involved with expanding the Burlington landfill cannot be quantified at this time. However, various illustrative calculations have been conducted to demonstrate the potential impact that could occur despite the fact that integral information regarding leachate and background groundwater chemistry is not known. These computations demonstrate the possibility of other impact scenarios that were not fully addressed in the GLAL report. For example, if there is a smaller flux of groundwater flowing through the area relative to the amount of leachate discharge to the groundwater flow regime then the resulting chemical impact could be much greater than identified in the GLAL report. However, if the groundwater then discharges at some point other than Burlington Bay or Lake Ontario then the impact on surface water, fauna, flora and most importantly any resident living in the area could also be great. However, the magnitude of this "impact scenario" is governed by the concentration and chemistry of the leachate and background groundwater, knowledge of the vertical component of hydraulic gradients both on the site and southeast of the site, groundwater velocities in the shale, the effectiveness of the RFD and the expansion toe drain, and quantification of volumes of leachate escaping from the site. Until these factors are properly addressed there can be no quantification of environmental risks.

13.2 Phases A and C (Un-engineered)

All of Phase A and part of Phase C will be located over the non-engineered section of the original landfill. The first thought that comes to mind is to question the rationale of such a decision.

Without sounding too repetitive there is no reliable information about the actual chemistry of the leachate or the background groundwater quality. Furthermore, the location and extent of migration of the existing plume is a topic of much debate. To add more refuse to an area where there are so many unknowns is not good practice. The additional refuse will probably not significantly alter leachate chemistry on a long term basis but "the time of leachate generation will be extended due to the increase in refuse volume" (pg. 0-64, GLAL, 1984).

It is recommended that if the proposed expansion is extended one is ratified a "rethinking" of the scheduling of Phases B and D should be investigated. Provided there are no operational constraints it would be desirable to start landfilling at Phases B and D which will be engineered with an underdrain collection system (Section 13.3 will outline Mr. Ridley's concerns about Phases B and D). In the event of a more detailed investigation would be conducted of the original non-engineered site. This would involve the installation of new monitors both on and off the site that are suitable for sampling of gases, determination of leachate chemistry from a monitor in the refuse or from a "rejuvenated" BH-8A, determination of background groundwater chemistry upgradient of the site, and extension of the retro-fitted toe drain, RTD in a northwesterly direction along the West Ditch (Figure 5-6) to connect into the underdrain system of the 1980 expansion. This extension would reduce the chances of underdrain failure as from in the proposed expansion area by virtue of providing another route for leachate to exit. It would also intercept a component of the plume flow from the original site to the north towards Indian Creek. Phases B and D would take about 11 months to complete. This would provide sufficient time to collect the data as well as provide more lead time to devote to plume definition.

Mr. Wells has given evidence concerning the placement of refuse in Phase A over the non-engineered site that deserves further investigation. Briefly, it involves placement of the refuse directly

on top of the final cover at the original site without puncturing the cover. The site is contoured so flow will be to the north and south along the original site cover, i.e., along the valley that presently houses the Bell Canada Line (Figure O-1). If direct hydraulic contact is made between Phase A and the RTD, Phase A would be an acceptable proposition. It is felt that if this plan is deemed acceptable, most of the leachate generated from Phase A will be collected by the RTD. Moreover, infiltration to the refuse beneath Phase A will be greatly reduced resulting in a reduction of leachate volumes from that portion of the non-engineered site. In order for this plan to be viable the RTD will have to be extended as per above.

13.3 Phases B and D (+ engineered portion of C)

Phases B and D and part of C will be located on the fill and will be underdrained. This appears to be acceptable, however, there are some concerns. No landfill underdrain system is 100% effective or fail safe. The proposed system is no exception.

GLAL (1984) has estimated that 10% of the leachate will exfiltrate from beneath the underdrained part of the landfill. The fate of the exfiltrate is a concern. As previously discussed it will contribute to the existing plume as well as migrate towards the upper reaches of Falcon Creek and part of the groundwater divide and southwest towards Indian Creek.

The long term integrity of the fill barrier in a leachate environment is another concern. If the fill and leachate are not compatible then short-term, duration, laboratory-determined hydraulic conductivities using distilled water as a permeant will not apply to the actual field setting. Hydraulic conductivities greater than those measured in the lab may be encountered. Consequently, leachate

leakage losses, efficiency of leachate collection and time for leachate breakthrough to occur could be different than estimated in the GLAL report.

It is recommended that longer term testing of the till be conducted using a more representative fluid as the permeant. If hydraulic conductivities are different than those contained in the GLAL report then other plans should be drawn up. These may involve the installation of a double underdrain system, use of an alternative lining material (natural, synthetic or admixture), decreasing the spacing of the [illegible] drains or any combination of [illegible]. This is by no means a complete list.

Monitoring should be installed in [illegible] Creek in the vicinity of [illegible] and in [illegible] Creek to [illegible] (i.e. [illegible] the [illegible] Marsh, Figure 5 6). [illegible] conform to the [illegible] previously discussed.

A rigorous analysis of the effectiveness of the [illegible] drain should be conducted. It should be designed to [illegible] of the leachate that exfiltrates from the underdrain system.

Finally, a contingency system similar to the one outlined in page 9 58 (GLAL, 1984) should be planned. Mr. [illegible] got the impression from the evidence given by Mr. Leech that the contingency system originally proposed by GLAL may not be [illegible]. However, it is felt that without a detailed evaluation of the effectiveness of the expansion toe drain, it may be premature at this time to rule out a contingency system.

13.4 Original Landfill Site

? why separate from phases A and C ?

It is Mr. Ridley's opinion that this site, in its present form should never have been selected for the landfilling of refuse. The main concerns with the original landfill site are:

- vertical and horizontal delineation of the plume
- velocity of plume migration
- [illegible]
- [illegible] of the [illegible]D

[illegible] the [illegible] of [illegible] sampling and [illegible] the [illegible] d. This [illegible] a lot of the [illegible] of [illegible] is [illegible] the [illegible] of [illegible]. [illegible] less, ground [illegible] on and off the site is still [illegible] d.

It [illegible] possible to [illegible] the [illegible] the [illegible]. [illegible] could be [illegible] using [illegible] [illegible] models.

[illegible] in a [illegible] of [illegible] of [illegible] 10 years to [illegible] slopes. They [illegible] be hydraulically [illegible] to the RTD but [illegible] they could be easily [illegible] for [illegible] and [illegible] this [illegible]

practical. However, it is worthwhile investigating the feasibility of installing horizontal drains. If they are practical, leachate volumes exfiltrating from the original landfill site would be greatly reduced.

Finally, although the logistics of a cleanup or management of the existing plume are not beyond the scope of this report the methodologies are. Since delineation of the plume has yet been firmly established plume management and/or cleanup cannot be evaluated. However, Mr. Leech has given evidence that investigations are ongoing. Thus, the feasibility of plume management and/or cleanup once the plume has been delineated should also be an ongoing [illegible]. If it can be [illegible] that the plume [illegible]:

[illegible]

[illegible] migrating to [illegible] within the [illegible] that it does not discharge to the [illegible] property between the landfill [illegible], i.e., discharge within the [illegible] of [illegible] is therefore not an environmental risk,

it would then be reasonable to [illegible] that no cleanup or [illegible] is necessary. However, based on information to [illegible] (.84) or any [illegible] no such conclusions can [illegible] at this time.

14.0 CONCLUSIONS

Based on Mr. Ridley's review of the available data the following conclusions are made.

14.1 The leachate from the toe drain collection system and monitors 8A and 11A are diluted by an unknown factor.

14.2 The quality of the background groundwater chemistry in the Queenston shale at the site is not known.

14.3 [illegible] of the chemical analyses of groundwater from [illegible] do [illegible] satisfy a condition of electroneutrality. [illegible] of the analyses [illegible]

14.4 The [illegible] groundwater flow velocity in the shale, [illegible] effective porosity that is [illegible], could be [illegible] than [illegible] in the [illegible] report.

14.5 Bearing in mind the disparities concerning the leachate chemistry, the background groundwater chemistry and the [illegible] groundwater flow velocity in the shale, conclusive statements regarding delineation of the plume is not possible.

14.6 Chlorides in the plume [illegible] the potential to [illegible] at a greater rate than simple seepage theory predicts.

14.7 Assuming there is no reaction of leachate with the till, one dimensional diffusion without advection predicts the breakthrough of leachate through the till in less time than analysis by simple seepage theory. If advection, anion

exclusion and adverse leachate-till reaction are incorporated into the analysis, the time for breakthrough will decrease even more.

14.8 The efficiency of the RTD for collection of leachate is low. Large volumes of leachate from the original non-engineered site are exfiltrating unimpeded into the shale.

14.9 The toe drain for the proposed continued use area is conceptual in nature. Consequently, the efficiency of collecting leachate that exfiltrates from the continued use area is not known. Thus, no definitive statement can be made concerning its ability to protect the upper reaches of Falcon Creek northwest of the groundwater divide and Indian Creek east of Phase B.

14.10 The potential impact of leachate that exfiltrates from the continued use area on the hydrogeologic regime could be substantial if the annual volume of exfiltrate is equivalent to the annual groundwater flow volume. However, the concentration of leachate and background groundwater chemistry must also be considered in the impact scenario.

14.11 A plume is presently migrating in a southeasterly direction from the original non-engineered site. The extent of this plume and the impact of the leachate on the hydrogeologic regime is not known.

14.12 It is not known if the leachate and till are compatible. Moreover, laboratory testing of the hydraulic conductivity of the till using distilled water as a permeant over short testing durations may have indicated falsely low hydraulic conductivities. If actual field hydraulic conductivities are greater than the lab testing has indicated then all calculations

concerning leachate leakage losses, efficiency of leachate collection, and time for leachate breakthrough will be incorrect.

14.13 The existing monitoring program is not suitable for sampling and analysis for dissolved organic constituents.

14.14 A new monitoring program is desirable on site. The monitors should conform to guidelines necessary for reliable sampling and analysis for dissolved organic constituents. They should be located upgradient of the landfill, within the refuse of the landfill, at the southeasterly toe of the landfill and at the southeasterly border of the landfill property.

14.15 There is no ground or surface water monitoring program off site.

14.16 A monitoring program is desirable off site. At least one monitor should be installed southeast of Highway 403 particularly if the on site monitoring program (14.14) has indicated that the plume has migrated off site. Surface water sampling and analysis should be conducted in Falcon Creek at locations within Aldershot.

14.17 There has been no known off site reconnaissance of the Falcon and Indian Creek courses delineating areas of bedrock outcrop and/or areas of groundwater discharge between the landfill site and Burlington Bay or Lake Ontario.

14.18 Hydrogeologically there is the potential for upward hydraulic gradients to exist southeast of the landfill site.

14.19 The original landfill site in its present form should never have been selected for landfilling of refuse.

14.20 It cannot be unequivocally stated that "the proposal can be carried out without creating unreasonable environmental risks" until the following conditions are addressed.

14.20.1 General

- accurate determination of leachate chemistry (A)
- vertical profile concentration of background groundwater chemistry to at least 30 m into the shale (B)
- new onsite monitoring program (C)
- delineation of plume (D)

can be worked on simultaneously with A+C

14.20.2 Phases A and C (over original site)

OK
- extension of RTD in a northwesterly direction parallel to the East Ditch to connect to the underdrain system (A)

OK
- investigate Mr. Well's proposal for Phase A (B)

14.20.3 Phases B, D and C (over engineered site)

- determination of the hydraulic conductivity of till using leachate or a representative fluid (A)
- determination of long term integrity of the till in a leachate environment (B)
- rigorous analysis of the effectiveness of the expansion toe drain (C)

- install monitors in the upper reach of Falcon Creek northwest of the groundwater divide and in Indian Creek east of the North East Ditch (D)

14.20.4 Original Landfill Site

- evaluate the effectiveness of the RTD for collection of leachate (A)

- investigate the use of horizontal drains in direct hydraulic contact with the RTD (B)

14.20.5 Offsite Monitoring and Reconnaissance

- ground and surface water monitoring offsite (A)

- field reconnaissance to determine areas of bedrock outcrop and/or areas of groundwater discharge (B)

particularly in Indian Creek Valley

15.0 BIBLIOGRAPHY

1. Acres Consulting Services Ltd., September 1982. Solid Waste Management Strategy Study.

2. Anderson, A., September 1982. Does Landfill Leachate Make Clay Liners More Permeable? Civil Engineering, ASCE.

3. Brown, K.W. and D.C. Anderson, 1983. Effects of Organic Solvents on the Permeability of Clay Soils. Project Summary, U.S.E.P.A., Municipal Environmental Research Laboratory, Cincinnati, OH.

4. Daniel, D.E., October 1981. Problems in Predicting the Permeability of Compacted Clay Liners, presented at the Symposium on Uranium Mill Tailings Management, Fort Collins, Colorado.

5. Freeze, R.A. and J.A. Cherry, 1979. Groundwater. Prentice-Hall.

6. Funk, G., 1979. Geology and Water Resources of the East and Middle Oakville Creeks, IHD Representative Drainage Basin, MOE, Water Resources Branch, Report 12.

7. Gartner Lee Associates Ltd., April 1981. Burlington Landfill Site Monitoring Program Interim Report.

8. Gartner Lee Associates Ltd., September 1982. Burlington Landfill 1981 Monitoring Program.

9. Gartner Lee Associates Ltd., May 1983. Hydrogeologic Considerations for Facilities Siting.

10. Gartner Lee Associates Ltd., August 1983. Burlington Landfill 1982 Monitoring Report.

11. Gartner Lee Associates Ltd., March 1984. Hydrogeological Study in Burlington Landfill Site Application for Continued Use, Volume 2.

12. Hewetson, J.P. and J.A. Cherry, April 1983 (draft). Hydrogeological Investigations at the Bayview Park Landfill, Burlington, Ontario, Progress Report May 1982 - February 1983.

13. Matrecon, Inc. September 1980. Lining of Waste Impoundment and Disposal Facilities. United States Environmental Protection Agency, Washington, D.C. PB81-166365

14. Mesri, G. and Olson, R.E., 1971. Mechanisms Controlling the Permeability of Clays. Clays and Clay Minerals, 19, pg. 151.

15. M.M. Dillon, October 1979. Burlington Landfill Site Hydrogeologic Report.

16. M.M. Dillon Ltd., March 1984. Burlington Landfill Site: Application for Continued Use, Volumes 1-3.

17. Morrison Beatty Ltd., June 1980. Phase II Hydrogeologic Investigation.

18. Morrison Beatty Ltd., November 1981. Phase III Hydrogeologic Investigation.

19. Olson, R.E. and Daniel, D.E., 1981. Measurement of the Hydraulic conductivity of Fine-Grained Soils. In: T.F. Zimmie and C.O. Riggs (Editors), Permeability and Groundwater Contaminant Transport, ASTM STP 746.

20. Pohland, F.G., November 1980. Leachate Recycle as a Management Option, presented at Leachate Management Seminar, University of Toronto.

21. Quigley, R.M., Crooks, V.E. and E. Yanful, May 1984. Contaminant Migration Through Clay Below a Domestic Waste Landfill Site, Sarnia, Ontario, Canada. Proceedings of the International Groundwater Symposium on Groundwater Resources Utilization and Contaminant Hydrogeology, Montreal, Quebec, Volume II, pg. 499.

APPENDIX A

Ontario

Environmental
Assessment
Board

(416)965-2531

1 St. Clair Avenue West
Toronto, Ontario
M4V 1K7

April ~~1~~ 27, 1984

Re: Burlington Landfill Expansion

To: Mr. Kevin J. D. Ridley

You are hereby appointed by the Environmental Assessment Board as its expert witness in hydrogeology and related fields pursuant to Section 18(9) of the Environmental Assessment Act in respect of the above Hearing. Section 18(9) of the Environmental Assessment Act reads as follows:

> The Board may appoint from time to time one or more persons having technical or special knowledge of any matter to enquire into and report to the Board and to assist the Board in any capacity in respect of any matter before it.

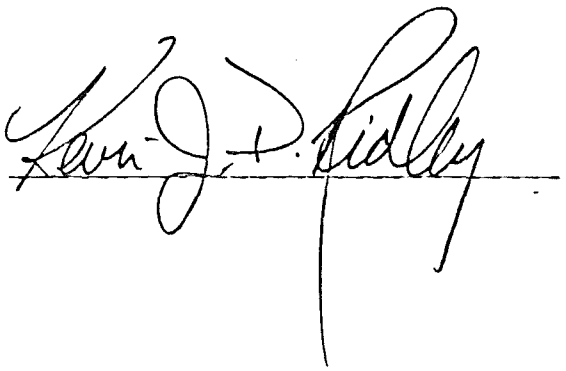
You are directed to investigate the hydrogeology and related matters involved in the proposal and to report to the Board and to the Hearing your findings as to the hydrogeological impact of the proposed expansion, its possible effects on the environment as defined by the Environmental Protection Act and whether, in your opinion, the proposal can be carried out without creating unreasonable environmental risks and, if so, under what terms and conditions.

During your investigation and during the course of the Hearing, you are directed to specifically consider the impact that the proposal will have on ground and surface water and also to consider the proposed plan for leachate collection and treatment.

You will be expected to submit a written report of your findings and conclusions; to be in attendance at the Hearing during the giving of evidence of other experts in the field of hydrogeology; to explain and evaluate such hydrogeological evidence as may be required by the Board; to testify orally; to render guidance and advice to the Canadian Environmental Law Association which represents West Burlington Citizens' group; and to generally render assistance to the Board in your area of expertise.

These terms of reference may be altered as the Hearing progresses and as circumstances require.

If you are in agreement with the above, please sign duplicate copy.



APPENDIX B

CONTAMINANT MIGRATION THROUGH CLAY BELOW A DOMESTIC WASTE LANDFILL SITE, SARNIA, ONTARIO, CANADA

Robert M. Quigley, Valerie E. Crooks and Ernest Yanful
Faculty of Engineering Science, The University of Western Ontario,
London, Ontario, Canada, N6A 5B9

ABSTRACT

The results of field and laboratory investigations of a domestic waste landfill overlying a 30 m deep natural clay deposit are presented.

Migration profiles of soluble constituents from the leachate, through the underlying clays, are presented for 1983 when the landfill was about 15 years old. Migration from the landfill is believed to have occurred for approximately 15 years, since the refuse attained saturation shortly after placement due to the construction practices employed.

Porewater concentration versus depth plots show that sodium, calcium, magnesium and chloride have migrated 0.7 to 1.0 m from the interface compared to an estimated advective advance of only 3.5 cm. Calculated values of the sodium adsorption ratio decrease from ~ 40 at the interface to ~ 12 about 0.5 m below the interface suggesting that up to 40% of the clay-exchange sites should be occupied by Na^+ near the interface, however, subsequent exchange experiments indicate that Na^+ is only adsorbed in minor quantities.

A preliminary study of heavy metal migration from the landfill suggests that migration has only occurred over a distance of 20 cm from the interface.

Preliminary measurements of dissolved organic carbon in the porewater indicate migration of organic substances to a depth of approximately 0.9 m.

INTRODUCTION

The design of a landfill facility situated in a hydro-geologically unsuitable area requires installation of a relatively impermeable liner, such as clay, to provide a final barrier between the landfill and any underlying pervious strata. Design of such a clay liner should be based on field measurements of pollutant migration through clay, in addition to numerical predictions and laboratory studies. Since investigation of an in situ clay liner could seriously disturb its integrity and promote contamination, landfills situated on thick natural clay deposits are more suitable for study. This paper presents additional results of continuing studies under way at such a landfill site near Sarnia, Ontario.

GEOLOGY AND SOIL MINERALOGY

The 30 m thick, homogeneous silty clay at Sarnia, Ontario is believed to be a waterlain till of late Wisconsin age composed mostly of rock flour obtained by glacial erosion of Silurian and Devonian carbonates and shales from the Lake Huron basin. A slight downward flow gradient exists in the area, and at the landfill site under study, piezometric observations indicate a small groundwater mound in the refuse and a steady downward flow velocity of approximately 0.24 cm/a in the till. In situ measurements of till hydraulic conductivity yielded values of about 1.5×10^{-8} cm/s at an in situ water content of 20-25%. Extensive studies of the geology and mineralogy of the site are summarized by Quigley and Ogunbadejo (1976) and Quigley and Crooks (1983). The hydrogeology was described by Goodall and Quigley (1977).

The soil in the 3 m zone directly below the waste is a carbonate-rich clayey silt containing 40% of < 2 μm sizes. The composition is approximately as follows: ~ 34% carbonate, ~ 25% illite, ~ 24% chlorite, ~ 15% quartz and feldspar, ~ 2% smectite. The effective cation exchange capacity is about 30 meq/100 g measured on the < 74 μm fraction.

PREVIOUS STUDIES

Two previous papers (Goodall and Quigley, 1977 and Crooks and Quigley, 1984) presented studies dealing with the migration of water soluble cations from the leachate through the underlying clays when the site was 6 and 12 years old. Both studies attributed the migration of Na, K, Ca and Mg to chemical diffusion. In the Crooks and Quigley study, profiles for Na^+ and $C\ell^-$ suggested migration by diffusion to depths of 1 to 1.5 m below the interface. Since man-made liners for domestic waste landfills are rarely greater than 1.2 m thick, the above field data indicate that a chemical flux of Na^+ and $C\ell^-$ will exit from most liners within 10 to 15 years of placement.

This paper presents concentration versus depth profiles for porewater and exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and porewater chloride now that the site is 15 years old. Preliminary profiles for heavy metal (Cu, Zn, Fe, Pb) migration and organic carbon dissolved in the porewater are also given.

CATION (Na^+, K^+, Mg^{2+}, Ca^{2+}) MIGRATION

Porewater and exchangeable cations were determined for two boreholes (designated BH83-2 and BH83-9) and the results are presented in Figs. 1 and 2. Sample preservation techniques and laboratory testing procedures are described in Crooks and Quigley (1984). Exchangeable cations on < 74 μm untreated soil were determined using the silver thiourea exchange method of Chabbra (1975).

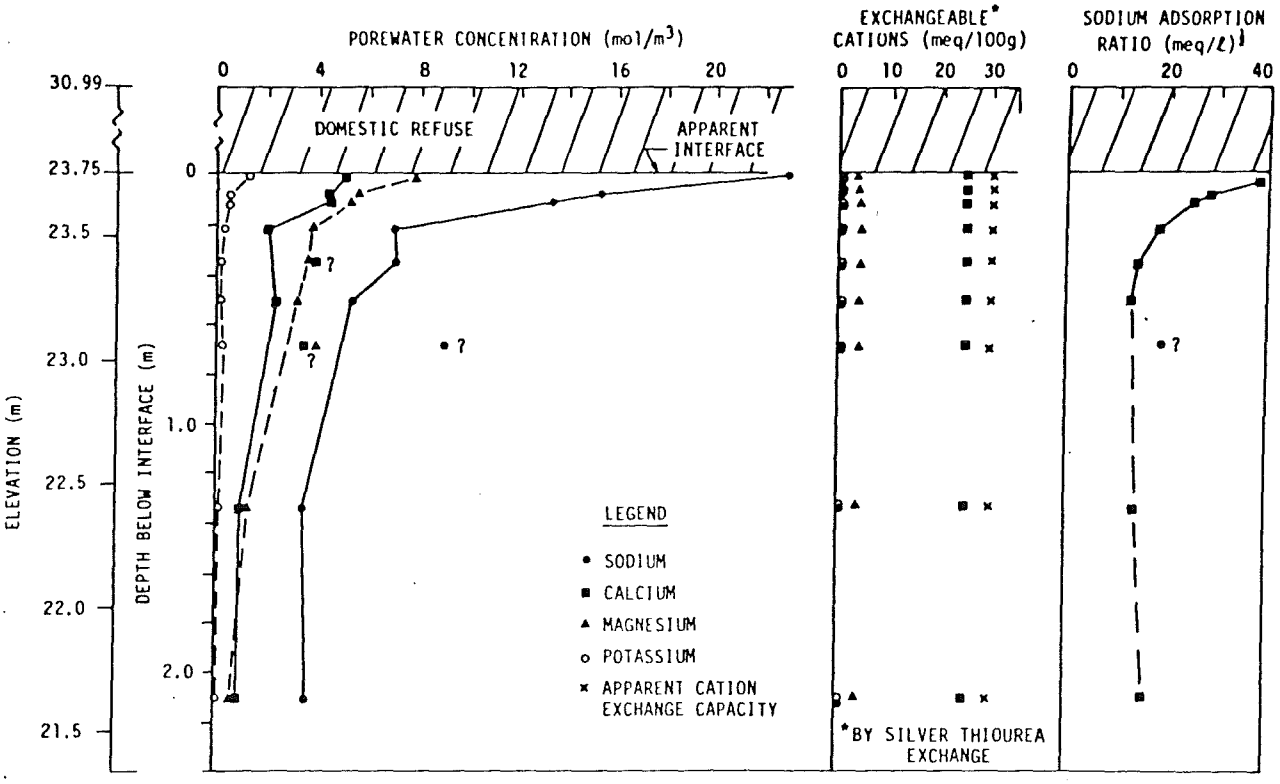


FIG. 1. POREWATER CATION CONCENTRATION, EXCHANGEABLE CATIONS AND SODIUM ADSORPTION RATIO (S.A.R.), BH83-2

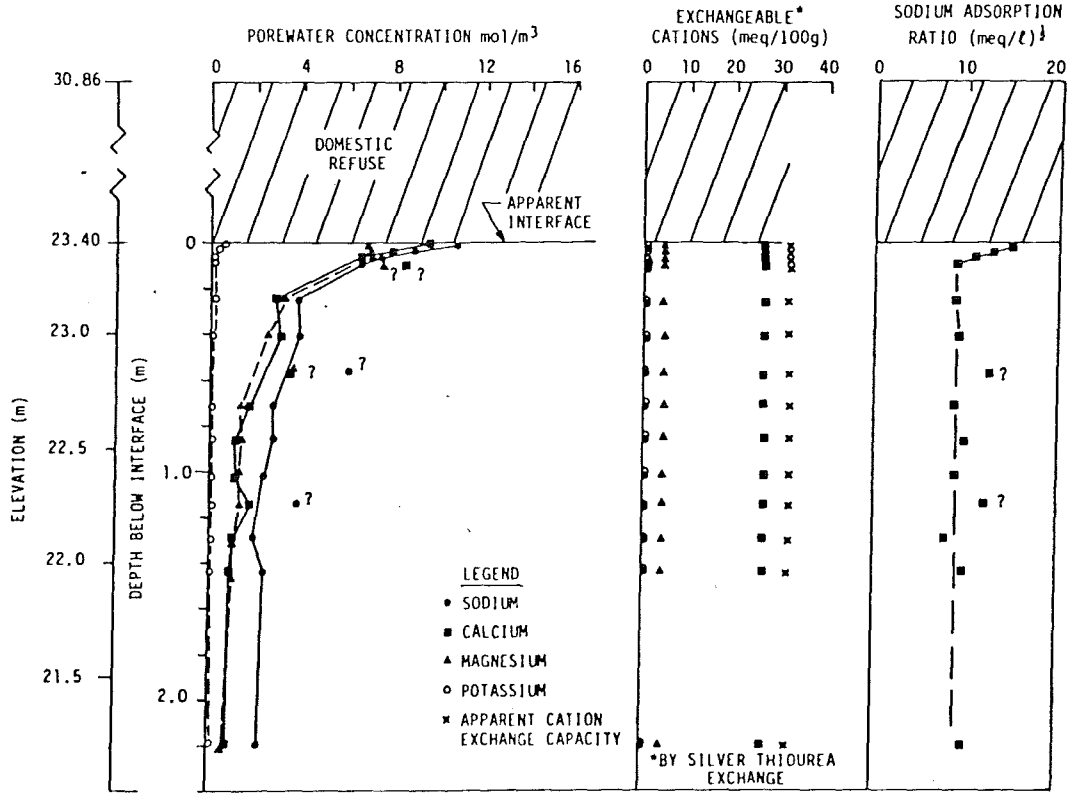


FIG. 2. POREWATER CATION CONCENTRATION, EXCHANGEABLE CATIONS AND SODIUM ADSORPTION RATIO (S.A.R.), BH83-9

The results for t = 15 years indicate that cation migration has occurred to depths of 0.7 to 1.0 m at these particular locations in the landfill. Previous results by Crooks and Quigley (1984) for boreholes located some distance away suggested that migration had occurred to a depth of approximately 1.5 m below the refuse/soil interface. It is believed that spatial variability in the refuse composition produces somewhat different migration profiles throughout the site. This phenomenon is illustrated by the migration profiles presented here for two boreholes located 7 m apart. Although the maximum depth of migration in both boreholes is similar, the maximum cation values at the refuse/soil interface are significantly different, e.g. Na^+ concentration of 23 mol/m^3 in BH83-2 compared to 10.6 mol/m^3 in BH83-9, both values at the interface. In both boreholes the dominant porewater cation is sodium.

Calculated sodium adsorption ratios (S.A.R.) versus depth often reflect the adsorbed cation distribution in the soil clay mineral fraction. Calculated S.A.R. values decrease from 40 at the interface to 12 at a depth of 0.5 m in BH83-2 (Fig. 1), suggesting that in this 0.5 m interval up to 40% of the clay exchange sites should be occupied by Na^+. Subsequent work using silver thiourea exchange indicated that calcium is the dominant adsorbed ion and that only minor amounts of Na^+ are adsorbed on the clay minerals. This situation may arise if the Na^+ concentration of the original leachate is not high enough to promote Na^+ for Ca^{2+} exchange, or if the clay exchange sites are preferentially occupied by other species such as heavy metal cations.

A similar but less significant decrease in S.A.R. for BH83-9 is shown in Fig. 2.

CHLORIDE MIGRATION

A porewater chloride migration profile was obtained for BH83-2, and is shown in Fig. 3. Chloride migration has apparently occurred to a depth of ~ 1 m.

A limited amount of analytical work was performed using this profile to obtain "best-fit" values of effective diffusion coefficient, D. The analytical solution used is that given by Ogata (1970) for the case of one-dimensional diffusion (without advection) from a constant source, and is applicable in our situation due to the negligible advection component (V_s = 0.24 cm/a) of transport from the landfill. The choice of the value for the interface concentration is somewhat difficult. Measured Cl^- leachate values of 86 mol/m^3 were obtained by Crooks and Quigley (1984), however the use of this value was shown to significantly overpredict the measured curve, although the maximum depth of migration could be modelled. Field observations of the zone of intermixed refuse and soil found above the undisturbed soil stratum suggest that the 'effective' interface for leachate migration may be as much as 30 cm above the location of undisturbed soil. Two profiles (A and B on Fig. 3) using different values of effective diffusion coefficient, D = 1 x 10^{-6} cm^2/s and D = 2 x 10^{-6} cm^2/s, were calculated from the analytical solution with C_o = 86 mol/m^3 and an 'effective' interface position located 25 cm above the apparent interface.

The use of $D = 2 \times 10^{-6}$ cm^2/s predicts the maximum depth of migration, although some overestimation of the upper part of the curve is obtained.

It has also been suggested that the appropriate value of initial concentration for use in the analytical solution is actually the maximum measured value in the profile, and that the 'effective' interface may be taken as the apparent interface. A third profile (C) calculated using this assumption, with a value of $D = 1 \times 10^{-6}$ cm^2/s, is also presented on Fig. 3. This profile exactly reproduces the upper 0.2 m of the measured profile, and predicts the maximum depth of migration, however this does not constitute a valid approach when reliable leachate concentration values are available. The "best-fit" value of $D = 2 \times 10^{-6}$ cm^2/s is comparable to the value of 3 to 6 $\times 10^{-6}$ cm^2/s given by Crooks and Quigley (1984) and to a value of 3×10^{-6} cm^2/s given by Desaulniers et al (1981).

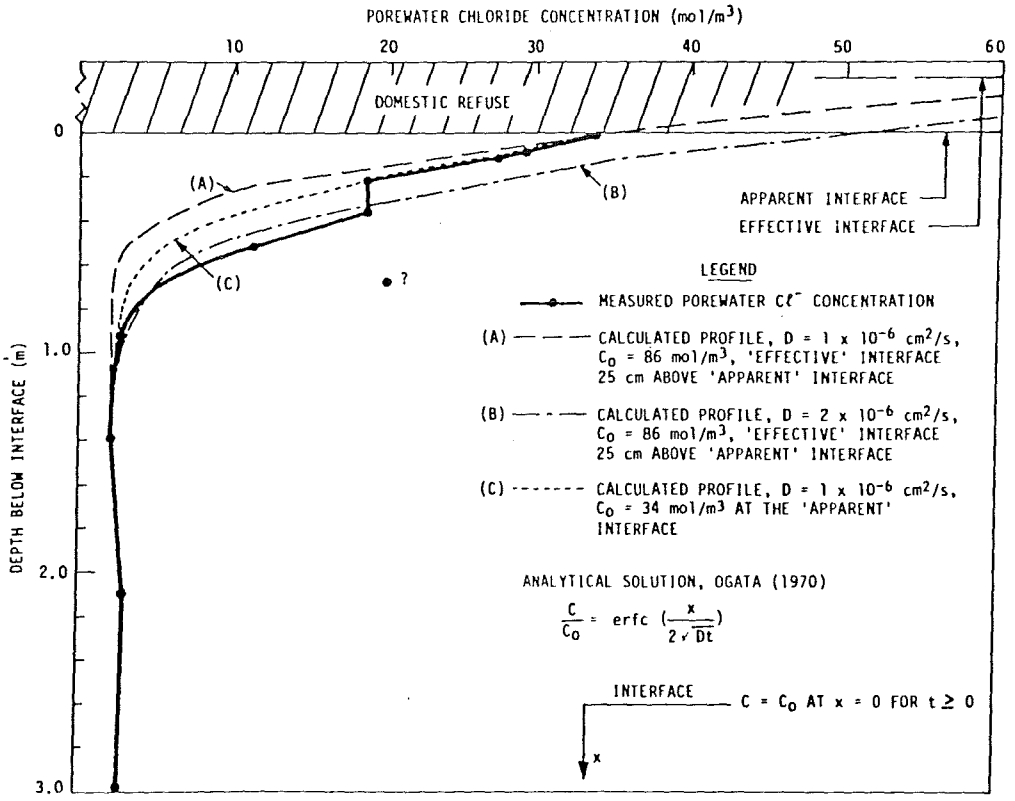


FIG. 3. MEASURED POREWATER CHLORIDE CONCENTRATION AND CALCULATED PROFILES, BH83-2

HEAVY METAL MIGRATION

Concentration profiles for Cu, Zn, Fe and Pb are presented in Fig. 4. These concentrations represent total acid extractible heavy metals both adsorbed and within the crystal structure of the clay minerals and other soil constituents. If the straight line portions of these profiles are considered to represent background or original in situ values, then the four metals have all migrated to a maximum depth of about 20 cm below the apparent interface.

The cumulative Cu, Zn and Pb concentrations are calculated to be 0.5 meq/100 g above their background values and these species could be adsorbed on the clay minerals without affecting the cation exchange measurements shown on Figs. 1 and 2. The amount of Fe in excess of background amounts to 34 meq/100 g which corresponds to the apparent exchange capacity of the soil. Obviously, this element is not adsorbed in these amounts and is possibly present as authigenic iron carbonate. Selective dissolution analyses are in progress to determine the mode of occurrence of the heavy metals.

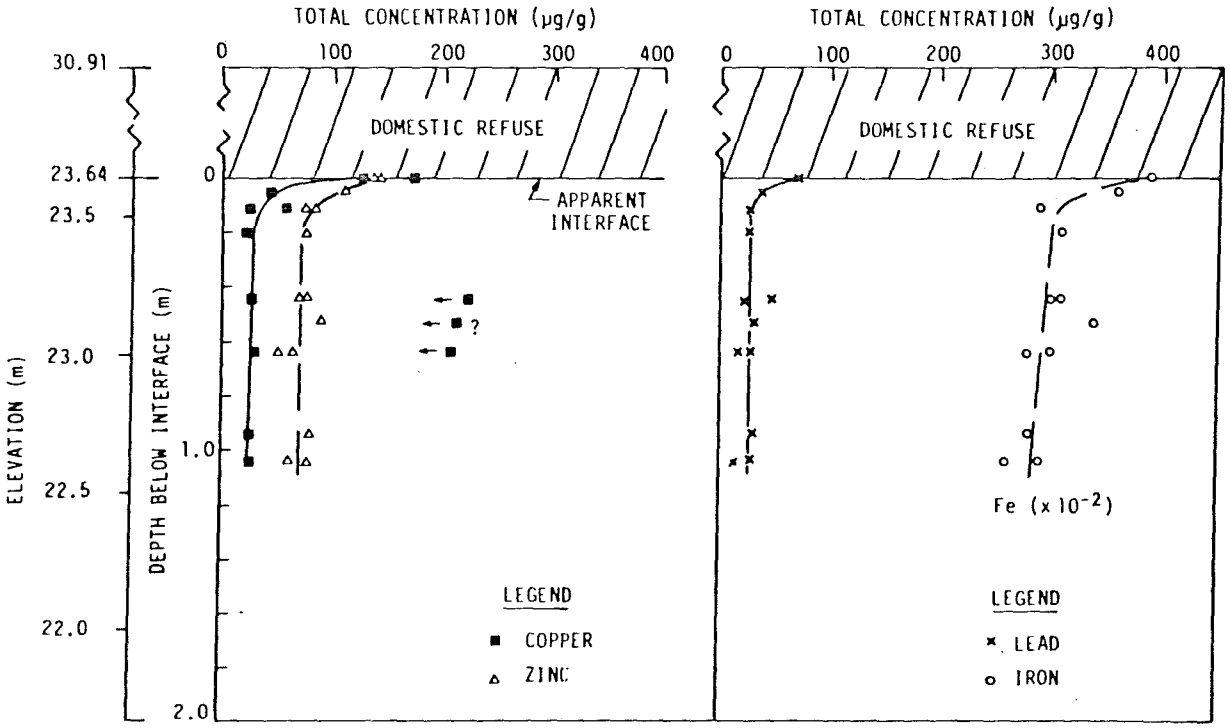


FIG. 4. TOTAL CONCENTRATION OF HEAVY METALS (COMBINED ANALYSIS U.W.O. AND X-RAY ASSAY LABORATORIES LTD.), BH83-7

DISSOLVED ORGANIC CARBON

A preliminary investigation of the migration of organic substances from the landfill was performed by measuring dissolved organic carbon (DOC) concentrations in the soil porewater. The borehole used for this study

c tained significant quantities of petroleum product in the interface region a... overlying refuse, which would tend to produce measurable migration of organic carbon in the soil porewater. The DOC profile is shown in Fig. 5 and indicates that migration has occurred to a depth of approximately 0.9 m. The measured concentrations reach a maximum value (41 mol/m^3) at a depth of 0.1 m from the apparent interface. This zone of lower DOC concentrations may result from bacterial activity in the soil or may simply indicate that the effective interface is 0.1 m below the one chosen. Similar results for DOC migration from the landfill were obtained by Crooks (1981) when the landfill was 12 years old.

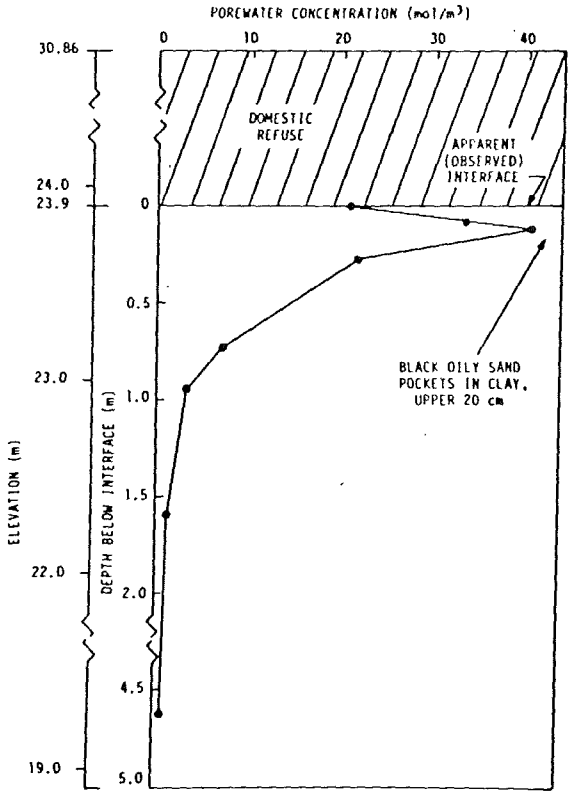


FIG. 5. POREWATER DISSOLVED ORGANIC CARBON, BH83-14 AND BH83-3

SUMMARY

Results of continuing studies at a 15 year old landfill situated on clay have been presented and indicate that migration has reached a depth of approximately 1 m. Cation (Na^+, K^+, Mg^{2+}, Ca^{2+}) migration has reached a depth of 0.7 to 1 m, as has $C\ell^-$ migration (depth ~ 1 m). Heavy metal (Cu, Zn, Fe, Pb) migration has occurred to a depth of about 20 cm below the interface. Dissolved organic carbon (representative of organic species) has migrated about 0.9 m. A limited amount of analytical work suggests the measured $C\ell^-$ profile may be predicted using an effective diffusion coefficient $D = 2 \times 10^{-6}$ cm^2/s in an expression for one-dimensional diffusion.

ACKNOWLEDGEMENTS

The recent work published in this paper has been financed by a Strategic Grant to the first author from the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Chabbra, R. 1975. The measurement of the cation exchange capacity and exchangeable cations in soils: A new method. Proceedings of the International Clay Conference, pp. 439-449.

Crooks, V.E. 1981. Leachate migration through clay by combined dispersive and convective transport. M.E.Sc. Thesis, The University of Western Ontario, 216 p.

Crooks, V.E. and Quigley, R.M. 1984. Saline leachate migration through clay: A comparative laboratory and field investigation. Canadian Geotechnical Journal, 21, No. 2, in press.

Desaulniers, D.E., Cherry, J.A. and Fritz, P. 1981. Origin, age and movement of pore water in argillaceous Quaternary deposits at four sites in southwestern Ontario. Journal of Hydrology, 50, pp. 231-257.

Goodall, D.C. and Quigley, R.M. 1977. Pollutant migration from two sanitary landfill sites near Sarnia, Ontario. Canadian Geotechnical Journal, 14, pp. 223-236.

Ogata, A. 1970. Theory of dispersion in a granular medium. U.S. Geological Survey Professional Paper 411-1.

Quigley, R.M. and Crooks, V.E. 1983. Chemical profiles in soft clays and the role of long term diffusion. Spec. Publ. on Geological Environment and Soil Properties, Ed. R.N. Yong, American Society of Civil Engineers, Geotechnical Engineering Division, Session 14, Houston, Texas.

Quigley, R.M. and Ogunbadejo, T.A. 1976. Till geology, mineralogy and geotechnical behaviour, Sarnia, Ontario. In: Glacial Till, An Inter-disciplinary Study, Ed. R.F. Legget. Royal Society of Canada, Special Publication, No. 12, pp. 336-345.