Written by: Rebecca Flynn Date: 25 October 2006 Reviewed by: Greg Corcoran Date: 10/26/06

Client: International Uranium (USA) Corporation Project: Cell 4A Project No.: SC0349 Task No.: 03

CALCULATION OF ACTION LEAKAGE RATE THROUGH THE LEAKAGE DETECTION SYSTEM UNDERLYING A GEOMEMBRANE LINER.

OBJECTIVE

In accordance with Part 254.302 of the USEPA Code of Federal Regulations, determine the action leakage rate (ALR) that a leak detection system (LDS) can remove, and not allow the maximum fluid head on the bottom liner to exceed 1 foot. The ALR shall be given as an average daily flow rate in gallons per day per acre for each sump associated with the LDS. The calculation shall include a margin of safety sufficient to allow for design uncertainties, operational changes, and material characteristics. The LDS shall have a surface area of approximately 40 acres, and consist of a 300-mil thick geonet and a network of gravel trenches that contain 4-inch diameter slotted PVC pipe, drainage aggregate, and a bottom cushion geotextile. There shall be one sump associated with the LDS. The primary liner shall consist of a smooth 60-mil HDPE geomembrane.

The method outlined by Giroud, et al. (1997) will be employed to calculate the ALR and confirm the maximum expected head.

ANALYSIS

Liquid flow through defect in primary geomembrane

Liquid migration through a liner occurs essentially through defects in the geomembrane. According to Giroud, et al. (1997) (see Attachment A, 3/6) the rate of liquid migration through a defect in the geomembrane is given by the following:

$$Q = (2/3)d^2\sqrt{gh_{prim}} \qquad \text{Equation (1)}$$

where:

Q = flow rate through one geomembrane defect, m^3/s
d = defect diameter, m
g = acceleration due to gravity, 9.81 m/sec^2
h_{prim} = head of liquid on top of primary liner, m

According to the EPA, common practice is to assume that the diameter of a leak in the geomembrane is equal to the thickness of the geomembrane (i.e. 60 mil, 0.001524 m).

Based on the proposed grading for Cell 4A (Attachment B, 1/1) and the operational constraint of maintaining 3 feet of freeboard within the cell, the maximum height of liquids above the primary geomembrane will be approximately 37 feet (11.3 m). Placing the above values into Equation 1 results in the following maximum flow rate per defect:

$$Q = (2/3)(0.001524m)^2\sqrt{(9.81)(11.2776m)} = 1.63 \times 10^{-5}\ m^3/sec$$
$$= 1.41\ m^3/day$$
$$= 372\ gal/day$$

Maximum flow rate within geonet

According to Giroud, et al. (1997) (see Attachment A, p. 2/6) the maximum flow rate within the leak detection layer geonet is given by the following:

$$Q_{full} = k\ t_{LCL}^2 \qquad \text{Equation 2}$$

Where:

Q_{full} = maximum flow rate within the geonet; *to be determined, m³/sec*
k = hydraulic conductivity of geonet; *see below, m/sec*
t_{LCL} = thickness of leak detection layer; *300 mil, 0.0076 m*

Hydraulic conductivity of Geonet, k

Attachment C, 2/2 shows a transmissivity curve for a 300 mil thick geonet sandwiched between two HDPE geomembranes tested for a duration of 100 hours. Based on the transmissivity and the thickness of the geonet, a hydraulic conductivity can be estimated for a variety of normal stresses and hydraulic gradient conditions.

Based on the site grading (Attachment B, 1/1), a maximum thickness of waste material (tailings/slimes) and final cover system of 40 feet will be placed above the liner system. Assuming a unit weight of 125 pounds per cubic feet (pcf), a normal stress of approximately 5,000 pounds per square foot (psf) will be exerted on the geonet.

Graphing the permeability data for the 300 mil thick geonet under a normal stress of 5,000 psf (Attachment D, 1/1), results in the following equation of the line:

$$k = 0.2868\ i^{(-0.4221)} \qquad \text{Equation 3}$$

The hydraulic gradient is based on the longest drainage path (950 feet), slope of the geonet (1%), and height of liquid above the liner system (37 feet, which accounts for the 3 foot freeboard). Based on this information, the hydraulic gradient can be estimated as follows:

$$i = (37\ ft + 950\ ft \times 0.01) / 950\ ft = 0.049$$

Placing the estimated hydraulic gradient of 0.049 into Equation 3 results in a hydraulic conductivity of 1.02 m/sec.

Accounting for intrusion (RF_{IN}), creep (RF_{CR}), chemical clogging (RF_{CC}), and biological clogging (RF_{BC}), Koerner (Attachment E, 3/3) suggests the following partial factor of safety values for secondary leak detection systems:

RF_{IN}	1.5 to 2.0	use 1.0 (no geotextiles on either side to intrude, test data accounts for geomembrane intrusion)
RF_{CR}	1.4 to 2.0	use 1.4 (low normal stress, 100 hour transmissivity data)
RF_{CC}	1.5 to 2.0	use 2.0 (very low pH)
RF_{BC}	1.5 to 2.0	use 1.0 (very low pH should preclude biological activity)

Applying these values to the hydraulic conductivity results in the following:

k = (1.02 m/sec) / (1.0 x 1.4 x 2.0 x 1.0) = $\mathbf{3.66 \times 10^{-1}}$ **m/sec**

Placing the geonet hydraulic conductivity and thickness into Equation 2 results in the following:

$\mathbf{Q_{full}}$ = (0.366 m/sec) (0.0076 m)^2 = $\mathbf{2.11 \times 10^{-5}\ m^3/sec}$

Based on the anticipated flow through defects in the primary geomembrane and the allowable maximum flow rate within the geonet, the following overall factor of safety results:

FS = (2.11×10^{-5} m^3/sec) / (1.63×10^{-5} m^3/sec) = **1.29**

Therefore, the proposed 300 mil thick geonet leak detection layer can accommodate the anticipated flow through defects in the primary geomembrane.

Action Leakage Rate (ALR)

The number of defects in a geomembrane is given by Giroud, et al (Attachment A, 4/6), as the following:

$$N = (F)(A_{LCL}) \qquad \text{Equation 4}$$

where:

N = number of defects

F = frequency of defects (per m^2 of geomembrane)
A_{LCL} = area of leakage collection layer; *40 acres, 161,900 m^2*

Using an assumed F = 1/2,500 m^2 (Attachment A, 4/6), the number of defects assumed in the primary geomembrane is as follows:

N = (1/2,500)(161,900) = 65 (rounded up to nearest whole number)

ALR = (Q)(N)/acre Equation (4)
= (1.41 m^3/day)(65)/40 acres = 2.29 m^3/day/acre
= **604 gal/day/acre**

Maximum flow rate to sump
Based on the area of the Cell 4A liner system, the following maximum flow rate to the sump is anticipated:

Q_{sump} = (604 gal/day/acre) (40 acres) = 24,160 gal/day = 16.8 gpm

A sump pump capable of a minimum flow rate of 20 gallons per minute at the head conditions present (approximately 42 vertical feet plus piping losses) will be utilized to remove liquids from the LDS.

Time of travel
According to Giroud, et al. (1997) (see Attachment A, 6/6) the travel time for the liquid to reach the LDS piping system from the defect in the primary geomembrane is given by the following:

t_{travel} = (nx) / (k sin β cos β) Equation 5

where:

t_{travel} = time for liquid to travel from defect in primary geomembrane to the LDS piping; *to be determined, sec*
n = porosity of geonet; *0.8*
x = distance from defect in primary geomembrane to LDS piping; *950 ft, 290 m*
k = hydraulic conductivity of the geonet; *0.366 m/sec from above*
β = slope of floor; *1%, 0.573 degrees*

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Substituting the values into equation 5 results in the following:

t_{travel} = (0.8) (290 m) / (0.366 m/sec) (sin 0.573) (cos 0.573) = 63,388 sec = 17.6 hours

Therefore, the leak detection system geonet will allow for timely detection of liquids.

Head Above Liner, (h):

Knowing the maximum potential flow rate through a specific defect in the primary geomembrane, and assuming a worst case condition where all primary liner defects are located at the higher end of the leakage collection layer slope, liquid head build-up on the secondary geomembrane is calculated using the following equation from Giroud, et al. (1997) (see Attachment A, 5/6):

$$t_{avgworst} = \frac{NQ}{kiB} \qquad \text{Equation 6}$$

where:

$t_{avg\ worst}$	= average thickness of liquid above secondary (bottom) geomembrane under worst case scenario; *to be determined, m*
N	= total number of defects in primary geomembrane; *65 from above*
Q	= flow rate through one defect in primary geomembrane; *1.63 x 10^{-5} m^3/sec*
k	= hydraulic conductivity of geonet layer above secondary geomembrane; *3.66 x 10^{-1} m/sec from above*
i	= hydraulic gradient in leakage collection layer; *0.049 from above*
B	= width of leakage collection layer; *1,125 feet, 343 m (Attachment B, 1/1)*

Placing the estimated geonet hydraulic conductivity, average thickness of liquid in the LDS, and the thickness of the leak detection layer geonet into Equation 6 results in the following:

$$t_{avgworst} = \frac{(65)(1.63x10^{-5})}{(3.66x10^{-1}\,\mathrm{m/sec})(0.049)(343\mathrm{m})}$$

$t_{avgworst}$ = 0.000172 m = 0.17 mm

The head on the secondary does not exceed 0.17 mm (0.006 inches), much less than the required 12 inch (1 foot) maximum.

SUMMARY AND CONCLUSIONS

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- Using the method outlined by Giroud, et al. (1997), and an N = 65, the ALR was calculated to be 604 gal/day/acre.
- Liquids entering the geonet LDS layer will take less than one day to travel from the leak to the LDS piping system.
- Assuming a worst case scenario under which all the primary geomembrane defects are located at the high end of the leakage collection layer slope, the liquid head on the secondary liner does not exceed 1-inch, well below the required maximum limit of 1-foot.
- The geonet provides sufficient flow rate to accommodate the ALR.

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J.P.G.

ATTACHMENT A, 1/6

Technical Paper by J.P. Giroud, B.A. Gross, R. Bonaparte and J.A. McKelvey

LEACHATE FLOW IN LEAKAGE COLLECTION LAYERS DUE TO DEFECTS IN GEOMEMBRANE LINERS

ABSTRACT: This paper provides analytical and graphical solutions related to the flow of leachate in a leakage collection layer due to defects in the overlying liner (i.e. the primary liner of a double liner system). The defects are assumed to be small (e.g. holes in geomembrane liners). It is shown that leachate flows in a zone of the leakage collection layer (the wetted zone) that is limited by a parabola. A simple relationship is established between the rate of leachate migration through the defect and the maximum thickness of leachate in the leakage collection layer; this relationship depends on the hydraulic conductivity (but not on the slope) of the leakage collection layer. Equations are provided to calculate the average head of leachate on top of the liner underlying the leakage collection layer (i.e. the secondary liner of a double liner system), which is useful for calculating the rate of leachate migration through that liner. Finally, the case of several leaks randomly distributed is considered, and equations for the surface area of the wetted zone and the average head are given for this case. Parametric analyses and design examples provide useful comparisons between the three types of materials used in leakage collection layers: gravel, sand and geonets.

KEYWORDS: Geomembrane, Defect, Leachate migration, Leachate collection, Leakage, Leakage collection, Liner system, Double liner, Geosynthetic leakage collection layer.

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It appears that, when the leakage collection layer is not full, there is an extremely simple relationship between the rate of leachate migration through the primary liner defect, Q, and the thickness of leachate in the leakage collection layer beneath the defect, t_o. It is interesting to note that this relationship does not depend on the size of the defect in the primary liner or on the slope of the leakage collection layer.

An approximation that was made to establish Equations 9 and 10 was to assume that the downslope flow line from A (i.e. AB in Figure 4a) is parallel to the liner. This assumption is close to reality as discussed in Section 2.2. However, the actual flow line from A is below Line AB as the flow thickness decreases in the downslope direction, as discussed at the end of Section 5.1.2. Therefore, t_o should only be regarded as the flow thickness at a primary liner defect, and it is the maximum flow thickness.

Since the simple relationship expressed by Equations 9 and 10 was demonstrated for the case when the leakage collection layer is not full, the condition expressed by Equation 1 must be met for Equations 9 and 10 to be valid. Combining Equations 1 and 10 gives the following equation, which is another way to express the condition that should be met to ensure that the leakage collection layer is not full:

$$t_{LCL} \geq t_{LCL\,full} = \sqrt{\frac{Q}{k}} \tag{11}$$

where $t_{LCL\,full}$ is the *minimum* thickness that a leakage collection layer with a hydraulic conductivity k should have to contain, without being full at any location, the leachate flow which results from a defect in the primary liner.

The following equation, derived from Equation 11, is another way to express the condition that should be met to ensure that the leakage collection layer is not full:

$$Q \leq Q_{full} = k\, t_{LCL}^2 \tag{12}$$

where Q_{full} is the *maximum* steady-state rate of leachate migration through a defect in the primary liner that a leakage collection layer, with a thickness t_{LCL} and a hydraulic conductivity k, can accommodate without being filled with leachate.

It is important to remember that the subscript *full* corresponds to a *minimum* thickness of the leakage collection layer and to a *maximum* rate of leachate migration (which is also the *maximum* flow rate in the leakage collection layer). It is noteworthy that the minimum thickness of the leakage collection layer, $t_{LCL\,full}$, and the maximum flow rate, Q_{full}, which are required to ensure that the leakage collection layer can contain, without being full, the flow that results from a defect in the primary liner, do not depend on the slope of the leakage collection layer.

It is not impossible to design a leakage collection layer with a thickness less than the value $t_{LCL\,full}$ given by Equation 11, i.e. where the flow rate is greater than Q_{full} defined by Equation 12. In this case, the leakage collection layer is filled with leachate in a certain area around the defect of the primary liner (i.e. "the leachate collection layer is full"). This case is discussed in Section 3.2.

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3.2 Rate of Leachate Flow When the Leachate Collection Layer is Full

If the thickness of the leakage collection layer is less than $t_{LCL\,full}$ expressed b tion 11 (or if the rate of leachate migration through a primary liner defect is grea Q_{full} expressed by Equation 12, which is equivalent), the leakage collection filled with leachate in a certain area around the defect. Following the appro scribed in Section 2.2, it may then be assumed that the leachate phreatic surfac leakage collection layer is a truncated cone (Figure 5). The virtual apex of the tr cone, A′, is above the leakage collection layer (i.e. above the primary liner, w the upper boundary of the leakage collection layer). The virtual leachate depth, the virtual leachate thickness, t_o, are related to the actual leachate head, h_o, t Equation 4, and the virtual leachate thickness t_o is greater than the thickness of chate collection layer:

$$t_o > t_{LCL}$$

The surface area of the vertical cross section of the flow in the leakage collectio (Figure 5) is expressed by:

$$S = \frac{D_o^2}{\tan\beta} - \frac{(D_o - D_{LCL})^2}{\tan\beta} = \frac{D_{LCL}(2D_o - D_{LCL})}{\tan\beta}$$

where D_{LCL} is the depth of the leakage collection layer.

The depth is measured vertically whereas the thickness is measured perpendi to the slope, hence, in accordance with Equation 3:

$$t_{LCL} = D_{LCL} \cos\beta$$

Using the demonstration presented in Section 2.2, i.e. combining Equations 8, 14 and 15, gives:

$$Q = k\, t_{LCL}(2t_o - t_{LCL})$$

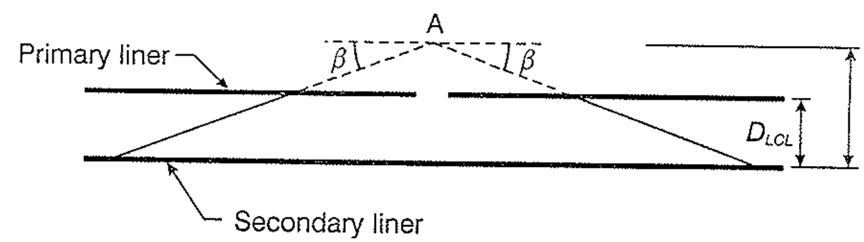

Figure 5. Vertical cross section of the assumed phreatic surface in the leakage coll layer in the case where the leakage collection layer is filled with leachate in a certai around the primary liner defect.

owing (or assuming) the leachate head, h_o, on top of the secondary liner vertically ath the primary liner defect, one may derive the virtual leachate thickness, t_o, using tion 4. Then, knowing t_o, t_{LCL} and k, one may use Equation 16 to calculate the rate chate flow through a defect that the leakage collection layer can convey.

e following equation can be derived from Equation 16:

$$t_o = \frac{t_{LCL}}{2}\left(1 + \frac{Q}{k\, t_{LCL}^2}\right) \tag{17}$$

e following equation can be derived from Equations 13 and 16:

$$t_{LCL} = t_o\left(1 - \sqrt{1 - \frac{Q}{k\, t_o^2}}\right) \tag{18}$$

uation 18 is valid only if the following condition is met:

$$Q \le k\, t_o^2 \tag{19}$$

hould be noted that if $t_{LCL} = t_o$, i.e. if the leakage collection layer is filled with lea- at only one point, i.e. at the location of the primary liner defect, Equation 16 is valent to Equation 9.

Parametric Study

ing the equations presented in Sections 3.1 and 3.2 it is possible to compare the capacity of different leakage collection layers in case of a defect in the primary . In Table 1, three different leakage collection layers are compared:

- geonet with a thickness of 5 mm and a hydraulic transmissivity resulting in a hy- aulic conductivity (obtained by dividing the hydraulic transmissivity by the thick- ss) of 1×10^{-1} m/s;
- gravel layer with a thickness of 300 mm and a hydraulic conductivity of 1×10^{-1} s; and
- and layer with a thickness of 300 mm and a hydraulic conductivity of 1×10^{-3} m/s.

e first two leakage collection layers have the same hydraulic conductivity and the wo have the same thickness. In the case of the geonet, the virtual leachate thick- t_o, considered in Table 1 is greater than, or equal to, the thickness of the leachate ction layer, t_{LCL}; therefore, in all cases considered in Table 1, the geonet is filled leachate over a certain area around the defect (this area being zero for t_o = 5 mm). e case of the gravel and sand layers, the leachate thicknesses considered in Table less than, or equal to, the thickness of the leakage collection layer; therefore, in ases considered in Table 1, the gravel and sand layer are not filled (or just filled) leachate, and for these two materials the leachate thicknesses, t_o, shown in Table actual (not virtual) thicknesses.

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Table 1. Rate of leachate flow in three different leachate collection layers resulting from a defect in the primary liner.

Leachate thickness (actual or virtual)		Leakage collection layer material: Geonet t_{LCL} = 5 mm, $k = 1 \times 10^{-1}$ m/s		Gravel t_{LCL} = 300 mm, $k = 1 \times 10^{-1}$ m/s		Sand t_{LCL} = 300 mm, $k = 1 \times 10^{-3}$ m/s	
t_o		Q		Q		Q	
(m)	(mm)	(m³/s)	(lpd)	(m³/s)	(lpd)	(m³/s)	(lpd)
0.005	5	2.5×10^{-6}	216	2.5×10^{-6}	216	2.5×10^{-8}	2.16
0.01	10	7.5×10^{-6}	648	1.0×10^{-5}	864	1.0×10^{-7}	8.64
0.05	50	4.75×10^{-5}	4,104	2.5×10^{-4}	21,600	2.5×10^{-6}	216
0.1	100	9.75×10^{-5}	8,424	1.0×10^{-3}	86,400	1.0×10^{-5}	864
0.3	300	2.975×10^{-4}	25,704	9.0×10^{-3}	777,600	9.0×10^{-5}	7,776

Notes: The leachate thickness, t_o, can be derived from the leachate head on top of the secondary liner using Equation 4. The leachate thickness, t_o, is the actual leachate thickness if $t_o < t_{LCL}$ and a virtual leachate thickness if $t_o > t_{LCL}$. The tabulated values of the rate of leachate flow, Q, were calculated using Equation 9 when $t_o < t_{LCL}$ and Equation 16 when $t_o > t_{LCL}$. Units: 1 m³/s = 86,400,000 liters per day (lpd).

It appears from Table 1, that for a given value of t_o, i.e. a given value of the head of leachate on top of the secondary liner, h_o (see Equation 4), the gravel and the geonet can convey significantly more leachate than the sand. It is interesting to compare the flow rates of Table 1 with rates of leachate migration through defects of geomembranes used alone (i.e. not part of a composite liner) calculated using Bernoulli's equation, which is expressed as follows:

$$Q = 0.6\,a\sqrt{2\,g\,h_{prim}} = 0.6\pi(d^2/4)\sqrt{2\,g\,h_{prim}} \approx \underline{(2/3)\,d^2\sqrt{g\,h_{prim}}} \tag{20}$$

where: a = defect area; d = defect diameter; g = acceleration due to gravity; and h_{prim} = head of leachate on top of the primary liner.

Table 2 gives rates of leachate migration through geomembrane defects calculated using Equation 20. It appears that, with the leachate heads that typically exist on the primary liners of actively operating landfills (i.e. landfills that are receiving waste), and provided that the geomembrane is used alone (i.e. is not part of a composite liner):

- a small geomembrane defect (e.g. 1 to 2 mm diameter), which may occasionally be undetected during construction, results in a rate of leakage on the order of 100 liters per day (lpd);
- a geomembrane defect (e.g. 3 to 5 mm diameter), which may occasionally occur during construction phases where defect detection may not be possible (e.g. placement of granular leachate collection material on geomembrane), results in a rate of leakage on the order of 1000 lpd (1 m³/day); and
- a large geomembrane defect (e.g. 10 mm diameter or more), which may occur under special circumstances, results in a rate of leakage of 10,000 lpd (10 m³/day) or more.

4.4 Wetted Fraction

4.4.1 *Scope of Section 4.4*

To calculate the rate of leakage through the secondary liner, it is useful to know what fraction of the total surface area of the secondary liner is wetted and what is the average head of leachate over this fraction of the secondary liner. The wetted fraction is determined in Sections 4.4.3 and 4.4.4, and the average head will be determined in Sections 5.1 and 5.2.

In the preceding sections, only one defect in the primary liner was considered. This is no longer the case in Section 4.4 because the wetted fraction depends on the number of defects per unit area. In Section 4.4, two scenarios of defect location will be considered: a scenario where the defects are located to give the maximum wetted fraction, and a scenario where the defects are at random.

In Section 4.4, a leakage collection layer whose length in the direction of the flow has a horizontal projection L, and whose width in the direction perpendicular is B, is considered (Figure 9). The projected surface area of this leakage collection layer is therefore:

$$A_{LCL} = L\,B \tag{98}$$

4.4.2 *Definitions*

Wetted Fraction. The wetted fraction, R_w, is defined as the ratio between the surface area of the total wetted zone and the surface area of the leakage collection layer:

$$R_w = \frac{\sum_{n=1}^{n=N} A_w}{A_{LCL}} \tag{99}$$

As shown by the numerator of the fraction, the surface area of the total wetted zone is the sum of the surface areas of the wetted zones that correspond to every defect in the primary liner, the number of defects being N.

Defect Frequency. The frequency of defects, F, in the primary liner (i.e. the liner overlying the leakage collection layer) is defined as the ratio of the total number of defects, N, in the liner and the surface area of the liner, which is equal to the surface area of the leakage collection layer:

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$$F = \frac{N}{A_{LCL}} \tag{100}$$

In typical design calculations the frequency of the defects in the primary liner, F, is assumed to be known. For example, if there are four defects per hectare (10,000 m^2), $F = 4/(10{,}000\ \text{m}^2) = (4/10{,}000)\ \text{m}^{-2} = (1/2{,}500)\ \text{m}^{-2} = 4 \times 10^{-4}\ \text{m}^{-2}$.

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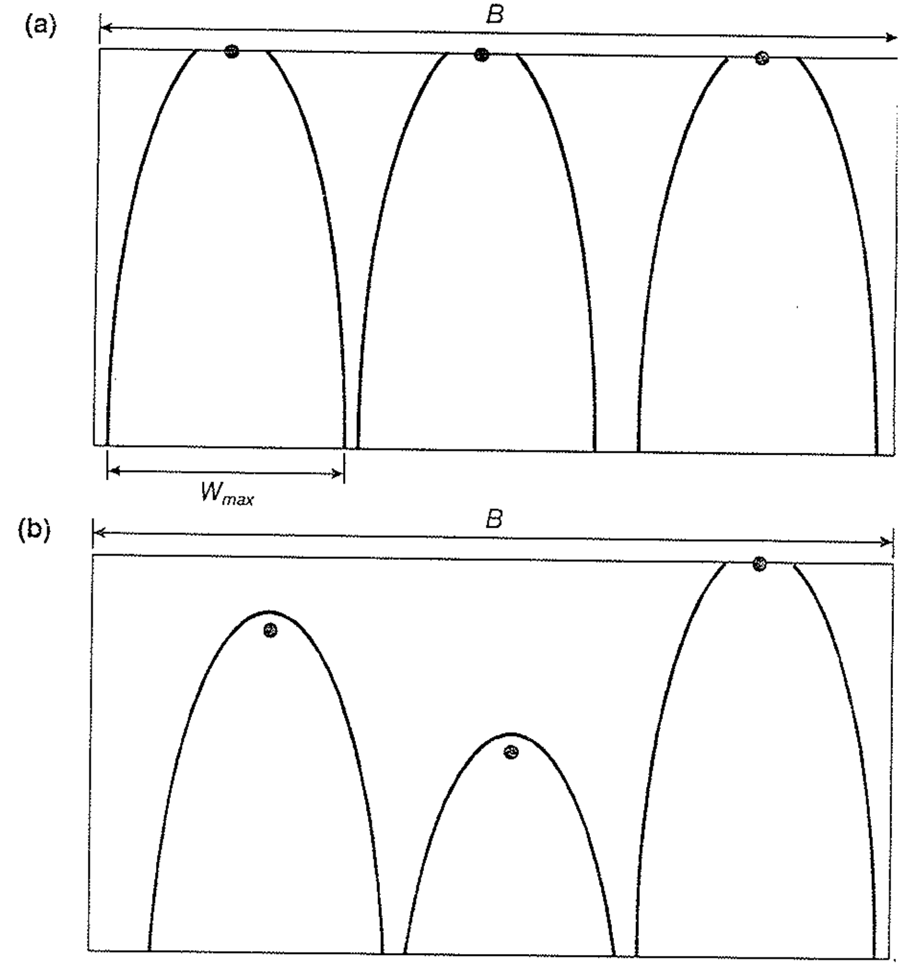

Figure 9. Leakage collection layer zones wetted by leachate migrating through sev defects in the primary liner, assuming no overlapping of wetted zones: (a) w scenario where all the defects are located at the high end of the leachate collection l slope; (b) random scenario where the defects are randomly distributed.

Notes: L is the horizontal projection of the length of the leakage collection layer in the direction of the fl and B is the width of the leakage collection layer. The dots represent the horizontal projection of the locati of the primary liner defects.

Scenarios. Two defect location scenarios will be considered: (i) the worst scen where all of the defects are at the high end of the leakage collection layer slope (Fig 9a); and (ii) the random scenario where the defects are randomly distributed (Fig 9b). In both scenarios it is assumed that the frequency of defects is small enough

$$\frac{t_{avg\,rand}\,\lambda_{rand}}{t_{avg\,worst}\,\lambda_{worst}} = \frac{2\,\mu}{9} + \frac{x_{rand}}{L} = \frac{\mu^{5/3}}{\left(10\sqrt{2}\right)^{2/3}}\left[\left(1+\frac{2}{\mu}\right)^{5/2} - 2\right]^{2/3} - \frac{5\mu}{18} \qquad (192)$$

Equation 192 is valid only for $\mu \leq 1.0696$. Values calculated using Equation 192 are given in Table 6. Values of $t_{avg\,rand}\,\lambda_{rand}/(t_{avg\,worst}\,\lambda_{worst})$ given in Table 6 for $\mu > 1.0696$ were calculated from numerical values of $\lambda_{worst}/\lambda_{rand}$ given in Table 4 and numerical values of $t_{avg\,rand}/t_{avg\,worst}$ given in Table 6.

5.2.4 *Average Leachate Thickness When Wetted Zones Overlap*

The values of the average leachate thickness given in Sections 5.2.2 and 5.2.3 are valid only if there is no overlapping of different wetted zones, i.e. if, as shown in Section 4.4.5:

$$R_{w\,worst} \leq \mathrm{Crit}\,(R_{w\,worst}) \qquad (193)$$

$$R_{w\,rand} \leq \mathrm{Crit}\,(R_{w\,rand}) \qquad (194)$$

If the conditions expressed by Equations 193 and 194 are not satisfied, there is overlapping between adjacent wetted zones. In this case, the best approach, from a practical standpoint, is to assume that the entire area of the leakage collection layer is wetted. Again, the worst scenario and the random scenario are considered. These two scenarios are defined in Section 4.4.2.

Worst Scenario. In the worst scenario all of the primary liner defects are located at the higher end of the leakage collection layer slope. Since the wetted zones have been assumed to overlap, it is approximately correct to consider that the entire leakage collection layer area is wetted. As a result, the leachate thickness is approximately uniform over the entire leakage collection layer area provided that the defects are uniformly distributed at the high end of the leakage collection layer slope. The average leachate thickness is then derived using the classical Darcy's equation, resulting in:

$$t_{avg\,worst} = \frac{N\,Q}{k\,i\,B} \qquad (195)$$

where: N = total number of defects in the primary liner; Q = rate of leachate migration through one defect of the primary liner, all defects being assumed identical and subjected to the same leachate head over the entire surface area of the primary liner; k = hydraulic conductivity of the leakage collection layer material; i = hydraulic gradient in the leakage collection layer; and B = width of the leakage collection layer.

Combining Equations 8 and 195 gives:

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$$t_{avg\,worst} = \frac{N\,Q}{k\,B\,\sin\beta} \qquad (196)$$

Combining Equations 98, 100 and 197 gives:

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$$t_{avg\,worst} = \frac{F\,L\,Q}{k\,\sin\beta}$$

Equations 195 to 197 are valid only if the leakage collection layer is not f the condition expressed by Equation 11 (or Equation 12 which is equivalent) is case where the leakage collection layer is *full over its entire surface area* is (i) Equations 16 to 18, which where established for the case where the leaka tion layer is *full in a limited area* around the primary liner defect, are not ap and (ii) assuming that the virtual thickness of leachate is a constant (t_{avg}) over area of the leakage collection layer allows Darcy's equation to be written as

$$N\,Q = k\,B\,t_{LCL}\,\sin\beta$$

which shows that there is no relationship between Q and t_{avg}. In other words, indeterminate. Therefore, no solution is proposed for the average leachate virtual thickness) for the case where the leakage collection layer is filled with

Random Scenario. In the random scenario, the primary liner defects are d at random. In the case where there are enough defects to assume that the entir collection layer area is wetted, the design of a leakage collection layer becom to the design of a leachate collection layer subjected to a uniform rate of leac eration. As shown by Giroud and Houlihan (1995), in most practical cases, a value of the leachate thickness is :

$$\frac{t_{avg}}{L} = \frac{\sum Q/(L\,B)}{2\,k\,\sin\beta}$$

With the notations used in this paper, Equation 199 becomes:

$$t_{avg\,rand} = \frac{N\,Q}{2\,k\,B\,\sin\beta}$$

Combining Equations 98, 100 and 200 gives:

$$t_{avg\,rand} = \frac{F\,L\,Q}{2\,k\,\sin\beta}$$

Comparing Equations 197 and 200 shows that the average leachate thicknes greater in the worst scenario than in the random scenario. (It should be rememl it has been assumed that, in both cases, the entire surface area of the leakage c layer is wetted.)

Equations 199 to 201 are valid only if the leakage collection layer is not f the condition is expressed by Equation 11 (or Equation 12 which is equivaler Also, for the reasons indicated after Equation 197, no solution is proposed fo where the leakage collection layer is full.

ence of Primary Liner Defect Frequency on Average Leachate Thickness

ant difference between Sections 5.2.2 and 5.2.3 on one hand, and Section other hand should be noted. Equations for $t_{avg\,worst}$ and $t_{avg\,rand}$ do not depend t frequency, F, in Sections 5.2.2 and 5.2.3, whereas they depend on F in 4. The reason for that is the following:

s 5.2.2 and 5.2.3, the wetted zones, that correspond to various defects in y liner, do not overlap. The average leachate thickness is the same in any dividual wetted zones and it is calculated for any of them. Consequently, leachate thickness does not depend on the frequency of defects. However, cy of defects governs the wetted fraction (i.e. the ratio between the total a of all wetted zones and the surface area of the leakage collection layer). 5.2.4, it is assumed that the entire surface area of the leakage collection ted. In other words, it is assumed that the wetted fraction is equal to one. the average leachate thickness is a function of all of the defects in the pri- and, consequently, is a function of the defect frequency.

ant to note that, when the wetted fraction exceeds the critical value (Sec- e design engineer must assume that the individual wetted zones (i.e. the that correspond to the individual defects in the primary liner) overlap and equations given in Section 5.2.4 to calculate the average leachate thick- ist, when the wetted fraction does not exceed the critical value, the design either use the equations given in Section 5.2.4 or use the equations given 2.2 and 5.2.3. The approach described in Section 5.2.4 is simpler: it con- ing that the entire leakage collection layer area is wetted. The approach Sections 5.2.2 and 5.2.3 is more complex but closer to reality: only a frac- kage collection layer is wetted and, in addition to calculating the average ness as shown in Sections 5.2.2 and 5.2.3, it is necessary to determine the ction using equations provided in Section 4.4. The use of both approaches y Example 6 in Section 6.1. roaches give values of the leachate thickness (and head) that are different wetted zones do not overlap, only the approach described in Sections 3 gives a correct value of the leachate thickness (or head). However, in verage leachate thickness is only calculated as a first step in the calcula- of leakage through the secondary liner. In this case, both approaches are e approach described in Section 5.2.4 gives a leachate thickness that is ormly distributed over the entire secondary liner, while the approach de- tions 5.2.2 and 5.2.3 gives a greater leachate thickness in the wetted area e outside the wetted area. The leakage rates calculated using the leachate rmined as indicated in Section 5.2.4 are conservative (i.e. greater than d using the leachate thickness determined as indicated in Sections 5.2.2 multiplied by the wetted fraction) because leakage rates typically vary to the head to a power less than one. This will be illustrated quantitative- .1, after Example 6.

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5.3 Time Required to Reach Steady-State Flow Conditions

5.3.1 *Equations*

The volume of liquid in a porous medium is less than the volume of porous medium that contains the liquid. As indicated by Equation 143, the volume of leachate in the leakage collection layer is equal to the volume of the leakage collection layer that contains the leachate multiplied by the porosity, n, of the leakage collection layer material. The time required for such a volume to pass through the primary liner defect, $\bar{t}_{req}$, gives a lower boundary of the time required to reach steady-state flow conditions, hence:

$$\bar{t}_{req} > \frac{nV}{Q} \tag{202}$$

Combining Equations 10, 153 and 202 gives the following equation for the case where the leakage collection layer is not full:

$$\bar{t}_{req} > \frac{n\,x}{k \sin\beta\,\cos\beta} + \frac{2\,n\,Q^{1/2}}{9 \sin^2\beta\,\cos\beta\,k^{3/2}} \tag{203}$$

The last term is generally negligible, because it represents the time required to fill the volume of the leakage collection layer that contains leachate between axes Oy and VY (Figure 6). This volume is either small or reduced by truncation (Figure 8). Therefore:

$$\bar{t}_{req} > \frac{n\,x}{k\,\sin\beta\,\cos\beta} \tag{204}$$

Equation 204 may be written as follows:

$$\bar{t}_{req} > \frac{x / \cos\beta}{k \sin\beta / n} \tag{205}$$

Combining Equations 8 and 205 gives:

$$\bar{t}_{req} > \frac{x / \cos\beta}{k\,i / n} \tag{206}$$

where the numerator is the distance between the primary liner defect and the low end of the leakage collection layer slope, and the denominator is the actual liquid velocity derived from Darcy's equation. Therefore, the right hand member of Equation 204 is the travel time, $\bar{t}_{travel}$, i.e. the time required by a drop of leachate to travel from the primary liner defect to the low end of the leakage collection layer, assuming that flow is not hampered by capillarity in the leakage collection layer:

$$\bar{t}_{req} > \bar{t}_{travel} = \frac{n\,x}{k\,\sin\beta\,\cos\beta} \tag{207}$$

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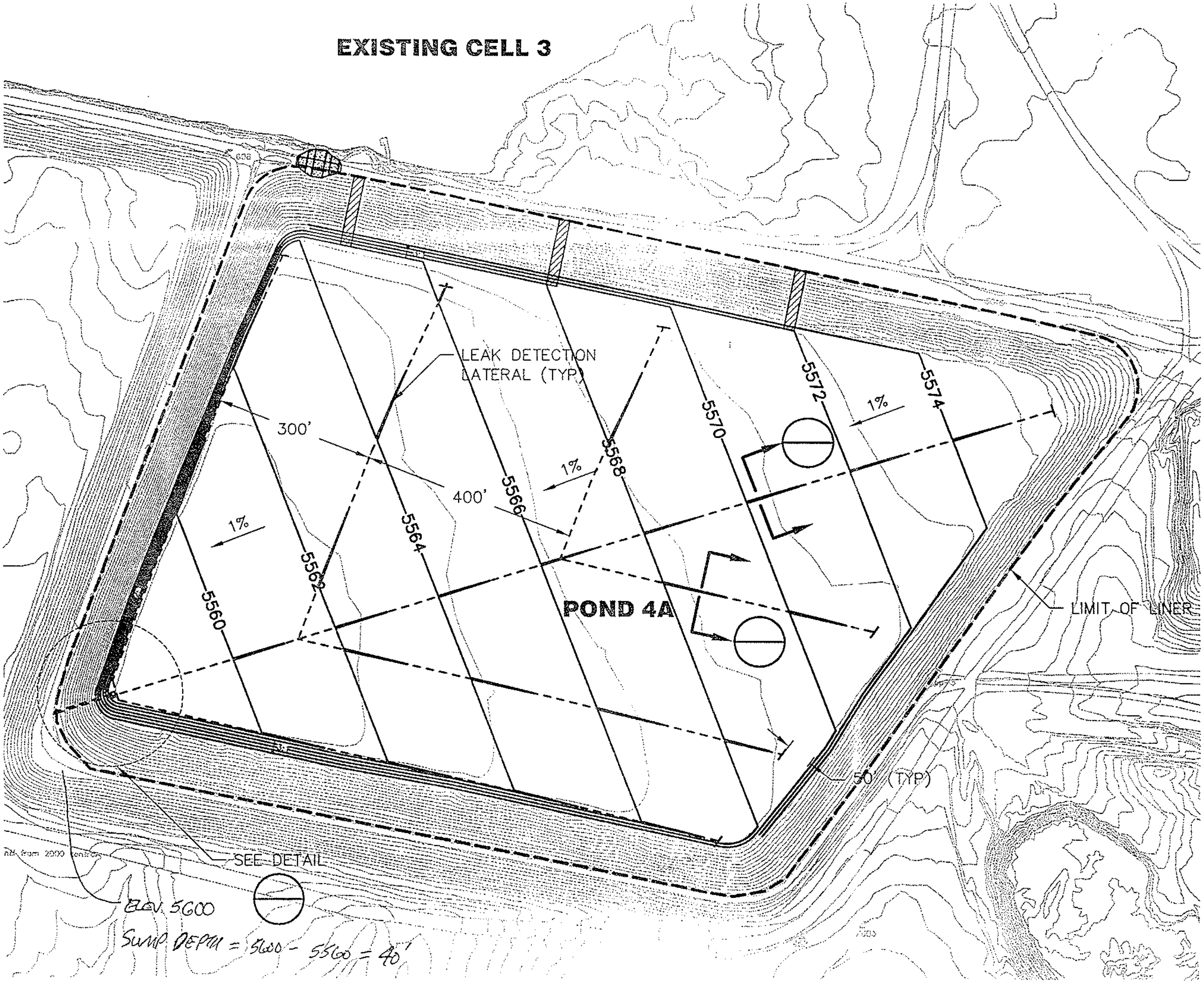

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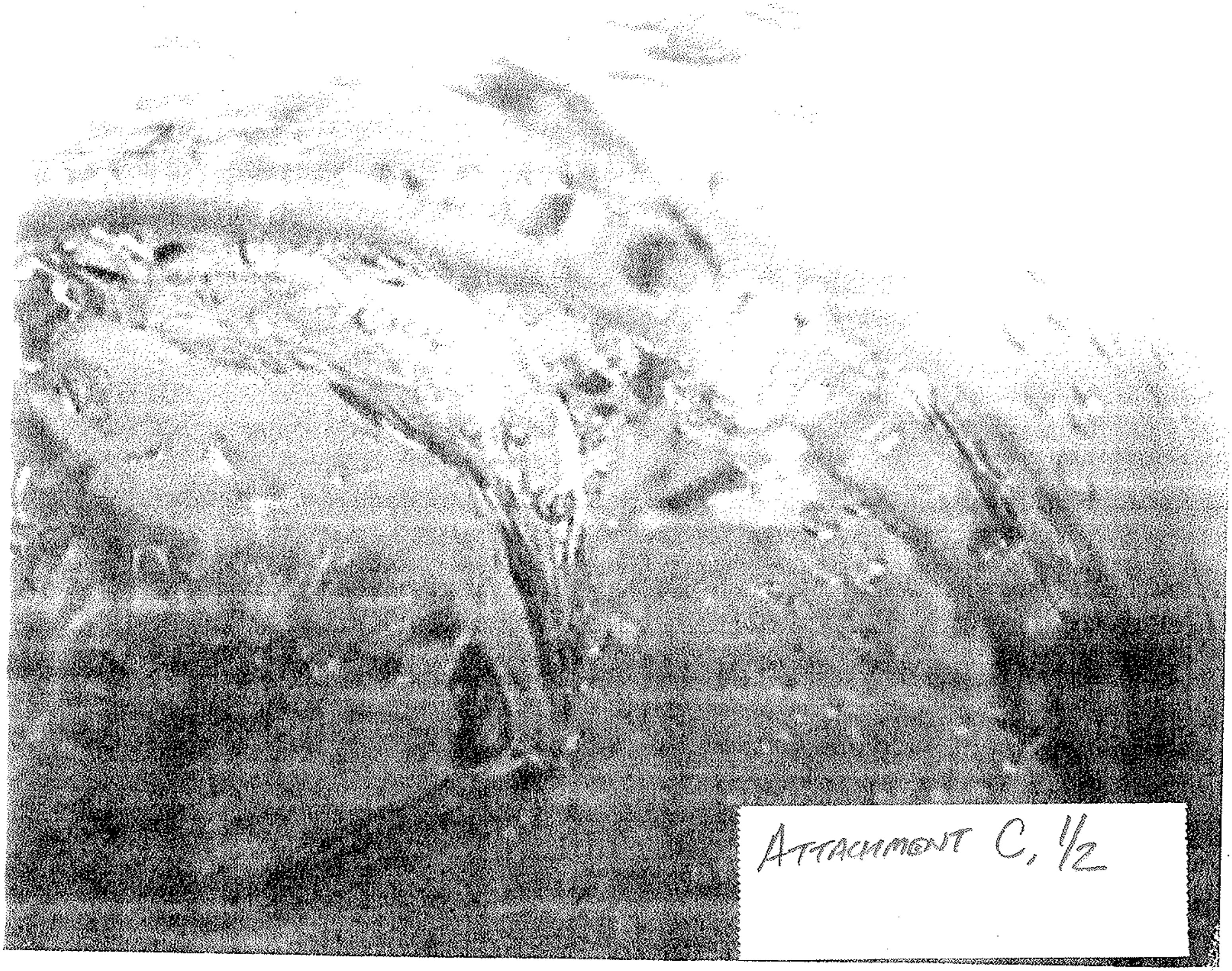

ATTACHMENT C, 1/2

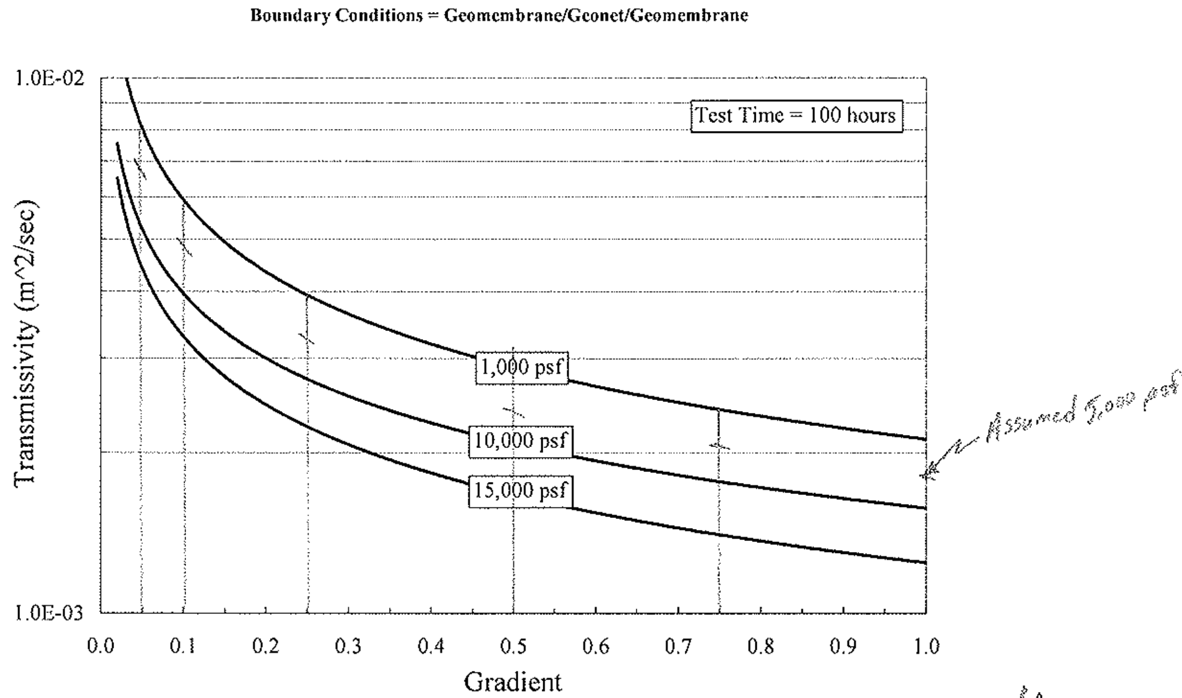

Figure A-7 100-hour transmissivity data for a 300 mil biplanar geonet between two geomembranes.

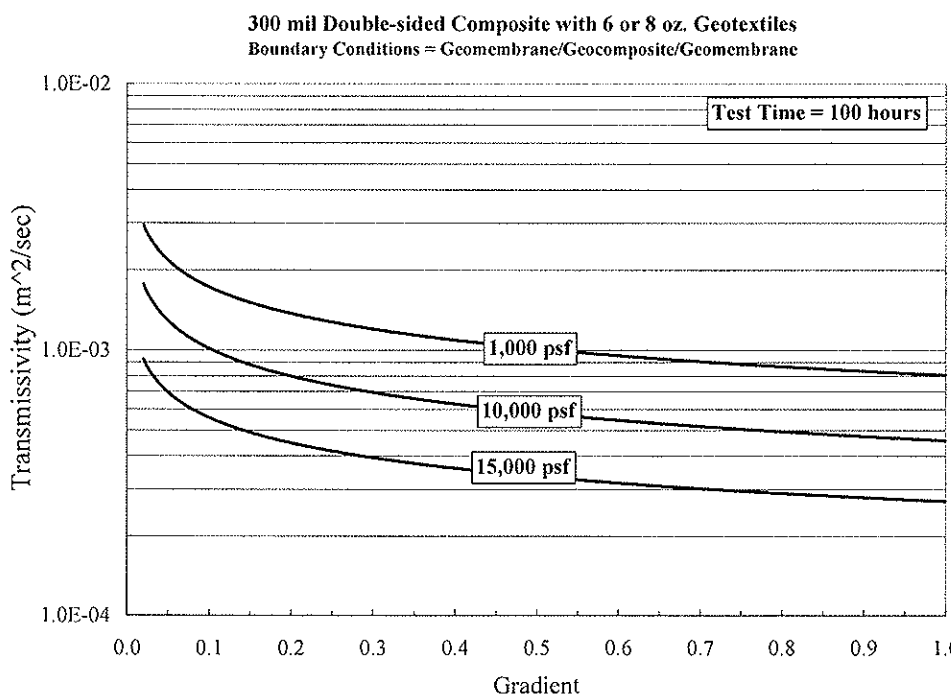

Figure A-8 100-hour transmissivity data for a 300 mil biplanar geonet geocomposite between two geomembranes.

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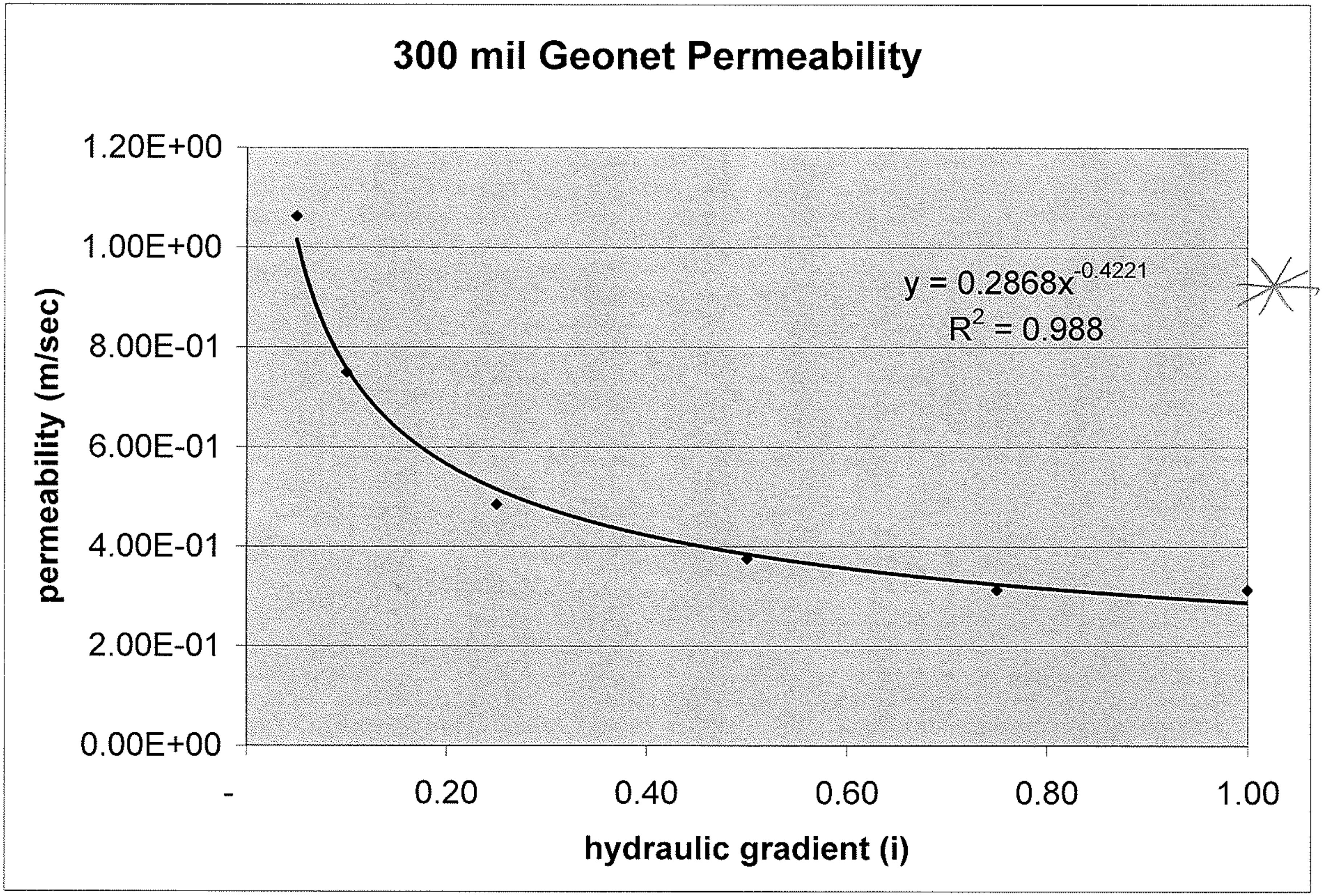

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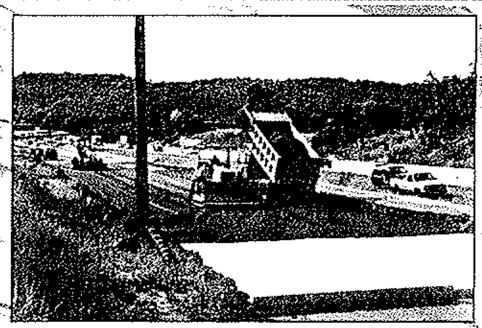
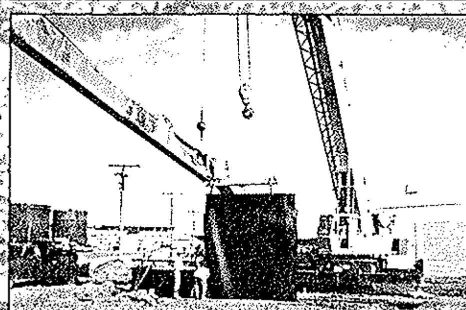
DESIGNING WITH GEOSYNTHETICS





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4.1.6 Allowable Flow Rate

As described previously, the very essence of the design-by-function concept is the establishment of an adequate factor of safety. For geonets, where flow rate is the primary function, this takes the following form.

$$FS = \frac{q_{\text{allow}}}{q_{\text{reqd}}} \tag{4.3}$$

where

- FS = factor of safety (to handle unknown loading conditions or uncertainties in the design method, etc.),
- q_{allow} = allowable flow rate as obtained from laboratory testing, and
- q_{reqd} = required flow rate as obtained from design of the actual system.

Alternatively, we could work from transmissivity to obtain the equivalent relationship.

$$FS = \frac{\theta_{\text{allow}}}{\theta_{\text{reqd}}} \tag{4.4}$$

where θ is the transmissivity, under definitions as above. As discussed previously, however, it is preferable to design with flow rate rather than with transmissivity because of nonlaminar flow conditions in geonets.

Concerning the allowable flow rate or transmissivity value, which comes from hydraulic testing of the type described in Section 4.1.3, we must assess the realism of the test setup in contrast to the actual field system. If the test setup does not model site-specific conditions adequately, then adjustments to the laboratory value must be made. This is usually the case. Thus the laboratory-generated value is an ultimate value that must be reduced before use in design; that is,

$$q_{\text{allow}} < q_{\text{ult}}$$

One way of doing this is to ascribe reduction factors on each of the items not adequately assessed in the laboratory test. For example,

$$q_{\text{allow}} = q_{\text{ult}}\left[\frac{1}{RF_{IN} \times RF_{CR} \times RF_{CC} \times RF_{BC}}\right] \tag{4.5}$$

or if all of the reduction factors are considered together.

$$q_{\text{allow}} = q_{\text{ult}}\left[\frac{1}{\Pi RF}\right] \tag{4.6}$$

where

- q_{ult} = flow rate determined using ASTM D4716 or ISO/DIS 12958 for short-term tests between solid platens using water as the transported liquid under laboratory test temperatures,

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q_{allow} = allowable flow rate to be used in Eq. (4.3) for final design purposes,
RF_{IN} = reduction factor for elastic deformation, or intrusion, of the adjacent geosynthetics into the geonet's core space,
RF_{CR} = reduction factor for creep deformation of the geonet and/or adjacent geosynthetics into the geonet's core space,
RF_{CC} = reduction factor for chemical clogging and/or precipitation of chemicals in the geonet's core space,
RF_{BC} = reduction factor for biological clogging in the geonet's core space, and
ΠRF = product of all reduction factors for the site-specific conditions.

Some guidelines for the various reduction factors to be used in different situations are given in Table 4.2. Please note that some of these values are based on relatively sparse information. Other reduction factors, such as installation damage, temperature effects, and liquid turbidity, could also be included. If needed, they can be included on a site-specific basis. On the other hand, if the actual laboratory test procedure has included the particular item, it would appear in the above formulation as a value of unity. Examples 4.2 and 4.3 illustrate the use of geonets and serve to point out that high reduction factors are warranted in critical situations.

Example 4.2

What is the allowable geonet flow rate to be used in the design of a capillary break beneath a roadway to prevent frost heave? Assume that laboratory testing was done at the proper design load and hydraulic gradient and that this testing yielded a short-term between-rigid-plates value of 2.5×10^{-4} m²/s.

Solution: Since better information is not known, average values from Table 4.2 are used in Eq. (4.5).

TABLE 4.2 RECOMMENDED PRELIMINARY REDUCTION FACTOR VALUES FOR EQ. (4.5) FOR DETERMINING ALLOWABLE FLOW RATE OR TRANSMISSIVITY OF GEONETS

Application Area	RF_{IN}	RF_{CR}*	RF_{CC}	RF_{BC}
Sport fields	1.0 to 1.2	1.0 to 1.5	1.0 to 1.2	1.1 to 1.3
Capillary breaks	1.1 to 1.3	1.0 to 1.2	1.1 to 1.5	1.1 to 1.3
Roof and plaza decks	1.2 to 1.4	1.0 to 1.2	1.0 to 1.2	1.1 to 1.3
Retaining walls, seeping rock, and soil slopes	1.3 to 1.5	1.2 to 1.4	1.1 to 1.5	1.0 to 1.5
Drainage blankets	1.3 to 1.5	1.2 to 1.4	1.0 to 1.2	1.0 to 1.2
Surface water drains for landfill covers	1.3 to 1.5	1.1 to 1.4	1.0 to 1.2	1.2 to 1.5
Secondary leachate collection (landfills)	1.5 to 2.0	1.4 to 2.0	1.5 to 2.0	1.5 to 2.0
Primary leachate collection (landfills)	1.5 to 2.0	1.4 to 2.0	1.5 to 2.0	1.5 to 2.0

*These values are sensitive to the density of the resin used in the geonet's manufacture. The higher the density, the lower the reduction factor. Creep of the covering geotextile(s) is a product-specific issue.

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