Part Three: Designing for a Target Leakage Rate

(and what can go wrong)

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1

Target Performance

- Groundwater modeling
- State/local/permit requirements specify Allowable Leakage Rate (ALR)?
  - Sites exceeding ALR will NOT be permitted to operate
  - This ONLY applies to double-lined facilities where leakage through the primary GM is monitored
- Zero leakage
  - "All liners leak." – J.P. Giroud
  - Vapor diffusion through intact geomembrane: = 0.2-20 lphd (≅1.0 gpad)
  - Possible target: Zero leaks (holes)
- Essential that any project with a leakage target use ELL methods to reduce risk
  - Understand project-specific configuration and materials
  - Method selection and specification (tailor to desired level of risk)
- How much leakage can I expect to have???

2

How much Leakage to Expect?

- Approach 1:
  - Source leakage rate statistics from double-lined facilities of similar design
- Approach 2:
  - Source leak type and frequency statistics
  - Use existing leakage equations to calculate anticipated leakage rate

3

EVOLUTION OF CONSTRUCTION QUALITY

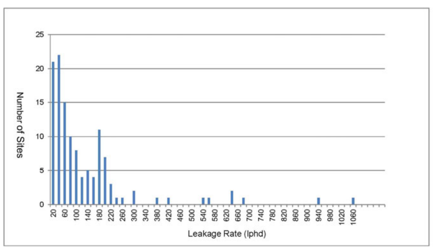
Leakage Rate (lphd) [b]	Percentage of Landfill Cells 1992 [a]	2012 [a]
<50	43%	73%
50 - 200	36%	24%
200 - 500	14%	3%
500 – 1,000	7%	0%
>1,000	0%	0%

(a) Year Data published (1992 values from Bonaparte and Gross)
(b) liters per hectare per day; l gpad = 9.3 lphd

Source: Beck, Abigail (2012). "How Much Does my Landfill Leak?". *Waste Advantage Magazine*, December Issue.

4

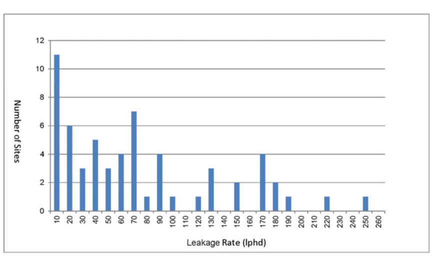
LEAKAGE STATISTICS – NO ELL APPLIED



Source: Beck, Abigail (2015). "Available Technologies to Approach Zero Leaks". *Geosynthetics 2015 Conference Proceedings.*

5

LEAKAGE STATISTICS – DIPOLE METHOD APPLIED



Source: Beck, Abigail (2015). "Available Technologies to Approach Zero Leaks". *Geosynthetics 2015 Conference Proceedings.*

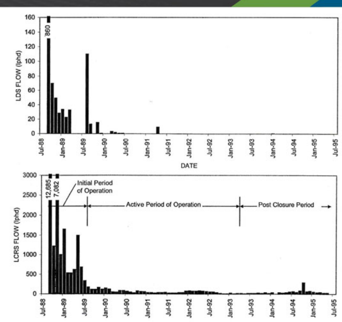
6

Double-Lined NYS LF Leakage Statistics

- Specific to NYS landfill design
- Already biased because of the enforced ALR of 20 gpad (189 lphd)
  - All cells reporting are already permitted
  - Monthly averaging is allowed
- Statistics taken from hundreds of cells of various ages
  - Leakage highest in beginning:
    - Overlying waste absorbs rainfall so less liquid gets down to primary GM
    - GCL consolidates as pressure from overlying waste increases

7

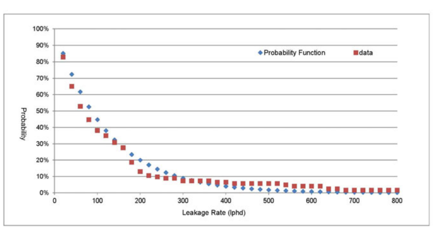
LEAKAGE DURING LIFE OF CELL



Source: National Research Council of the National Academies (2007). "Assessment of the Performance of Engineered Waste Containment Barriers". *The National Academy Press,* Washington, D.C.

8

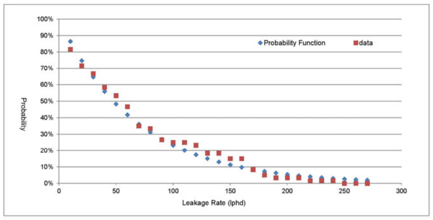
PROBABILITY FUNCTION – NO ELL APPLIED



Source: Beck, Abigail (2015). "Available Technologies to Approach Zero Leaks". *Geosynthetics 2015 Conference Proceedings.*

9

PROBABILITY FUNCTION – DIPOLE APPLIED



Source: Beck, Abigail (2015). "Available Technologies to Approach Zero Leaks".
Geosynthetics 2015 Conference Proceedings.

10

Probability Equation

Y(x) = exp[(-1/**mean**) · **x**]

- Where:

  mean = average leakage value for data set

  x = target leakage rate (ALR)

  Y(x) = probability of EXCEEDING target leakage rate

Calculate probability of exceeding a specified leakage rate based on:

- Most likely leakage value for project (average leakage for many similar projects)
- What if average is not known???
  - **Approach 2:** Source leak frequency statistics

    Use existing leakage equations to calculate anticipated leakage rate

11

Leak Frequency is a function of:

- Experience/Skill of Installer
- Presence and quality of CQA
- Geomembrane thickness
- Cover material specification / conformance to spec
- Cover material placement method / CQA
- Site Conditions / weather
- Thoroughness of Design / Material Testing
- Location of Project
- Which method is used to generate statistics
- **LEVEL OF CARE**

Simply applying liner integrity survey biases statistics!

12

Leak Frequency Statistics

- Generated by ELL (potentially missed leaks)
- Biased by method used to test, project age and location
- Outdated (installation quality continually gets better):
  - 0.7 – 11 Holes per hectare (Rollins, Jacquelin, 1999)
  - Up to 15 holes per hectare for leachate impoundments (Rollins, Jacquelin, 1999)
  - Exposed geomembranes: 4 holes per hectare with CQA, 22 holes per hectare without CQA (Forget, 2005)
  - Covered geomembranes: 0.5 holes/ha with CQA and bare survey, 16 holes/ha without CQA or bare survey (Forget, 2005)
  - 73% damage occurs during cover soil placement, 24% occur during geomembrane installation, 2% occurs during post construction (Nosko, 1996)
- Expressing leak frequency as average does not capture the variability of projects
- Projects tend to have very few or many leaks, rarely stated average

13

2005 STATISTICS - INTERNATIONAL

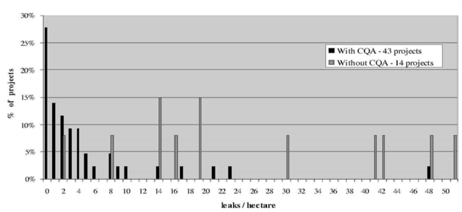


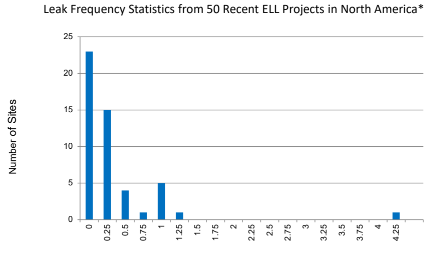
Figure 3. Leak Densities – With and Without a Rigorous CQA Program (Exposed Geomembranes).

Forget et al., 2005; summary of 57 projects over 10 years

14

LEAK FREQUENCY STATISTICS – >1.5 mm HDPE GM, Good CQA

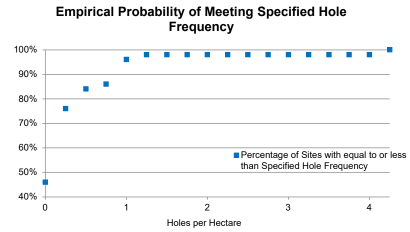
Leak Frequency Statistics from 50 Recent ELL Projects in North America*



*Gilson-Beck, A. "Controlling Leakage through Installed Geomembranes Using Electrical Leak Location". *Geotextiles and Geomembranes*, 47 (2019) 697-710.

15

LEAK FREQUENCY STATISTICS – ≥1.5 mm HDPE GM, Good CQA



*Gilson-Beck, A. "Controlling Leakage through Installed Geomembranes Using Electrical Leak Location". *Geotextiles and Geomembranes*, 47 (2019) 697-710.

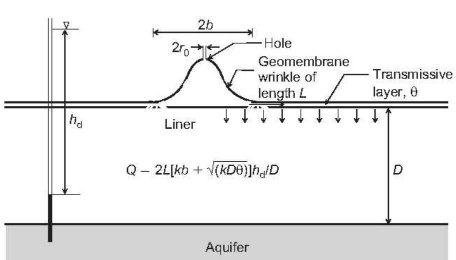
16

Leakage Equations

- Bernoulli equation: $Q = 0.6 * a * \sqrt{2gh}$
  - Free flow below geomembrane
- Giroud equation: $\frac{Q}{A} = n \cdot 0.976 C_{qo} \cdot [1 + 0.1 \cdot (h/t_s)^{0.95}] \cdot d^{0.2} \cdot h^{0.9} \cdot k_s^{0.74}$
  - Geomembrane underlain by low permeability layer
  - In intimate contact
- Rowe equation: $Q=2L[k_b b+(k_a \theta D)^{0.5}]*h_d/D$
  - Geomembrane underlain by low permeability layer
  - Geomembrane not in intimate contact with underlying layer (leak on wrinkle)

17

ROWE EQUATION



Source: Rowe, K.(2012). "Modelling of Contaminant Transport through a hole in the GMB". *Canadian Geotechnical Journal.*

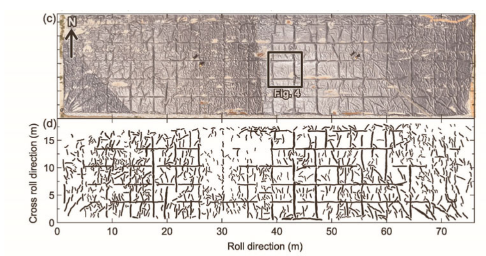
18

Compounded Problem

- Wrinkles do not disappear when they area covered; rather, they are encapsulated
- Locations where wrinkles are more likely tend to also be locations where holes are more likely
- Most ELL methods not likely to be effective on wrinkles
- A hole on a wrinkle results in **100-1000** times more leakage than that same sized hole in intimate contact with the underlying layer
- A geomembrane "has a performance, when it exhibits wrinkles, **only slightly better** than the performance of a low-permeability soil liner alone". – J.P. Giroud

19

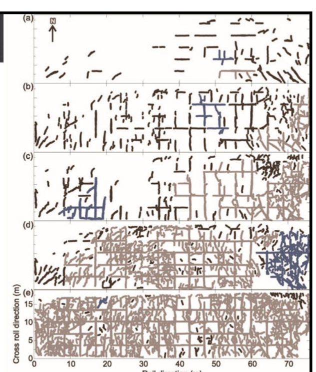
EVALUATION OF WRINKLE EXTENT



Source: Rowe, et al. (2012). "Field Study of wrinkles in a geomembrane at a composite liner test site". Canadian Geotechnical Journal.

20

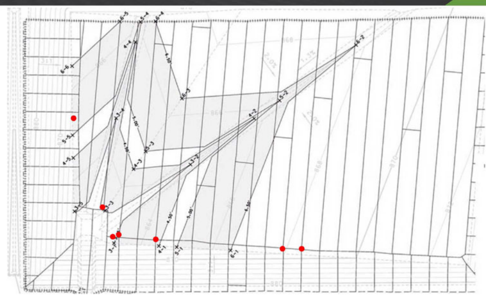
WRINKLE EXTENT VS TIME OF DAY



Source: Rowe, et al. (2012). "Field Study of wrinkles in a geomembrane at a composite liner test site". Canadian Geotechnical Journal.

21

CASE STUDY : 5 GPAD LANDFILL



Source: Beck, Abigail (2014). "Designing to Minimize Geomembrane Leakage". *Geosynthetics Magazine, August Issue.*

22

CASE STUDY : LEAK LOCATIONS

Source: Beck, Abigail (2014). "Designing to Minimize Geomembrane Leakage". *Geosynthetics Magazine, August Issue.*

23

CASE STUDY : ACTUAL LEAKAGE VS. THEORETICAL EQUATIONS

Leakage (gpad) [1]				
Column 1	Column 2	Column 3	Column 4	Column 5
Actual Leakage Before Repairs (Recorded Daily)	**Good Contact (Giroud Eq. [2])**	**Poor Contact (Giroud Eq. [2])**	**Leakage On Wrinkle (Rowe Eq. [3])**	**Calculated Post-Repair Leakage (Column 1 – Column 4)**
30.00	0.41	2.26	26.14	3.86
30.67	0.48	2.62	28.59	2.08
30.89	0.49	2.70	29.11	1.78
28.89	0.37	2.00	24.30	4.59

Notes:
(1) 1 gpad = 9.35 lphd
(2) Assuming actual estimated hole size and geometries and actual estimated hydraulic head at location of leak(s) at time of leakage measurement, GCL thickness of 0.006 m, GCL hydraulic conductivity of 5.0 x 10-11 m/s and GCL thickness of 0.006 m.
(3) Assuming wrinkle width of 0.31 m, wrinkle length of 190 m, GCL hydraulic conductivity of 5.0 x 10-11 m/s, GCL thickness of 0.006 m and transmissivity of geomembrane/GCL interface of 2.0 x 10-10 m2/s (for low compressive stress condition).

Source: Beck, Abigail (2014). "Designing to Minimize Geomembrane Leakage". *Geosynthetics Magazine, August Issue.*

24

Designing for a Leakage Rate

Y(x) = exp[(-1/**mean**) · **x**]

- Where:
  mean = average leakage value for data set
  x = target leakage rate (ALR)
  Y(x) = probability of EXCEEDING target leakage rate
- Calculate expected leakage rate (mean) based on:
  - ELL technologies applied (what kinds of leaks might remain?)
  - Potential for "poor contact" between liner and subgrade

25

Designing for a Leakage Rate: Finding Mean

- Use average number of holes per acre based on level of CQA
  - ~4 leaks/ha with CQA* (use old stats for conservative estimate)
- Assume that **ELL locates all leaks with good contact** down to minimum detectable leak size, dependant on method used (1-6.4 mm)
  - Giroud equation can be used to calculate leakage through the smaller leaks with good contact but leakage value will be negligible
- **Use Rowe equation** to calculate leakage from holes falling on wrinkles
  - Assume percentage of area covered by wrinkles based on geomembrane type, time of day liner covered, field conditions, etc.
  - Multiply assumed leaks/ha by the wrinkle percentage to find number of leaks/ha remaining after ELL applied

*Source: Forget et al.(2005). "Lessons Learned from 10 Years of Leak Detection Surveys on Geomembranes". *Sardinia Conference.*

26

Designing for a Leakage Rate: Example

- Assumptions:
  - Leaks possible in all locations with equal probability
  - 4.9 leaks per ha
  - **ELL will not detect leaks on wrinkles**
  - Percentage of wrinkled area (17% typical GM, 7% white GM)
  - Wrinkle geometry (0.31 m wide, 190 m long)
  - GCL hydraulic conductivity and GM/GCL interface transmissivity (5.0 x 10-11 m/s, 2.0 x 10-10 m2/s)
  - Hydraulic head of 0.3 m

27

DESIGNING FOR A LEAKAGE RATE: EXAMPLE

Applied Technology	Probability of Exceeding 187 lphd (20 gpad)	Probability of Exceeding 47 lphd (5 gpad)
ELL Applied after cover material placement only*	6.6%	50.7%
ELL Applied both before and after cover material placement	0.02%	11.7%
ELL Applied both before and after cover material placement, plus white geomembrane	8.9 x 10-10%	0.55%

*From NYS landfill statistics

28

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Controlling Leakage Caused by Wrinkles

- Maximum wrinkle height specification
- Controlling time of day when liner is covered
- Specifying white geomembrane
  - White geomembrane limits solar radiation absorption
- Specifying conductive-backed geomembrane
  - "Virtually" eliminates wrinkles to enable ELL methods
- Controlling ELL testing conditions
  - Standing water above geomembrane

29

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Goal: Zero Leaks

- Holes caused by mistakes; possible to install a geomembrane without any mistakes
- ELL will find all mistakes if:
  - Project has appropriate and thorough ELL specifications
  - **Testing conditions are ideal** (specifications help with this)
  - Testing performed properly
- Conductive-backed GM enhances ELL testing conditions (resolves poor contact issues)
  - Following logic of previous probability analysis, use of conductive-backed GM reliable way to attain zero leakage
  - Still needs all other testing conditions to be idea (not panacea)

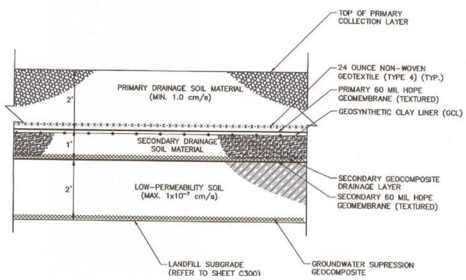
30

Testing Condition Goals

- Four "Boundary Conditions":
1. Conductive medium above geomembrane (or exposed)
2. Conductive medium **in holes** through geomembrane for covered geomembrane testing (in intimate contact with subgrade for exposed geomembrane testing)
3. Conductive medium under geomembrane
4. Medium above liner (if applicable) not in contact with medium below liner (except through leaks) (**SURVEY AREA ISOLATION**)
- **Current flows through leaks and ONLY leaks**
  - Otherwise: false positives, decrease in sensitivity, method ineffectiveness

31

LINING SYSTEMS AND CONSTRUCTION MATERIALS



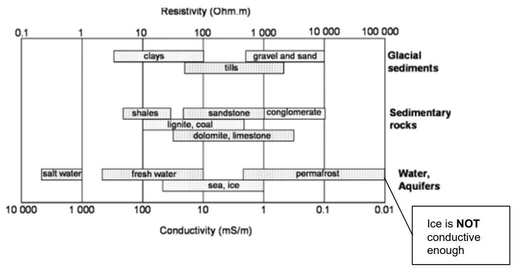
32

Geosynthetic Layers

- Geotextile
  - Biggest issue is reducing/removing contact through hole
  - Typically not a problem as long as it is wet
  - Tends to wick moisture and hold onto it when kept covered
- Geocomposite
  - Geonet core is problem
  - Must be saturated in order to detect installation damage
  - If not saturated, will only find damage caused by cover material placement
- GCL
  - Wicks moisture from subgrade
  - Desiccation only a problem for encapsulated GCL
  - Problems with conductivity with less than 8% M.C. (product specific)*

33

SOIL AND WATER AS RESISTORS



34

Earthen Material

- Clay/Subgrade
  - Sufficiently conductive with minimal moisture (less than 1%)
  - Only issue; surface desiccation when used as cover material
- Gravel/Stone
  - Dirty or clean?
  - Usually Requires recent irrigation
  - Large diameter clean stone needs to be watered immediately prior to test
- Sand
  - Requires higher moisture content (>6%)
- Concrete
  - Conductive with very little moisture content
  - Can have false positive problems with rebar
- Minerologically rich/(bio)chemically active soils
  - Can create “noise” throughout survey area with rogue voltage differentials

35

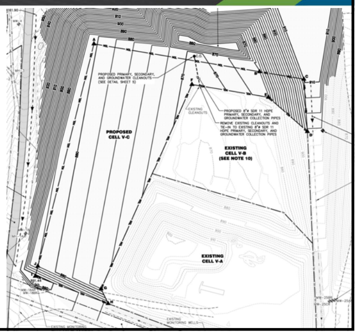
Solutions

- Rain water
  - NOT conductive
  - Grabs ions from any earthen material that it touches for conductivity
- Brine
  - Highly conductive
  - Exacerbates isolation issues
  - Creates highly localized leak signal (smaller leak detection distance)
- Chemically active (biological, industrial)
  - Can be problem for electrodes
  - Can create “noise” throughout survey area with rogue voltage differentials

36

THE REQUIREMENT FOR IRRIGATION

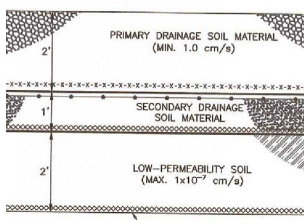
- Most problems solved with water addition
- Sufficient rainfall
- Geomembrane should be forced to LEAK before testing
- Can there be too much water???
- Free draining slopes will reduce detectability
- No industry standard guidance for minimum moisture content for ELL
- ELL contractor may only advise to water if surface desiccation is issue



37

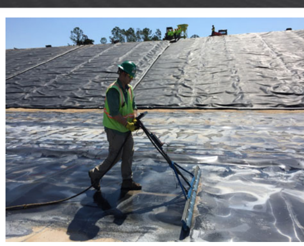
TESTING SEQUENCING – DOUBLE LINED

- Testing one or both geomembranes?
- Must test secondary (lower) geomembrane before primary (upper) geomembrane placement
- Interim "isolated" condition
- Install "electrodes" under primary geomembrane to enable testing
  - Bare copper wires, per ELL contractor recommendation

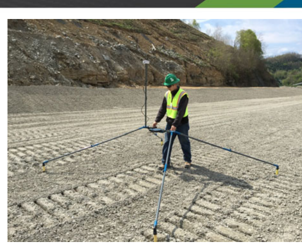


38

ELL METHOD SELECTION



Bare Geomembrane Method?



Covered Geomembrane Method?

Or Both?

39

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Method Selection

- Design goals (leakage)
- Project configuration
- Reference: ASTM D6747-21 Standard Guide for "Selection of Techniques for Electrical Leak Location of Leaks in Geomembranes"
- All ASTM-based bare geomembrane methods have "equivalence" clause:
  - "All of the methods…are effective at locating leaks in exposed geomembranes. Each method has specific site and labor requirements, survey speeds, advantages and limitations…Alternative ASTM Standard Practices for electrical leak location survey methods should be allowed when mutually agreeable and warranted by adverse site conditions, clearly technical superiority, logistics, or schedule."

40

BARE LINER TESTING – 3RD PARTY

41

BARE LINER TESTING – INSTALLER

42

Special Configurations / Details

- Inlet/outlet structures
  - Can usually only test up to attachment(s)
  - Specify non conductive materials for thorough test
- Pipe Boots
  - Field-fabricated pipe boot mostly likely place for leaks and difficult to test
  - Spark testing of extrusion welds (done by installer)
- Liner Tie-in area(s) and tie-in seam(s) (landfill expansion cells)
  - Prone to leaks due to difficulty welding (winkles, moisture, dirty existing liner, different liner materials)
  - When tie-in seam falls inside of soil-covered area, tie-in easy to test unless there are excessive leaks
  - When tie-in seam is exposed, it is sometimes not tested
  - Some designers and regulators call for arc testing of tie-in in addition to dipole method after cover material placement

43

INLET-OUTLET STRUCTURES

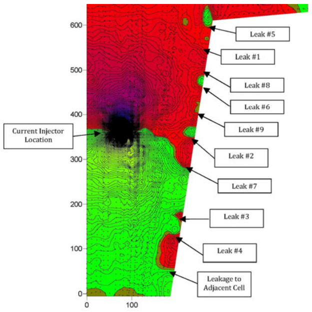
44

PIPE BOOT TESTING

- Method will depend on:
  - Whether newly installed (dry) or has already been leaking
  - Whether pipe flows to ground (can install bladder?)
  - Type of liner (conductive-backed?)
- Arc testing will work if penetration has leaked
- Newly installed must be forced to leak
- Water puddle or dipole method

45

TIE-IN SEAM TESTING – SOIL COVERED



46

TIE-IN SEAM/AREA TESTING – EXPOSED

47

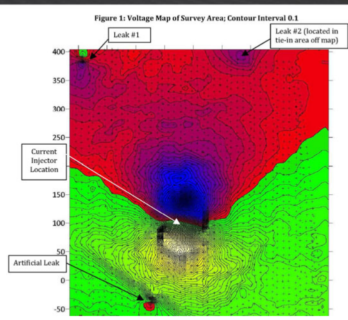
TIE-IN SEAM/AREA TESTING – RAIN FLAP ISOLATION

48

TIE-IN SEAM/AREA TESTING – RAIN FLAP ISOLATION

49

TIE-IN SEAM/AREA TESTING – RAIN FLAP ISOLATION



50

IMPORTANCE OF TIE-IN TESTING

51

IMPORTANCE OF TIE-IN TESTING

- Issues occur with tie-in weld because:
  - This area can be constantly wet from run-off from existing landfill
  - This area is frequently filled prone to wrinkles
- Whole area subject to damage from:
  - Excavating existing landfill material to uncover existing liner for tying into
  - Working in area with tools
  - Cleaning Efforts
- Many designers and regulators don't realize that this area is typically not testing during dipole method testing!

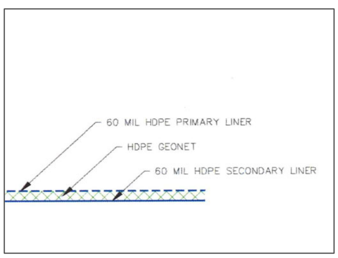
Table 1: Leak Descriptions

Damage Designation	Description
1	~1" Linear puncture
2	Leak in Extrusion weld
3	Leak in Extrusion weld
4	~3/4" Linear puncture
5	~3/4" Linear puncture
6	Circular Pinhole Puncture
7	~3/4" Linear puncture
8	~1" Long Knife Slice
9	~1/4" Puncture
10	~2" Long Knife Slice
11	~3/4" Long puncture adjacent to Extrusion Weld
12	Circular Pinhole Puncture
13	~1/2" Puncture
14	(2) Punctures, ~1/4" and ~1-1/2" Long
15	~3/4" Long puncture adjacent to Extrusion Weld
16	~1/4" Puncture
17	~1/2" Long Knife Slice
18	Leak in Extrusion weld
19	~3/16" Circular Puncture
20	Pinhole Puncture on Scrape Marks
21	~3/4" Linear puncture
22	~3/4" Linear puncture
23	~1/4" Puncture
24	Leak in Extrusion weld
25	(2) Punctures, ~1/2" and ~1" Long
26	~1" Long Linear Scrape
27	~1/4" Puncture
28	~3/4" Linear puncture
29	~3/4" Linear puncture
30	~3/4" Linear puncture
31	~3/4" Linear puncture
32	~1/4" Puncture
33	Multiple Pinholes on Scrape Marks
34	~1/4" Linear puncture
35	Bad Extrusion Weld
36	~1/4" Puncture
37	~1/2" Linear puncture
38	~1/4" Puncture
39	~1/4" Puncture
40	~1" Long Linear Scrape
41	~1/4" Puncture

52

SPECIAL CASE: DOUBLE-LINED POND

- Options:
  - Specify conductive-backed geomembrane as primary
  - Specify conductive geotextile under the primary geomembrane
  - Fill leak detection layer with water to enable testing
- Fill leak detection layer to test:
  - Water dipole wading survey
  - Filled pond test



53

Project Specifications

- Think about how to test critical area(s)
- Specify method(s)
- Address site and design specific isolation requirements
- Address moisture content issues (know your materials)
- Outline contractor support for testing
- Recognize need for electrode placement for testing primary of double-lined facility
- Require minimum qualifications for ELL Contractor
- Get chosen ELL contractor involved with project from the beginning
- **When in doubt, just ask!**

54

Complying with ALR: What can go wrong?

- Liquid can report to leak detection layer even if there are no leaks in the primary lining system
  - Can enter through anchor trenches or other unsealed locations
  - Vapor diffusion through geomembrane (very small amount)
  - Holes in the secondary geomembrane can allow groundwater to enter
  - Construction water trapped in leak detection layer during construction can slowly weep from granular drainage layer
- Construction water trapped in leak detection layer can be significant for an extended period of time
- Check: Is leakage responsive to rainfall?
- 2020 case study of landfill expansion cell where 20 gpad ALR compliance could not be achieved due to trapped construction water*

*Gilson and Shilling. (2020). "Construction water flow dynamics of the leak detection layer". *Geosynthetics Magazine, April/May Issue.*

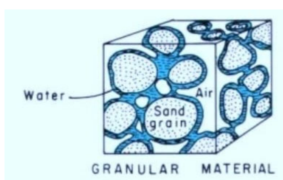
55

DRAINAGE MATERIAL PROPERTIES

- Specific Retention
  - Function of material type
  - Highly dependent on temperature
- Specific Yield
  - Specific Yield = Porosity – Specific Retention

Table 2-2. Specific yield and retention percentages (values in percent by volume)

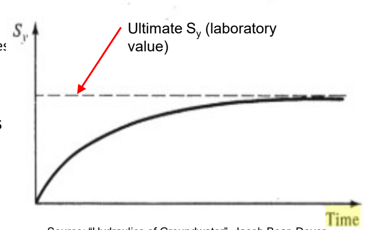
Material	Porosity	Specific Yield	Specific Retention
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (semiconsolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (young)	11	8	3



56

SPECIFIC YIELD

- Sand column test*:
  - 39.7% drained in first 30 minutes
  - 18.1% occurred in second 30 minutes
  - Additional 32.5% took 9 days
  - Remaining 9.7% took **2.5 YEARS**
- Laboratory value
  - Standardized temperature
  - Sample subjected to extremely high suction
  - Very good correlation to "ultimate" value

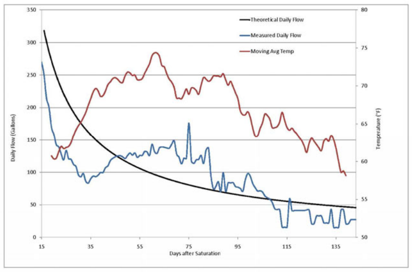


Source: "Hydraulics of Groundwater", Jacob Bear. Dover Publications, Inc. Mineola, New York. 1979

*King, F.H. (1899). "Principles and conditions of the movements of ground water". *U.S. Geological Survey 19th Annual Report, pt. 2, 86-91.*

57

CASE STUDY: LEAKAGE VS TIME



Source: Gilson and Shilling. (2020). “Construction water flow dynamics of the leak detection layer”. *Geosynthetics Magazine, April/May Issue.*

58

Conclusive Remarks

- All liners leak, but it is possible to install a geomembrane without holes in it
- Electrical leak location (ELL) best tool in industry for controlling geomembrane leakage and achieving zero leaks
- Throwing ELL in at the end of a project (after issues are present) is not 100% guaranteed to solve the problem
- Good ELL test starts with project specifications
- The devil is in the details!

59

QUESTIONS?

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60