Lecture 18

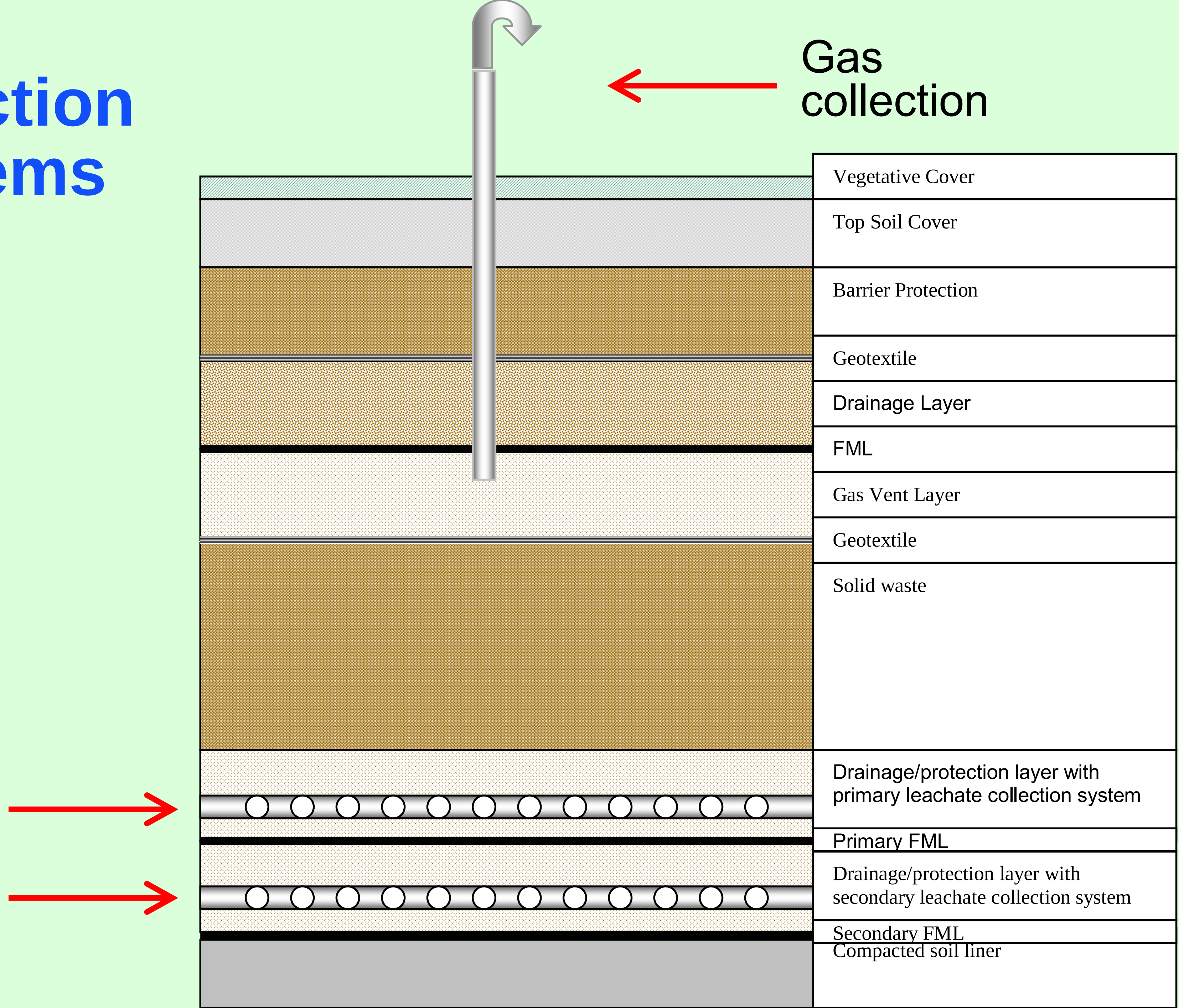
Leachate and gas production in landfills

Mass balance for MSW landfill

Waste in → Leachate + gas + transformed mass
+ waste remaining

Precipitation and ground-water inflow → leachate
+ moisture in waste

Collection systems

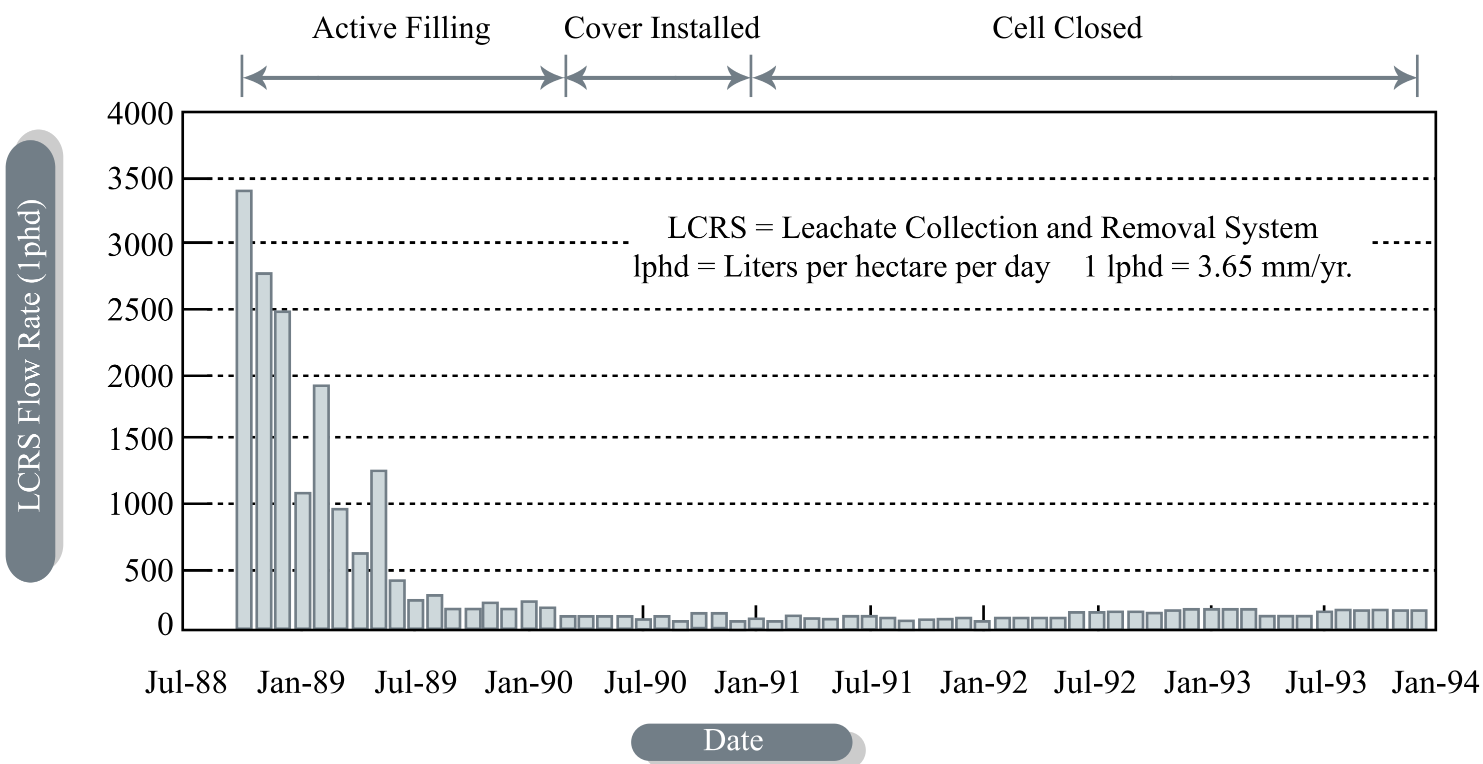


Leachate collection

Factors that influence leachate generation

- Precipitation
- Ground-water intrusion
- Moisture content of waste
  - Particularly if sludge or liquids are disposed
- Daily cover during filling period
- Final cover design

Leachate generation at MSW landfill



Average annual precipitation: 1000 mm/yr (39.4 in/year). Closure included placement of a geomembrane cover.

1000 mm/yr = 27,400 lphd

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

Estimating leachate generation in active landfill

$L_A = P + S - E - WA$

L_A = leachate from active area

P = precipitation

S = pore squeeze liquid from waste

E = evaporation

WA = waste moisture adsorption

(all in units of L^3/T)

Precipitation

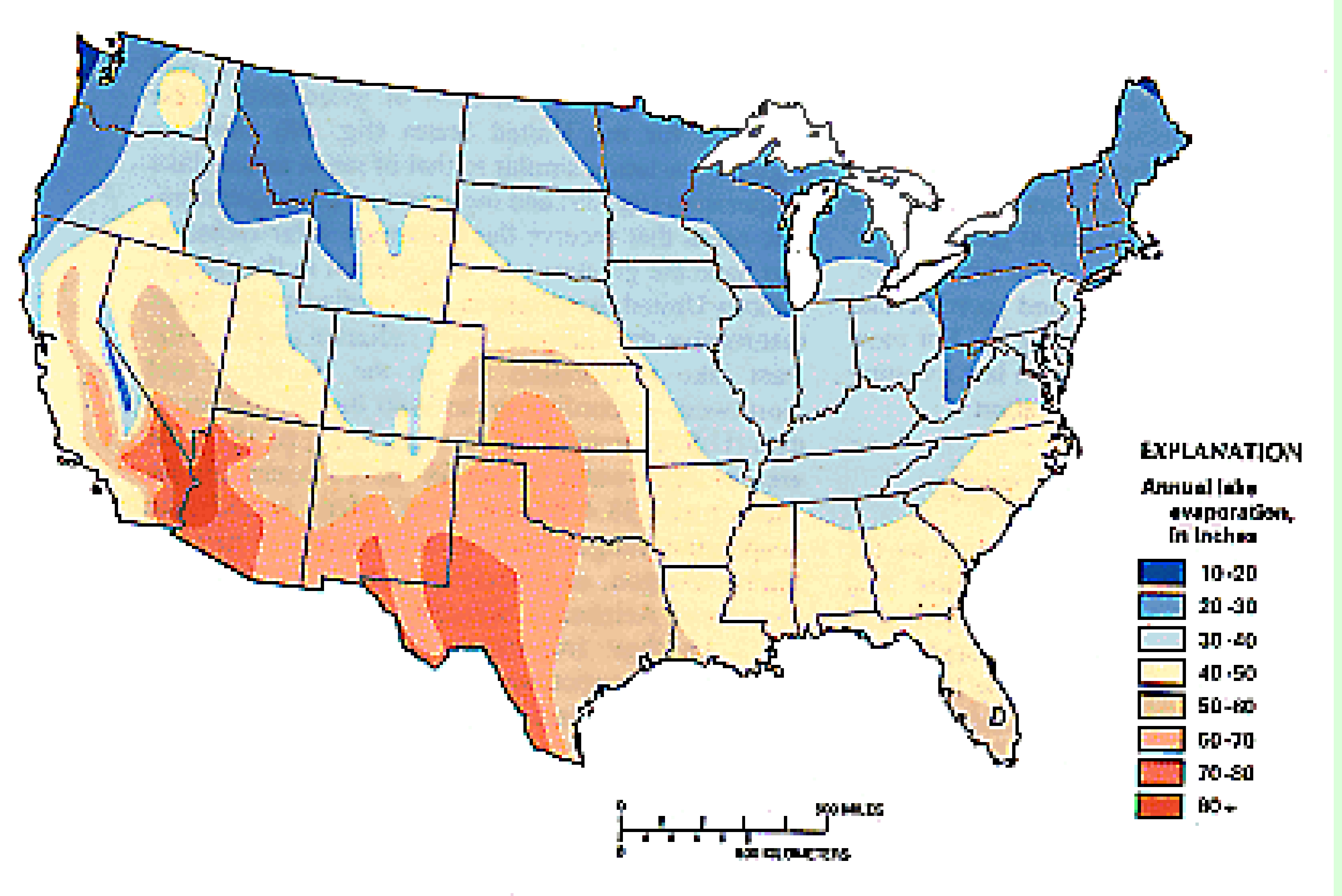
See image at the Web site of the
National Atmospheric Deposition Program,
http://nadp.sws.uiuc.edu/isopleths/maps2002/ppt.gif
Accessed May 13, 2004.

Pore squeeze liquid

Negligible for most wastes

Can be significant for wastewater sludges – measured in laboratory tests

Evaporation



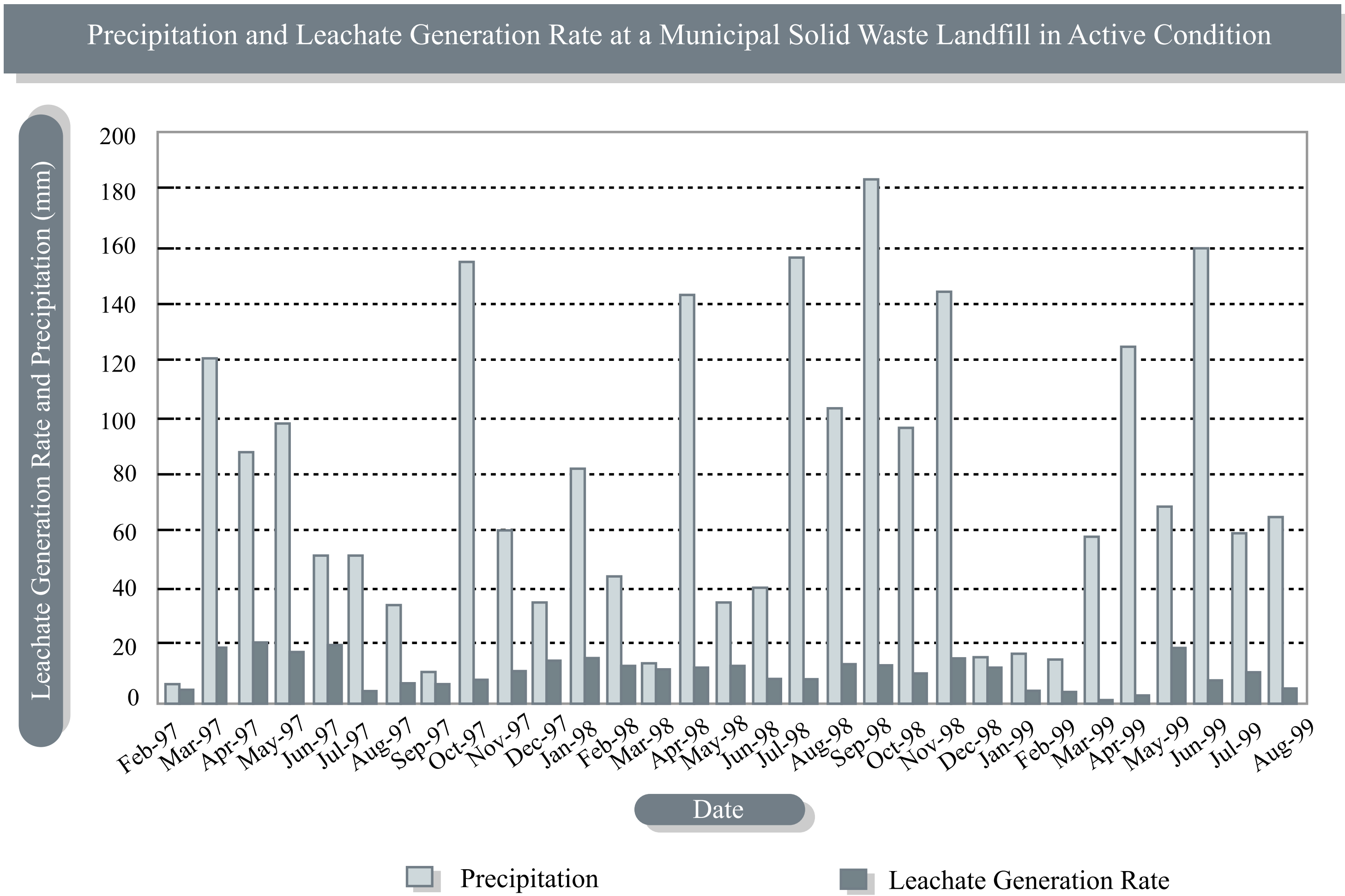
Source: Hanson, R.L., 1991, Evapotranspiration and Droughts, in Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., Compilers, National Water Summary 1988-89--Hydrologic Events and Floods and Droughts: U.S. Geological Survey Water-Supply Paper 2375, p. 99-104. http://geochange.er.usgs.gov/sw/changes/natural/et/

Moisture adsorption by waste

Typical initial moisture content of waste	1.5 in/ft	12 cm/m
Field capacity of waste	4 in/ft	33 cm/m
Available moisture adsorption capacity of waste	2.5 in/ft	21 cm/m

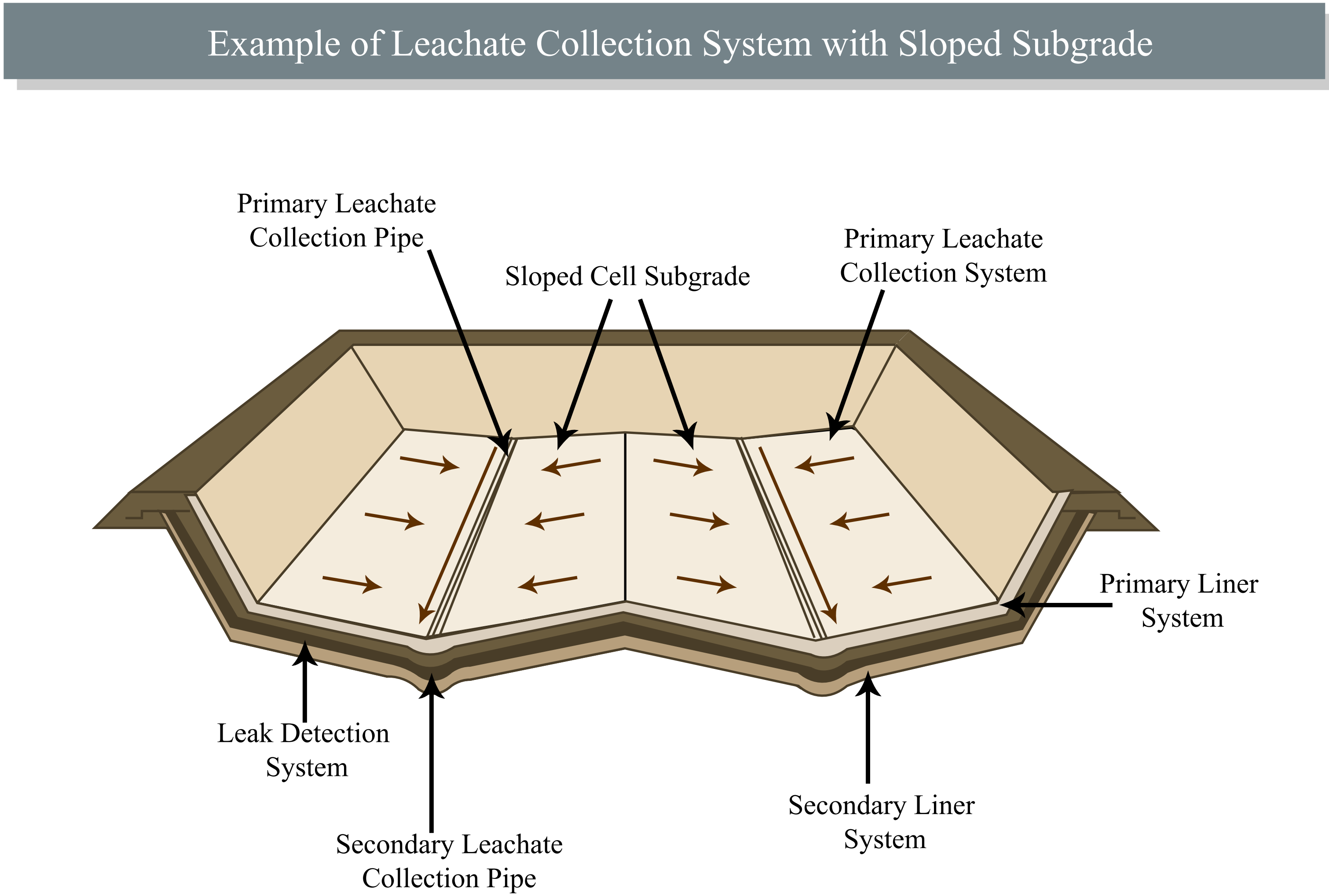
Source: Bagchi, A., 1994. *Design, Construction, and Monitoring of Sanitary Landfill*, Second Edition. John Wiley & Sons, New York.

Leachate generation at active MSW landfill



Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

Leachate collection system



Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction.* Upper Saddle River, New Jersey: Prentice Hall, 2002.

Installing leachate collection pipe

See image at the Web site of Biometallurgical Pty Ltd.
www.users.bigpond.com/BioMet/photos/photos1.htm.
Accessed May 13, 2004.

Installing drainage layer

See image at the Web site of Biometallurgical Pty Ltd. www.users.bigpond.com/BioMet/photos/photos1.htm. Accessed May 13, 2004.

Leachate drainage layer

- Drainage layers are considered as small aquifers:
  - flow characteristics defined in terms of transmissivity (or thickness and hydraulic conductivity), length, and width
- Use Darcy’s Law to predict flow per unit width
- Darcy’s Law may not apply to some geonets, etc., because flow may be turbulent
  - Geonet manufacturers quote the transmissivity of geonets however since there is not a good alternative calculation procedure

Primary leachate collection system (PCLS)

EPA minimum technology guidance regulations in 1985

Requirements:

- Granular soil drainage material
- 30 cm thick
- $K \geq 0.01$ cm/sec ($T > 3 \times 10^{-5}$ m^2/sec = 0.02 ft^2/min)
  (equivalent to sand and gravel)
- Slope > 2%
- Include perforated pipe
- Include layer of filter soil
- Must cover bottom and side walls of landfill
  (side walls can be difficult to construct and maintain)

Source: U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989. Chapter 1.

Geonet drainage layer

Geonets of equivalent performance can be substituted for sand and gravel drainage layer

$T \cong 10^{-4}$ m^2/sec for typical geonet

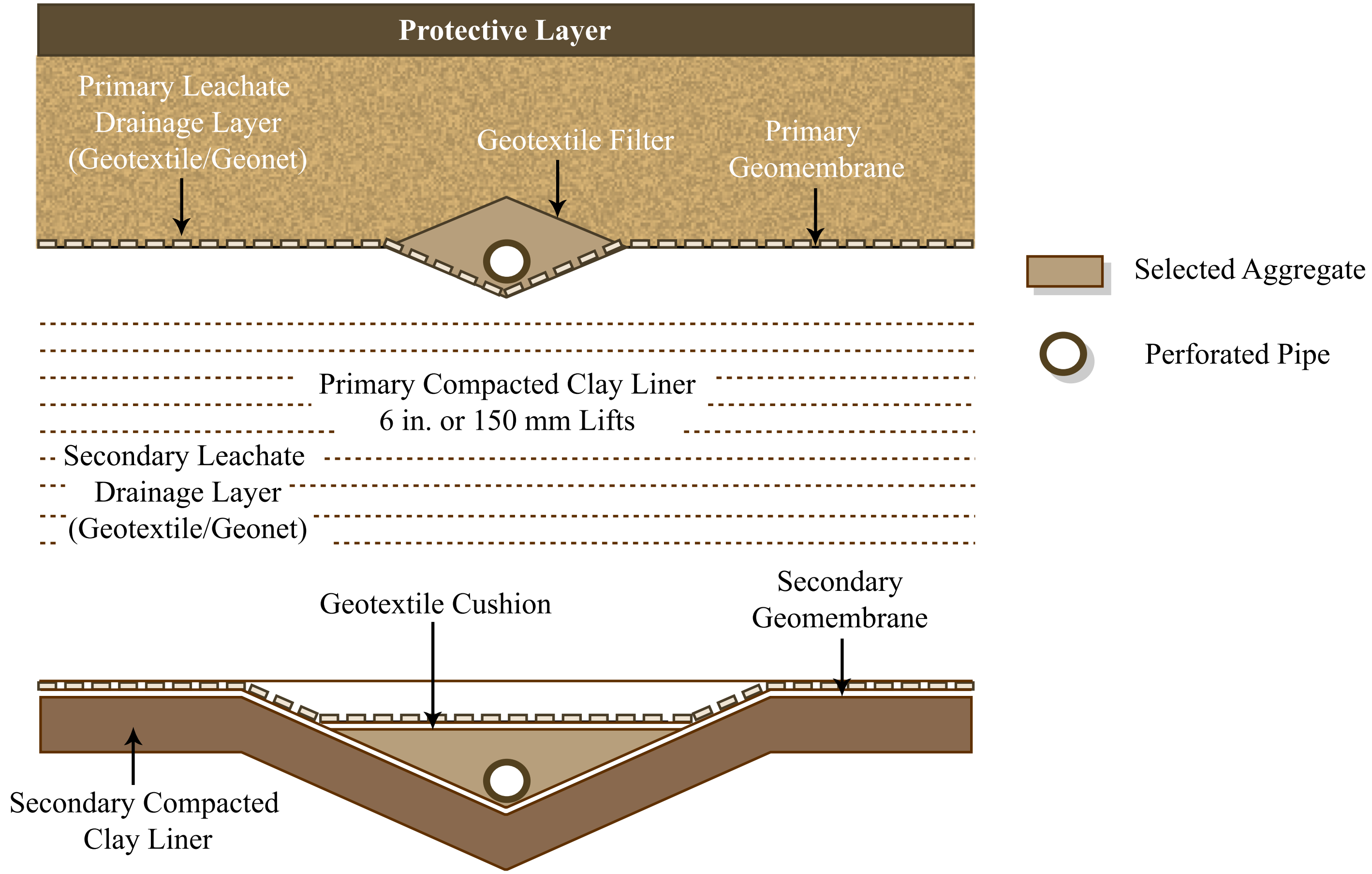
See image at the Web site of Tenax Corporation, Landfill Drainage Design, http://www.geogrids.com/landfill/ Accessed May 13, 2004.

Geonet installation

See image at the Web site of Tenax Corporation, Installation of Tri-planar drainage geonet at Sarasota landfill project, http://www.geogrids.com/landfill/usa00014.htm. Accessed May 13, 2004.

Leachate collection system

Example of Leachate Collection Pipe and Trench for Double Geomembrane/Compacted Clay Composite Liner System



Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction.* Upper Saddle River, New Jersey: Prentice Hall, 2002.

Drainage pipe

See images at the following Web sites:
Binder, B., 2001. “Flatirons Open Space Committee, Index to Picture Collections, Destruction in Wetlands, Spring 2001.” http://bcn.boulder.co.us/environment/fosc/pic-index1.html

Lindsell, D., undated. “Pasture Management for Horses.” http://www.denislindsell.demon.co.uk/pasture/soils/index.htm

Accessed May 13, 2004.

Pipe installation at landfill

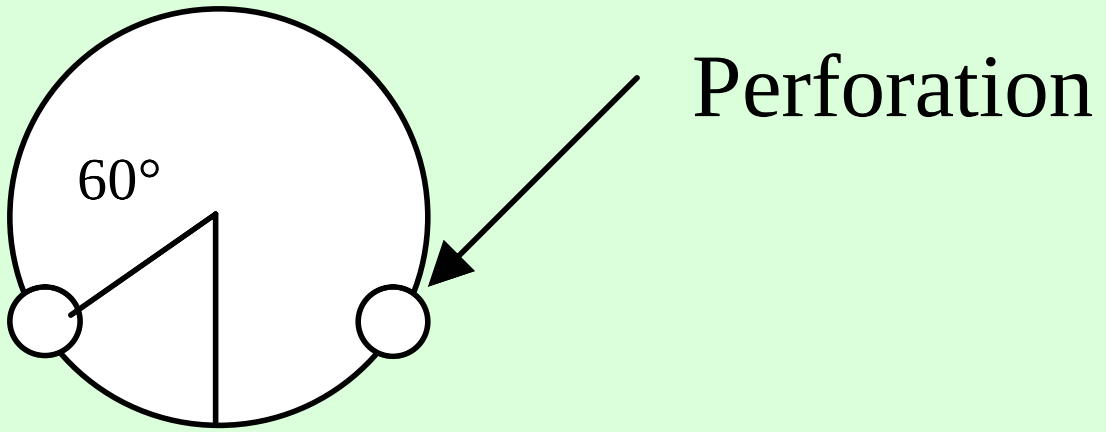
See image at the Web site of Camino Real Environmental Centers, Inc., http://www.creci.com/operations.htm

Accessed May 13, 2004.

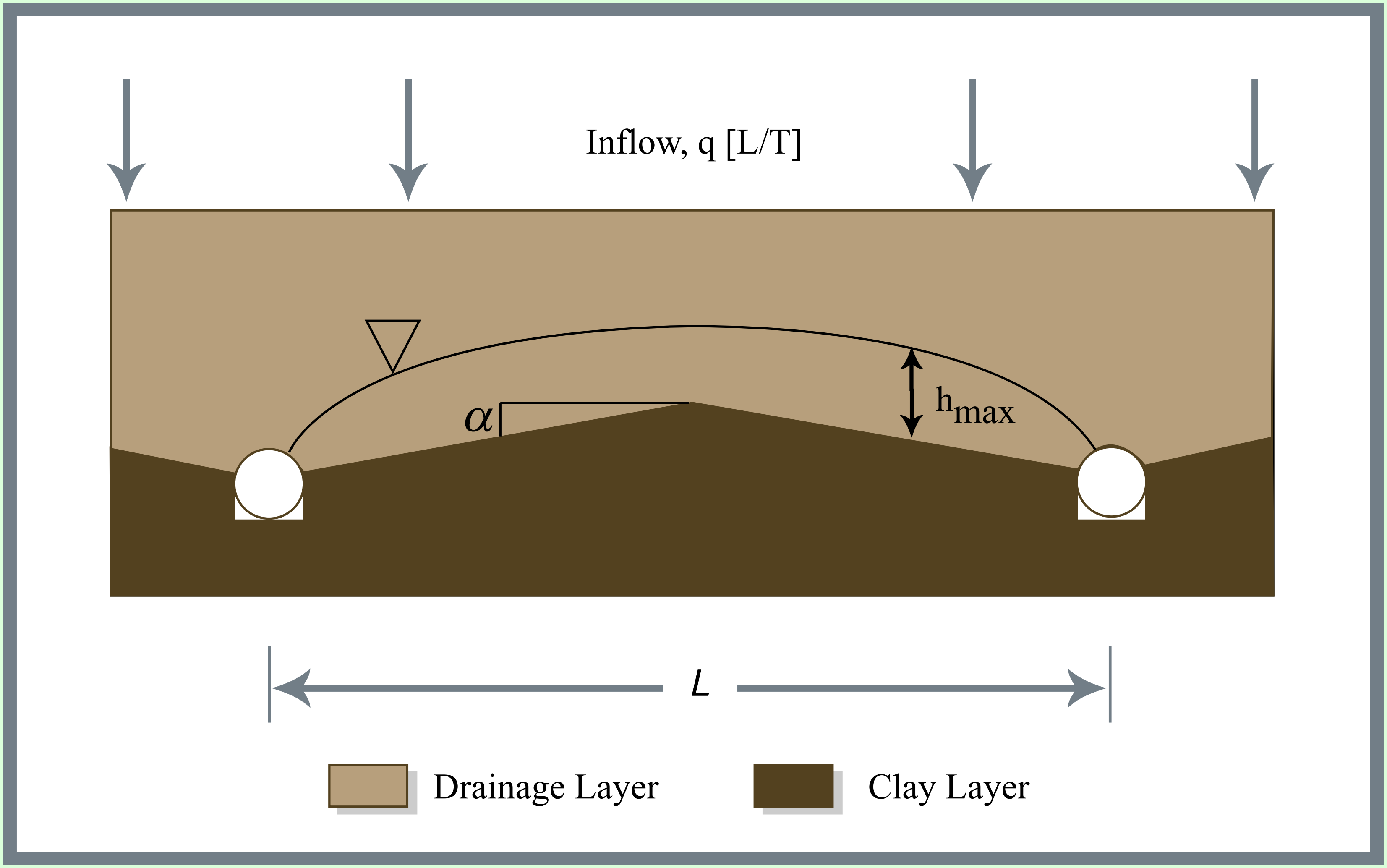
Pipe installation

Usually plastic pipe (PVC or HDPE) is used

Perforated pipe is manufactured with perforations separated by 120 degrees – centerline between perforations faces down



Drain design

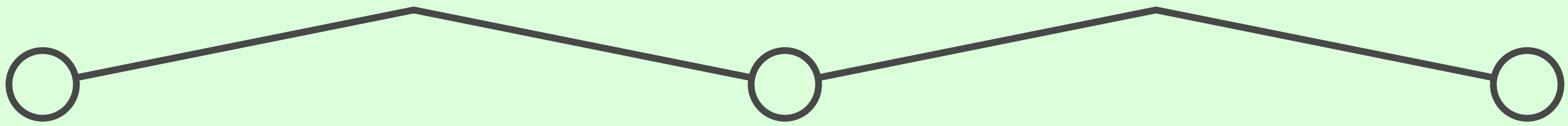


Design goal: h_{max} < 30 cm

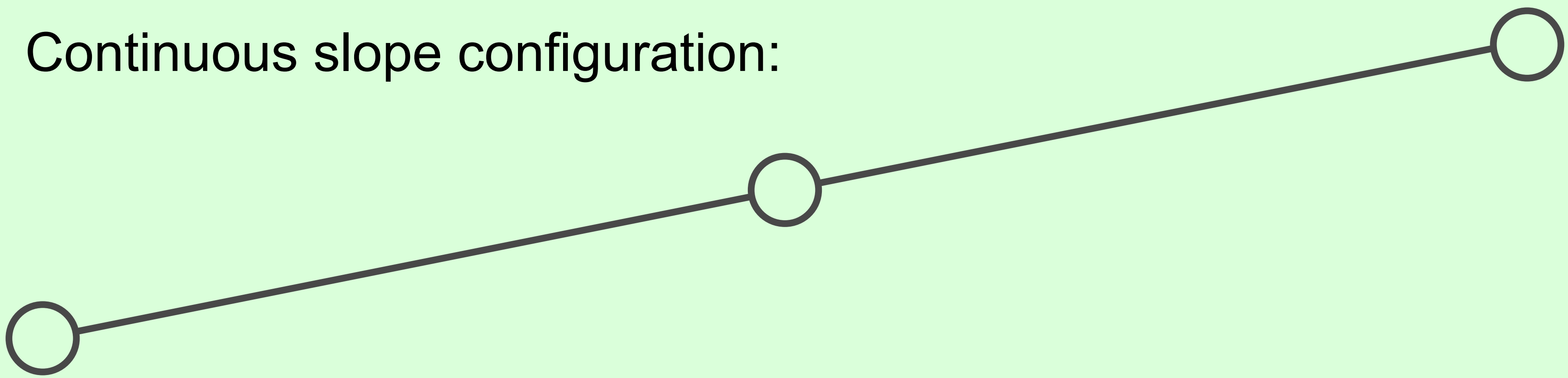
Keep leachate mounding within 12-inch (30-cm) drainage layer

Drain design configurations

"Saw-tooth" configuration:



Continuous slope configuration:



Mound model for drainage spacing

Mound model gives mounding height for “saw-tooth” as:

$$h_{max} = \frac{L\sqrt{c}}{2}\left[\frac{\tan^2\alpha}{c} + 1 - \frac{\tan\alpha}{c}\sqrt{\tan^2\alpha + c}\right]$$

where:

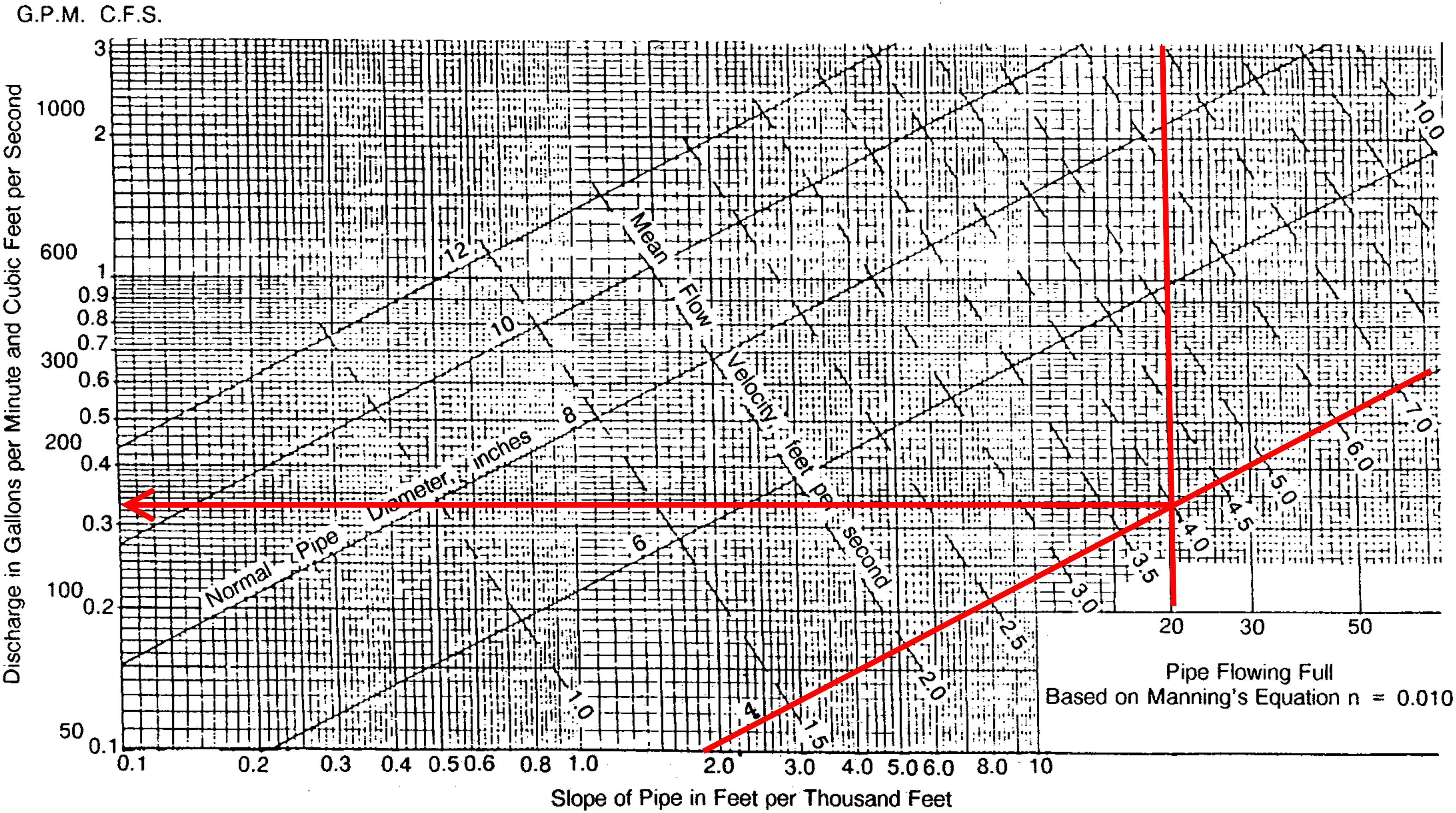
h_{max} is height of mound [L]
L is drain spacing [L]
c = q/k
q = infiltration rate [L/T]
k = hydraulic conductivity of drainage layer [L/T]
α = slope of ground surface between pipes

Sizing of leachate collection pipes

Pipe size is designed based on Manning's equation

Following design chart gives flow versus slope for range of pipe diameters assuming n = 0.010

Pipe capacity design chart



F U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

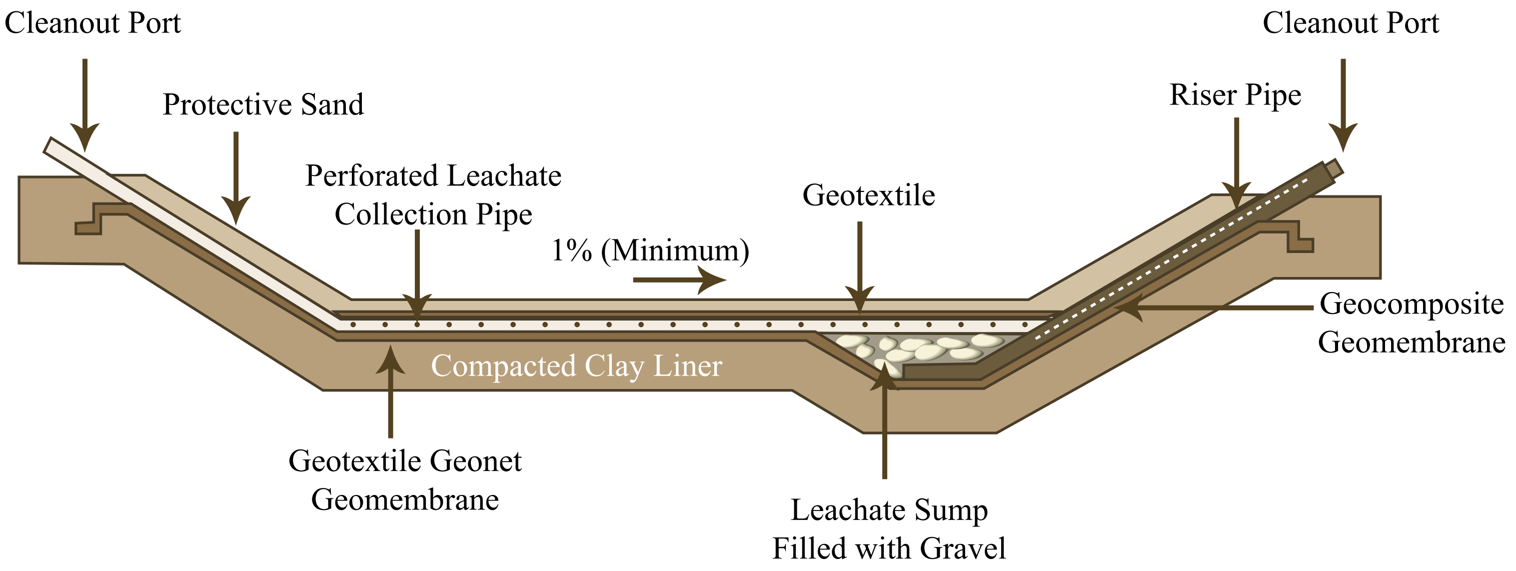
Leachate collection pipe design

Other design considerations include:

- pipe strength (to resist crushing)
- chemical resistance of pipe
- maintenance – annual pipe cleaning is typical

Leachate collection via riser pipes above single liner

Cross Section of a Landfill Leachate Collection and Removal System



Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction.* Upper Saddle River, New Jersey: Prentice Hall, 2002.

Leachate sump design

Leachate generally does not leave a landfill by gravity flow—not a recommended design configuration due to difficulty in capturing and controlling leachate

Sumps are depressions in liner filled with gravel to accommodate collected leachate

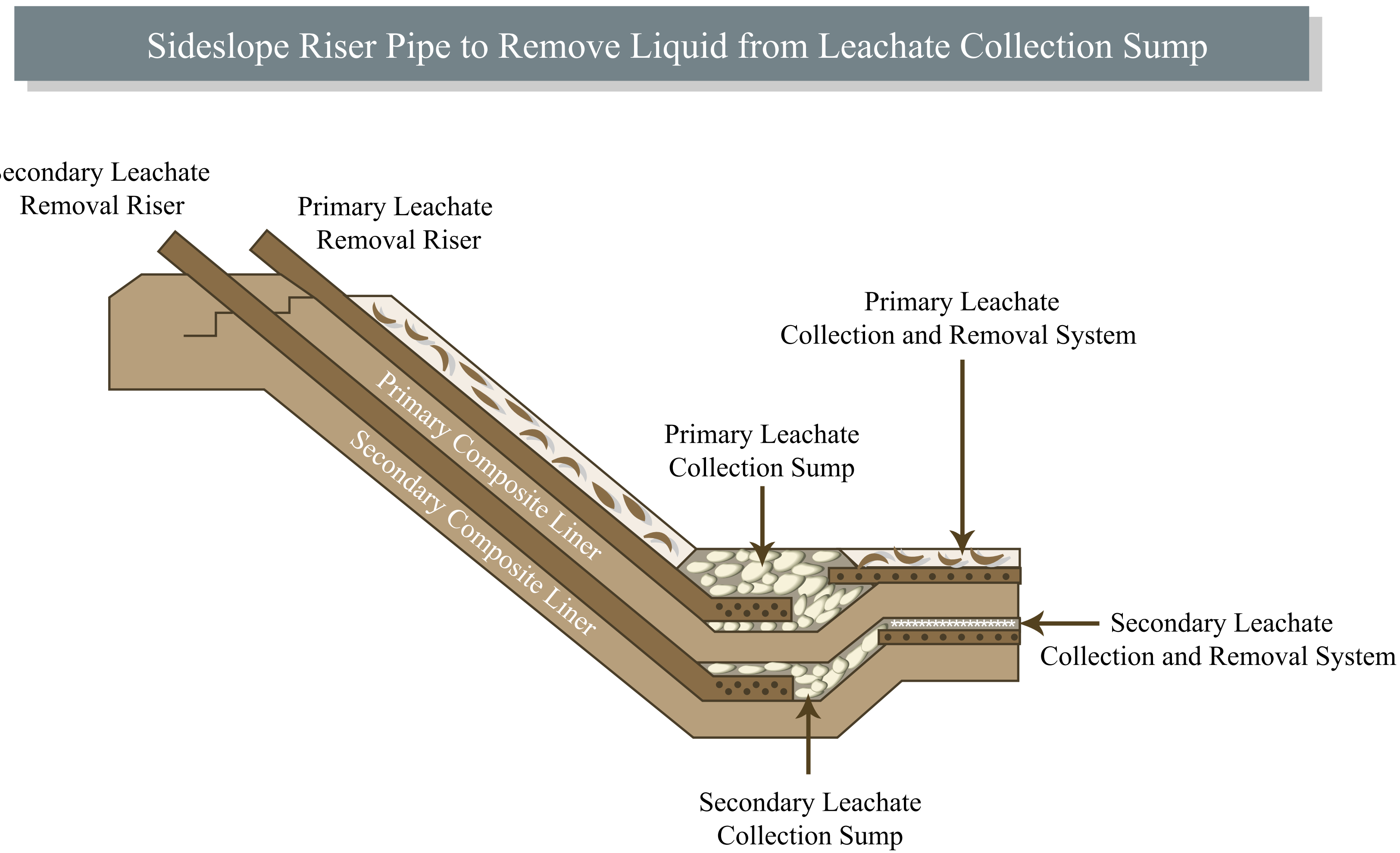
Liner is usually doubled up at sumps

Leachate sump design

Sumps can be accessed by:

- Sideslope riser pipes that follow the landfill sideslope
- Access ways (manholes) or vertical risers
  - But HDPE or special concrete is required due to high sulfates in leachate!
- Leachate is extracted by pumps—often cycled intermittently using level-sensing switches
  - Pump must be sized for lift and anticipated flow

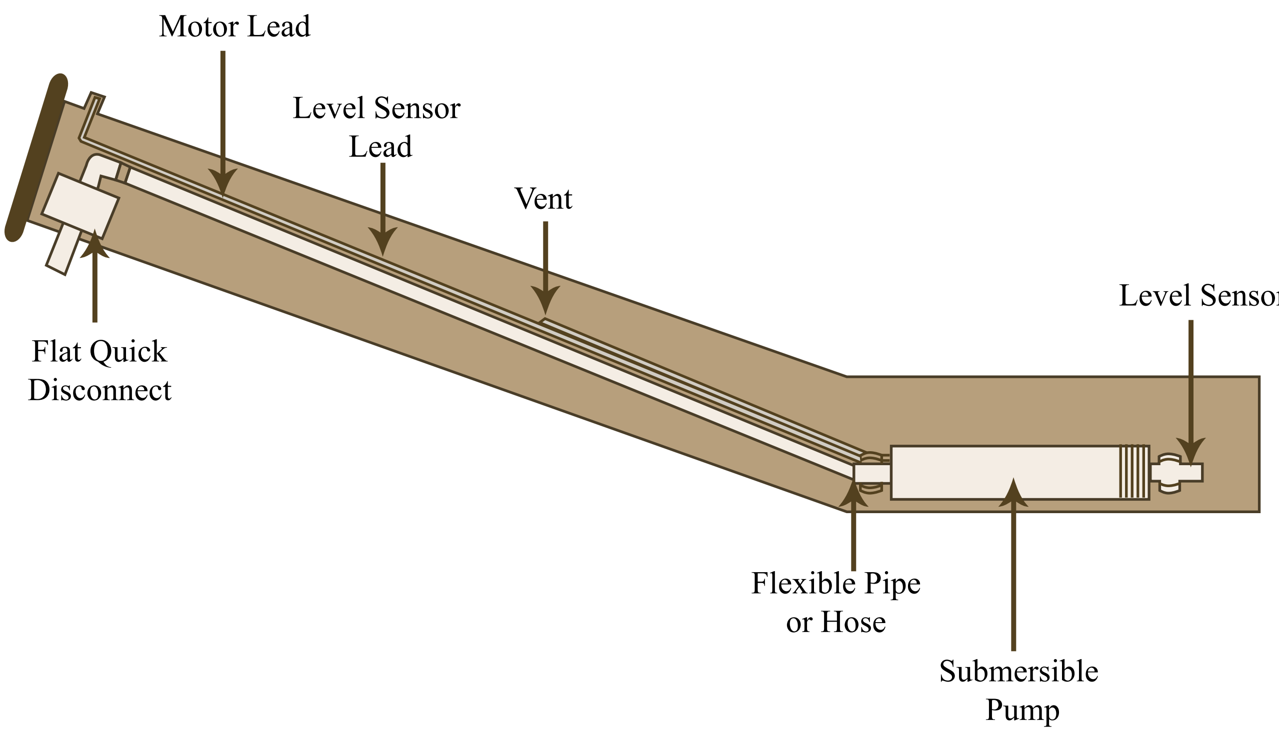
Leachate collection – double liner



Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction.* Upper Saddle River, New Jersey: Prentice Hall, 2002.

Leachate collection pump

Schematic Diagram of Installation of a Leachate Collection Pump in Sideslope Riser Pipe



Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction.* Upper Saddle River, New Jersey: Prentice Hall, 2002.

Leachate pipes at Crapo Hill landfill

Image courtesy of Peter Shanahan.

New cell and leachate storage at Crapo Hill landfill

Image courtesy of Peter Shanahan.

Leachate sump riser pipe

See image at the Web site of Tompkins County Solid Waste Management Program, Solid Waste Management Division Office. www.co.tompkins.ny.us/solidwaste/collects.html

Accessed May 13, 2004.

Filter layer design

Filter medium keeps sediment out of drainage layer

Must not clog over decades of use and post-closure

Design flow parameter is “permittivity” [1/T]

$$\Psi = k/t$$

where

k = cross-plane (vertical) hydraulic conductivity [L/T]
t = thickness [L]

Filter layer design

Consider drainage layer design goal to limit h_{max}

$Q = kiA$

$Q/A = q = k\,(h_{max}/t)$

$q = k/t \;\; h_{max}$

$q = \Psi \, h_{max}$

Filter layer design

Required permittivity is:

$$\Psi = \frac{q}{h_{max}}$$

where:

$q = Q/A$ = vertical inflow per unit area of landfill $[(L^3/T)/L^2]$

h_{max} = maximum allowable mounding height [L]

Filter layer design

Criteria:

- Soil from above cannot penetrate into filter layer
- Filter layer must have adequate K
- Soil from filter layer must not penetrate drainage layer

See Qian et al. for formulae for soil filter layers and geotextiles

Geotextile clogging

Long-term clogging potential evaluated with gradient ratio test:

$$\textbf{Ratio} = \frac{\textbf{Hydraulic gradient through 1 inch of soil plus geotextile}}{\textbf{Hydraulic gradient through 2 inches of soil}}$$

Ratio > 3 indicates geotextile will probably clog with sediment

Reference: U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

Secondary leachate collection system (SLCS)

EPA requirements for secondary leachate collection systems:

- 30 cm thick drainage layer
- $K \geq 0.01$ cm/sec (T > 3 x 10^{-5} m^2/sec = 0.02 ft^2/min) (equivalent to sand and gravel – same as PLCS)
- Cover bottom and side walls of landfill
- Must have response time for leak detection of less than 24 hours

Secondary leachate collection system (SLCS)

If SLCS performs as desired, it will generate very little leachate

Often drained with geonet – reduces space and eliminates pipe requirement

Response time calculated from velocity by Darcy's Law:

$$v = k\, i/n$$

Calculate separately for side slope and bottom

For gradient, i, use constructed side or bottom slope

For geonets use n = 0.5

Prefabricated drains

See the following images at the Web site of American Wick Drain Corporation:

AMERDRAIN® sheet drain and AKWADRAIN™ strip drain keep landfills dry and remove leachate: http://www.americanwick.com/landfill.html

AKWADRAIN™ soil strip drain: http://www.americanwick.com/prodstrip.html.

Accessed May 13, 2004.

Landfill Biogeochemistry

1. Aerobic decomposition:

Degradable waste + $O_2 \rightarrow CO_2 + H_2O$ + biomass + heat

$$CH_aO_bN_c + \frac{1}{4}(4a - 2b - 3c)O_2 \rightarrow CO_2 + \frac{1}{2}(a - 3c)H_2O + cNH_3$$

2. Acid-phase (nonmethanogenic) anaerobic decomposition

Degradable waste $\rightarrow CO_2 + H_2O$ + biomass + organic acids

Landfill Biogeochemistry

3. Methanogenic anaerobic decomposition:

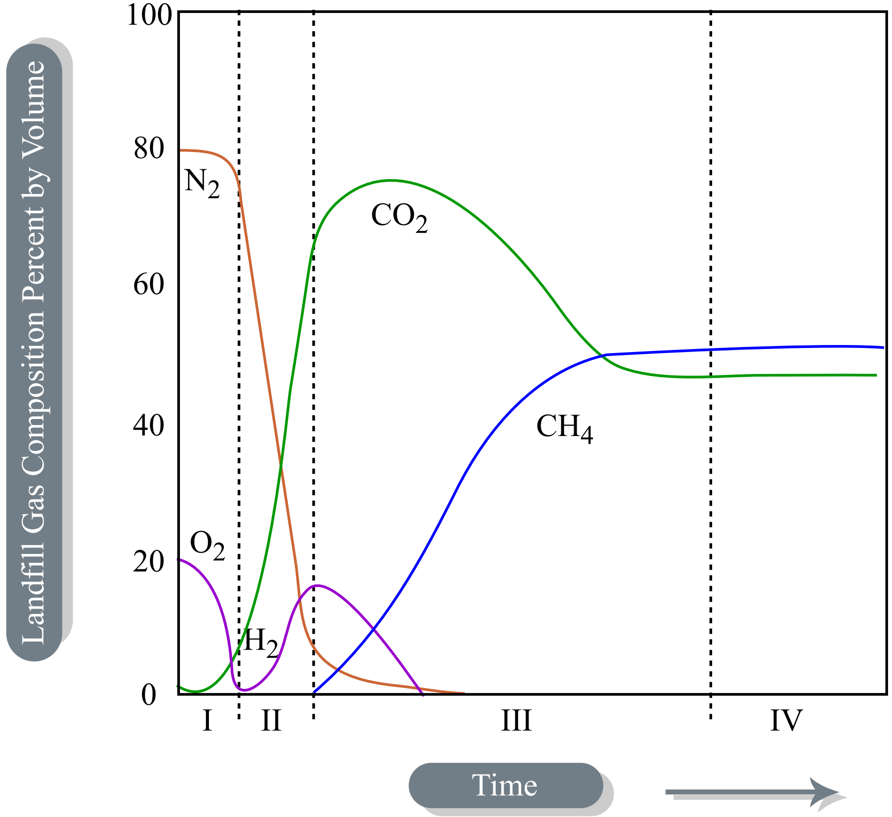
Degrade products of Stage 2

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

Landfill Gas Production

Landfill Gas Production Pattern Phases



Phases	Condition
I	Aerobic
II	Anoxic
II	Anaerobic, Methanogenic, Unsteady
II	Anaerobic, Methanogenic, Steady

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Upper Saddle River, New Jersey: Prentice Hall PTR, 1995.

Problems with landfill gas

Explosive hazard !!!

Methane is explosive above 5 to 15% by volume

Subsurface migration offsite (up to 150 m)

Accumulation beneath buildings or structures

Vegetation stress

Toxicity due to H_2S and VOCs

Corrosion due to CO_2–created acidity

Greenhouse gases and air emissions

Landfill gas composition

Typical Landfill Gas Composition

Component	Source	Typical concentration (% by volume)	Concern
Methane (CH_4)	B[a]	50-70	Explosive
Carbon Dioxide (CO_2)	B	30-50	Acidic in groundwater
Hydrogen (H_2)	B	<5	Explosive
Mercaptans (CHS)	B	.1-1	Odor
Hydrogen Sulfide (H_2S)	B	<2	Odor
Solvents			
Toluene	C[b]	.1-1	Hazardous
Benzene	C	.1-1	Hazardous
Disulfates	C	.1-2	Hazardous
Others	B and C	traces	Hazardous

[a]B = Product of biodegradation [b]C = A contaminant in the MSW

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR, 1995.

Landfill gases

Methane is lighter than air – accumulates beneath structures, buildings

Carbon dioxide is heavier than air – accumulates in landfill

Landfill gas production

Theoretical estimate: 520 L / kg of MSW (53% is methane)

Actual: 160 L / kg (mean), 50 – 400 L / kg (range)

Theoretical estimate is based on complete degradation of wastes such as:

- cellulose – 829 L/kg, 50% methane
- protein – 988 L/kg, 52% methane
- fat – 1430 L/kg, 71% methane
- Theoretical gas production is $CO_2 + CH_4$

Hydrocarbons in landfill gas

Hydrocarbons in Landfill Gas in mg/m^3 Based on Airless Landfill Gas

		(mg/m^3)
Ethane	C_2H_6	0.8-48
Ethene (ethylene)	C_2H_4	0.7-31
Propane	C_3H_8	0.04-10
Butane	C_4H_{10}	0.3-23
Butene	C_4H_8	1-21
Pentane	C_5H_{12}	0-12
2-Methylpentane	C_6H_{14}	0.02-1.5
3-Methylpentane	C_6H_{14}	0.02-1.5
Hexane	C_6H_{14}	3-18
Cyclohexane	C_6H_{12}	0.03-11
2-Methylhexane	C_6H_{16}	0.04-16
3-Methylhexane	C_6H_{20}	0.04-13
Cyclohexane	C_6H_{12}	2-6
Heptane	C_7H_{16}	3-8
2-Methylheptane	C_8H_{18}	0.05-2.5
3-Methylheptane	C_8H_{18}	0.05-2.5
Octane	C_8H_{18}	0.05-75
Nonane	C_9H_{20}	0.05-400
Cumole	C_9H_{12}	0-32
Bicyclo(3,2,1)-octane-2,3-methyl-4-methylethylene	$C_{10}H_{16}$	15-350
Decane	$C_{10}H_{32}$	0.2-137
Bicyclo(3,1,0)hexane-2,2-methyl-5-methylethylene	$C_{10}H_{13}$	12-153

		(mg/m^3)
Undecane	$C_{11}H_{24}$	7-48
Dodecene	$C_{12}H_{24}$	2-4
Tridecane	$C_{13}H_{28}$	0.2-1
Benzene	C_6H_6	0.03-7
Ethylenbenzene	C_8H_{10}	0.5-238
1,3,5-Methylbenzol	C_7H_8	10-25
Toluene	C_7H_8	0.2-615
m/p-xylol	C_8H_{10}	0-378
o-Xylol	C_6H_{10}	0.2-7
Trichlorofluoromethane	CCl_3F	1-84
Dichlorofluoromethane	$CHCl_2F$	4-119
Chlorotrifluoromethane	$CClF_3$	0-10
Dichloromethane	CH_2Cl_2	0-6
Trichloroemethane (chloroform)	$CHCl_3$	0-2
Tetrachloromethane (carbon tetra-chloride)	CCl_4	0-0.8
1,1,1-Trichloroethane	$C_2H_3Cl_3$	0.5-4
Chloroethane	C_2H_5Cl	0-284
Dichloroethene	$C_2H_4Cl_2$	0-294
Trichloroethene	C_2HCl_3	0-182
Tetrachloroethene	$C_2H_2Cl_4$	0.1-142
Chlorobenzene	C_6H_5Cl	0-0.2

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR, 1995.

Hydrocarbons in Landfill Gas in mg/m^3 Based on Airless Landfill Gas

		(mg/m^3)			(mg/m^3)
Ethane	C_2H_6	0.8-48	Undecane	$C_{11}H_{24}$	7-48
Ethene (ethylene)	C_2H_4	0.7-31	Dodecene	$C_{12}H_{24}$	2-4
Propane	C_3H_8	0.04-10	Tridecane	$C_{13}H_{28}$	0.2-1
Butane	C_4H_{10}	0.3-23	Benzene	C_6H_6	0.03-7
Butene	C_4H_8	1-21	Ethylenbenzene	C_8H_{10}	0.5-238
Pentane	C_5H_{12}	0-12	1,3,5-Methylbenzol	C_7H_8	10-25
2-Methylpentane	C_6H_{14}	0.02-1.5	Toluene	C_7H_8	0.2-615
3-Methylpentane	C_6H_{14}	0.02-1.5	m/p-xylol	C_8H_{10}	0-378
Hexane	C_6H_{14}	3-18	o-Xylol	C_6H_{10}	0.2-7
Cyclohexane	C_6H_{12}	0.03-11	Trichlorofluoromethane	CCl_3F	1-84
2-Methylhexane	C_6H_{16}	0.04-16	Dichlorofluoromethane	$CHCl_2F$	4-119
3-Methylhexane	C_6H_{20}	0.04-13	Chlorotrifluoromethane	$CClF_3$	0-10

	(mg/m³)	
Cyclohexane	C_6H_{12}	2-6
Heptane	C_7H_{16}	3-8
2-Methylheptane	C_8H_{18}	0.05-2.5
3-Methylheptane	C_8H_{18}	0.05-2.5
Octane	C_8H_{18}	0.05-75
Nonane	C_9H_{20}	0.05-400
Cumole	C_9H_{12}	0-32
Bicyclo(3,2,1)-octane-2,3-methyl-4-methylethylene	$C_{10}H_{16}$	15-350
Decane	$C_{10}H_{32}$	0.2-137
Bicyclo(3,1,0) hexane-2,2-methyl-5-methylethylene	$C_{10}H_{13}$	12-153

		(mg/m³)
Dichloromethane	CH_2Cl_2	0-6
Trichloroemethane (chloroform)	$CHCl_3$	0-2
Tetrachloromethane (carbon tetra-chloride)	CCl_4	0-0.8
1,1,1-Trichloroethane	$C_2H_3Cl_3$	0.5-4
Chloroethane	C_2H_5Cl	0-284
Dichloroethene	$C_2H_4Cl_2$	0-294
Trichloroethene	C_2HCl_3	0-182
Tetrachloroethene	$C_2H_2Cl_4$	0.1-142
Chlorobenzene	C_6H_5Cl	0-0.2

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR, 1995.

Gas generation rates

Waste degradation is generally modeled as a first-order process:

$$V = V_0 \, e^{-kt}$$

where

- V = gas production rate (function of time)
- V_0 = initial gas production rate
- t = time
- k = first-order degradation rate = $0.69 / t_{1/2}$
- $t_{1/2}$ = half-life

Half-lives of degradation:

- Food, garden wastes – ½ to 1½ years
- Paper, wood – 5 to 25 years

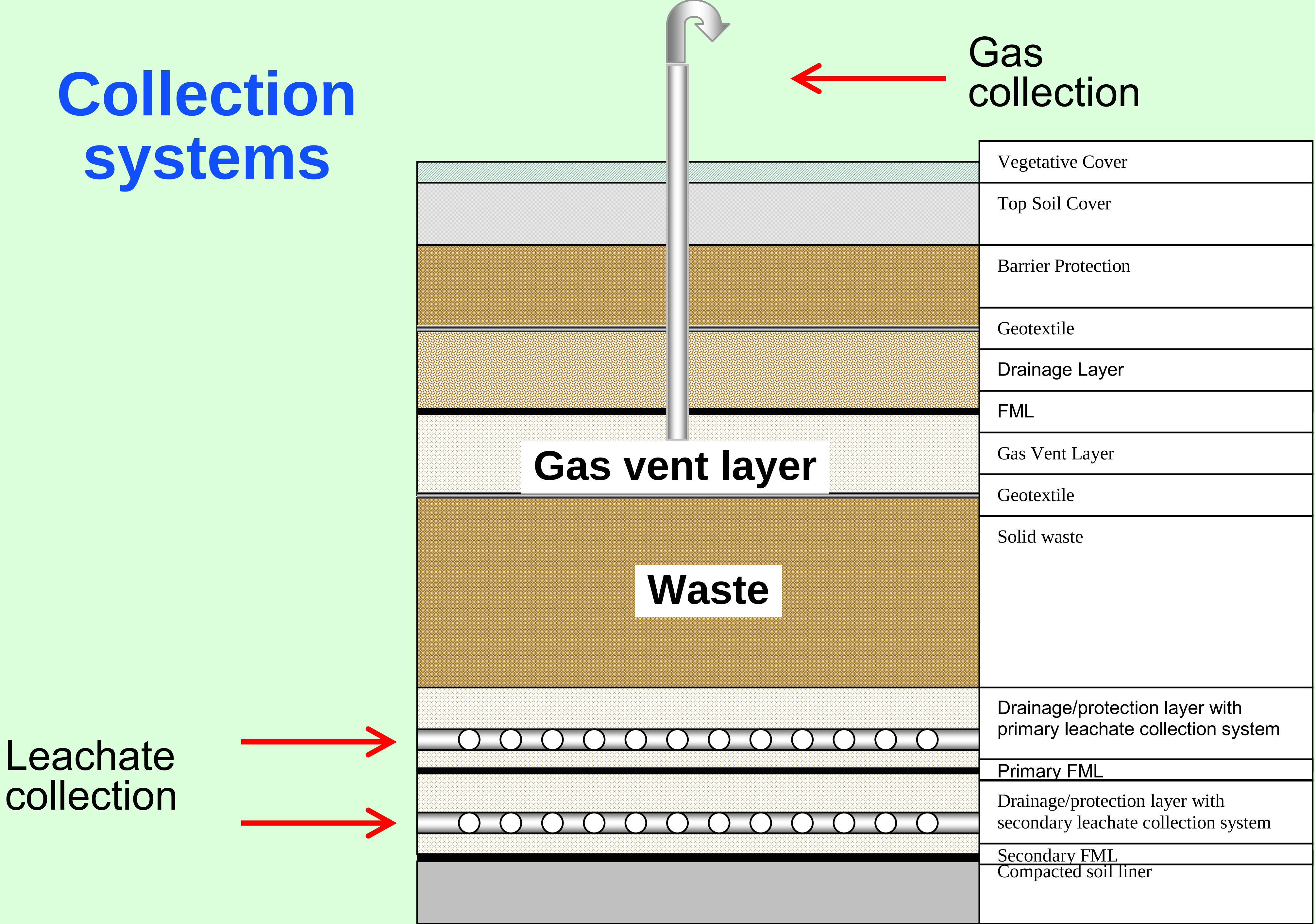
Landfills typically generate gas for 5 to 20 years

Landfill gas collection

Large landfills are required by EPA Clean Air regulations to implement a gas collection and control plan – concern is non-methane organic compounds (NMOC)

Gas collection may be passive or active

Collection systems



Passive gas venting

Vent layer atop waste – typically 12 to 30 cm thick (5 to 12 inches)

Perforated pipe (usually only short section at landfill high points) leading to “candy-cane” vent pipe or flares

Design is by trial and error since it is site-specific

Rule of thumb is 1 vent for 7500 m^3 of waste

Active gas collection at Crapo Hill Landfill

Image courtesy of Peter Shanahan.

Active gas collection

- Utilized when gas emissions create problems, gas is desired for commercial use, passive venting is inadequate
- Entails connecting a vacuum pump or blower to discharge end of piping system
- Gas extraction wells may be installed during operating period or as an “after design”
- Rules of thumb: space wells at three times the waste depth
- Radii of influence of gas extraction wells in MSW landfills are 100 to 500 feet

Design considerations for gas collection

Flexible connection (bellows) required at perforations of cap liner

Condensate can collect in gas collection pipes – require water traps to remove accumulated condensate

Flare for gas disposal at Crapo Hill Landfill

- Flares work when methane is greater than 20% by volume
- Generally enclosed in stack to effect longer residence times and greater combustion
- Contains flame sensor which turns off valve when flame goes out

Image courtesy of Peter Shanahan.