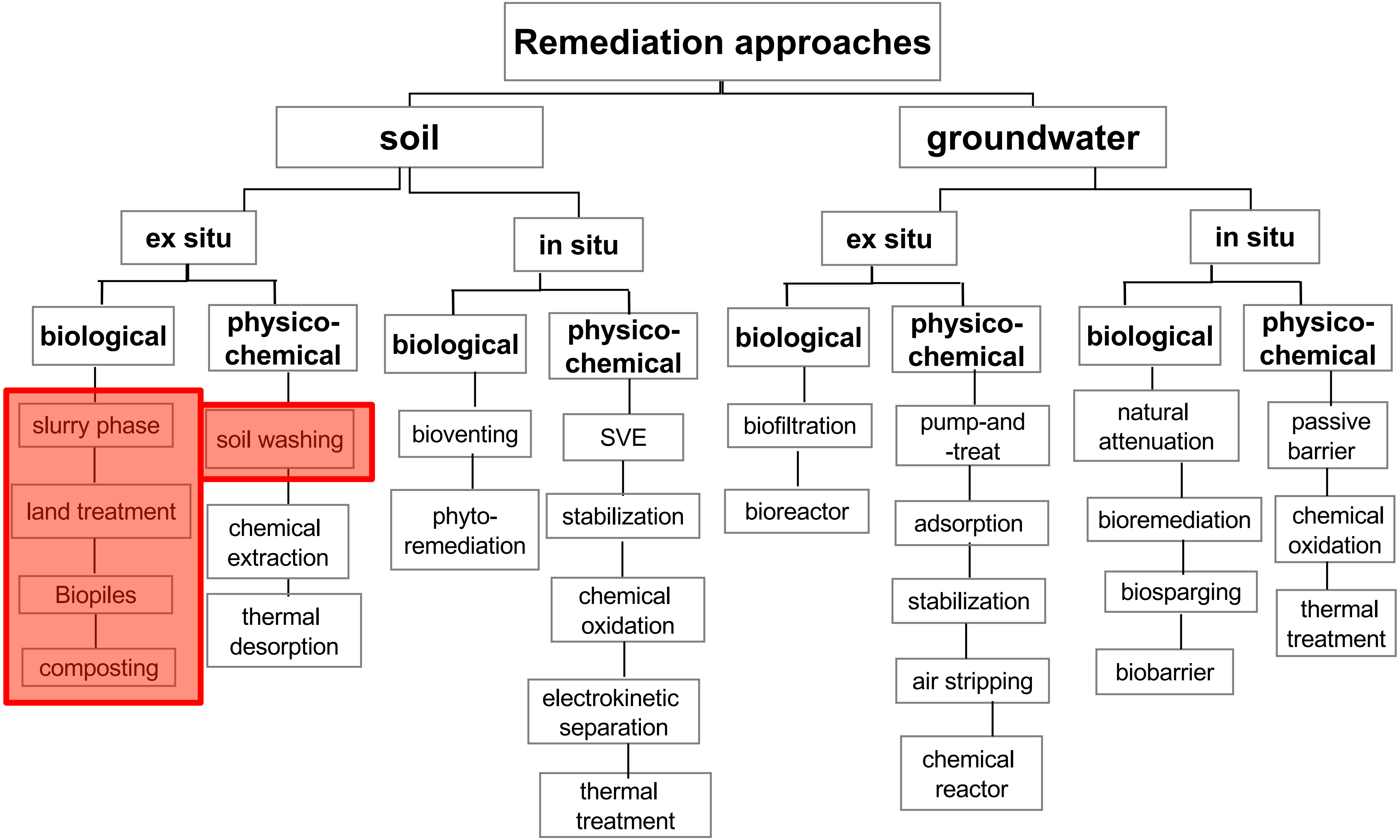
Land and soil treatment + soil washing

Lecture 7

Learning outcomes

- Land treatment
- Composting (windrows and biopiles)
- Slurry biodegradation

Today's lecture



Land Treatment

Windrows

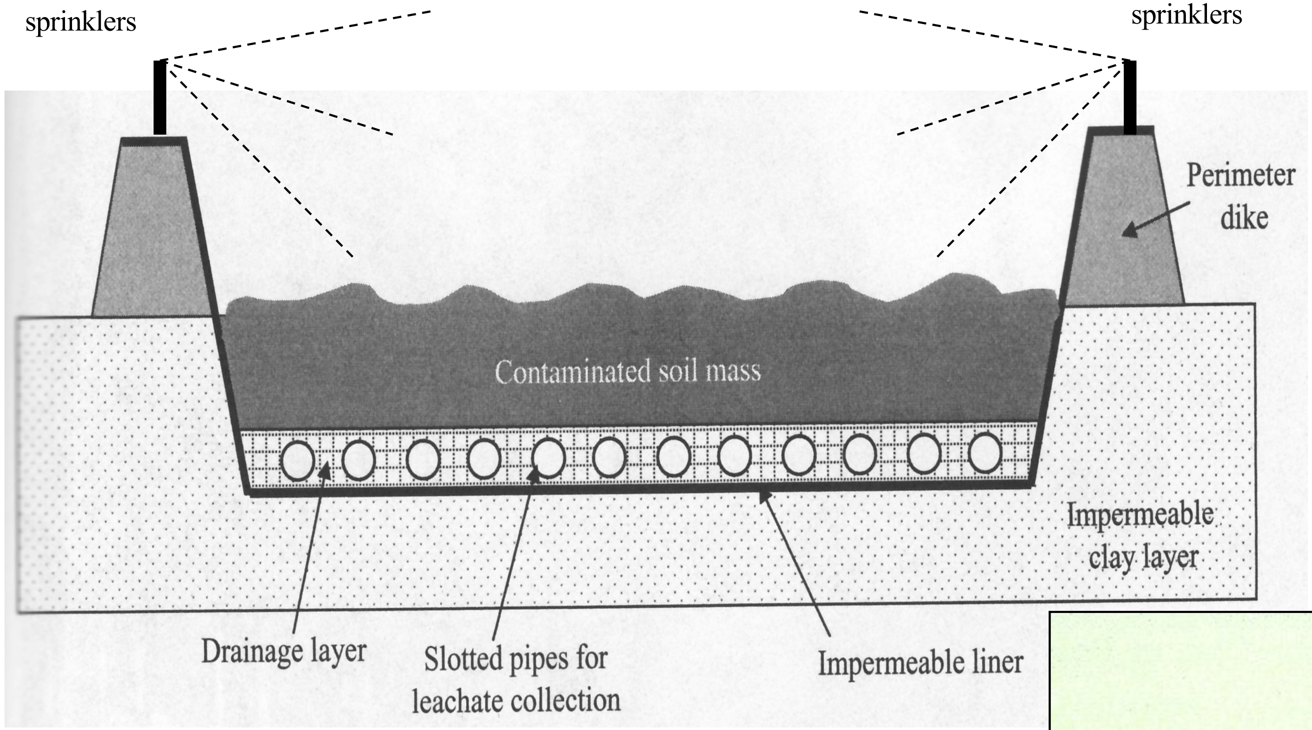
Biopiles

Land treatment

Land treatment

- Material excavated, **transported** in fixed facility
- Application of contaminated soil to the land at a **controlled rate**
- Use cultivation tools (rototiller or disk harrow) for mixing/spreading
- Large surface areas
- ZOI=zone of incorporation (10-30 cm) < Zone of treatment (<1.5 m)
- Max 150 g sludge/kg soil
- Used historically by the oil industry
- Debate over how much biodegradation and how much volatilization
- **Perimeter dike**: prevent runoff based on 25-year flood
- **Leachate control**: high-integrity liner, slotted lateral pipes in gravel, slope 0.5-2%

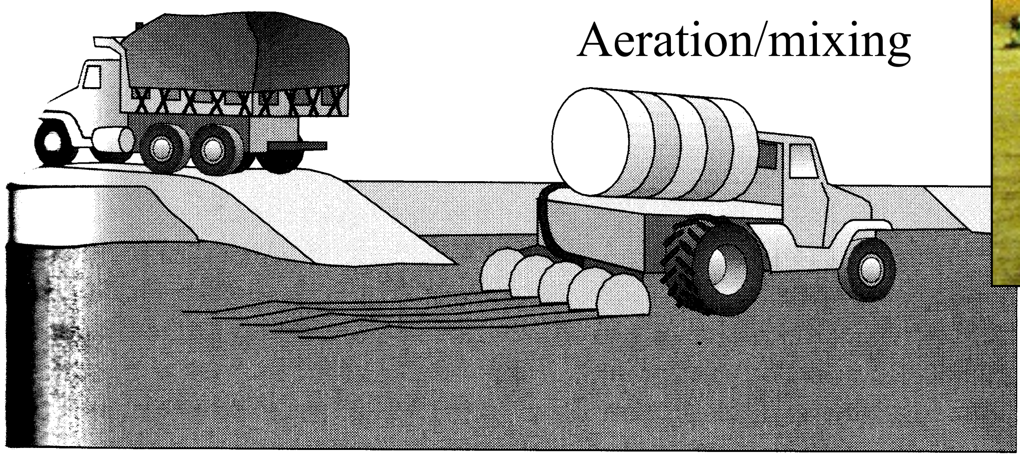
Land treatment



< 50 cm

+ a cover for T and gaz control

Aeration/mixing



75-100 CHF/m^3

Land treatment

Aeration and Zone of incorporation

O_2 penetration by diffusion

$$L = \sqrt{\frac{2\varepsilon D C_0}{r_0}}$$

L= depth at which O_2 conc. reaches zero
ε = porosity (m^3/m^3)
D= diffusion coefficient (m^2/s)
C_0= oxygen concentration at surface (g/m^3)
r_0= rate of oxygen consumption ($g/m^3.s$)

-> ZOI=zone of incorporation is typically 10-30 cm
Soil layer typically < 50 cm

Land treatment

Organic compounds are degraded by microorganisms

- Cumulative amount applied *must be* < cumulative amount degraded
- Volatilization is a possible issue

Heavy metals adsorb to soil particles

- Immobilization of metals is pH dependent -> interest of lime/soil amendments
- Presence of cationic and anionic metals can challenge immobilization
- Concentrations will rise and become toxic to microorganisms

	Precipitation	Ion exchange	Neutralization	Volatilization	Migration	Fixation	Adsorption	Biological or chemical degradation	Plant uptake
Organics	●	●	●	●	●		●	●	●
Oils				●	●			●	
Metals	●	●			●	●	●	●	●
Inorganic acids, bases, and salts	●	●	●		●		●		

Land treatment

Assimilative capacity of a site is limited

- Capacity limit: cumulative amount
  - for conservative, immobile wastes (metals, ex. Pb, or high molecular weight PAHs) that accumulate
  - > saturation
  - > toxicity
- Rate limit:
  - cumulative amount applied< cumulative amount degraded
  - typical half-life for a petroleum-derived sludge is 200-500 days
- Application limit:
  - For mobile elements that migrate from the site (ex. volatile organic)
  - Maximum hydraulic loading that infiltrates without runoff

Feasibility testing

Soil characteristics:

- Assess important parameters in the soil to be tested
- And their **variability**

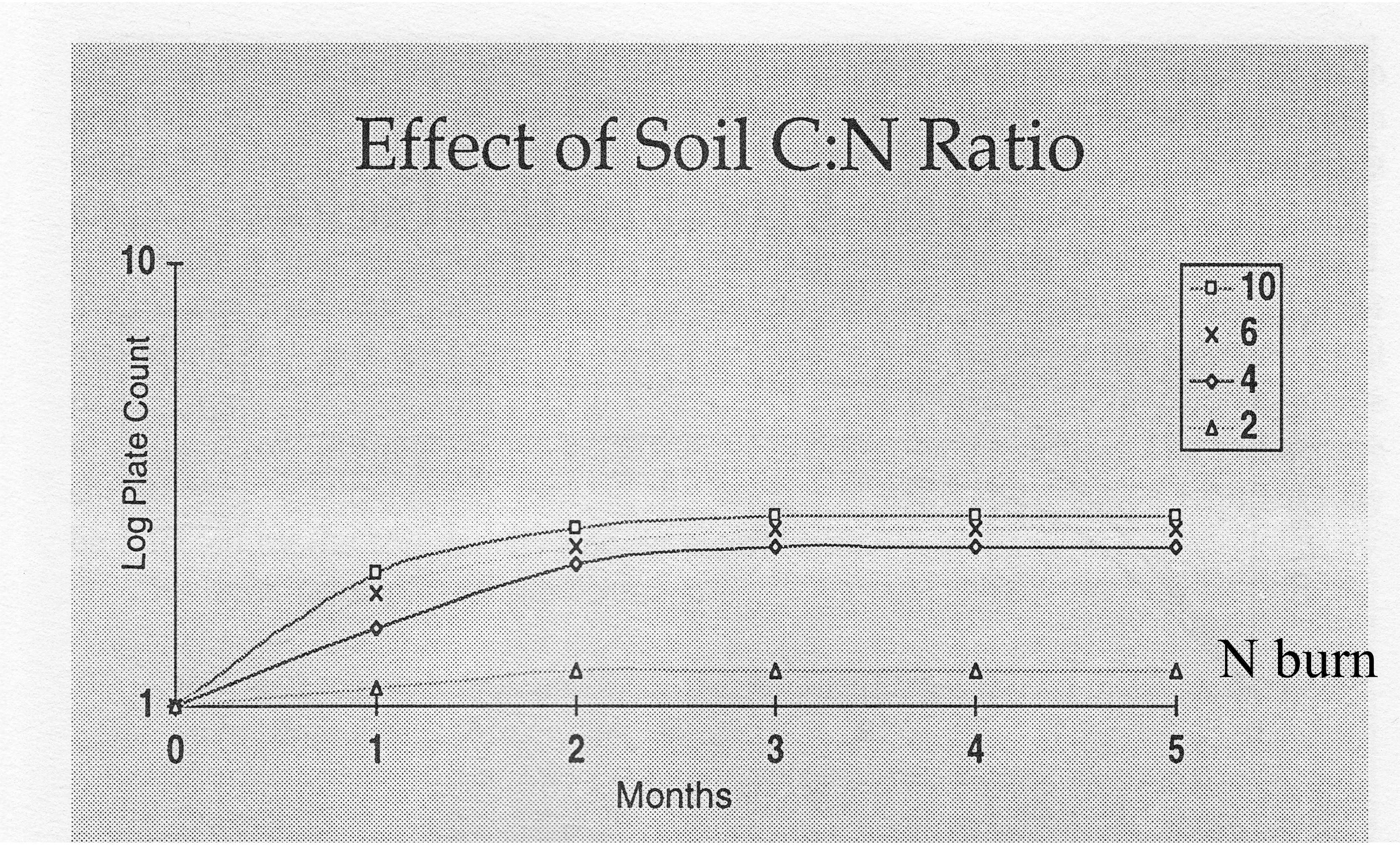
Microcosm stimulation test:

- Run by adding nutrients to soil
- C:N:P is 400:10:1- empirically determined
- Soil pH adjusted to 6.5-8.0 (ex. with crushed limestone)
- Water added to 50-80% of field capacity
- After 1-4 weeks, soil tested for hydrocarbon content (determine a good **criterion of success**! Which parameter to follow?)

-> Ability of native microorganisms to degrade the contaminant?

-> Adjust the treatment for optimization (test several microcosm treatments)

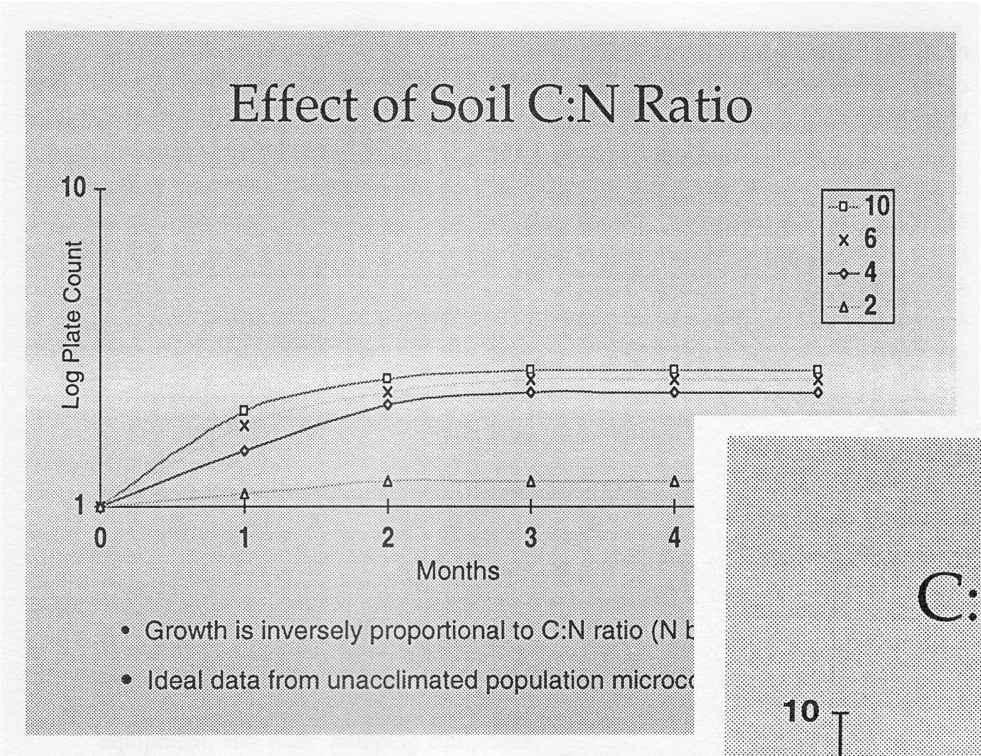
Effect of soil C:N ratio



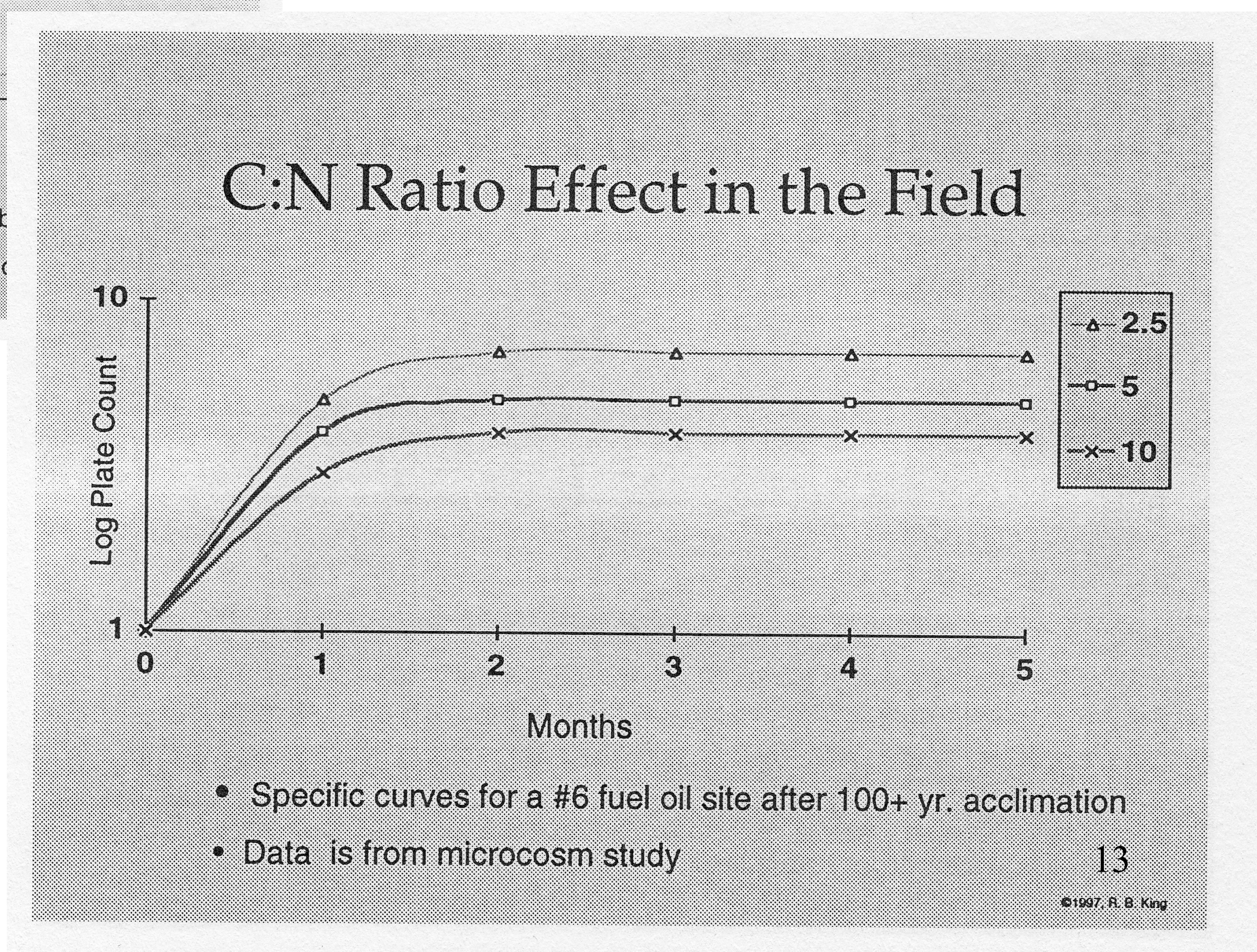
Ideal data from unacclimated population microcosms

R. B. King, 1997

Effect of soil C:N ratio



Conditions in the field are always somewhat different.



-> importance of proper testing

Land treatment

- Placing contaminated material
- Aeration (soil is tilled)
- Watering (sprinkler system)
- Nutrient addition: slow-release fertilizer
- Removal when treated (also limits metal accumulation)

Land treatment

- Placing contaminated material
- Aeration (soil is tilled)
- Watering (sprinkler system)
- Nutrient addition: slow release fertilizer
- Removal when treated

Big issue with water management:

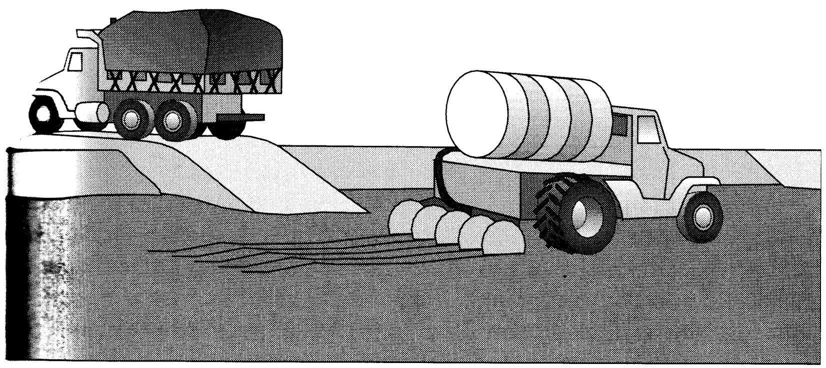
- Migration from the incorporation zone and infiltration
- Storm water runoff

Issue with air-mediated migration:

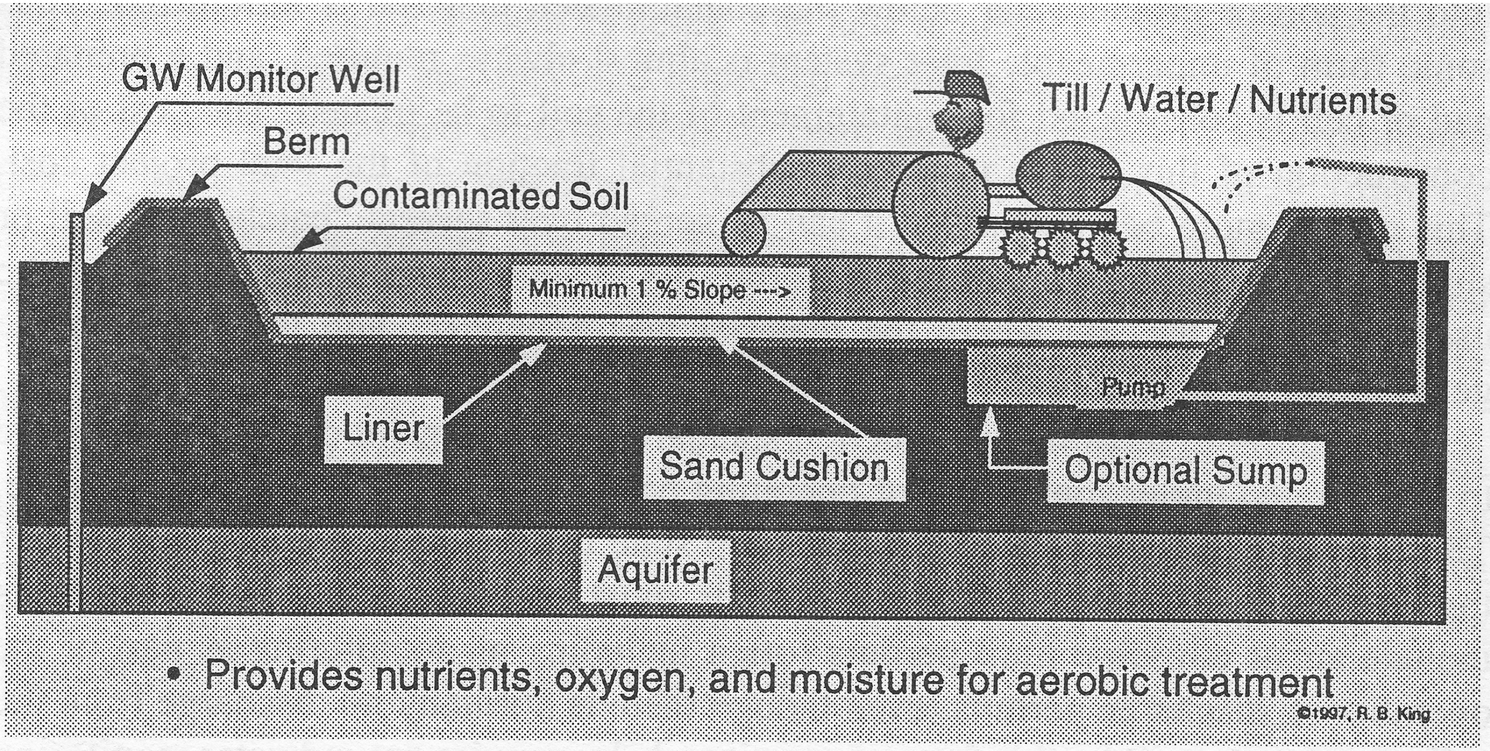
- Volatilization
- Windblown dust

Land treatment – basic principles of the design

- **Choice of the site** to minimize environmental impact
- Provide **enough surface area** to spread fluffed soil to 45 cm depth on liner
- Slight **slope** (0.5-1% slope) for drainage to sump pump
- Collection sump at low end to **collect rainwater**
- Retaining berm walls to keep soil contained and **prevent outside water**
- Provide access with ramp for tilling, nutrient addition equipment
- Provide sand over the liner to **promote drainage** and protect from tilling
- Cover if needed (for rainwater, T, and gas)



Land treatment – basic principles of the design



Treatment cell layout

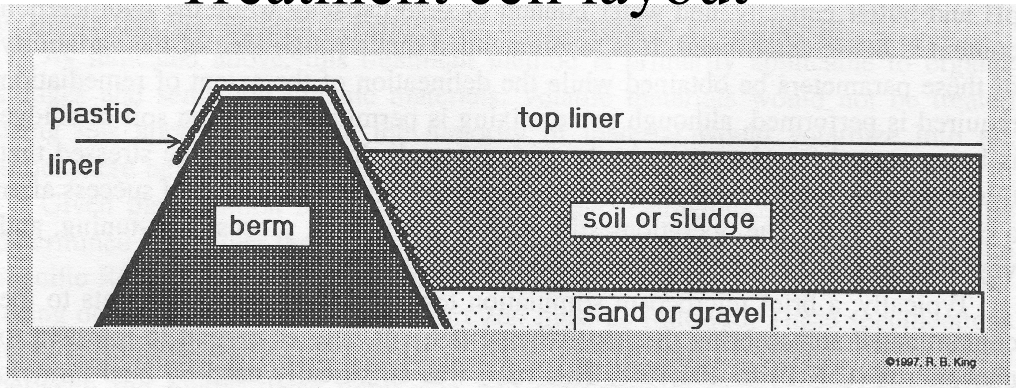
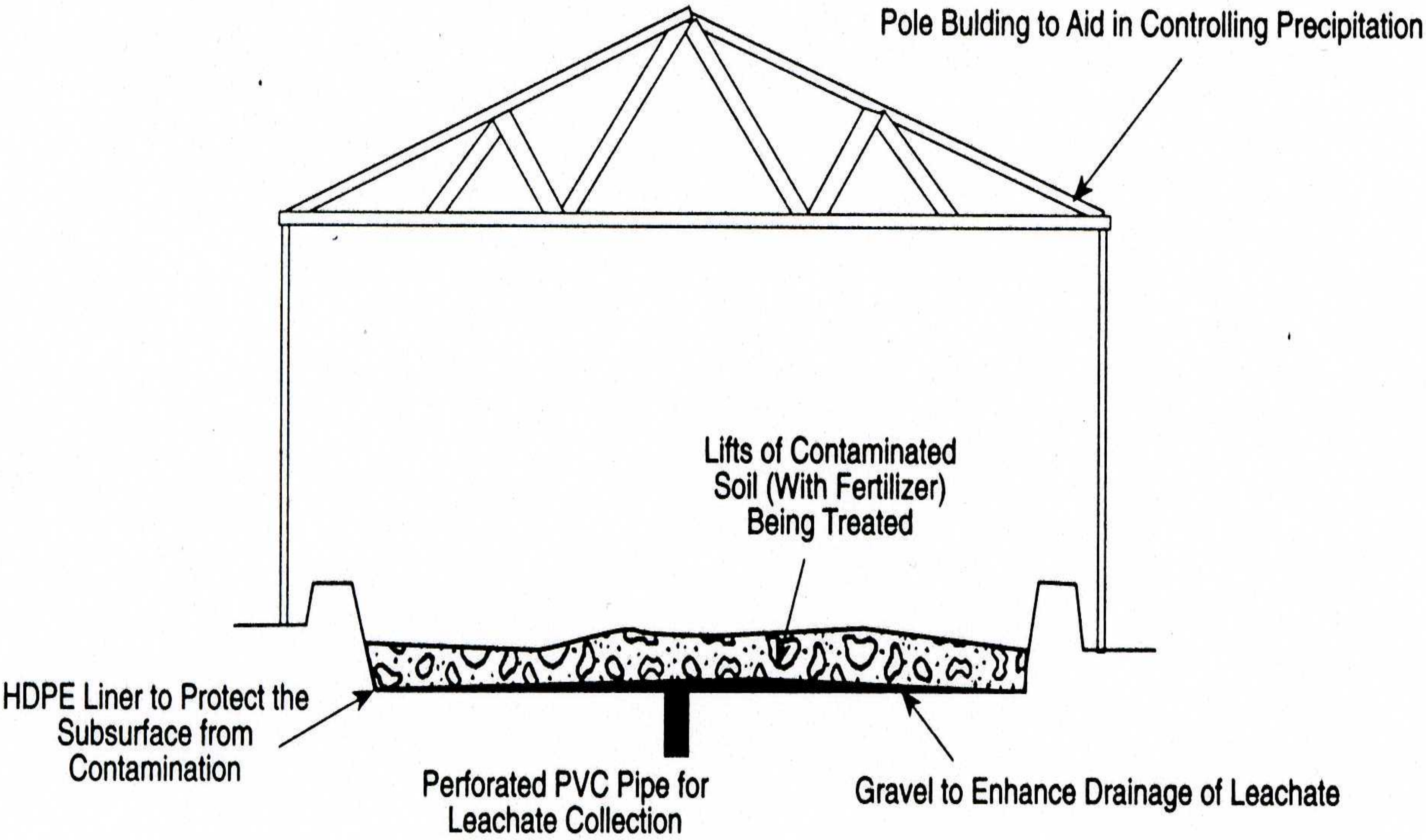


Figure 7-2 Treatment cell layout

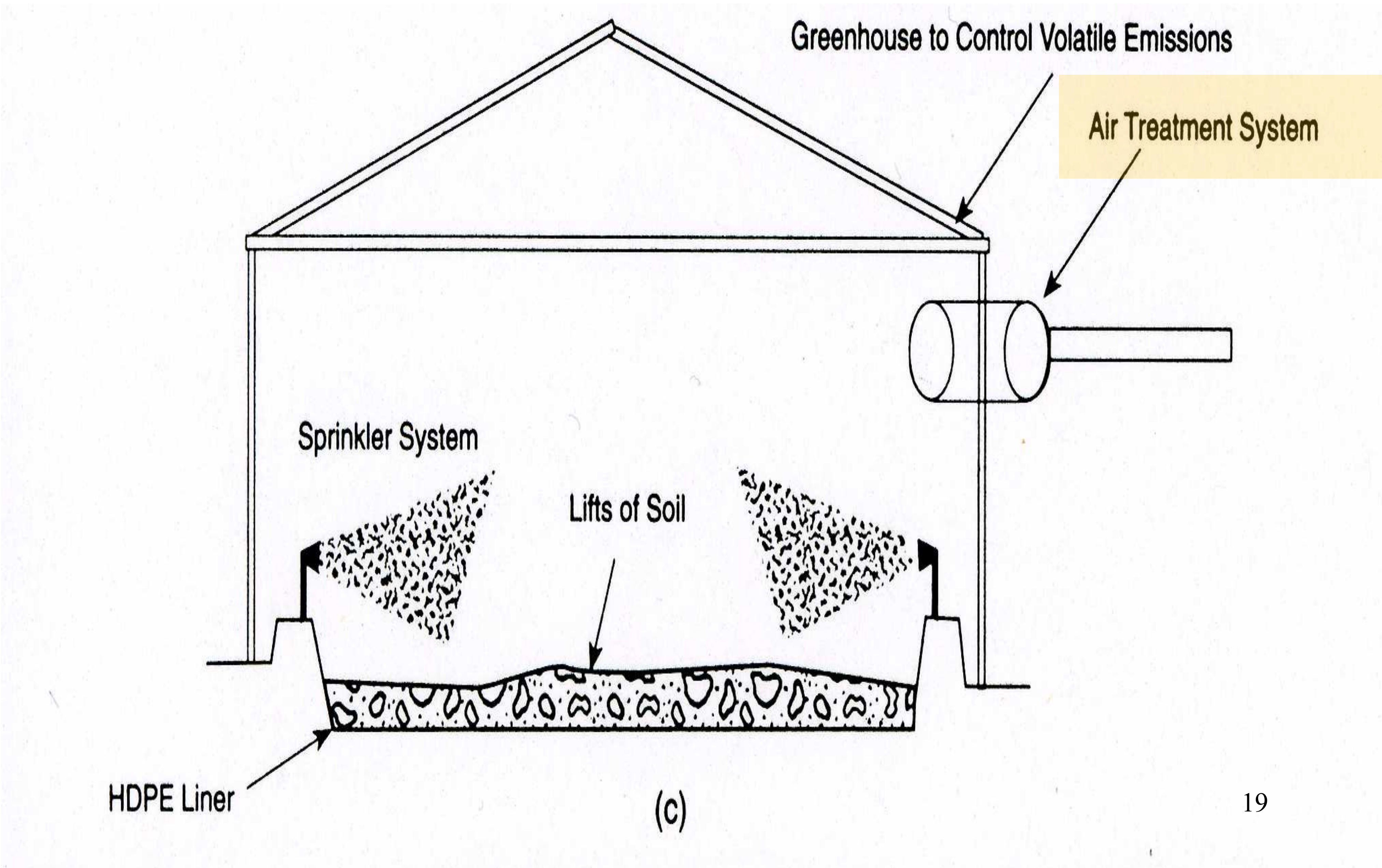
NB: a thick layer of clay may replace the bottom liner

Conceptual design of land treatment units (2)



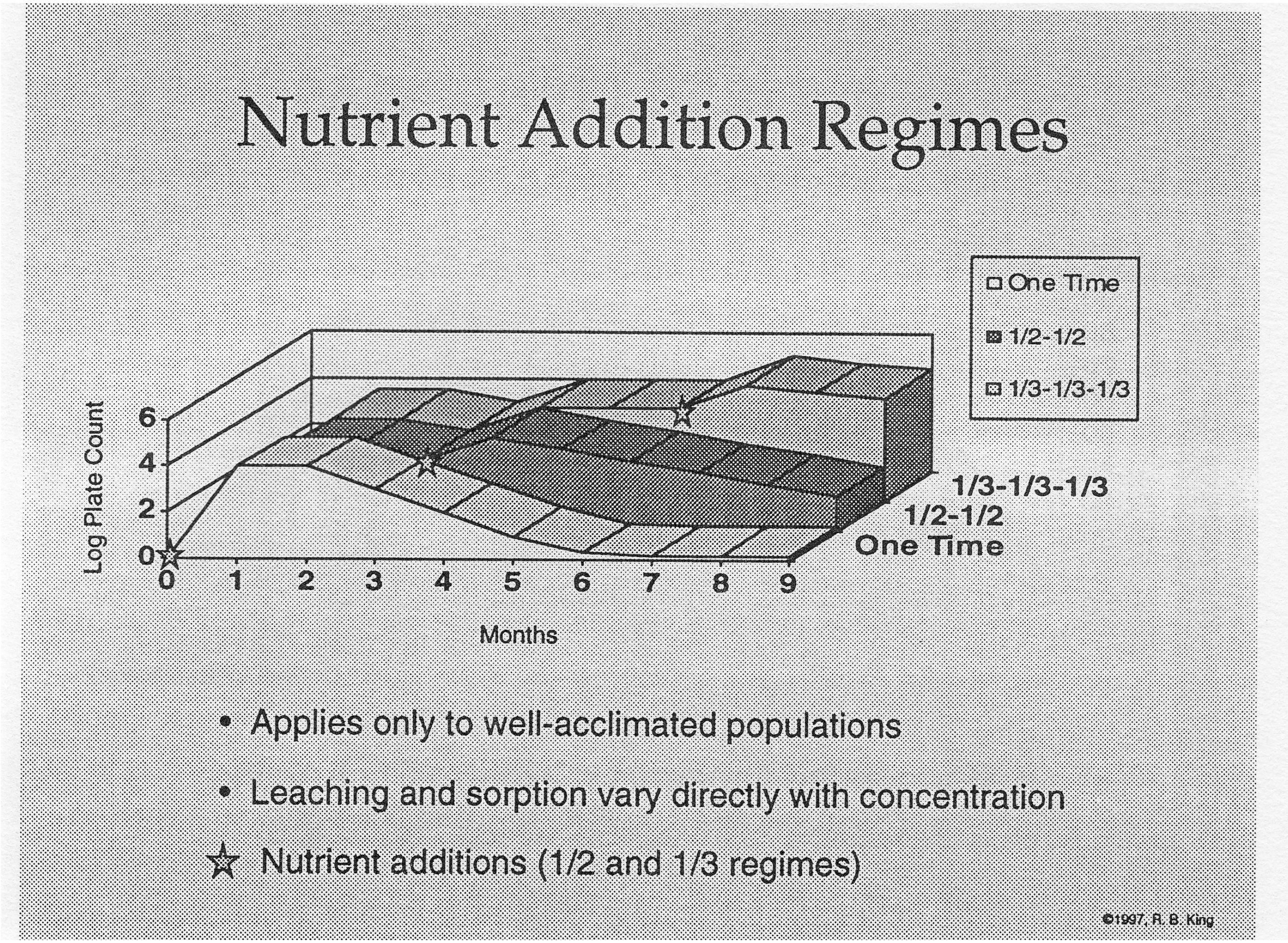
(b)

Conceptual design of land treatment units (3)



Nutrient addition

- Aerobic bacteria will act on contaminant
- Need high NH_4-N fertilizer
- **Periodic addition** outperforms single addition
- 50 mg/kg N and 5 mg/kg P

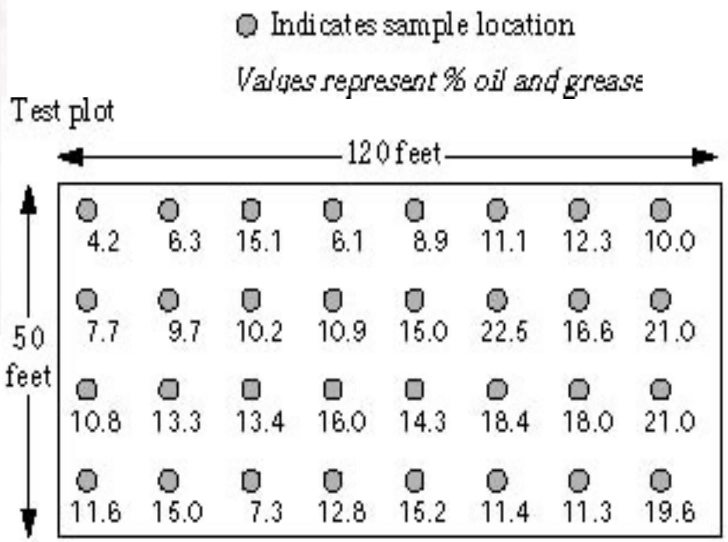


Land treatment case study

- BP Oil refinery in Louisiana conducted a pilot land treatment project to demonstrate degradation of refinery waste
- Used soil with high clay content. Area= 15m*36m; wet bulk density=1538 kg/m^3
- Added soil (1 m deep) and a dike (hydrology management)
- Sludge added and zone of incorporation (ZOI = 0.1 m) tilled weekly
  - The waste contained six volatile organics, 12 metals
- Moisture, nutrient balance and pH monitored
- Measure remainder after 368 days: average residual oil = 13% at 368 days

Land treatment of petroleum refinery sludge

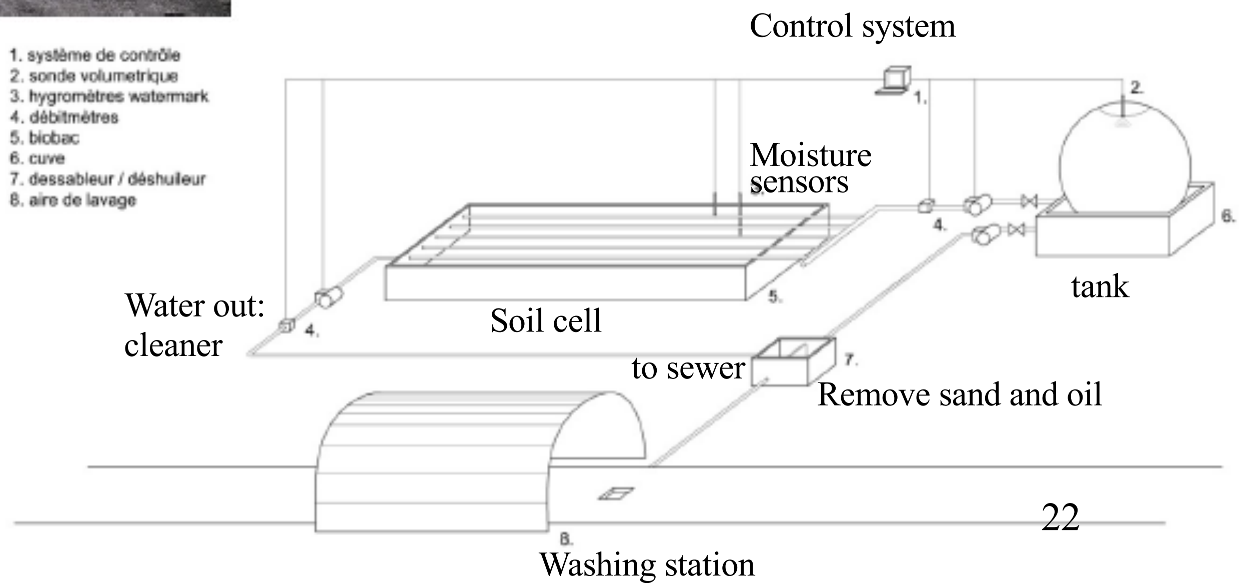
Time of application, days after initial application	Amount of applied waste, tons	Oil and grease concentration of applied waste, %
0	20.1	16.5
110	30.6	13.1
229	30.6	16.8
298	24.7	18.5



1. Calculate soil loading
2. Calculate the incremental increase of oil concentration to the ZOI, in %
3. Estimate the degradation rate k ‘and the half-life of the oil phase

Swiss example

Washing station for agricultural equipment in Denens
(pesticide contamination management)

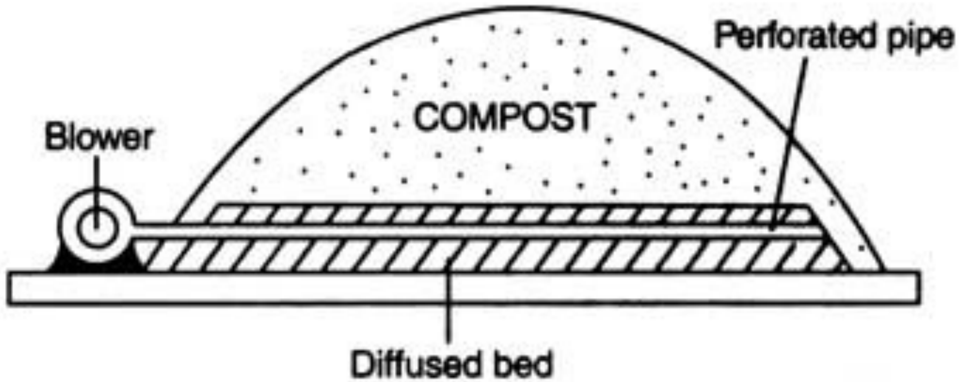


Composting (windrows and biopiles)

Composting

- ex. biopiles, windrows, composting reactor
- Similar to land treatment in basic principle (but can be more efficient for complex organic solids – less appropriate for low-organic contents)
- Soil excavated and heaped for treatment
- Aerobic process
  - **Aeration** of piles by tilling
  - or by forcing air through the composting material placed in containers or on platforms

Waste Treatment Compost at a Chevron Texaco Site (Source: ChevronTexaco)



Composting

Typical parameters to control:

- T (degradation typically occurs in the thermophilic range (55-65 C)
- Too high T kill the microorganisms
- Moisture
- Oxygen level
- Organic content

Composting

Windrows:

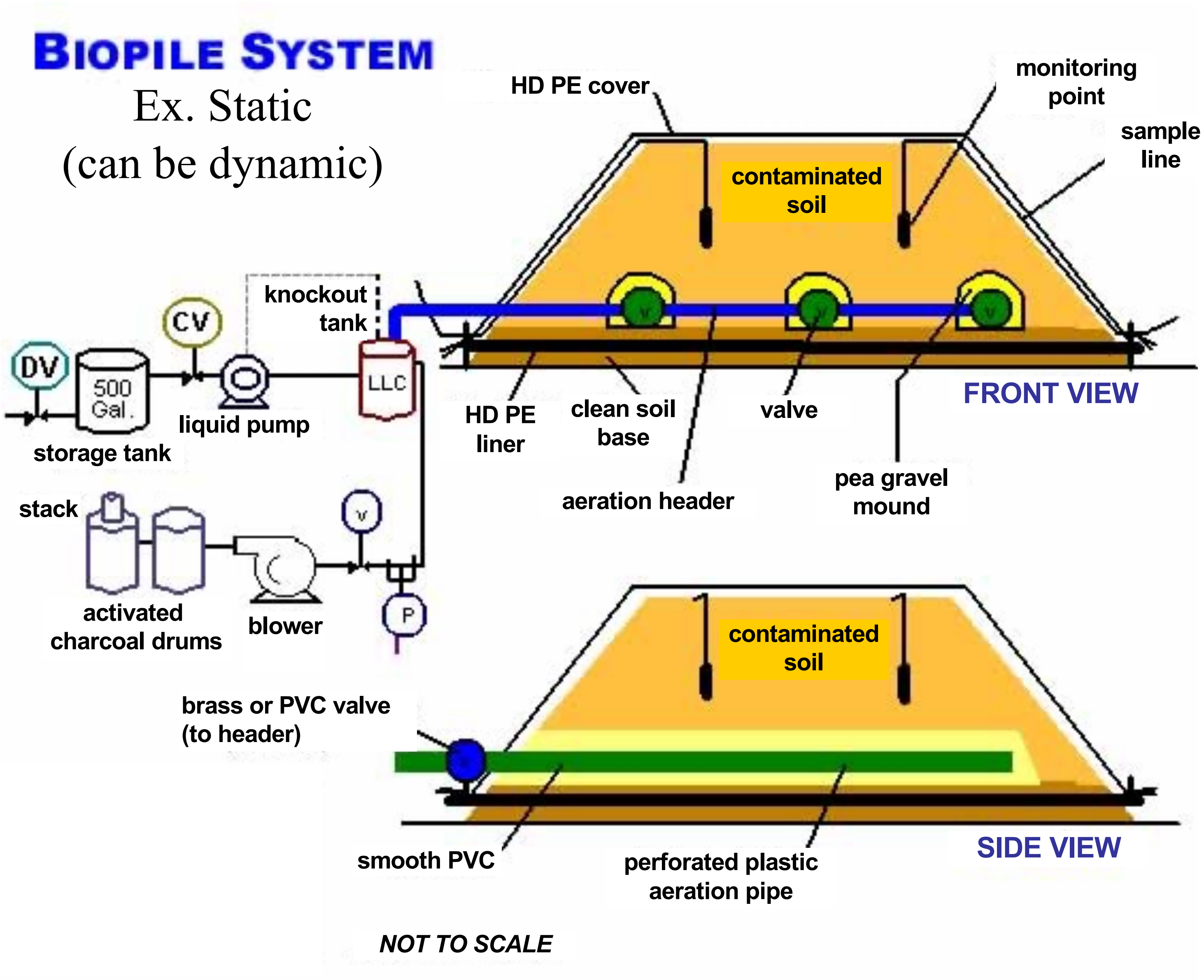
- bulking agent (ex. Wood chips) added to increase porosity and decrease moisture levels
- Piled in **long rows**
- maximum size: 1.5 m tall and 3.5 m wide
- mechanically **mixed** (1-2/week)
- front-end loader or **turner needed for aeration**
- turning to aerate pile and **release heat**

Biopiles

- **static or dynamic**
- need aeration system
- can be bigger than windrows
- typically 3 m high

Composting

Static piles



Biopiles

- Design critical for optimal performance
- Temporary and permanent (concrete base)
- Considerations:
  - Height limited by reach of front-end loader
  - Height also limited by aeration (passive vs. forced aeration)
  - Slope too steep: aeration of sides not center
  - Slope too shallow: waste space

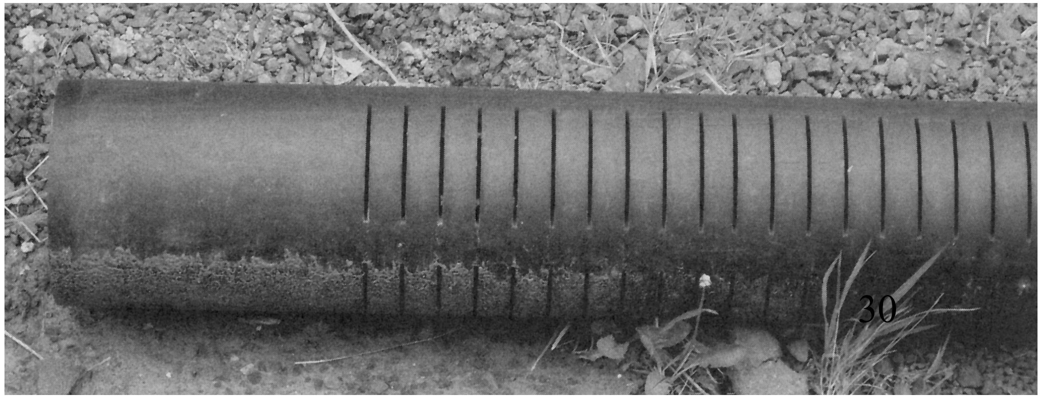
Biopile

- Biopile base
  - Solid surface, usually soil /clay foundation
  - impermeable liner (HDPE) 1-2 mm
  - trench for leachate
  - Clean soil on top of liner to protect it
  - Slope of 1 or 2%

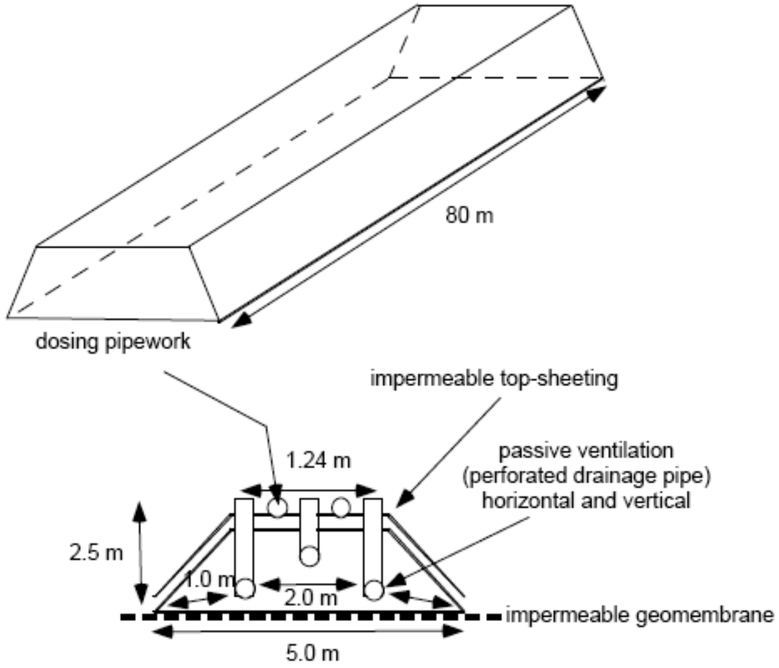
- Graded, sieved soil (30-50 mm)
- Add bulking agents (wood chips, straw), water, P, N

Aeration systems

- Constructed on top of liner
- Slotted plastic pipes embedded within gravel or wood chips
- Low power blowers- too rapid airflow dries soils; too slow insufficient aeration
- Passive aeration: not as effective- zones of local oxygen deficit
- Issue of VOC: can operate in vacuum mode
  - treat the gas (GAC)- 15 pore volumes per day
  - entrain condensate: need water knockout and collection
- Fixed rate aeration: can be turned on or off but not changed. Disadvantage is that pile can be over-aerated when low microbial activity (beginning) and then under-aerated when high microbial activity
- Variable rate: not used much- need day to day monitoring. Rate of aeration starts out high and decreases with time.
- Automated: computer controlled in response to temperature in pile.



Example design

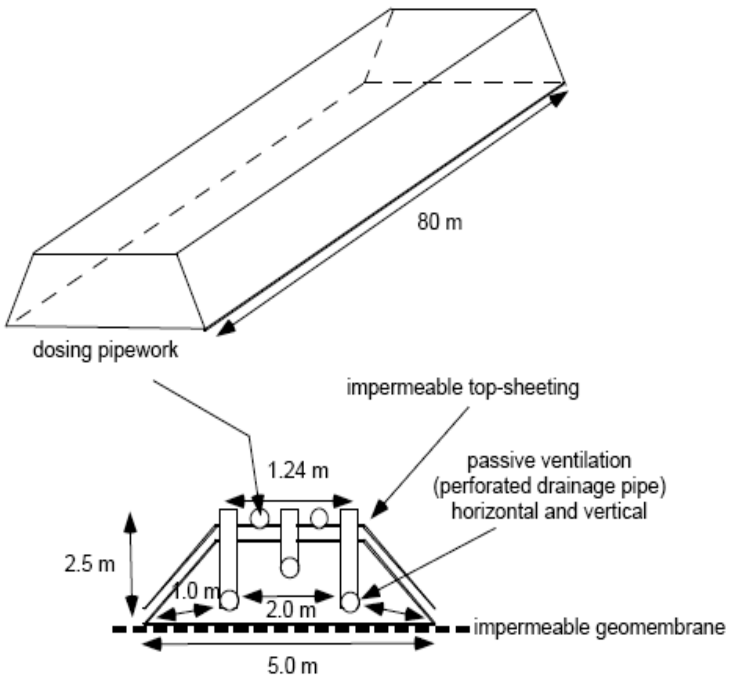


Height: 2.5 m
Upper width: 1.24 m
Lower width: 5 m
Length: 80 m
Total volume: 624 m^3
Total mass: 7.49×10^5kg
Area: $((5+1.24) \times 2.5)/2 = 7.8\ m^2$
Volume: $7.8*80 = 624 m^3$
Total mass: 7.49×10^5 kg = 749 tonnes with bulk density of 1200 kg/m^3)

1. Water: 80% of field capacity (v/v),
field capacity of sandy loam (SL) soil: 20%
Water volume = $624m^3 \times 0.16 = 99.84m^3$

2. At 50% porosity, water + air = 50%
Air volume = $312\ m^3 – 99.84\ m^3 = 212.16\ m^3$

Example design



3. 2% organic matter, 48% inorganic matter v/v
Volume of 2% organic matter = 624m^3 x 0.02 = 12.48 m^3
Volume of 48% inorganic matter = 624m^3 x 0.48 = 299.52 m^3

4. $TPH_{t=0}$: 80,000 mg oil/kg soil = 0.08 kg oil/kg soil,
Density of heavy oil (NAPL): 0.97 g/cm^3,
NAPL volume = 0.08 kg oil/kg soil = 61.72 m^3
Assume NAPL shares air volume with air
Air volume = 212.16 m^3 – 61.7 2m^3 = 150.44 m^3

So overall:
Volume of soil = 321 m^3
Volume of water= 100 m^3
Volume NAPL = 62 m^3
Volume of air = 150 m^3

Example design

Design biopile calculations example for 286 m^3 gasoline-contaminated soil with low organic content:

mg/L to ppmV

$$ppmV = \frac{mg}{L} \times (10^3) \times \frac{1}{Molecular\ Weight_{contaminant}\ [g/mole]} \times 8.3144 \left[\frac{L \cdot kPa}{mol \cdot K}\right] \times T_{air}[K] \times \frac{1}{P_{air}[kPa]}$$

1. Moisture for biopile:

Assume:

porosity, n = 30% and initial saturation, S = 20%

Desired water content = 25 to 85%, use 60%

Therefore:

The water needed = 286 × 0.30 × (0.6 – 0.2) = 34.3 m^3 = 34,300 L

2. Nutrient requirement for biopile

158 kg spill of gasoline (C_7H_{16})

Nutrient sources: Ammonium sulfate ($(NH_4)_2SO_4$); Trisodium phosphate ($Na_3PO_4 \bullet 12H_2O$)

MW of gasoline = 7 × 12 + 1 × 16 = 100 g/mole

Moles of gasoline = 158 × 10^3 / 100 = 1580 moles

Moles of C = 7 × 1580 moles = 1.1 × 10^4 moles

Molar ratio C: N: P = 120:10:1

Moles of N needed = 10/120 × 1.1 × 10^4 = 920 moles

Moles of ($(NH_4)_2SO_4$) needed = 920 / 2 = 460 moles MW of ($(NH_4)_2SO_4$) = (14 + 4) × 2 + 32 + 4 × 16 = 132 g/mole

Mass of ($(NH_4)_2SO_4$) needed = 132 × 460 = 6.1 × 10^5 g = 61 kg

By similar calculation:

Mass of ($Na_3PO_4 \bullet 12H_2O$) needed = 35 kg

Example design

mg/L to ppmV

$$ppmV = \frac{mg}{L} \times (10^3) \times \frac{1}{Molecular\ Weight_{contaminant}\ [g/mole]} \times 8.3144 \left[\frac{L \cdot kPa}{mol \cdot K}\right] \times T_{air}[K] \times \frac{1}{P_{air}[kPa]}$$

3. Oxygen requirement for biopile

$C_7H_{16} + 11\ O_2 \rightarrow 7CO_2 + 8H_2O$

1 mole (100 g) gasoline requires 11 moles ($16 \times 2 \times 11 = 352$ g) O_2

Oxygen content of air = 21% by volume = 210,000 ppmv

4. Oxygen needed for 158 kg spill of gasoline ($\cong C_7H_{16}$)

100 g gasoline needs ~350 g oxygen

158 kg gasoline $\times$ 3.5 = 553 kg O_2= 0.553×10^6 g O_2

5. Water in pile = 286 m^3 (0.30) (0.6) = 51.5 m^3 = 51,500 L

At saturation at 20ºC and 1 atm (101.325 KPa), Dissolved Oxygen = 9.2 mg/L

Mass of oxygen in soil moisture = 51,500 L x 9.2 mg/L x 0.001 g/mg = 473.8 g O_2

473 g O_2 in soil moisture is much less than 0.553×10^6 g O_2 required

At 0.28 g/L air, air requirement is:

0.553×10^6 g / 0.28 g/L = 1.975×10^6 L = 1.975 m^3 air

Air void volume in pile = 286 m^3 (0.30) (0.4) = 34 m^3

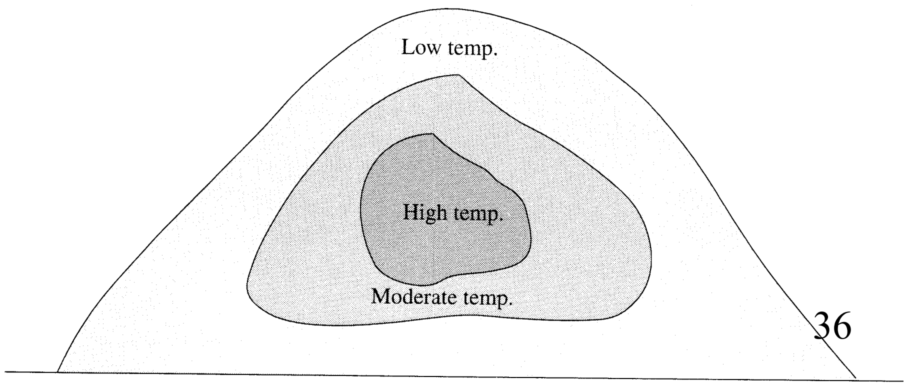
Need to exchange 1975 / 34 = 58 void volumes to fulfil oxygen requirement

Windrow composting

Piles are **turned**
front-end loader or turner needed for aeration
Releases excess heat
And volatiles…

Windrow composting

- Organics added to the windrows
- Increase metabolic rate of indigenous hydrocarbon oxidizers
- Increase bioavailability of hydrophobic pollutants
- If moisture content too high, gas transfer rates decrease significantly
- Optimal moisture content about 50%
- Does not reach very high temperatures (<45ºC)
- **Turnover to dissipate heat**
- Add bulking agents to aid in heat dissipation
- Frequency of turning varies between once a day to once a month
- Piles that are not turned: passive aeration. Temperature gradient causes convective airflow. Such aeration is limited by porosity and pile depth



Covers

- Many projects without covers
- Waterproof plastic sheet
- Fleece liners (PP). Resist to rainfall, not impermeable, gas permeable. Equipment to remove/replace liner
- Offer advantages:
  - Prevent leachate formation
  - Lose little water so no need to irrigate
  - Still must monitor water content since forced aeration remove water

Considerations

- Apply manure, sewage sludge, garden waste
- Shaped as a triangular prism
- Windrow turner needed-saves space
- No need for pipes for aeration
- Issues: odors, VOC emissions, climate-dependance
- Slower than enclosed reactor

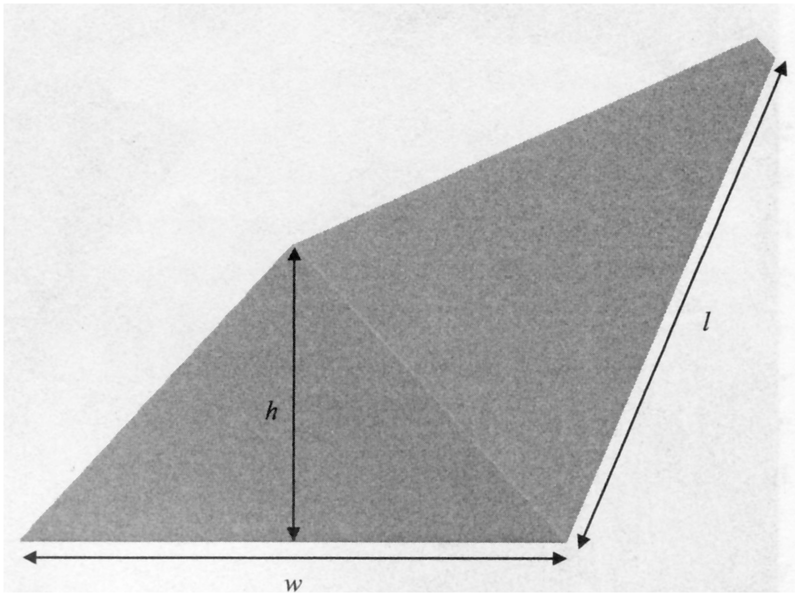


TABLE 8.6 Comparison of Three Composting Systems

Control level	Windrow system	Static pile system	In-vessel system
Operational skill level	Low	Moderate	High
Process flexibility	High	Medium	Low
Material load flexibility	High	Medium	Medium
Process control	Low	Medium	High
Moisture control	Low	Medium	High
Air emission control	Low	Medium	High
Runoff control	Medium	Medium	High
Space requirement	High	Medium	Low
Pathogen destruction	Medium	High	High
Climatic dependency	High	Medium	Low
Capital cost	Low	Medium	High
Maintenance cost	Low	Medium	High

Conclusions

- Disruptive techniques
- Need a large amount of space
- Useful for certain applications (e.g., hydrocarbons)
- Limitation in terms of:
  - Capacity (amount that can be treated)
  - Rate (amount per given time < degradation rate)
  - Loss via volatilization and leaching
- Adaptable concept, many variations

Slurry biodegradation

Slurry biodegradation

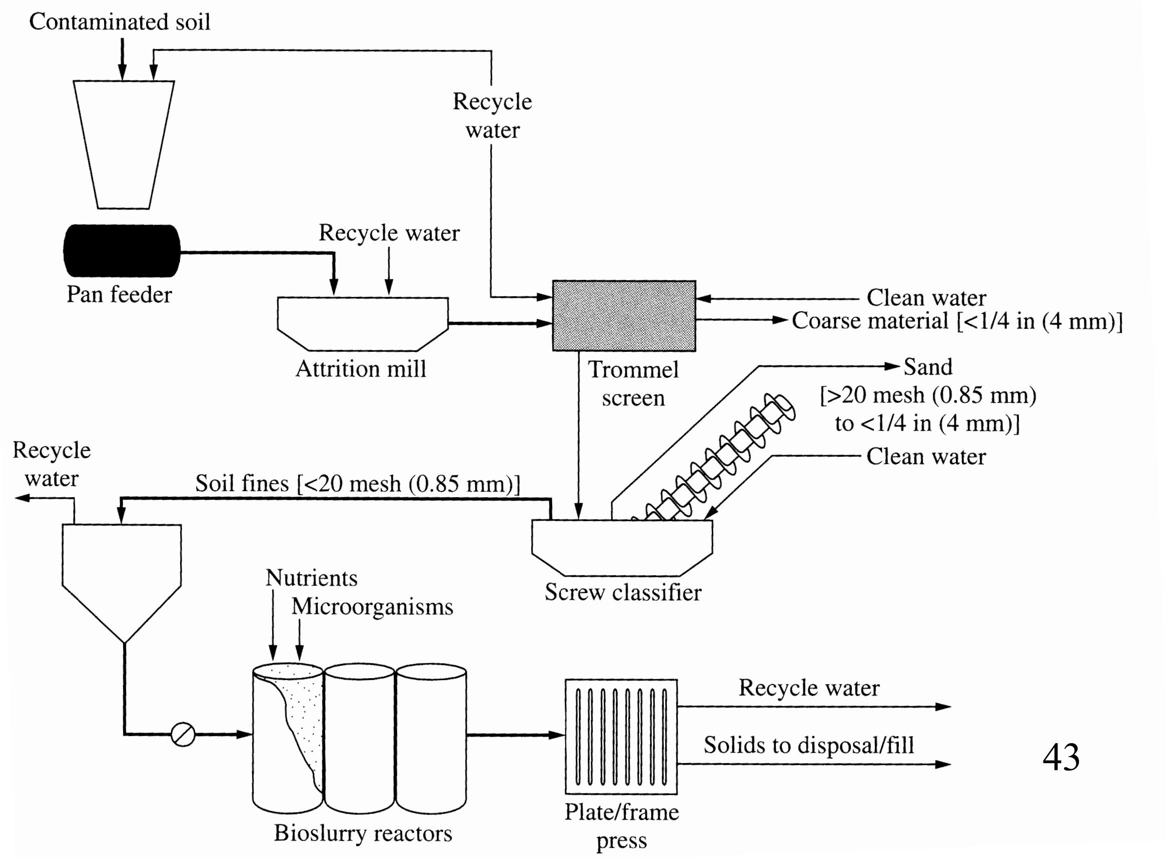
- Slurry: suspension of a solid phase in liquid
- Slurry biodegradation is used to treat soil that is excavated
- Suspended in aqueous medium (water or wastewater) until reach target density
- Amended with nutrients, pH adjusted
- Mixing energy needs increase with density
- For high contaminant concentration: require higher O_2 transfer so more dilute slurry
- Keep solids in suspension to increase contact with microorganisms
- Mixing and aeration to break up clumps and increase mass transfer rate
- Treatment with most contact btw contaminant and microorganisms
- Desorption of waste from solid particles

Slurry biodegradation

Fundamental treatment steps:

- Mixing aeration
- (Pre-treatment)= enhance desorption (surfactant), or concentrate waste (select particle size)
- Desorption= contaminant must be in solution for biodegradation- rate limiting step
- Biodegradation

Can be done in a single reactor or in multiple stages



General mass balance

$$V\frac{dC}{dt} = \sum Q_{in}C_{in} - \sum Q_{out}\, C_{out} \pm \mathrm{V} * \mathrm{r}$$

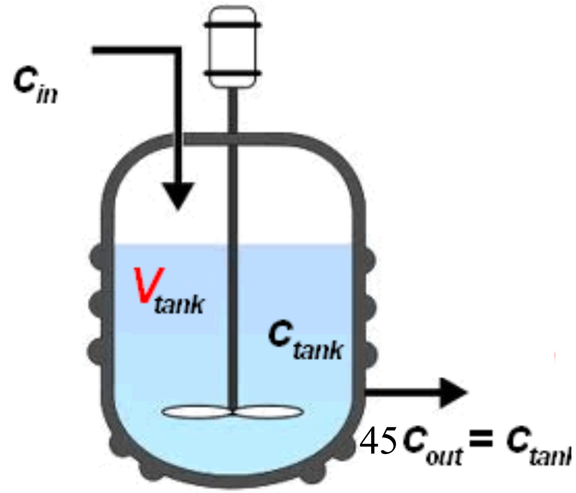
V= volume of reactor
Q=flow rate
C= concentration
r= reaction rate (concentration/time)
T= time

The change in mass of the compound as a function of time is equal to the sum of the incoming mass minus the outgoing mass either minus the reacted amount or plus the produced amount.

Reactors: types

- Batch= reactor that is filled and reaction occurs, then emptied.
  - Low volume of soil
  - No restriction on time required to treat
  - Holding tanks to keep inoculum and nutrient mix
  - First order kinetics: fast initial rate at high contaminant conc.
  - Lag period for bacteria to adapt to reactor environment

- Continuous-flow stirred tank reactor (CSTR)=mixing is critical as perfect mixing is assumed (composition of effuent is the same as that of the reactor)- steady state conditions
  - No lag because active bacteria remain in reactor
  - Instantaneous dilution of feed mitigates toxicity
  - Faster than batch (no wait)
  - Continuous pumping=high cost
  - Residence times order days-weeks



Types of reactors

$$V\frac{dC}{dt} = \sum Q_{in}C_{in} - \sum Q_{out}\,C_{out} \pm \mathrm{V} * \mathrm{r}$$

- Batch: $Q_{in}=Q_{out}=0$

$$\boxed{V\frac{dC}{dt} = \mathrm{V} * \mathrm{r}}$$

Types of reactors

$$V\frac{dC}{dt} = \sum Q_{in}C_{in} - \sum Q_{out}\, C_{out} \pm \mathrm{V} * \mathrm{r}$$

- Batch: $Q_{in}=Q_{out}=0$

$$\boxed{\frac{dC}{dt} = \mathrm{r}}$$

- Continuous-Flow stirred tank reactor (CSTR)

$Q_{in}=Q_{out}$ and steady-state, no change in C

$$\boxed{0 = \quad QC_{in} - QC_{out} \pm \mathrm{V} * \mathrm{r}}$$

Reactors: batch operation

- Single reactor vessel
- Soil, nutrients, inoculum, water added
- Mixing and aeration
- Monitor degradation till reaches acceptable level
- Allow solids to settle
- Return soil to original area
- Liquid: treated or recycled

$$C_t = C_0\, e^{-kt}$$

Assuming 1st order kinetics with
k= rate constant **(unit= 1/time)**

$$C_t = C_0 - kt$$

For 0th order kinetics
k=rate constant
unit= mass.volume^{-1}.time^{-1}

$$C_t = \frac{C_0}{1 + kt * C_0}$$

For 2nd order kinetics
k=rate constant-
unit= volume.mass^{-1}.time^{-1}

Example

A batch reactor is being designed to treat soil containing 200 mg/kgdry soil of organic contaminant. The degradation rate constant is 0.5 h^{-1}. The total volume of liquid is 0.1 m^3 and the mass of (dry) solid is 5 kg. K_D= 2 m^3/kg. What is the residence time required if the desired concentration is 10 mg/kg?

Reactors: CSTR

CSTR

$$\frac{C_{out}}{C_{in}} = \frac{1}{1 + kt}$$

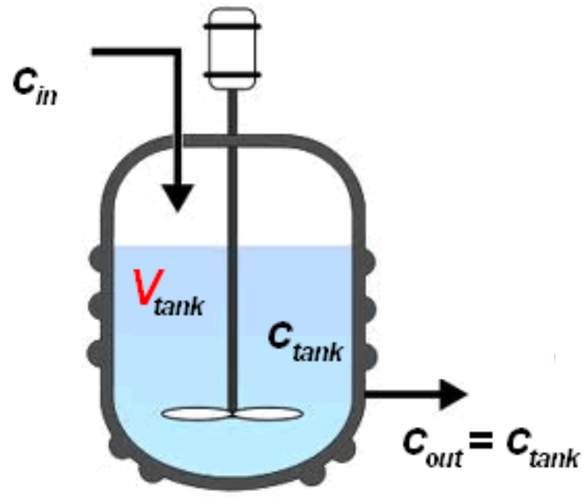
For 1st order kinetics

$$C_{out} = C_{in} - kt$$

For 0th order kinetics

$$\frac{C_{out}}{C_{in}} = \frac{1}{1 + kt * C_{out}}$$

For 2nd order kinetics



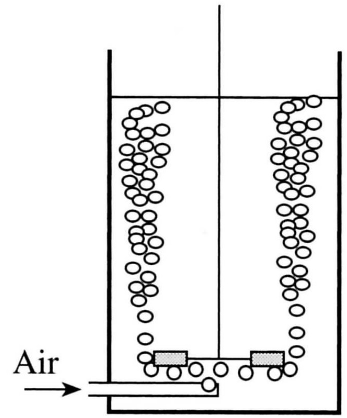
CSTR consists of a stirred tank reactor that has feed streams of the reactants and discharge streams of reacted materials.
Assumed to be perfectly mixed
The discharge stream and the reactor content have the same composition

Example

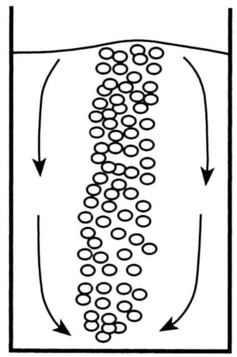
A CSTR reactor is being designed to treat soil containing 200 mg/kg of organic contaminant. The degradation rate constant is 0.5 h^{-1}. The total volume of liquid is 0.1 m^3 and the mass of solid is 5 kg. K_D= 2 m^3/kg. What is the residence time required if the desired concentration is 10 mg/kg?

Oxygen supply

- O_2 electron acceptor of choice
- Turbine spargers:
  - combine mechanical & diffuse aeration
  - air released below flat-blade turbine
  - bottom reactor
  - Turbulence breaks up bubbles
  - Better mass transfer
- Diffused aeration:
  - air forced through porous device
  - bottom of tank
  - as bubbles rise, O_2 diffuses into water
  - contact time depends on depth (>5m)



b. Turbine sparger



a. Diffused aeration

Oxygen uptake rate

$$r_{O_2} = r_0\left(1 - \frac{0.6}{1+0.05\tau}\right)$$

r_{O2}=oxygen uptake rate, mg O_2/L.h
r_0= rate of reaction (mg/L.h)
τ= solids residence time, days

Mixing

- Completely mixed fluid preferable to maximize desorption rates & minimize toxicity
- Turbulent regime to avoid soil settling $N_{Re}>10{,}000$
- Radius of influence of a turbine mixer is 2-3 x impeller diameter

$$N_{\mathrm{Re}_i} = \frac{N D_i^2 \rho}{\mu}$$

$N_{Re,i}$= impeller's Reynolds number

N=rotational speed of impeller, rps

D_i=impeller diameter, m

ρ= density of the suspension, kg/m^3

μ= dynamic viscosity of suspension, kg/m.s

Pre-treatment

- Necessary to remove uncontaminated sediment
- Rocks, gravel and sand usually uncontaminated and will not stay suspended
- Soil fractionation
- Soil washing

Microbial inoculum

- Develop adequate microbial community
  - Mixed cultures often most stable to carry out process
  - A single bacterium often cannot break up pollutant to CO_2
  - Product sometimes toxic to microorganism so downstream degradation mitigates toxicity
  - Variation in community with time or spatial heterogeneity
- Insure suitable concentration of microorganisms
- Control toxicity

Sizing reactor

Determining the residence time:

Batch (1st order): $\tau = -\frac{1}{k}\ln(\frac{C}{C_0})$

CSTR (1st order): $\tau = \frac{C_{in}/C_{out} - 1}{k}$

V= reactor volume, m^3

Q= flow rate, m^3/day

τ= residence time, day

k= first-order degradation constant, day^{-1}

$V = Q\,\tau$

Reactor configurations- in series

Flow rates of all reactors are the same and equal to the influent flow rate of the first reactor

$$\xrightarrow{Q,\ C_0} \boxed{V_1} \xrightarrow{Q,\ C_1} \boxed{V_2} \xrightarrow{Q,\ C_2} \boxed{V_3} \xrightarrow{Q,\ C_3}$$

- For CSTR: a few small reactors will yield a lower concentration than a large reactor

$$\frac{C_3}{C_0} = \left(\frac{C_3}{C_2}\right)\left(\frac{C_2}{C_1}\right)\left(\frac{C_1}{C_0}\right) = \left(\frac{1}{1 + k_3 t_3}\right)\left(\frac{1}{1 + k_2 t_2}\right)\left(\frac{1}{1 + k_1 t_1}\right)$$

Example

Subsurface soil at a site is impacted by diesel fuel at a concentration of 1,800 mg/kg. Aboveground remediation, using CSTR slurry bioreactors, is proposed. The treatment system is required to handle a slurry flow of 0.04 m^3/min. The required final diesel concentration in the soil is 100 mg/kg. The reaction is first order with a rate constant of 0.1 min^{-1}. Four different in series configurations are considered. Which meet the clean-up requirements?

(a) One 4 m^3 reactor; (b) Two 2 m^3 reactor; (c) One 1 m^3 and one 3 m^3 reactor; (d) One 3 m^3 and one 1 m^3 reactor.

C_{in}= 1,800 mg/kg

k= 0.1 min^{-1}

Q= 0.04 m^3/min

(a) V= 4 m^3

(b) $V_1 = V_2 = 2\ m^3$

(c) $V_1 = 1\ m^3$ $\quad V_2 = 3\ m^3$

(d) $V_1 = 3\ m^3$ $\quad V_2 = 1\ m^3$

Example

(a) Residence time: $t = V/Q = 4\ m^3/0.04\ m^3/min = 100\ min$

Final effluent concentration

$$\frac{C_{out}}{C_{in}} = \frac{1}{1+kt}$$

$C_{out} = 1/\ (1+ kt) = 1/(1+0.1\ min^{-1}*100\ min)*1{,}800\ mg/kg$

$C_{out} = 164\ mg/kg$

(b) Residence time: $t = V/Q = 2\ m^3/0.04\ m^3/min = 50\ min$ each

Final effluent concentration

$$\frac{C_2}{C_0} = \left(\frac{1}{1+k_2 t_2}\right)\left(\frac{1}{1+k_1 t_1}\right)$$

$C_2 = 1{,}800 mg/kg*1/(1+ min^{-1}*50\ min)^2$

$C_{out} = 50\ mg/kg$

(c) Residence time: $t_1 = V_1/Q = 1\ m^3/0.04\ m^3/min = 25\ min$

and $t_2 = V_2/Q = 3\ m^3/0.04\ m^3/min = 75\ min$

Final effluent concentration

$$\frac{C_2}{C_0} = \left(\frac{1}{1+k_2 t_2}\right)\left(\frac{1}{1+k_1 t_1}\right)$$

$C_2 = 1{,}800*1/(1+0.1*25)*1\ /(1+0.1*75)$

$C_{out} = 60.5\ mg/kg$

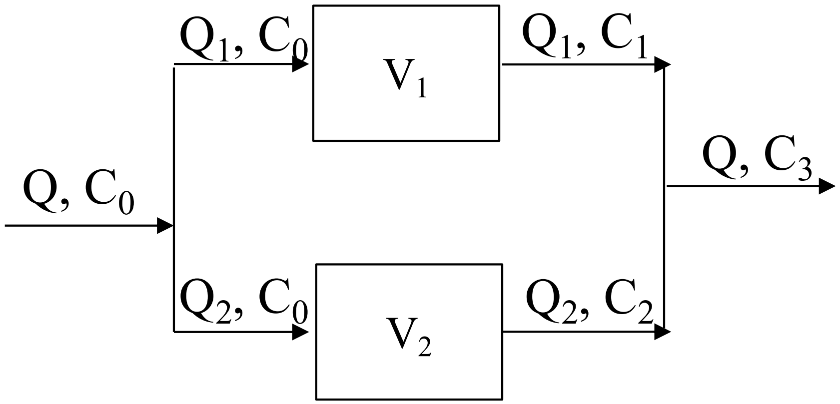
(d) Residence time: $t_1 = V_1/Q = 3\ m^3/0.04\ m^3/min = 75\ min$

and $t_2 = V_2/Q = 1\ m^3/0.04\ m^3/min = 25\ min$

Same as above

Reactor configurations- in parallel

- Reactors in parallel



$$C_3 = \frac{Q_1C_1 + Q_2C_2}{Q_1 + Q_2}$$

The reactors share the same influent (split across reactors) but the concentration is the same

They are used when a single reactor cannot handle the flow rate, the total influent rate fluctuates, the reactors require frequent maintenance.

Example

Subsurface soil at a site is impacted by diesel fuel at a concentration of 1,800 mg/kg. Aboveground remediation, using CSTR slurry bioreactors, is proposed. The treatment system is required to handle a slurry flow of 0.04 m^3/min. The required final diesel concentration in the soil is 100 mg/kg. The reaction is first order with a rate constant of 0.1 min^{-1}. Four different parallel configurations are considered. Which meet the clean-up requirements?

(a) One 4 m^3 reactor; (b) Two 2 m^3 reactor (0.02 m^3/min each); (c) One 1 m^3 and one 3 m^3 reactor (0.02 m^3/min each); (d) One 3 m^3 (0.03 m^3/min) and one 1 m^3 reactor (0.01 m^3/min).

C_{in}= 1,800 mg/kg

k= 0.1 min^{-1}

Q= 0.04 m^3/min

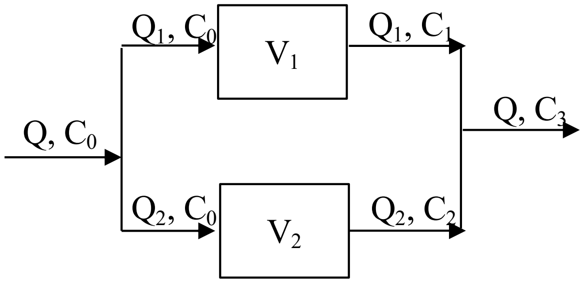
(a) V= 4 m^3

(b) $V_1 = V_2 = 2\ m^3$; $Q_1 = Q_2 = 0.02\ m^3/min$

(c) $V_1 = 1\ m^3$ $V_2 = 3\ m^3$; $Q_1 = Q_2 = 0.02\ m^3/min$

(d) $V_1 = 3\ m^3$ $V_2 = 1\ m^3$; $Q_1 = 0.03\ m^3/min$ and $Q_2 = 0.01\ m^3/min$

Example



(a) Residence time: V/Q= 4 m^3/0.04 m^3/min= 100 min

Final effluent concentration

$$\frac{C_{out}}{C_{in}} = \frac{1}{1+kt}$$

C_{out}=1/(1+0.1*100)*1800= 164 mg/kg

(b) Residence time: t= V/Q= 2 m^3/0.02 m^3/min= 100 min each

Final effluent concentration: Q_1=Q_2= 0.02 m^3/min

$$\boxed{C_3 = \frac{Q_1C_1 + Q_2C_2}{Q_1 + Q_2}}$$

C_1 = C_2 =1/(1+0.1*100)*1800=164 mg/kg;

C_3 = 0.02*164*2/0.04= 164 mg/kg

(c) Residence time: V_1/Q_1= 1 m^3/0.02 m^3/min= 50 min= t_1

and V_2/Q_2= 3 m^3/0.02 m^3/min= 150 min= t_2

Final effluent concentration

C_1 =1/(1+0.1*50)*1800=300 mg/kg;

C_2 =1/(1+0.1*150)*1800=112.5 mg/kg;

C_3=(0.02*300+0.02*112.5)/0.04

C_3 = 206 mg/kg

(d) Residence time:V_1/Q_1= 3 m^3/0.03 m^3/min= 100 min= t_1

and V_2/Q_2= 1 m^3/0.01 m^3/min= 100 min= t_2

Final effluent concentration

C_1 =1/(1+0.1*100)*1800=164 mg/kg;

C_2 =1/(1+0.1*100)*1800=164 mg/kg;

C_3=(0.03*164+0.01*164)/0.04

C_3 = 164 mg/kg

EXTRA SLIDES

Soil-washing (same slide as last week)

- Soil washing is a volume reduction/waste minimization treatment process
- The soil fine fraction carrying the largest amount of contaminant is separated from the bulk soil
- The rest of the soil (depending on its contaminant content) can be used as backfill, or disposed of as non-hazardous material
- **Physical soil-washing: separation based on particle grain size, settling velocity, specific gravity, surface chemical behavior. Some removal of contaminant is possible through particle attrition**
- Chemical soil-washing: transferring the contaminants from the soil surface into solution using chemical compounds. The resulting suspension is separated from the aqueous solution (the latter is treated).

Physical soil washing