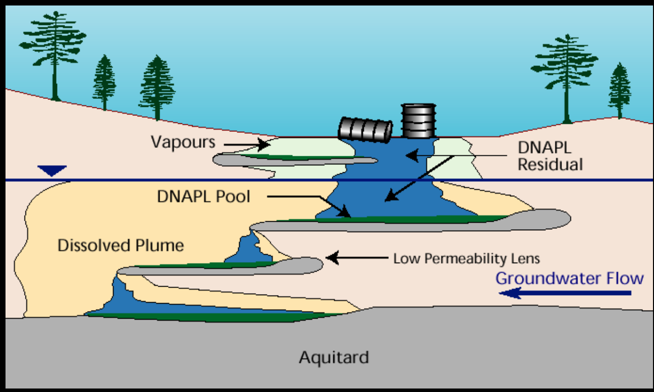
Biodegradation of Chlorinated Solvents



Jim A. Field
Department of Chemical and Environmental Engineering, University of Arizona
jimfield@email.arizona.edu

1

Literature Review


Reviews in Environmental Science & Bio/Technology (2004) 3: 185–254 © Springer 2004

Biodegradability of chlorinated solvents and related chlorinated aliphatic compounds

J.A. Field* & R. Sierra-Alvarez
*Department of Chemical and Environmental Engineering, University of Arizona, P.O. Box 210011, Tucson, Arizona 85721-0011, USA (*author for correspondence: e-mail: Jimfield@email.arizona.edu; phone: +1-520-626 5858; fax: +1-520-621 6048)*

Received 30 June 2004; accepted 12 October 2004

Key words: biodegradation, chloroacetic acids, chlorobutadienes, chloroethanes, chloroethenes, CFC, chlorofluorocarbons, chlorinated aliphatic compounds, chloromethanes, chloropropanes, chloropropenes, epichlorohydrin, halorespiration, microbial dechlorination, PCE, TCE.

Abstract

The biodegradability of chlorinated methanes, chlorinated ethanes, chlorinated ethenes, chlorofluorocarbons (CFCs), chlorinated acetic acids, chlorinated propanoids and chlorinated butadienes was evaluated based on literature data. Evidence for the biodegradation of compounds in all of the compound categories evaluated has been reported. A broad range of chlorinated aliphatic structures are susceptible to biodegradation under a variety of physiological and redox conditions. Microbial biodegradation of a wide variety of chlorinated aliphatic compounds was shown to occur under five physiological conditions. However, any given physiological condition could only act upon a subset of the chlorinated compounds. Firstly, chlorinated compounds are used as an electron donor and carbon source under aerobic conditions. Secondly, chlorinated compounds are cometabolized under aerobic conditions while the microorganisms are growing (or otherwise already have grown) on another primary substrate. Thirdly, chlorinated compounds are also degraded under anaerobic conditions in which they are utilized as an electron donor and carbon source. Fourthly, chlorinated compounds can serve as an electron acceptor to support respiration of anaerobic microorganisms utilizing simple electron donating substrates. Lastly chlorinated compounds are subject to anaerobic cometabolism becoming biotransformed while the microorganisms grow on other primary substrate or electron acceptor. The literature survey demonstrates that, in many cases, chlorinated compounds are completely mineralised to benign end products. Additionally, biodegradation can occur rapidly. Growth rates exceeding 1 d^{-1} were observed for many compounds. Most compound categories include chlorinated structures that are used to support microbial growth. Growth can be due to the use of the chlorinated compound as an electron donor or alternatively to the use of the chlorinated compound as an electron acceptor (halorespiration). Biodegradation linked to growth is important, since under such conditions, rates of degradation will increase as the microbial population (biocatalyst) increases. Combinations of redox conditions are favorable for the biodegradation of highly chlorinated structures that are recalcitrant to degradation under aerobic conditions. However, under anaerobic conditions, highly chlorinated structures are partially dehalogenated to lower chlorinated counterparts. The lower chlorinated compounds are subsequently more readily mineralized under aerobic conditions.

Abbreviations: A – ethane; BTEX – benzene-toluene-ethyl benzene-xylene; CA – chloroethane; CAA – chloroacetic acid; 2-CBD – 2-chloro-1,3-butadiene; cDCE – *cis*-dichloroethene; CF – chloroform; CFC – chlorofluorocarbons (*see* Table *15 for CFC-nomenclature*); Cl – inorganic chloride; CM – chloromethane;

Field, J.A. & R. Sierra-Alvarez (2004) Biodegradability of chlorinated solvents and related chlorinated aliphatic compounds. *Reviews in Environmental Science & Bio/Technology* **3**:185-254.

2

Biodegradation Reaction

- **Biodegradation = Redox Reactions**

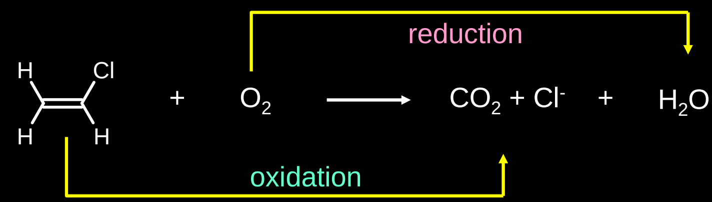
reduction

E-donor + E-acceptor → Oxidized E-donor + Reduced E-acceptor

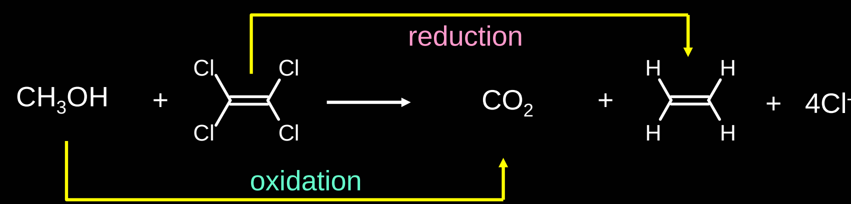
oxidation

3

- **Example:** vinyl chloride as electron donor



- **Example:** perchloroethylene as electron acceptor

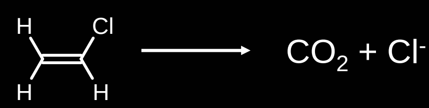


4

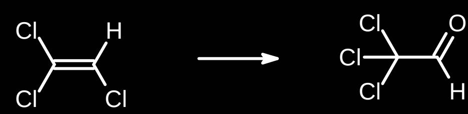
Definitions Biodegradation

- **Biodegradation:** biologically catalyzed transformation of chemical resulting in simpler forms

- **Mineralization:** Conversion of organics to mineral products



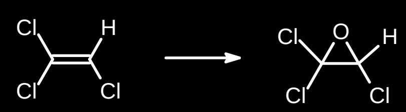
- **Biotransformation:** Transformation of pollutant by a biological process



5

Definitions Biodegradation

- **Growth Substrate, Primary Metabolism:** Pollutant (substrate) used as the primary energy and carbon source for microbial growth
  - as pollutant is degraded biocatalyst concentration increases
- **Cometabolism:** Accidental conversion of pollutant by enzymes and cofactors used for the metabolism of a primary substrate



MMO

$$CH_4 \longrightarrow CH_3OH \longrightarrow \longrightarrow \longrightarrow CO_2$$

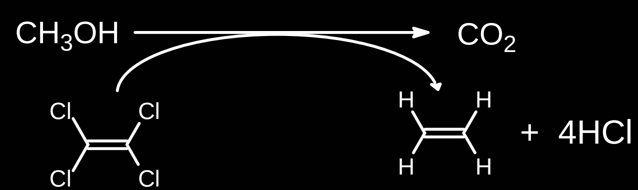
6

Definitions Biodegradation

- **Reductive Dehalogenation:** Microbially catalyzed replacement of a halogen atom on an organic compound with a hydrogen atom

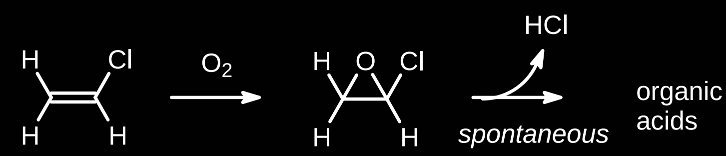
  $R\text{-}Cl + 2e^{-} + 2H^{+} \longrightarrow R\text{-}H + HCl$

- **Halorespiration:** An organohalogen is used as an electron acceptor in an energy yielding metabolism
  - as pollutant is degraded biocatalyst concentration increases

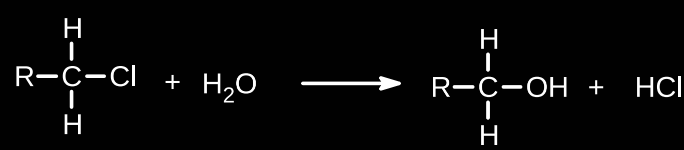


Mechanisms of Dechlorination

- **Oxygenolytic:**



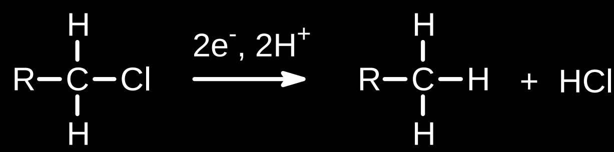
- **Hydrolytic:**



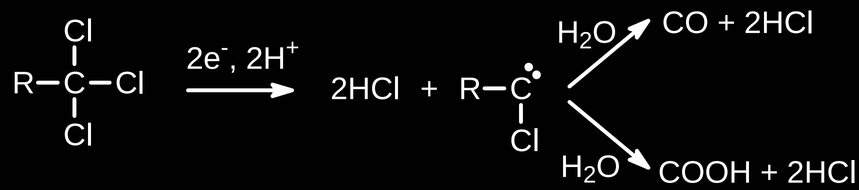
8

Mechanisms of Dechlorination

- **Reductive Hydrogenolysis:**



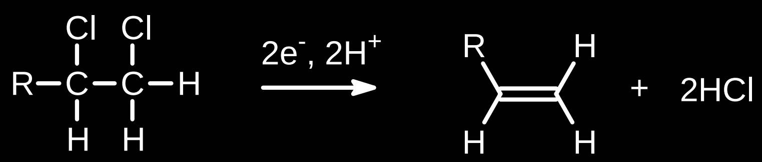
- **Hydrolytic Reduction:**



9

Mechanisms of Dechlorination

- **Reductive Dichloroelimination:**

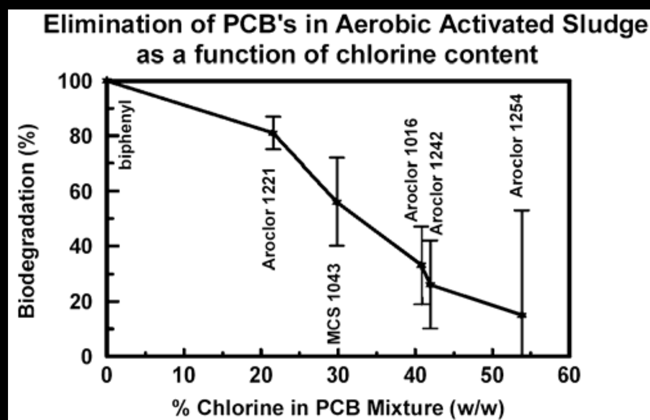


10

Important Trends

- **Aerobic Degradation**

  Chlorine # increases ↑ Biodegradation decreases ↓



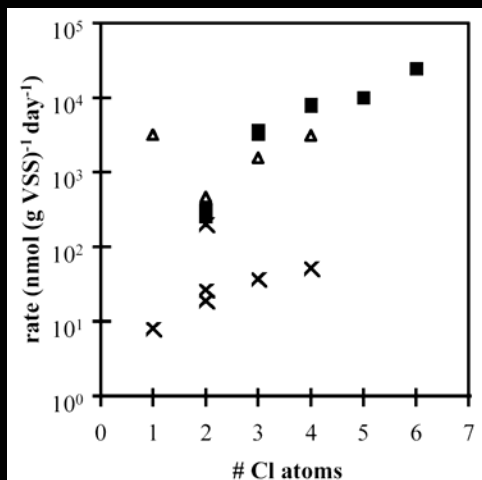
Tucker et al. 1975. *Bull. Environ. Contam. Toxicol.* **14**, 705-713

11

Important Trends

Anaerobic Degradation

Chlorine # increases ↑ Biotransformation increases ↑



Cometabolism of chlorinated solvents by anaerobic sludge

Van Eekert 1999. PhD Dissertation (no. 2638). Wageningen University, The Netherlands, p. 129.

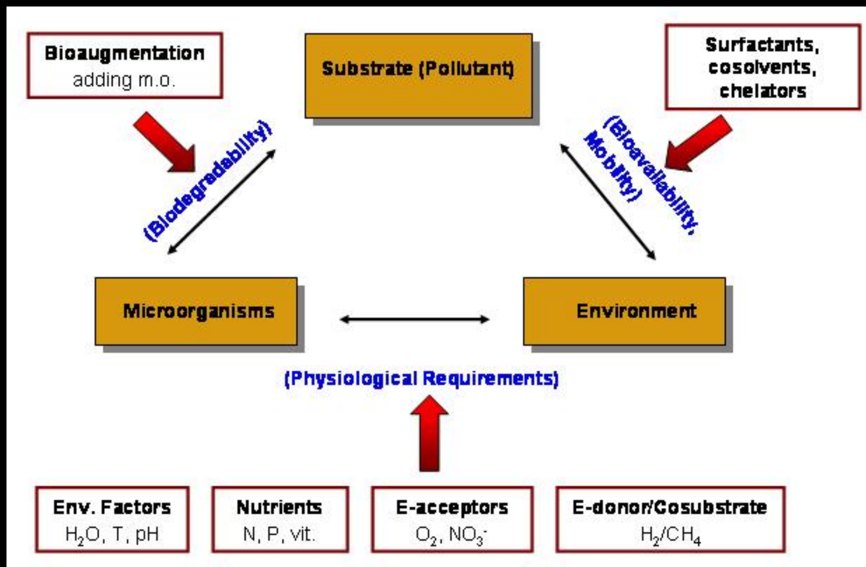
12

Five Physiological Roles

1st: aerobic carbon and energy source		ED-A
2nd: aerobic cometabolism	(cooxidation)	CoM-A
3rd: anaerobic carbon and energy source		ED-AN
4th: anaerobic electron acceptor	(halorespiration)	EA-AN
5th: anaerobic cometabolism	(reduced cofactors)	CoM-AN

13

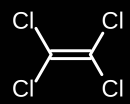
Strategies of Bioremediation



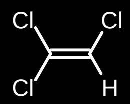
Modified from: Tiedje, J. M. 1993. Bioremediation from an ecological perspective. In: *In Situ Bioremediation: When Does it Work?* National Academy of Sciences, Washington DC, pp. 110-120.

14

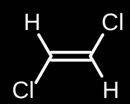
Abbreviations Chloroethenes



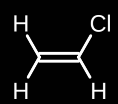
Perchloroethylene (PCE)



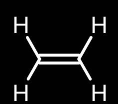
Trichloroethene (TCE)



cis Dichloroethene (cDCE)



Vinyl chloride (VC)



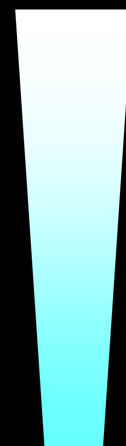
Ethene (E)

15

Biodegradation Chloroethenes

- **ED-A** **VC;** cDCE
- **CoM-A** **VC; cDCE; TCE**
- **ED-AN** VC (?), cDCE (?)
- **EA-AN** VC; cDCE; **TCE; PCE**
- **CoM-AN** VC; cDCE; TCE; PCE

faster

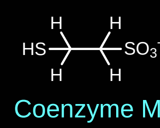


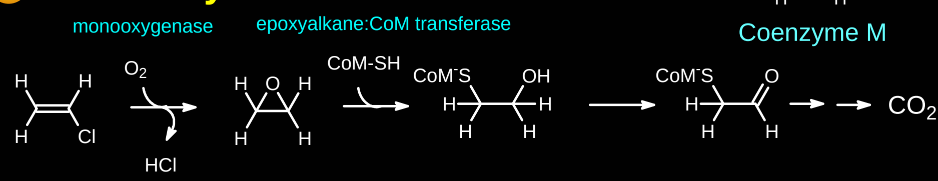
slower

16

Chloroethenes ED-A

- **Microorganisms Involved:** *Mycobacterium*, *Nocardioides*, *Pseudomonas*
- **Pathway**





Coleman & Spain 2003 JB 185:5536

- **Kinetics**

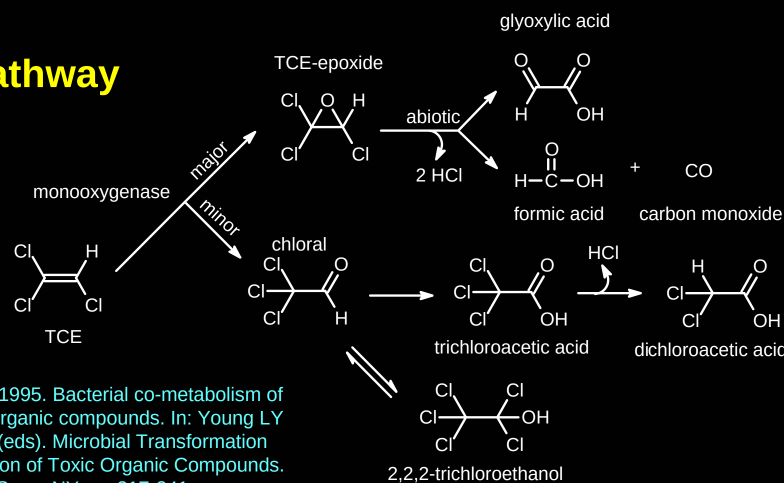
Growth rates	0.05 to 0.96 d^{-1}
Activity	226 to 4950 mg g^{-1} dwt d^{-1}
K_m or K_s	0.07 to 0.70 mg l^{-1}

17

Chloroethenes CoM-A (cooxidation)

- **Microorganisms Involved:** *Methylosinus*, *Peudomonas*, *Burkholderia*, *Nitrosomonas*, *Mycobacterium*, *Rhodococcus*, *Alcaligenes*

- **Pathway**



Wackett L. P. 1995. Bacterial co-metabolism of halogenated organic compounds. In: Young LY & Cerniglia C (eds). Microbial Transformation and Degradation of Toxic Organic Compounds. John Wiley & Sons, NY, pp 217-241.

18

Chloroethenes CoM-A (cooxidation)

- **Primary Substrates Supporting Cooxidation:** methane, toluene, phenol, ammonium, ethane, ethene, propane *etc*
  - Substrates for which monooxygenases are utilized for biodegradation

- **Kinetics**

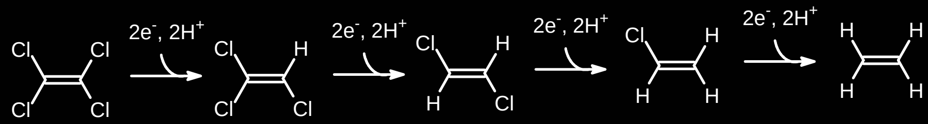
Activity	57 to 55,000 mg g^{-1} dwt d^{-1}
Transformation Capacity	86 to 150 mg TCE g^{-1}dwt
K_m	0.4 to 29.6 mg l^{-1}

19

Chloroethenes EA-AN (Halorespiration)

- **Pathway**

Successive Steps of Reductive Hydrogenolysis



PCE TCE cDCE VC E

High Biodiversity	Low Biodiversity
7 genera from 4 major bacterial phyla	1 genus

Chloroethenes EA-AN (Halorespiration)

- **Microorganisms Involved:** **PCE to cDCE**

Low G+C gram +	*Desulfitobacterium*	H_2, lactate, formate, etoh
	Clostridium	YE, glucose
	Dehalobacter	H_2
δ Proteobacteria	*Desulfuromonas*	acetate,pyruvate
ε Proteobacteria	*Dehalospirillim*	H_2, lacate, formate, etoh
	Sulfurospirillum	lactate
Green non-sulfur	*Dehalococcoides*	H_2

- **Microorganisms Involved:** **cDCE to E**

Green non-sulfur	*Dehalococcoides*	H_2

21

Chloroethenes EA-AN (Halorespiration)

- **Biochemistry**
  - Reactions catalyzed by specific reductive dehalogenases
    - All contain vitamin B12
    - Most are membrane bound enzymes
- **Kinetics: PCE to TCE and/or cDCE**

Growth rates	0.23 to 6.65 d^{-1}
Activity	856 to 37,312 mg g^{-1} dwt d^{-1}

- **Kinetics: VC to E**

Growth rates	0.32 to 0.40 d^{-1}
Activity	3047 to 6030 mg g^{-1} dwt d^{-1}
K_m or K_s	0.16 to 0.31 mg l^{-1}

22

Chloroethenes EA-AN (Halorespiration)

Hypothetical Example

Assumptions: t_0 = 1 bacterium per m^3

1 bacterium = 1×10^{-12} g

Ideal conditions for growth

Kinetic data:

	Dehalosprillium multivorans	*Dehalococcoides* strain VS
Growth rate (d^{-1})	6.65	0.40
Activity (mg g^{-1} dwt d^{-1})	5970	3047

Growth Equation:

$$C_{xt} = C_{x0} e^{ut}$$

C_{x0} & C_{xt} = cell biomass conc. at time 0 & t (g dwt l^{-1})

μ = growth rate (d^{-1}), t = time (d)

23

Chloroethenes EA-AN (Halorespiration)

Hypothetical Example *(continued)*

Question: How long will it take for a bioconversion rate of 10 mg l^{-1} chloroethenes per day?

Initial Biomass: 1×10^{-15} g dwt l^{-1}

Final Biomass: $10/5970 = 1.675 \times 10^{-3}$ g dwt l^{-1} *Dehalosprillium*

$10/3047 = 3.282 \times 10^{-3}$ g dwt l^{-1} *Dehalococcoides*

Time:

$$t = \frac{\ln\left(\frac{C_{xt}}{C_{x0}}\right)}{\mu}$$

4.2	days	*Dehalosprillium*
72.1	days	*Dehalococcoides*

24

Chloroethenes CoM-AN

- **Microorganisms Involved:** Methanogens, Acetogens
- **Pathway** Successive Steps of Reductive Hydrogenolysis
  - Reactions catalyzed by reduced enzyme cofactors
    - Cobalt containing vitamin B12; Nickel containing Factor 430
- **Kinetics: PCE to TCE and/or cDCE**

  Activity 0.006 to 20 mg g^{-1} dwt d^{-1}
- **Kinetics: cDCE or VC to E**

  Activity 0.001 to 0.366 mg g^{-1} dwt d^{-1}

Chloroethenes Bioremediation

- **Anaerobic - Aerobic**

  First: Rapid reductive dehalogenation to TCE & cDCE

  Second: Rapid cooxidation of TCE and cDCE to CO_2 & Cl^-

  $$PCE \xrightarrow[\text{+ electron donor}]{\text{anaerobic}} cDCE \xrightarrow[\text{+ } O_2 \text{, + primary substrate}]{\text{aerobic}} CO_2, Cl^-$$

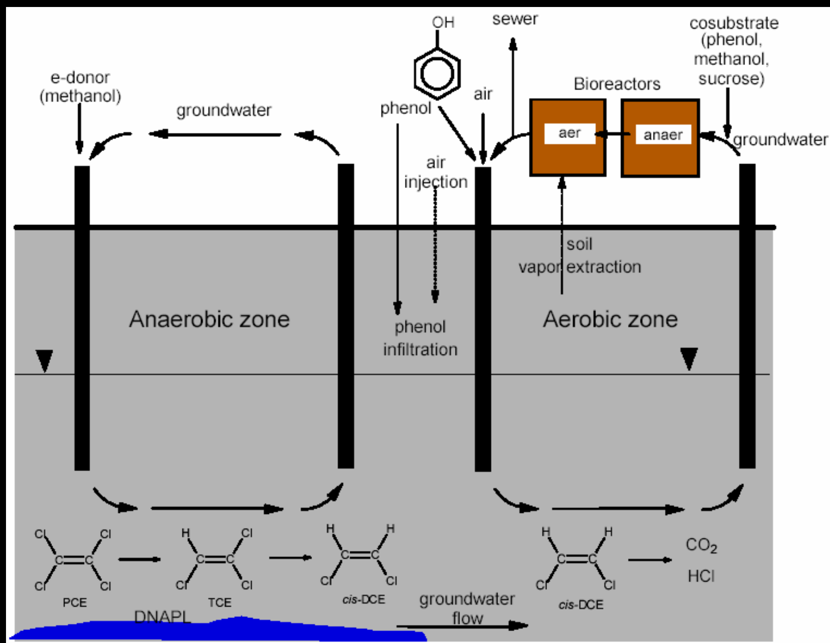
- **Anaerobic with *Dehalococcoides***

  Promote complete halorespiration to ethene

  $$PCE \xrightarrow[\text{+ electron donor, + \textit{Dehalococcoides} (if absent)}]{\text{anaerobic}} E$$

26

Bioremediation Breda (Holland)



Bioremediation Breda (Holland)

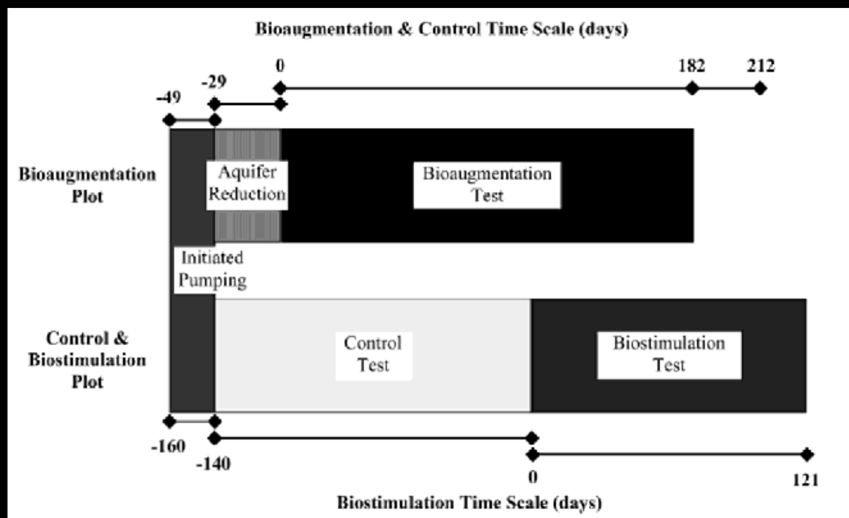
- **Facts about Full-Scale Bioremediation**
  - 85% removal of PCE in situ within 6 months
  - Inorganic chloride concentration in anaerobic zone increased from 1 to 6 mM
  - In the aerobic zone all of the cDCE and VC as well as injected phenol was removed
  - After one year the total mass of chloroethenes decreased from 1500 to 550 mol

Spuij et al. 1997. Full-scale application of in situ bioremediation of PCE-contaminated soil. *4th Int. In Situ and On Site Bioremediation Symp., New Orleans, LA*, Columbus, OH: Battelle Vol 5, pp. 431–37.

28

Bioremediation (Bachman Rd, Mi)

- Comparison Bioaugmentation vs Biostimulation

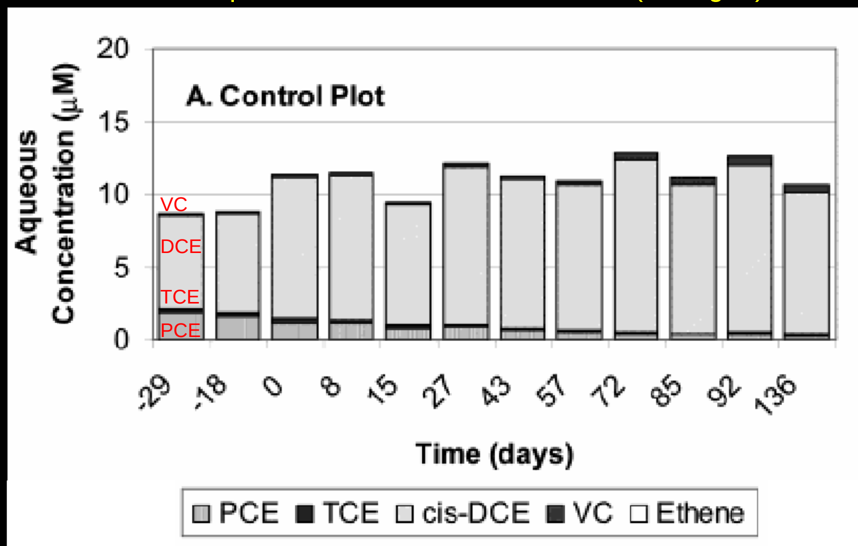


Lendvay et al. 2003. Environ. Sci. Technol. 37:1422

29

Bioremediation (Bachman Rd, Mi)

Control Experiment at Bachman Road Site (Michigan)

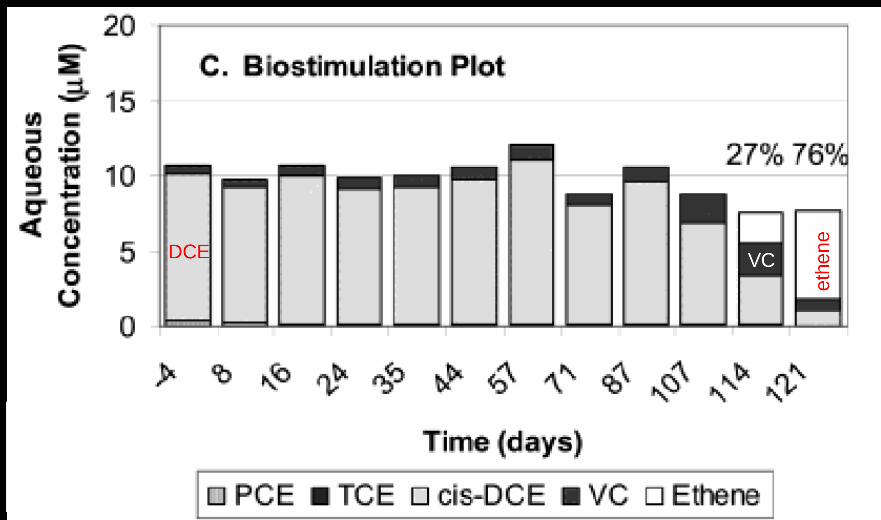


Lendvay et al. 2003. Environ. Sci. Technol. 37:1422

30

Bioremediation (Bachman Rd, Mi)

Biostimulation Plot: Day 0 = lactate addition

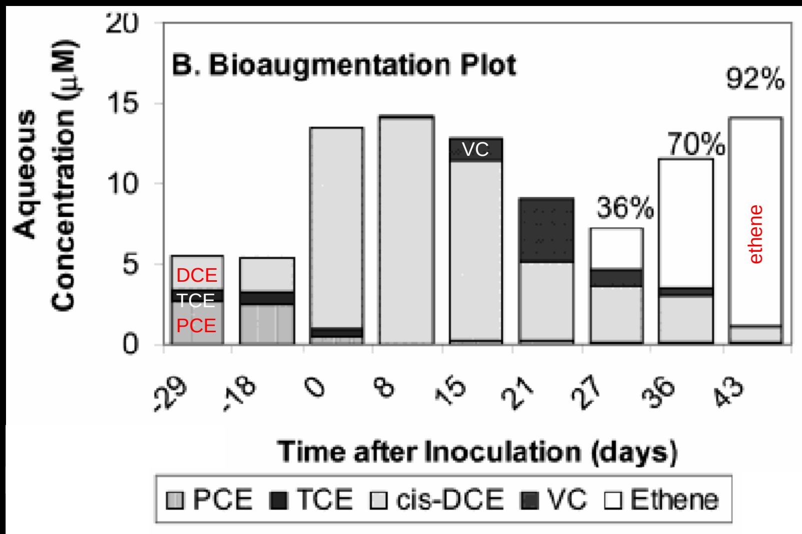


Lendvay et al. 2003. Environ. Sci. Technol. 37:1422

31

Bioremediation (Bachman Rd, Mi)

Bioaugmentation Plot: Day –29 = lactate addition; Day 0 = *Dehaloccocoides* addition



Lendvay et al. 2003. Environ. Sci. Technol. 37:1422

32

Bioenhancement DNAPL Dissolution

- **Dissolution equation**

$$r_{TA} = K_L a(C_s - C_b)$$

r_{TA} = dissolution rate (mg l^{-1} s^{-1})
K_L = mass transfer coefficient m s^{-1}
a = interfacial surface area m^2 m^{-3}
C_s = maximum aqueous solubility
C_b = actual concentration

  - Biodegradation can increase (C_s-C_b) and enhance dissolution

- **Reported enhancements**

PCE dehalogenation feasible at saturated concentrations	Yang and McCarty 2000. EST 34:2979
16 × dissolution enhancement	Cope and Hughes 2001. EST 35:2014
5 × based on model	Christ *et al.* 2005. EHP 113:465

33

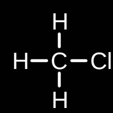
Bioenhancement DNAPL Dissolution

- **Combine Surfactant/Cosolvent Assisted Dissolution DNAPL with Biodegradtion**
  - Biodegradable surfactants/cosolvents will be used as electron donors
    - Residual PCE remaining after flushing reductively dehalogenated
    - Residual surfactant biodegraded

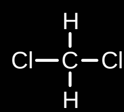
Christ *et al.* 2005. EHP 113:465

34

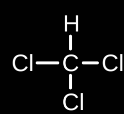
Abbreviations Chloromethanes



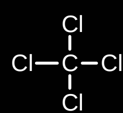
Chloromethane (CM)



Dichloromethane (DCM)



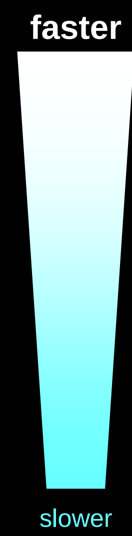
Chloroform (CF)



Carbon Tetrachloride (CT)

Biodegradation Chloromethanes

- **ED-A** **CM; DCM**
- **CoM-A** **CM, DCM; CF**
- **ED-AN** CM, DCM
- **EA-AN** ?
- **CoM-AN** DCM, CF, CT



Chloromethanes CoM-AN

- **Microorganisms Involved:** Methanogens, acetogens, fermentative bacteria, sulfate reducing bacteria, iron reducing bacteria, denitrifiers
- **Pathway** Reductive Hydrogenolysis
  Hydrolytic Reduction
  - Reactions catalyzed by reduced enzyme cofactors, chelating agents, magnetite, quinones

    Cobalt containing vitamin B12

    Zinc containing porphorinogens

    Pyridine-2,6-bis(thiocarboxylic acid)

    Quinones, humus

    Biogenic magnetite

37

Chloromethanes CoM-AN

- **Kinetics: CF dechlorination**

  Activity 0.3 to 36 mg g^{-1} dwt d^{-1}

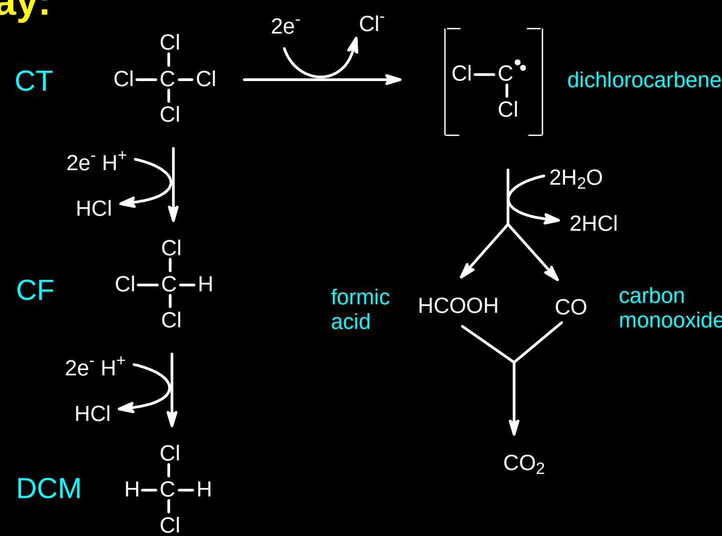
- **Kinetics: CT dechlorination**

  Activity 3 to 1198 mg g^{-1} dwt d^{-1}

38

Chloromethanes CoM-AN

- **Pathway:**



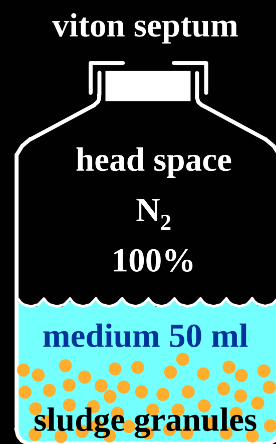
39

Chloromethanes CoM-AN

Effect Redox Mediators

Experimental

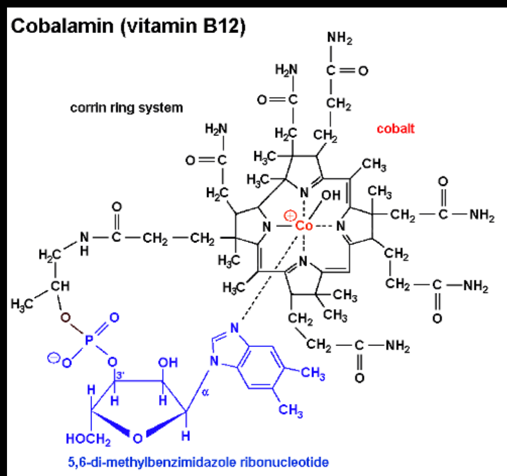
- Phosphate buffer pH 7.0
- mineral medium (Cl^- free)
- methanogenic sludge (0.5 g VSS/L)
- VFA mixture (0.25 g COD/L)
- CT or CF (100 uM)
- Redox Mediators (10 uM)



Guerrero-Barrajas & Field. 2005. Enhancement of anaerobic carbon tetrachloride biotransformation in methanogenic sludge with redox active vitamins. Biodegradation 16: 215–228.

Chloromethanes CoM-AN

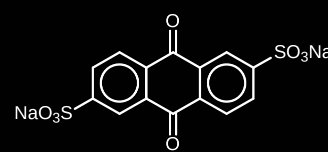
- **Effect Redox Mediators**



(B12)

Riboflavin

(RF)



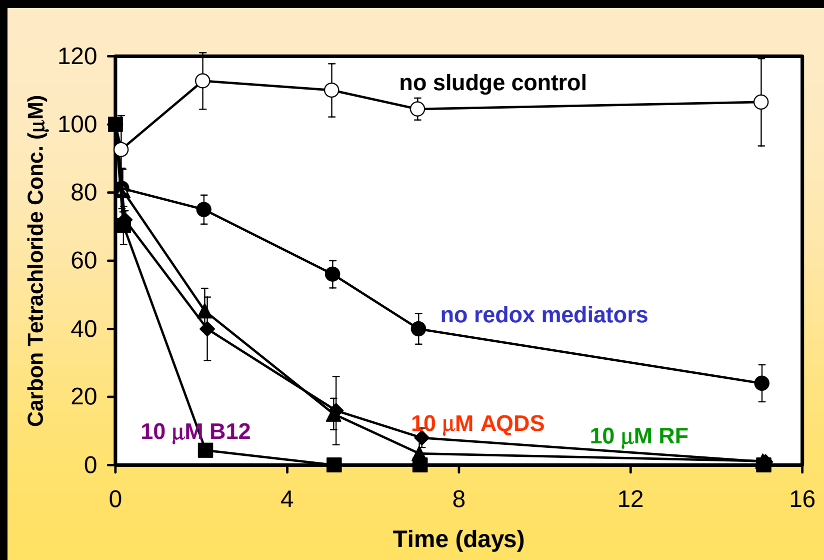
Anthraquinone Disulfonate (AQDS)

(AQDS)

41

Chloromethanes CoM-AN

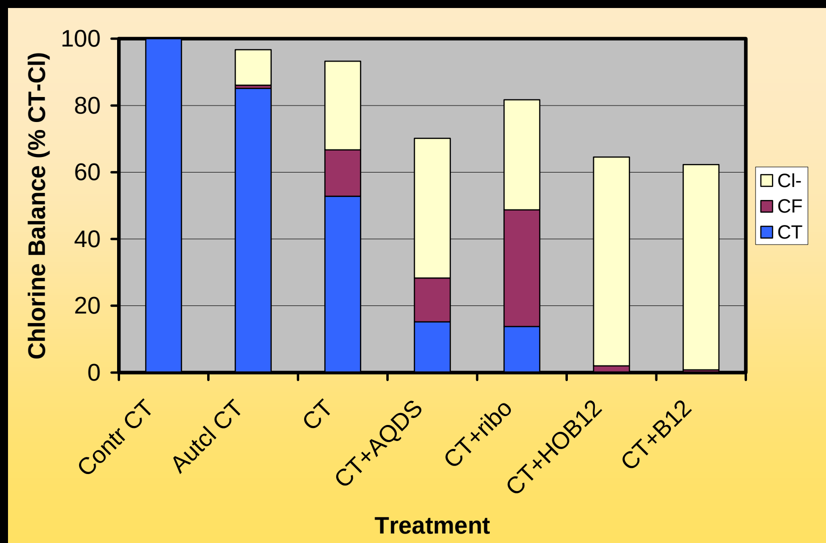
- **Effect Redox Mediators:** CT Concentration



42

Chloromethanes CoM-AN

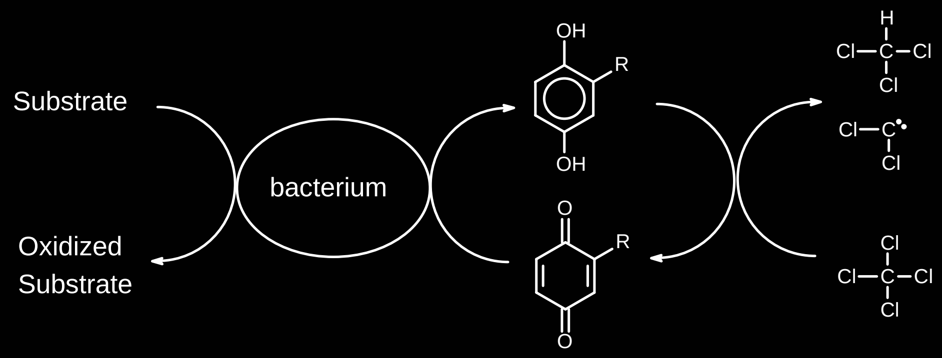
Effect Redox Mediators: Chlorine Balance day 5



43

Chloromethanes CoM-AN

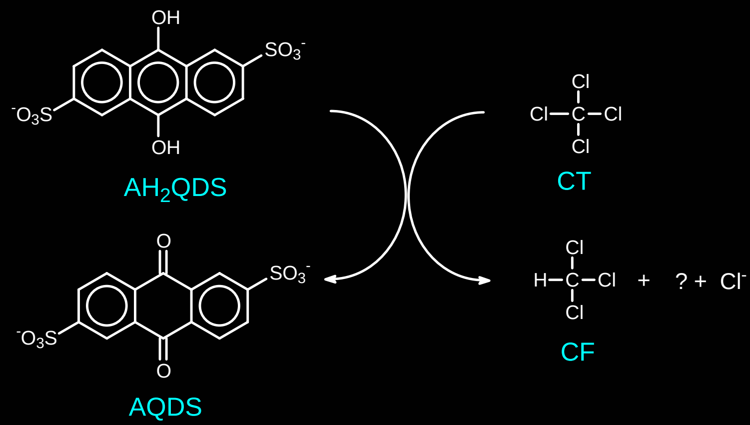
- **Role Redox Mediators:**



44

Chloromethanes CoM-AN

- **Evidence of Direct Dechlorination by Hydroquinone**



Curtis & Reinhard. 1994. EST 28:2393

45

Conclusions 1

Biodegradation Chloroethenes

- High biodiversity for rapid halorespiration PCE to cDCE; halorespiration cDCE to E restricted to one genus, *Dehaloccocoides*
- Slow anaerobic cometabolism of PCE, TCE, cDCE and VC (dominant process reductive hydrogenolysis)
- Rapid aerobic cooxidation of VC, cDCE, TCE feasible
- Aerobic biodegradation of VC (and cDCE) as growth substrates feasible with newly discovered bacterial strains

Bioremediation Chloroethenes

- Anaerobic halorespiration (PCE → cDCE) followed by aerobic cooxidation (cDCE → CO_2, Cl^-)
- Complete reductive dechlorination with *Dehaloccocoides* (PCE → E)

46

Conclusions 2

Biodegradation Chloromethanes

- Rapid aerobic or anaerobic biodegradation of CM or DCM as growth substrates
- Aerobic cooxidation CM, DCM and CF feasible
- Slow Anaerobic cometabolism of DCM, CF and CT
  1) hydrolytic reduction to CO_2
  2) reductive hydrogenolysis to lower chlorinated methanes
- Redox mediators can greatly enhance anaerobic biotransformation CT, CF

Bioremediation

- Anaerobic cometabolism for CF and CT

47

What is Phytoremediation?



48

What is Phytoremediation?

A solar driven, biological system that is used to Contain, Sequester, Remove, or Degrade Organic and Inorganic Contaminants in Air, Soils, Sediments, Surface Water, and Groundwater

49

Types of Phytoremediation

- Artificial Wetlands
- Phytostabilization
- Phytoextraction
- Rhizofiltration
- Rhizosphere enhancement
- Phytovolatilization
- Phytodegradation
- Air purification
- Water and Wastewater Management
- Landfill caps
- Green Roofs
- Combination technologies

50

Wide Range of Contaminants

Organic: hydrocarbons, chlorinated solvents, phenols, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), agricultural wastes

Inorganic: metals, radionuclides, salinity, nitroaromatics, amines, excess fertilizers, pesticides, CCA (chromium copper arsenic)

51

Different Types of Impacted Media

- **Solid phase:** soils, sediments, sludges
- **Liquid phase:** run-off, stormwater, wastewater, groundwater, leachate
- **Gaseous phase:** greenhouse gases, VOCs, NO_x

52

Advantages

Safety

- Minimized emissions & effluent and low secondary waste volume
- Controls erosion, runoff, rain infiltration, and dust emissions

Ecological

- Habitat friendly, habitat creation, promotes biodiversity
- Sequesters greenhouse gases (carbon dioxide)

Public / Regulatory

- Acceptable brownfields applications
- Aesthetics, green technology
- Increasing regulatory approval and standardization

53

Limitations or Common Regulatory Issues

Depth

- Only effective if within the relative rooting depth of the vegetation

Time

- Requires longer periods to become effective (establishment)
- May requires longer periods to reach clean up targets
- Seasonal effects

Phytotoxicity

- Generally considered applicable for low to moderate concentrations
- In most cases, the vegetation must survive in order to operate

Media Transfer / Food Chain Impacts

- Fate and transport often unclear
- Air emissions, leaf litter
- Harvesting, hazardous waste?
- Toxicity of parent vs. by-products

55

Web Addresses

http://www.rtdf.org/public/phyto/phytodoc.htm

http://www.itrcweb.org/gd_Phyto.asp

http://www.dsa.unipr.it/phytonet/

http://plants.usda.gov/

http://clu-in.org/techdrct/

http://www.acap.dri.edu/

56

Books

Phytoremediation (Hardcover)
Tsao

Phytoremediation
McCutcheon and Schnoor

Phytoremediation of Contaminated Soil and Water (Hardcover)
Terry and Banuelos

Plants That Hyperaccumulate Heavy Metals: Their Role in Phytoremediation, Microbiology, Archaeology, Mineral Exploration and Phytomining (Hardcover)
Brooks

57

Companies

- Edenspace – Metals
- Applied Natural Sciences – Organics
- Phytokinetics – Organics
- Applied Phytogenetics – Genetically Engineered Plants
- Thomas Engineering - Organics
- Ecolotree – Landfill caps and riparian restoration
- Phytoextraction Associates – Metals and phytomining

Journals

International Journal of Phytoremediation
Environmental Science and Technology
Environmental Pollution
Plant and Soil
Chemosphere
Journal of Environmental Quality
New Phytologist
Plant Physiology

59

Conferences

EPA International Applied Phytotechnologies Conference

Battelle

American Society for Agronomy

American Chemical Society

Association for Environmental Health and Sciences

60

Phytodegradation

Using plants to themselves take up and degrade organic contaminants.

61

Enzyme Systems

Green Liver Concept

P-450's

Peroxidases

Dehalogenases

Reductases

Glutathionone-s-transferases

Conjugation enzymes

62

Anaerobic Degradation of TCE

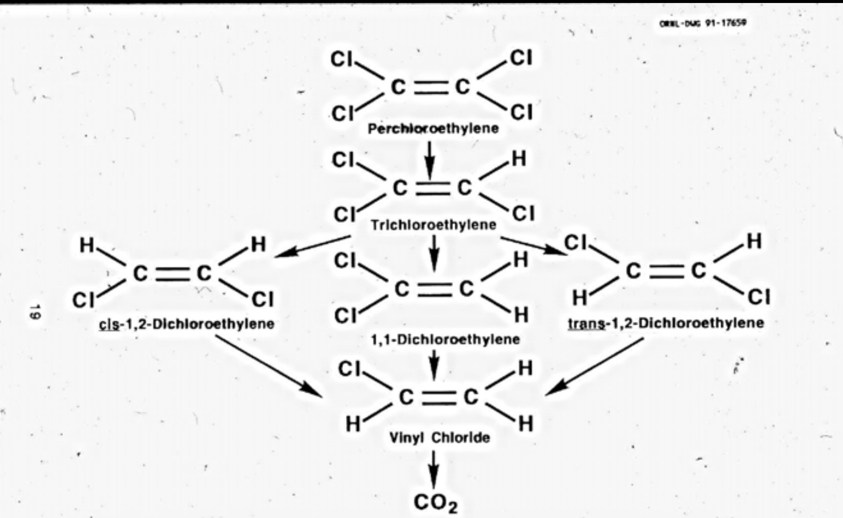


Figure II - 1. Reductive dechlorination of chlorinated ethylenes under anaerobic (methanogenic) conditions.

Mammalian Degradation

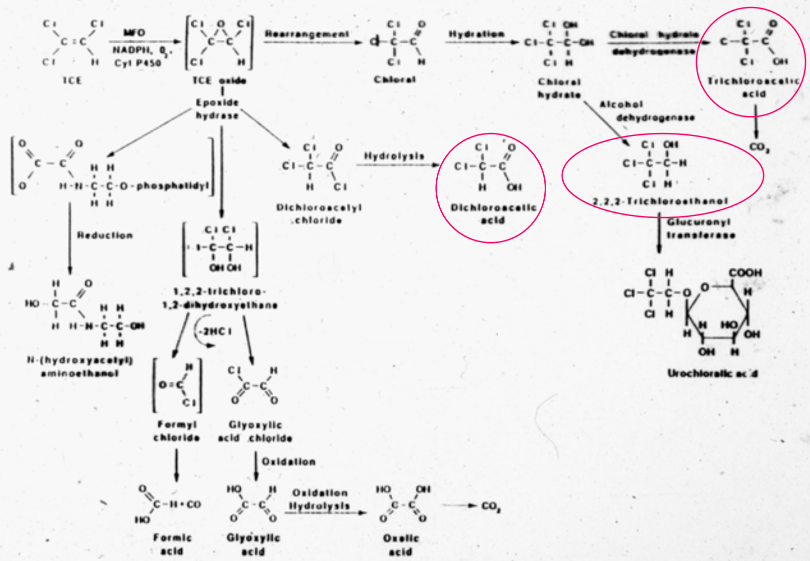
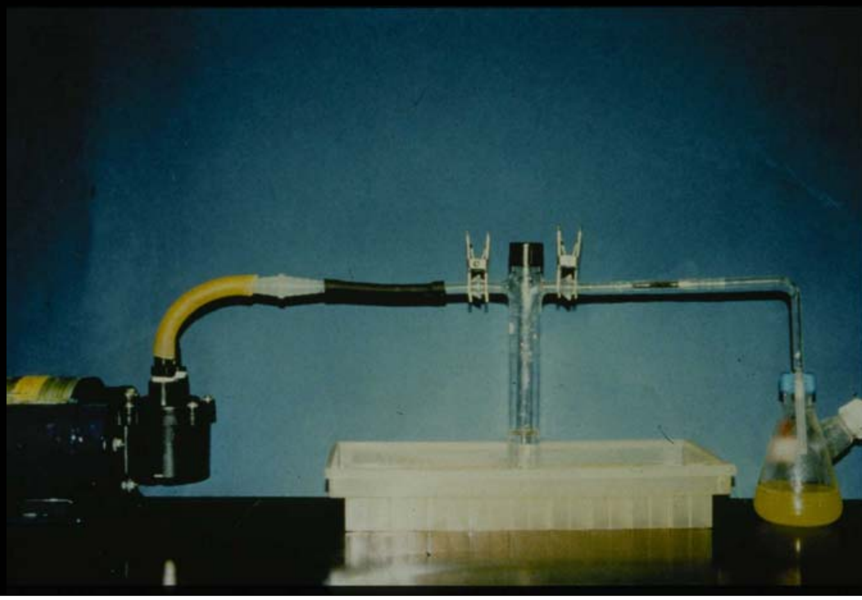


Figure 1. Metabolism of trichloroethylene.

64

Cell Culture Studies



65

Greenhouse Studies

66

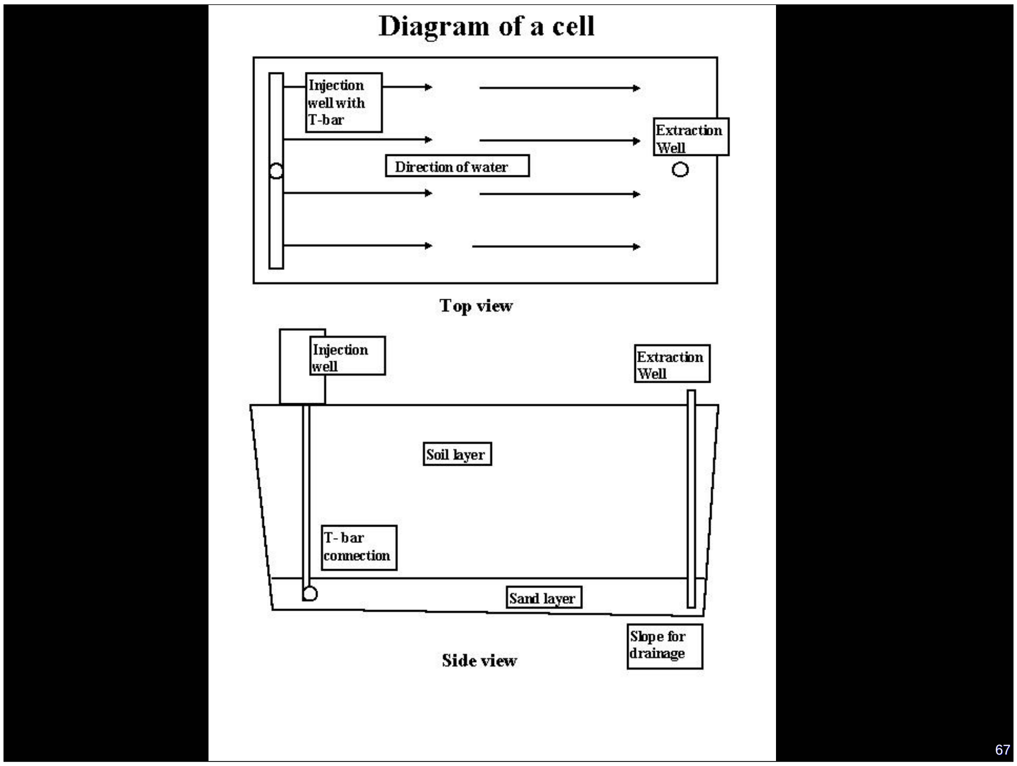
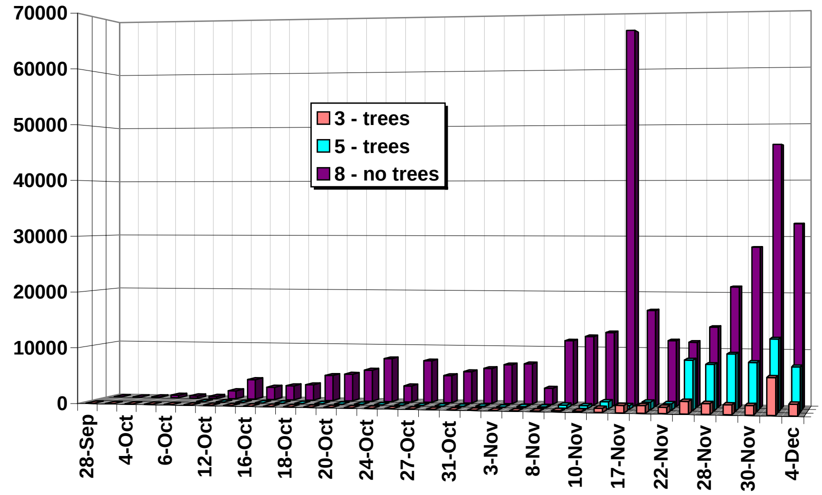
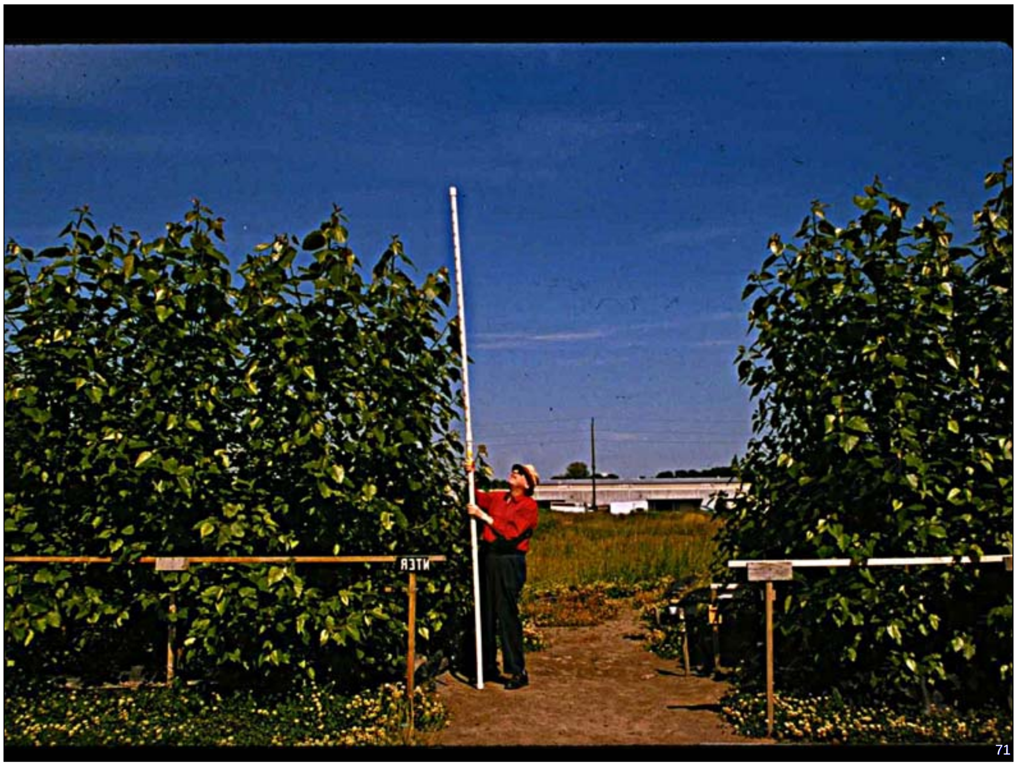


Diagram of a cell
Injection well with T-bar
Extraction Well
Direction of water
Top view
Injection well
Extraction Well
Soil layer
T- bar connection
Sand layer
Slope for drainage
Side view
67

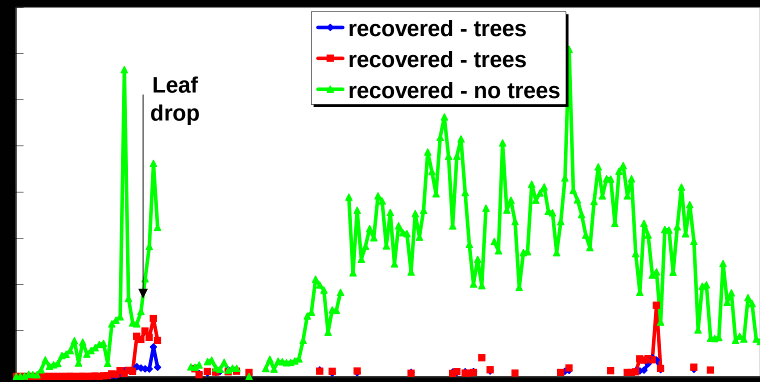
Micromoles of TCE and metabolites recovered 28 September through 4 December 1995



70

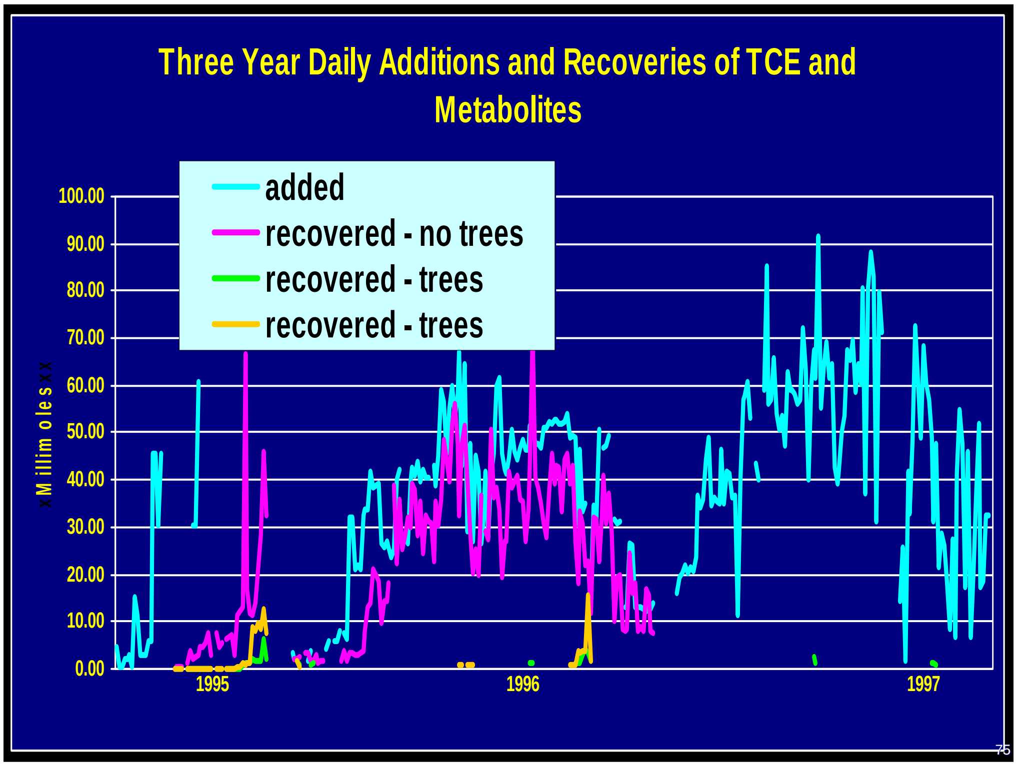

71

TCE and Metabolite Recovery 1995-96

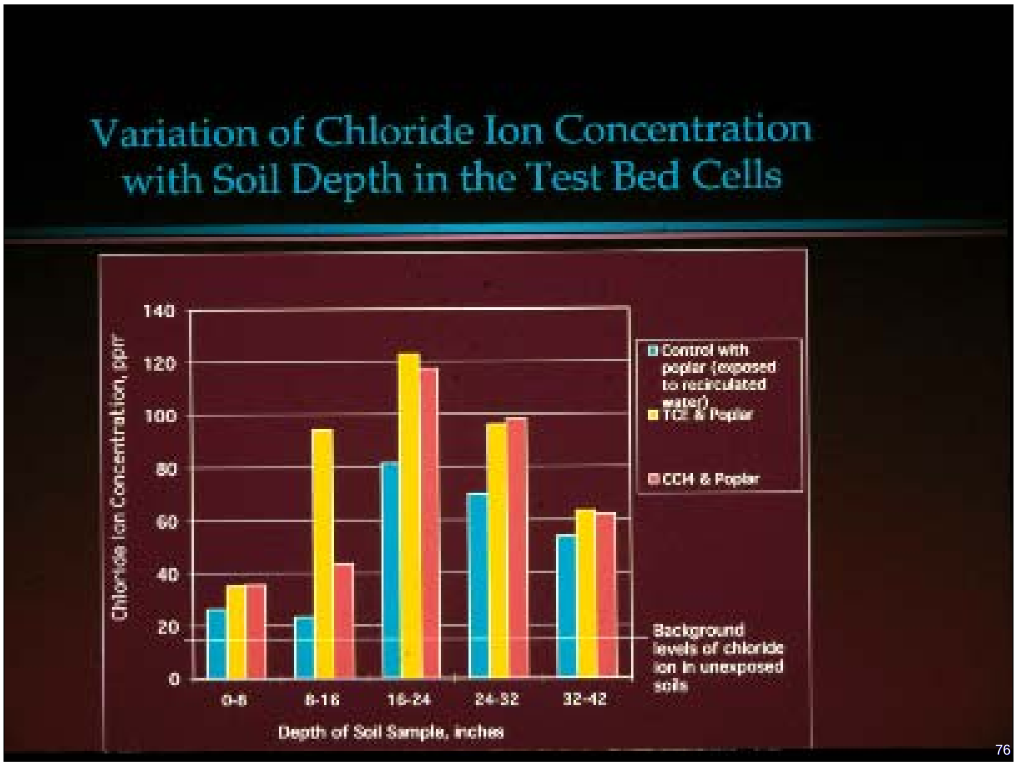


72

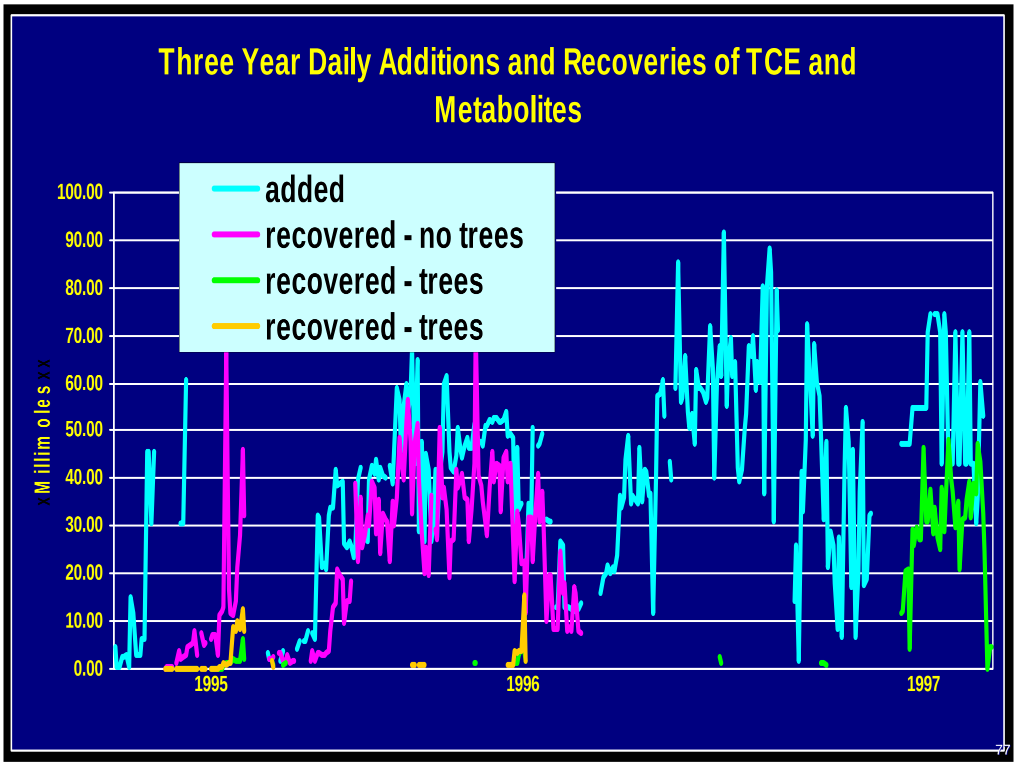

73



Three Year Daily Additions and Recoveries of TCE and Metabolites
added
recovered - no trees
recovered - trees
recovered - trees
x M illim o le s x x
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
1995
1996
1997
75



Variation of Chloride Ion Concentration with Soil Depth in the Test Bed Cells
Chloride Ion Concentration, ppm
140
120
100
80
60
40
20
0
0-8
8-16
16-24
24-32
32-42
Depth of Soil Sample, inches
Control with poplar (exposed to recirculated water)
TCE & Poplar
CCM & Poplar
Background levels of chloride ion in unexposed soils
76


Three Year Daily Additions and Recoveries of TCE and Metabolites
added
recovered - no trees
recovered - trees
recovered - trees
x M illim o le s x x
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
1995
1996
1997
77

Other Compounds

MtBE , Benzene, other gasoline additives
Pesticides; Ethylene dibromide, lindane
Explosives; TNT, RDX, perchlorate
Solvents; TCE, CT, PCE
Deicing agents; benzotriazoles

78

Regulatory Concerns

How to convince the regulators that this is a good idea.

79

Regulatory Issues

Regulator unfamiliarity with process

Not knowing all the answers to assure the regulator

80

Testing and Monitoring

- How often
- What needs to be tested
  - Soil
  - Air
  - Water
  - Plant tissues
- How do you analyze these crazy samples???

81

Unusual Monitoring Parameters

- Tree health or why are all my plants brown?
- Water issues
- Nutrient availability
- Is the soil itself killing the plants
- Fungus, bugs and other munching critters
- Convincing the regulators that plant health is a measurable criteria for success
- Where do those roots go?

Weather Impacts on Monitoring

Why doing transpiration measurements in the rain is not a good idea.

Temperature and light intensity have strong effects on plant metabolism and thus your test results.

83

What do you mean by success?

Do you need different standards for success?

What are actually testing?

- Plant survival
- Root depth
- Root penetration
- Transpiration
- Presence of metabolites
- Groundwater depression
- Soil analysis
- Transpiration rates

84

Security Issues

Securing a field can be more challenging than securing a building.

Squatters/Vagrants on the site.

Community member access on sites.

- Involving the community with site protection.

Problems with radical groups.

85

Do Contaminants Enter the Food Chain?

86

Food chain transfer

Insects munching

Animals munching on the plants or insects

Local people taking the plants

87

Trees and Deer Don’t Mix Well

88

And children want to play

89

Decision making

How to decide if phytoremediation is right for the site.

90

Site Evaluation

Evaluating a site as a potential phytoremediation site involves some different parameters.

- Weather
- Water availability
- Soil fertility
- Toxicity

91

Site Evaluation

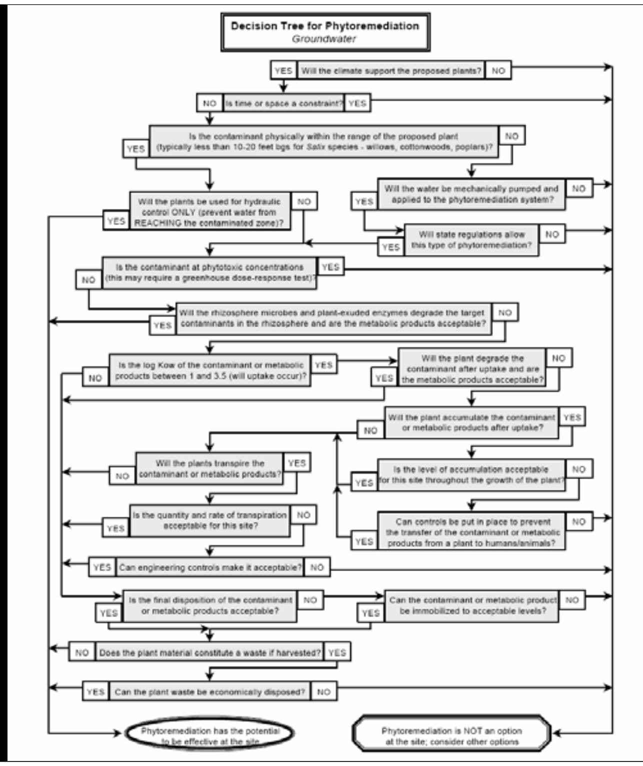
- Will phyto work with the contaminant I have on the site?
- How will the plants and contaminants interact?
- Is this acceptable to the regulators?

92

Site Evaluation

- Is the site now, or could it be, applicable to plant growth?
  - Blacktop and plants do not mix
  - Shade/sun issues
  - Soil toxicity that is not related to contaminant

93



Decision Tree for Phytoremediation
Groundwater
Will the climate support the proposed plants?
Is time or space a constraint?
Is the contaminant physically within the range of the proposed plant (typically less than 10-20 feet bgs for Salix species - willows, cottonwoods, poplars)?
Will the water be mechanically pumped and applied to the phytoremediation system?
Will the plants be used for hydraulic control ONLY (prevent water from REACHING the contaminated zone)?
Will state regulations allow this type of phytoremediation?
Is the contaminant at phytotoxic concentrations (this may require a greenhouse dose-response test)?
Will the rhizosphere microbes and plant-exuded enzymes degrade the target contaminants in the rhizosphere and are the metabolic products acceptable?
Is the log Kow of the contaminant or metabolic products between 1 and 3.5 (will uptake occur)?
Will the plant degrade the contaminant after uptake and are the metabolic products acceptable?
Will the plant accumulate the contaminant or metabolic products after uptake?
Will the plants transpire the contaminant or metabolic products?
Is the level of accumulation acceptable for this site throughout the growth of the plant?
Is the quantity and rate of transpiration acceptable for this site?
Can controls be put in place to prevent the transfer of the contaminant or metabolic products from a plant to humans/animals?
Can engineering controls make it acceptable?
Is the final disposition of the contaminant or metabolic products acceptable?
Can the contaminant or metabolic product be immobilized to acceptable levels?
Does the plant material constitute a waste if harvested?
Can the plant waste be economically disposed?
YES
NO
Phytoremediation has the potential to be effective at the site
Phytoremediation is NOT an option at the site; consider other options

94

Designing a site

How do we make this work?

95

Unique Site Prep Problems

Concrete is not dependent on soil nutrients, but your plants will be.

Soil compaction can be an issue for planting.

Shades from buildings or other plants can be a major issue.

96

Security Issues

Securing a field can be more challenging than securing a building.

Squatters/Vagrants on the site.

Problems with radical groups.

97

Weather

Why doing transpiration measurements in the rain is not a good idea.

Temperature and light intensity have strong effects on plant metabolism and thus your test results.

98

Working With Mother Nature

Construction can go on anytime of the year, but planting has to be in sync with the seasons.

When dealing with natural systems we have to deal with all of nature (ie. bugs and birds are now a fact of life).

99

Selecting Plants For Your Site

You need to research and find the plant type that can handle the contaminant you are dealing with on the site

You need to find a plant that will SURVIVE on your site, or why brown trees don't impress anyone…

100

Screening Trees

101

Plant Trials

Before You Install, or Why Feasibility Testing is a Good Idea

Better to have a few plants die in the greenhouse, rather than have a field full of dead plants…..

103

Preparing the Site for Planting, or Why You Need to Learn to Think Like a Farmer

- Weather plays an important role
- Why plowing mud is a BAD idea…
- Plants have their own time schedules, and you have to meet theirs, not the other way around

104

Sometimes That Extra Plowing is NOT a Good Idea…

105

Department of Energy – Ash Basin

Understanding how your preparations will affect the site

106

Know How Your Treatment Will Work

Tilled, no compost

107

Consider Combination Technologies

- Pump and irrigate
- Water management behind a plume containment wall
- Reactive barriers and plants
- Combined bioremediation and phytoremediation
- Using plants to minimize recharge zones

108


Spray systems
109

Tritium Irrigation System

110

Medford

- Timing of the installation can be critical
- Timing the herbicide application to remove existing vegetation can be vital
- Digging up irrigation lines does not help

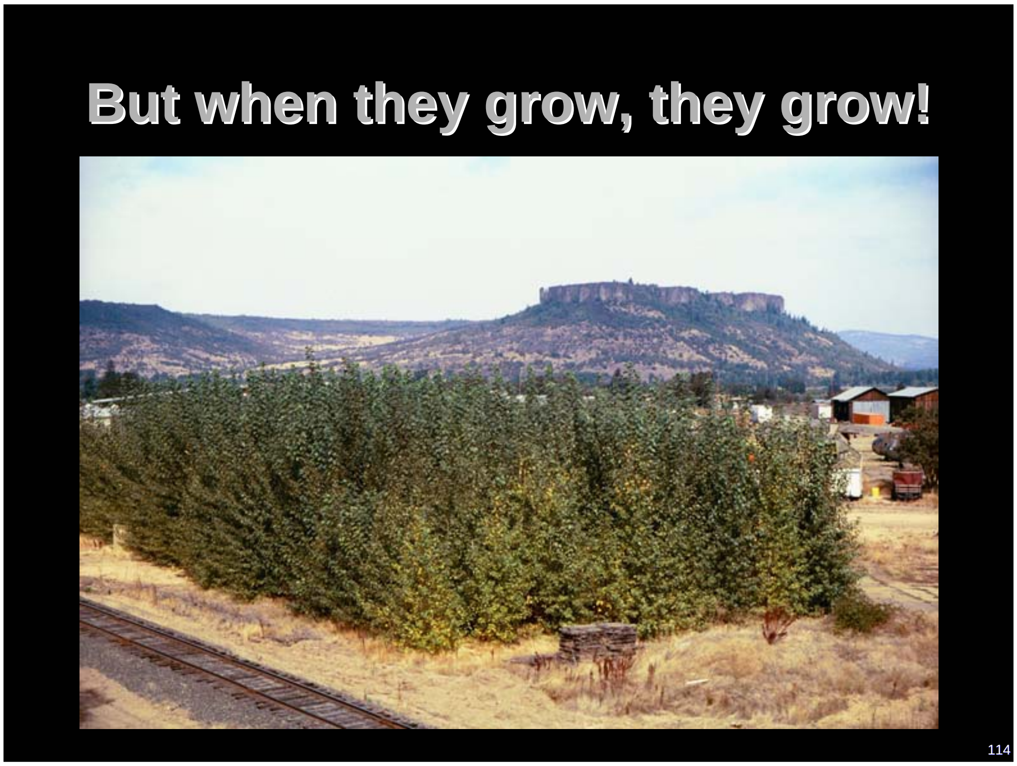
111

Mud, Anyone?

112

Or how about rocks?

113


But when they grow, they grow!
114

Navy Base I

- Plowing and moving mud
- Meeting unrealistic time schedules
- Why a wood chip road is NOT a good idea
- Hydrologic problems
- Poplars don’t swim real well

115

Plowing and Moving Mud

116

Water Problems

117

Earth Day 1999

Wood Chips are Not Always a Good Idea

119

Start of third year

120

Saginaw Mill

- Drainage problems
- Trees and deer don't mix well
- The problems with weeds
- Why community knowledge is a good thing

121

Lake Saginaw

122

Surviving the weeds, the deer, the fire…

123

And finally they grow

Portland

- Why plowing mud is a bad idea or adobe is not a good growing medium
- Plant selection can be crucial

125

Adobe, anyone?

126

Plant Selection + Poor Growing Conditions…

127

Navy Base II

- You need to know what is happening all around you, even if it is not related to what you are doing

128

A Little Asphalt, Anyone?

129

Vale

- What do you mean there is too much fertilizer or when wood chips ARE a good idea
- Didn’t you say the pesticides were burned?
- Why more mixing is not always better

A Little of Everything…

131

Wood Chips Just Might be a Good Idea Here!

132

And Then There Were Pesticides…

133

Still Not a Good Idea…

134

Okay, the Plants are Finally in the Ground and Growing. What Can Go Wrong Now???

Mechanical breakdowns

Invaders of the four-legged kind

Don’t forget the “Save the Trees Society”

Nutrient needs

Droughts are Mother Nature’s way of saying “Gotcha!”

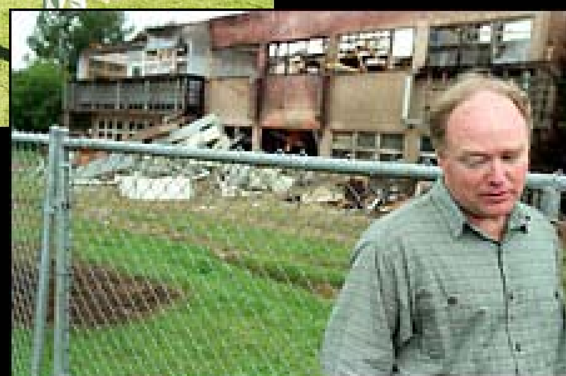
135

Poplars Can’t Swim!

136

Trees and Deer Don't Mix Well

137



University of Washington

Center for Urban Horticulture

138

Sigh.............

- Plants are Growing, Everything is Looking Green and Healthy. Time to Start Testing. Now What?

- Weather can still be a big issue
- Sample collection can pose some unique problems (getting liquid nitrogen into the field is NOT fun)
- Where do I ship the samples for analysis?

Tell Me Again…….

WHY Do I Want to Put Myself Through This???

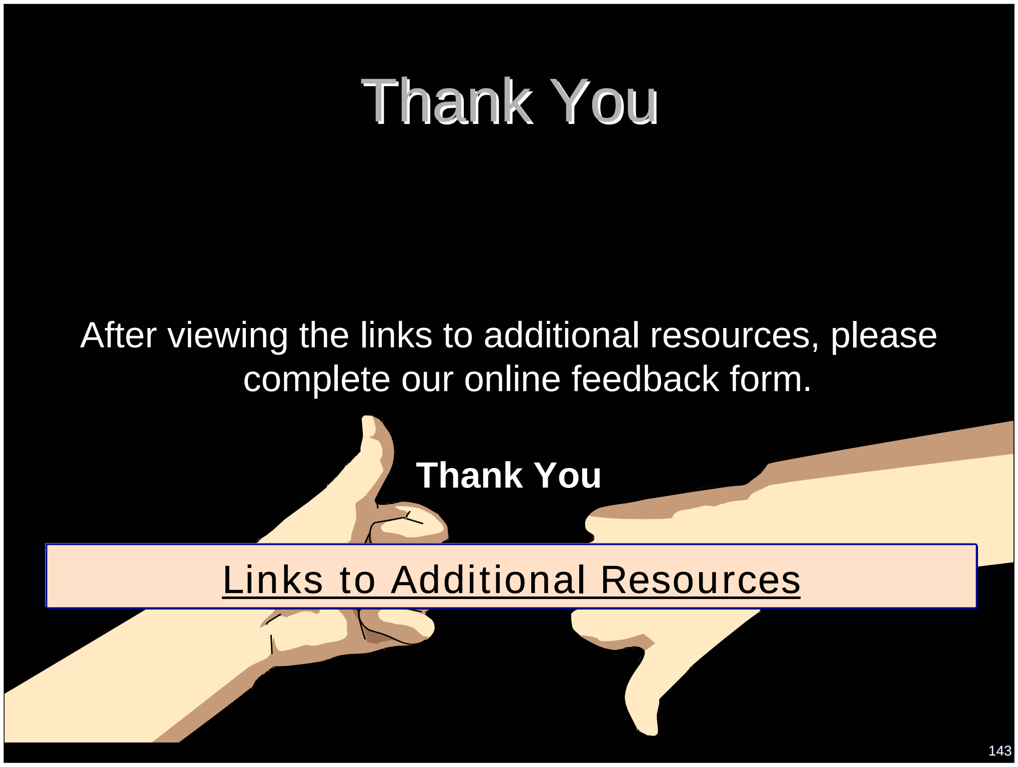
- Less expensive
- Citizens groups LIKE trees
- Many regulatory agencies are looking favorable at groups that try innovative technologies
- Because it is a great technology that will have you constantly learning as you go

140

Have faith in the trees!

141


Thank you!
142


Thank You
After viewing the links to additional resources, please complete our online feedback form.
Thank You
Links to Additional Resources
143