Conceptual System Design

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Presentation Outline

- Introduction – focus on chlorinated ethenes
- Data needs
  - Site characterization
  - Bench scale testing
  - Environmental molecular diagnostics
  - Pilot testing
- Amendment injection design
  - Amendment selection
  - Injection methods and layout
- Monitoring needs

Conceptual Design for Bioremediation

- Conceptual Site Model: Geo-Hydro & DNAPL/Plume Characteristics
- Microbial Status and Bio-Geochemistry
- Amendment Characteristics
- Injection/Delivery Approach

Successful Design Approach Must Be Appropriate for All These Factors

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Data Needs - Site Characterization

Contaminants
- Parent chlorinated aliphatic hydrocarbons (CAH) compounds and their dechlorination products
- PCE, TCE, cis-DCE, VC, ethene, and ethane
- Co-contaminants that may impact bioremediation rate and extent
  - BTEX compounds can stimulate reductive dechlorination
  - Other solvents can inhibit reductive dechlorination (e.g. TCA, CT, CF)

Data Needs - Site Characterization (cont.)

Electron donor parameters
- Indicators of bioavailable carbon
- Chemical oxygen demand (COD), total organic carbon (TOC), or specific volatile fatty acids (VFA’s)
- Indicators of prevailing redox conditions
  - Oxidation-reduction potential (ORP), dissolved oxygen (DO), ferrous iron, sulfate, and methane
- Biological activity indicators and water quality parameters
  - pH, temperature, specific conductance, alkalinity
  - metals
Data Needs – Environmental Molecular Diagnostics

- Advanced diagnostics can be useful during site characterization
- Quantitative polymerase chain reaction (qPCR) for *Dehalococcoides spp.* (DHC) and for functional genes (vcrA, bvcA, and tceA)
  - Useful to assess whether bioaugmentation may be needed
  - Absence of bacteria during pre-bioremediation characterization doesn’t always mean bioaugmentation will be needed

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Monitoring for DHC using qPCR

**Extract DNA from whole cells**

**AMPLIFY TARGET:** Quantitative - # targets/extraction

**TARGET DHC:**
1. General:
   - 16S rDNA
2. Specific:
   - tceA, vcrA, bvcA

**Enzymes | Contaminant Degradation Pathway**

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Contaminant</th>
<th>Degradation Pathway</th>
</tr>
</thead>
<tbody>
<tr>
<td>tceA</td>
<td>PCE</td>
<td>TCE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cis-DCE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vinyl Chloride</td>
</tr>
<tr>
<td>vcrA</td>
<td>TCE</td>
<td>Ethene</td>
</tr>
<tr>
<td>bvcA</td>
<td></td>
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</tr>
</tbody>
</table>

- The reaction is energy yielding, directly benefiting the bacteria
- The reaction is cometabolic, not directly benefiting the bacteria
Data Needs – Environmental Molecular Diagnostics (cont.)

- Other tools can be useful but are not required to design a bioremediation system
  - Phospholipid Fatty Acid (PLFA)
    - Provides information on entire bacterial community through analysis of microbial membranes
  - Denaturing gradient gel electrophoresis (DGGE)
    - DNA-based technique which generates a genetic profile of the microbial community
  - Compound specific isotope analysis (CSIA)
    - Generates isotopic characterization of individual compounds which can be used to quantitatively assess degradation processes.

Data Needs – Bench scale testing

- Bench scale testing purposes
  - Assess whether bioremediation will work
  - Determine design parameters
- Bench scale testing to assess whether bioremediation can be stimulated is not required at most sites
  - Many limiting conditions can be overcome through design (i.e. low pH, high sulfate, etc.)
  - Site characterization should identify any site conditions that would preclude bioremediation
- Exception – presence of co-contaminants that are known to inhibit reductive dechlorination.
Data Needs – Bench scale testing (cont.)

- Bench scale testing can provide some useful design information
  - Relative comparison of electron donors in terms of concentration, longevity, dechlorination rate, etc.
  - Relative comparison of bioaugmentation cultures
- Use caution when applying degradation/growth rates from lab studies to the field
- In situ microcosms can overcome these limitations

Data Needs – Pilot Testing

- The most useful and accurate design information is derived from pilot studies
- Small-to-moderate scale electron donor injection(s) and periodic monitoring
- Provides site-specific information:
  - Electron donor distribution
  - Time to onset of degradation
  - Time to complete dechlorination
  - Need for bioaugmentation
**Fundamental Bioremediation Design**

**Goals**
- Inject and distribute electron donor into the target treatment area in order to:
  - Manipulate the aquifer’s redox status
  - Expand populations of fermenting bacteria
  - Enhance early-stage dechlorination metabolism
  - Initiate (if necessary) and expand late-stage dechlorination
  - Dissolve and desorb DNAPL mass (for source area applications)

**Considerations for Source Zones**
- Bioremediation can be successfully implemented in chlorinated solvent source zones (ITRC, 2008)
- Design must account for:
  - Delineation of source mass
  - Source area hydrogeology
  - Context of monitoring data

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Kueper, BH et al., 2003 – An illustrated handbook of DNAPL transport and fate in the subsurface
Effect of Source Zone Geologic Heterogeneity

Subsurface Conditions Affecting Injection Designs

- Heterogeneity and/or low permeability strata
- DNAPL distribution
  - Area
  - Volume
  - Depths below grade
  - Depths below water table
- Target treatment zone
  - Location
  - Extent
- Depth to groundwater
  - And other factors influencing injection well costs
- Groundwater flow rates
- Geochemical conditions affecting
  - Bioremediation
  - Groundwater quality

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Elements of Bioremediation Injection Design

- Electron donor selection
- Delivery method
- Injection volume and concentration
- Injection frequency
- Need for bioaugmentation

Electron Donor Amendment Characteristics

- Carbon donors vary in several properties
  - Manner of hydrogen production
  - Chemical composition
  - Electron equivalents released per unit mass of amendment
  - Microbiological responses
  - Geochemical impact
  - Chemical / physical properties
  - Transport characteristics
  - Longevity
Electron Donor Amendments

- Soluble (i.e. Fast-release)
  - Lactate / other organic acids
  - Methanol / ethanol
  - Molasses / other carbohydrates
  - Dairy whey
- Slow-release
  - Edible oils and oil mixtures
  - Chitin (glucosamine polymer)
  - Lactate polymers
  - Mixtures of lactate and long-chain fatty acids
  - Solids (mulch)
- Key point: amendment choice and injection design are closely linked

Increasing Product Development Creating a Continuum

Transport Considerations for Highly Soluble Amendments

- Extract, treat, amend and re-inject
- Extraction wells
- Injection well

Background TOC

Distance (meters)

30 90 days
20 60 days
10 30 days

Monitoring well

Injection wells

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Transport Considerations for Slow Release Amendments

Injection radius of influence (ROI) of slow-release donor

Heavily reduced conditions

Moderately reduced conditions

Groundwater flow direction

Volatile fatty acid (VFA) and dissolved organic carbon concentration (DOC) transport and consumption downgradient

Scale of process is highly dependent on site conditions

Secondary Amendments

- pH buffers
  - Carbonate/bicarbonate
  - Offset the production of hydrogen ion (H+) and volatile fatty acids (VFAs)
- Nutrients
  - Nitrogen (N), phosphorus (P) and potassium (K); also vitamin B12
  - Generally not needed for anaerobic bioremediation
  - Can compete as electron donors
- Bioaugmentation
  - May be needed if process is stalled at cis-DCE or VC
  - Not needed if appropriate microbial consortium is present
  - May accelerate process at some sites
- Chemical reagents
  - e.g., zero valent iron (ZVI), other reductants
Overview of Delivery Techniques – Trenching

Trenching

- Generally used to emplace solid phase amendments (i.e. bark or mulch)
- Usually configured as one or a series of permeable reactive barrier oriented perpendicular to groundwater flow
- Installed using conventional excavation or biopolymer slurry.

Overview of Delivery Techniques – Trenching (cont.)

Advantages:
- Can mitigate uncertainty caused by subsurface heterogeneity because it allows distribution across an entire cross-section of the plume
- Can be most cost effective means to emplace large mass of amendments

Disadvantages
- Can only be performed at shallow sites
- Not effective for delivering liquid amendments
Overview of Delivery Techniques - Fracturing

Fracturing

- This delivery technique applies high pressure to the subsurface to create cracks (fractures) in the soil
  - Hydraulic fracturing delivers a “proppant” into the fractures (such as sand) to prop them open; amendment can be mixed with the proppant
  - Pneumatic fracturing uses air or nitrogen as a carrier to deliver amendments into the fracture
  - Generally used to deliver solid phase amendments

Overview of Delivery Techniques – Fracturing (cont.)

Advantages:

- Can successfully deliver amendments at low permeability sites and at sites with deep contamination
- Can actually increase the hydraulic conductivity of a formation; flow preferentially flows through fractures
- Individual fractures can be mapped, providing an accurate depiction of amendment distribution.

Disadvantages

- Radius of influence decreases at shallower sites
- Not effective for delivering liquid amendments
- Requires specialized equipment and specialty vendors
Overview of Delivery Techniques – Injection Wells

Passive injection wells

- Standard wells installed at regular spacing used to inject amendments
- Well spacing and construction can be varied depending on goals
- Generally used to emplace aqueous amendments
- Amendments are injected and allowed to transport advectively

Advantages:
- Can distribute large volumes of amendments over large areas with relatively few injection locations
- Standard technology readily available almost anywhere
- Can be used at sites with deep water table and at fractured rock sites, although costs may be high

Disadvantages
- Radius of influence decreases at low permeability sites
- May not be effective at sites with low groundwater velocity
- Not effective for delivering solid amendments
Overview of Delivery Techniques – Direct Push Technology

Direct Push Technology
- Injections are performed into temporary borings created using DPT
- DPT spacing can be varied depending on goals
- Generally used to emplace aqueous amendments
- Amendments are injected and allowed to transport advectively

Advantages:
- Many DPT points can be installed to inject over large areas
- Standard technology readily available almost anywhere
- Among the most cost effective techniques for delivering aqueous amendments

Disadvantages
- Radius of influence decreases at low permeability sites
- May not be effective at sites with low groundwater velocity
- Not effective for delivering solid phase amendments
- Infeasible for deep sites or fractured rock
- Generally not efficient at injecting large volumes
Overview of Delivery Techniques – Active Recirculation

Active Recirculation

- Injection and extraction wells used to recirculate groundwater across the treatment area
- Amendment “pulsed” into extracted water
- Amendments are injected and are transported under forced advection

Advantages:

- Can distribute large volumes of amendments over large areas with relatively few injection locations
- Standard technology readily available almost anywhere
- Can be used at sites with deep water table and at fractured rock sites, although costs may be high
- Can distribute amendment at sites with low groundwater velocity

Disadvantages

- Requires a significant amount of infrastructure
- O&M requirements high compared to inject and drift
**Application Suggestions**

<table>
<thead>
<tr>
<th>Method</th>
<th>Aquifer permeability</th>
<th>Groundwater velocity</th>
<th>Aquifer matrix</th>
<th>Depth to contamination</th>
<th>Type of Substrate emplaced</th>
<th>Volume of Substrate emplaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trenching</td>
<td>Any</td>
<td>Any</td>
<td>Unconsolidated</td>
<td>Shallow (&lt;40 ft)</td>
<td>Solid</td>
<td>High</td>
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<tr>
<td>Fracing</td>
<td>Low to moderate</td>
<td>Any</td>
<td>Unconsolidated</td>
<td>Deeper than 25 ft</td>
<td>Solid</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Passive injection</td>
<td>Moderate to high</td>
<td>Moderate to high (&gt;0.25 ft/day)</td>
<td>Any</td>
<td>Any</td>
<td>Aqueous</td>
<td>Low to high</td>
</tr>
<tr>
<td>DPT</td>
<td>Moderate to high</td>
<td>Moderate to high (&gt;0.25 ft/day)</td>
<td>Unconsolidated</td>
<td>Shallow to moderate (up to 50 ft)</td>
<td>Aqueous</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Active Recirculation</td>
<td>Moderate to high</td>
<td>Low to moderate</td>
<td>Any</td>
<td>Any</td>
<td>Aqueous</td>
<td>Low to high</td>
</tr>
</tbody>
</table>

**Amendment Dosage**

- The goal is to account for the demand imposed by all of the electron acceptors in the system
  - There is uncertainty in accurately determining or estimating the native electron donor demand
  - Typical safety factors of 5-10 or higher are commonly applied to the calculated dose to reflect the uncertainty
  - Significantly higher dosing may be used for source area applications
- Reasons for safety factors include
  - Unknown mass of electron acceptors (e.g., Fe$^{3+}$) present within the treatment zone
  - Difficulty accurately predicting electron acceptor influx over time
  - “Wasteful” microbial activity (not linked to dechlorination)
**Amendment Injection Frequency**

- Injection frequency depends on amendment that is being used and on type of application
  - Fast release donors may need to be injected every 4-12 weeks
  - Slow release donors may last up to two years or longer
  - Trenches/barrier application can be designed to be “recharged” with amendments
- Source area applications may require more frequent injections in order to maintain biologically active zone

**Bioaugmentation**

- Bioaugmentation can be used to overcome microbiological limitations at sites
- Several cultures are commercially available for chlorinated solvents
- Several options for bioaugmentation exist
  - Add electron donor and only bioaugment when a microbiological limitation is evident
  - Bioaugment at the outset in order to reduce lag times and ensure that complete degradation will occur
  - Add electron donor for a short period of time to “pre-condition” the aquifer
Monitoring during Operations

Monitoring needs generally reduce as bioremediation projects progress from pilot studies to long-term operations

- Pilot studies and initial operations will show which parameters are key at a given site
- A “core list” of parameters still will be needed during operations, but frequency may decrease
- Some parameters may be important based on site-specific needs (e.g. metals, co-contaminants)

Monitoring during Operations (cont.)

- Contaminants and degradation products
- Electron donor
  - COD or TOC
- Redox sensitive parameters
  - Ferrous iron
  - Sulfate
  - Methane
- Biological activity indicators and water quality parameters
  - pH
  - Alkalinity
  - Metals (site-specific basis)
Monitoring during Operations (cont.)

- EMD’s can be useful during operations
- qPCR for DHC
  - commercially available and should be used during initial phases of operations
  - Location/frequency may be decreased over time
- CSIA
  - Can be useful at sites to demonstrate complete degradation is occurring
  - Probably more common during pilot studies/technology demonstration
- Others
  - Less common during operations

Summary

- Standard groundwater chemistry parameters are needed to design a bioremediation system
- EMD’s are advanced diagnostic tools that can provide valuable information
- Bench scale studies can be useful but generally are not required
- Pilot studies are very useful at most sites
- Continuum of bioremediation amendments is available, with selection dependent on site conditions and remedial goals
- Amendment selection and delivery techniques are linked
- Monitoring needs generally decrease during bioremediation operations