ANAEROBIC BIOREMEDIATION OF A CHLORINATED SOLVENT GROUNDWATER PLUME – LESSONS LEARNED

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Site Location and Conditions

- 29 acre groundwater plume; TCE (<500 ppb), 1,1-DCE (<100 ppb).
- private airport and 3 manufacturing facilities.
- Highly stratified sand, silts, and clays with $k_H$ 80 to 380 gpd/ft$^2$
- Aerobic, low DO, acidity increases, pH decreases, and permeability decreases downward.
- ROD - In-situ bioremediation to 10 ppb TCE, then MNA 1 ppb
Project Scope of Work

- 100 ppb TCE plume delineation
- Amendment, mixing, distribution, and injection system for biostimulation and bioaugmentation
- Multi-screened injection wells (IW) chosen for reinjection capability
- Later use of direct injection and a horizontal well.
- Amendment injection from 2010 through 2015
  - Inject potable water containing sodium bicarbonate (SB) and emulsified vegetable oil (EVO), followed separately by bioaugment culture with *Dehalococcoides*
  - 5,800 gal of aqueous amendment (4,000 lb. SB and 1,630 lb. of EVO) per IW screen
Plume Modeling/Well Design

- Highest TCE levels in 30 to 50-ft thick zone at 40 to 70 ft below ground surface (bgs)

- IWs with 2 or 3 10-ft screens per location
Lessons Learned

• Amendment Injection System Design
  • Mechanical Equipment/Materials Handling
  • Z-Loy Pretreatment System
  • Mixing System - Simplification
  • Manifolds
  • Wells
    ▶ Vertical
    ▶ Horizontal

• Treatment
  • Amendment injection rates
  • Amendment travel rates and
  • Amendment persistence
Handling/Mixing of Amendments

- Lessons learned:
  - Dispensing SB from 50 lb bags not practical.
  - Mixing in small (1,300 gal) tanks very labor intensive.
  - Cool weather (<45°F) limits SB solubility

- Response:
  - Dispense bicarbonate using forklift and 2K lb totes into 18K gal frac tank with hopper, gate and mixers.
Nano-Scale Zero-Valent Iron (n-ZVI) Included in Initial Treatment Design

- nZVI is injectable material for in-situ abiotic reductive dechlorination
- Design loading of 0.25 g/L in amendment solution.
- Pre-treatment of injection water by coarse (less expensive ZVI) required to reduce sacrificial loss of n-ZVI activity.

Lesson Learned:

- Loading rate for a dilute plume too expensive
- Deoxygenation vessel maintenance very expensive
- Water pre-treatment required.
- nZVI more cost effective for concentrated source.
Mixing System Simplification

2010 →

2015 →

2016 Design and Construction Issues at Hazardous Waste Sites
**Injection Well Designs**

- **Initial IW and MP Well Design:**
  - HSA in Common borehole.
  - Bentonite:water seals and grout.

- **Final IW Design:**
  - RotarySonic
  - Neat cement grout.

- **Original well construction overview:**
  - 290 IWs and 50 groundwater monitoring points (MPs)
  - Observed Problems IWs:
    - Wellhead subsidence.
    - Slow acceptance rates

- **Revised Well Constructions:**
  - Rotary-sonic with or without coring.
  - Vibro-sonic with coring.

- **Results:**
  - Vibro-sonic drilling methods inefficient.
  - No apparent differences between cored and un-cored wells by Rotary-sonic.
Lessons Learned: Horizontal Well

HIW End
53.3 ft bgs

45.7 ft bgs
Lessons Learned: Horizontal Well

- Horizontal driller installed the well as single-ended or blind end, rather than double-ended. Cost savings appx $20 to $30K,
- Borepath design with a gently inclined screen to maximize intercept the of contaminated sediments/layers
- 80.5k gallons amendment injected into Horizontal Injection Well (HIW) to treat inaccessible area along Rt 34 and western portion of property on east side of Rt 34
Project Summary: 2010 - 2015

- Total Amendment Injections:
  - 5.9M gal. of amendment.
  - 5.7M gal. of potable water.
  - 3.6M lbs. of sodium bicarbonate.
  - 1.3M lbs. (147K gal) of EVO.
  - 1,365 L of KB-1 injected into 677 injection well screens.

- Treatment Results:
  - Removed 75% of TCE and 1,1-DCE contaminant mass

<table>
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<th>Isocontour (ppb)</th>
<th>10</th>
<th>35</th>
<th>50</th>
<th>100</th>
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<tr>
<td>Size reduction</td>
<td>48%</td>
<td>70%</td>
<td>77%</td>
<td>73%</td>
<td>88%</td>
<td>100%</td>
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TCE Time Series: January 2011
TCE Time Series: October 2015
Injection Costs

Cost Reductions:

- Increase injection volumes and rate using more efficient mix and delivery systems
- Eliminate nZVI as amendment

Cost/Gallon of Amendment Injected

- 2009: $0.99
- 2010: $1.17
- 2011: $1.03
- 2012: $1.20
- 2013: $1.30
- 2014: $4.71
- 2015: $1.30
- 2016: $1.30
IW Acceptance Rates
Lesson Learned: Direct Injection

**Effect \( N_2 \) Pulsing on Flow Rate**
- Improved injection rates only HS-3 area
- Flow increased ~ 2-fold (9.4 vs 4.6 gpm)

**Effect \( N_2 \) Pulsing on Inject Pressure**
- Higher pressures in deeper intervals only HS-1 area
- No correlation with increased flows
Lessons Learned:

- Average injection rates decreased with time due to slower IWs
- Cost/gal. increased significantly with decreasing total injection rates due to fixed costs.
- Focus on slower wells/site areas early in injection campaign
Amendment Travel Evaluations

• **Approach:** Evaluate correlation of amendment distribution between IWs to MPs with average time from injection.

• **Result:** Weak relationship ($R^2 = 0.68$) between distance vs response time.

• **Lesson Learned** – Factors other than distance and injection rate influence amendment migration: heterogeneous lithology
Amendment Persistence/Exhaustion

**Amendment Persistence**

- **Findings:**
  - Amendment has persisted from 18 to 54 months (variance due to distribution effectiveness)
  - Amendment has become exhausted in ~35% of MPs over last two years

- **Lessons Learned:**
  - Reinjection likely required for final treatment of some areas due to amendment exhaustion, poor distribution, or incomplete TCE degradation.
Summary of Lessons Learned

• Large injection volumes achieved most economically with large-scale mixing and distribution equipment
• Cost of $1/gal dilute amendment injection can be achieved when well acceptance rates remain on the order of 1 gpm/10 ft screen
• Stacked injection screens most efficient for vertical target > 15 ft
• Direct injection approach beneficial in difficult lithology, however costs per gallon of injected amendment are higher
• Horizontal well beneficial for difficult to access locations where plume resides
• Contaminant treatment efficacy dependent on success of amendment distribution
• Amendment persistence is 18 months to 3 years