Maximizing Performance During *In Situ* Bioremediation

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Introduction

**Food**
Electron Donor

**Respiration**
Electron Acceptor

Energy & Reproduction

Food + Respiration = Energy & Reproduction

EOS PRO

BAC-9
Emulsified Oil Process

- Install temporary or permanent injection points or use DPT
- Dilute the emulsified vegetable oil (EVO)
- Inject typically under very low pressure
- Oil droplets eventually stick to sediment surfaces
- Oil ferments producing hydrogen and acetate, thus driving biodegradation
Post-Remediation Evaluation

How do we improve performance?

Lessons Learned

- PCE & TCE \( \rightarrow \) cis-DCE \( \rightarrow \) FAST
- cis-DCE \( \rightarrow \) VC \( \rightarrow \) Ethene \( \rightarrow \) SLOW

Slow conversion to ethene is not always a “cis-stall” aka lack of DHC

- **Poor EVO distribution**
- pH less than 6 (not discussed today)

184 well review by Tillotson & Borden, 2017
Understanding Oil Fermentation

Soybean oil hydrolysis
• 1 glycerol ($C_3H_8O_3$)
• 3 long chain fatty acids ($C_{18}H_{32}O_2$)
• Fermentation releases both $H_2$ and acetate

PCE & TCE degradation to cis-DCE
• Use BOTH $H_2$ and acetate

DCE & VC degradation to Ethene
• Use ONLY $H_2$
• $H_2$ turns over very rapidly (Fe(III), SO$_4$, CH$_4$)
• $H_2$ only occurs near fermentable carbon
Fermentable Carbon

**Direct Contact: Complete Dechlorination**

- Injection Well
  - Acetic Acid
  - Propionic Acid
  - Butyric Acid
  - Other Fatty Acids

- Good hydrogen formation due to mix of fatty acids

**Some Contact: Poor Conversion to Ethene**

- 10 Ft Downgradient
  - Acetic Acid
  - Propionic Acid
  - Butyric Acid
  - Other Fatty Acids

- Poor hydrogen formation, acetic acid does not release hydrogen
Good Treatment Requires Good Contact

How to Improve contact
• Inject the right amount and type of EVO = $$$
• Inject the right amount of water to drive distribution = $$$
• Increase injection well/point density = $$$

Which do you focus on?
Improving EVO Distribution

Maximum Oil retention ($OR_M$)

- Emulsion transport is very similar to colloid transport (e.g. bacteria)

- Factors effecting Oil Retention:
  - Droplet size
  - Zeta potential of sediment
  - Ionic strength of the groundwater
  - Surfactant type used
Design Calculation

Mass of oil = x • y • z • ne • ρ_B • OR

x = Treatment zone length parallel to GW flow (ft)

y = Design width perpendicular to GW flow (ft)

z = height (ft)

ne = Effective porosity (unit less)

ρ_B = Sediment bulk density (lb./ft³)

OR = Oil retention (wt./wt.)

Early Measurements of OR_M

<table>
<thead>
<tr>
<th>Site-Specific Aquifer Material</th>
<th>Emulsion</th>
<th>Test Condition</th>
<th>Maximum Retention (g/g)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine clayey-sand</td>
<td>Homemade</td>
<td>Lab Column</td>
<td>0.0054</td>
<td>Coulibaly and Borden, 2004</td>
</tr>
<tr>
<td>Fine clayey sand amended with kaolinite</td>
<td>Homemade</td>
<td>Lab Column</td>
<td>0.0061</td>
<td>Coulibaly and Borden, 2004</td>
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<tr>
<td>Fine clayey sand amended with kaolinite</td>
<td>Homemade</td>
<td>Lab Column</td>
<td>0.0095</td>
<td>Coulibaly and Borden, 2004</td>
</tr>
<tr>
<td>Clayey sand alluvium</td>
<td>EOS® 598842</td>
<td>Lab Column</td>
<td>0.0037</td>
<td>Borden, 2007a</td>
</tr>
<tr>
<td>Low K, weathered rock</td>
<td>EOS® 598842</td>
<td>Field (estimated)</td>
<td>0.0030</td>
<td>Borden et al., 2007</td>
</tr>
<tr>
<td>Coarse grained sand and gravel</td>
<td>EOS® 598842</td>
<td>Field (estimate)</td>
<td>0.0004</td>
<td>Kovacich et al., 2007</td>
</tr>
<tr>
<td>Medium grain sand</td>
<td>EVO</td>
<td>Lab Column</td>
<td>0.0024</td>
<td>Konzuk et al., 2006</td>
</tr>
</tbody>
</table>
Oil Retention Results

- New data shows some sites with very high oil retention
- Cause not completely understood

Ionic strength & Oil retention

<table>
<thead>
<tr>
<th>Site material</th>
<th>Ave Oil Retention (g oil /g soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DI Water</td>
</tr>
<tr>
<td>SA17 (15-23&quot;)</td>
<td>0.003</td>
</tr>
<tr>
<td>OU2 (37-40&quot;)</td>
<td>0.014</td>
</tr>
</tbody>
</table>
Substrate Properties

Properties of “water-less” oil products (EOS 100)
- High vegetable oil content (85% by wt.)
- Emulsifiers and other additives
- Once mixed with water have a large droplet diameter (~5-10 microns)

Properties of traditional EVO products (EOS Pro)
- Low to medium vegetable oil content (60% by wt.)
- Include nutrients & vitamin B12
- Droplets as delivered <1 micron
Oil Retention Results

![Graph showing oil retention results for Clean Sand and Silty Sand using EOS 100 and EOS Pro.](image-url)
Life Cycle Cost: Why Substrate Selection Matters

ESTCP Emulsion Tool Kit:
200ft Barrier
GW Velocity 1.6 ft./day
Geology: medium sand with silt
Are you injecting enough water?

Good Treatment = Good Contact

ROI² x π x screen height x nₑ x 7.48 = gallons of pore volume

10ft² x π x 10ft x 0.2 x 7.48 = 4,699 gallons

Due to heterogeneity and storage capacity, you can assume ~ 50% of pore volume (or ~2,300 gals)
Effect of Injection Sequence

• Simultaneous injection of multiple wells causes:
  • Stagnation zones
  • Lower contact efficiency

• Instead, inject into every other well and be sure your diluting and/or chasing with enough water
Thank You