Starting Soon: Optimizing Injection Strategies and In Situ Remediation Performance

- Optimizing Injection Strategies and In Situ Remediation Performance (OIS-ISRP-1, 2020)
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Optimizing Injection Strategies and In Situ Remediation Performance

Optimizing Injection Strategies and In Situ Remediation Performance (OIS-ISRP-1, 2020)

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Meet the ITRC Trainers

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**Kristopher (Kris) McCandless** has worked for the Virginia Department of Environmental Quality (DEQ) in Woodbridge, Virginia since 2016. As an Environmental Geologist in the petroleum storage tank remediation division, he manages the characterization and remediation of numerous leaking petroleum storage tank sites, as well as assists the Land Protection Program with chlorinated solvent sites. Kris has spent most of his career as a project manager and hydrogeologist in the environmental consulting field. In the past two decades, his projects were focused on investigating and managing petroleum and chlorinated solvent sites in the Mid-Atlantic Piedmont states. Kris spearheaded investigations for Alternate Water Supplies for the DEQ Petroleum Program for State Lead sites as a contractor for DEQ, including locating new supply well locations, tracking groundwater flow through fractured media, performing packer testing to sample and isolate impacted zones within a supply well, performing pump tests in fractured rock, and assessing bedrock sites for remediation of chlorinated solvents. While reaping the benefits of many ITRC webinars during his consulting career, Kris joined the Fractured Bedrock team soon after employment with DEQ. Kris is actively engaged as a chapter lead for the ITRC Optimization of In situ Pump tests in fractured rock, and assessing bedrock sites for remediation of chlorinated solvents. While reaping the benefits of many ITRC webinars during his consulting career, Kris joined the Fractured Bedrock team soon after employment with DEQ. Kris is actively engaged as a chapter lead for the ITRC Optimization of In situ Remediation team beginning in 2018. Kris earned his Bachelor of Science degree in Geology from George Mason University in 1988 in Fairfax, Virginia and is a Certified Professional Geologist (CPG) in Virginia.

**Richard Desrosiers** is Vice President/Hydrogeologist for GZA GeoEnvironmental, Inc. in Glastonbury, Connecticut. Beginning his environmental career in the mid-1980s, Richard has focused on large complex geologic, hydrogeologic and geochemistry fate & transport problems associated with soil and groundwater contamination. He designed and led site investigations and remediation actions at a site with chlorinated solvents and hexavalent chromium encompassing a one square mile using high resolution site characterization and designing in-situ remediation remedies using chemical oxidation for VOC and biochemical reduction to treat hexavalent chromium and volatile organic compounds. Richard has completed RCRA/CERCLA hazardous waste investigations/closures; implemented in-situ innovative recirculation well technology to capture, treat and reinject remediate groundwater within the same well; identified and developed high yielding groundwater supplies in surficial and bedrock aquifers; completed numerous hydrogeologic evaluations and groundwater models; and has provided depositions, bench and jury expert testimony regarding litigation issues. Most recently, Richard leads GZA’s PFAS initiative and has participated on CT PFAS Task Force Committees. Since 2015, Richard has been an active member on the Interstate Technology & Regulatory Council (ITRC) “Characterization and Remediation in Fractured Rock”, “Optimization of In-Situ Remediation and Injection Strategies” and “Per- and Polyfluoroalkyl Substances (PFAS)” teams. Richard earned a bachelor’s degree in Geology from Northeastern University in Boston, Massachusetts in 1982. He is a Licensed Environmental Professional in Connecticut and a licensed Professional Geologist in New Hampshire and Tennessee.

**Suzanne O’Hara** is a senior contaminant hydrogeologist with Geosyntec Consultants based in Ontario Canada. She has over 20 years of field and project management experience focusing on remediation of groundwater and soil containing recalcitrant compounds using innovative and more conventional technologies. She has directed, managed, or provided technical support for multiple projects ranging from overall strategy development, site investigation, remedial design, costing and implementation, contaminant fate and transport, and conceptual site model (CSM) development. Her technical experience involves dense non-aqueous phase (DNAPL) fate and transport in fractured media and the design, implementation and interpretation of innovative in situ remediation technologies for complex contaminated sites. Suzanne’s remediation technology experience includes enhanced in situ bioremediation (EISB), in situ chemical oxidation (ISCO) and reduction (ISCR), Self-sustaining Treatment for Active Remediation (STAR) thermal remediation, passive treatment using zero-valent iron barriers, and reductive dechlorination using emulsified zerovalent iron (EZVI) for DNAPLs. Suzanne has been involved in ITRC since 2017 as a team member of the Optimizing Injection Strategies and In Situ Remediation Performance team. Suzanne earned a bachelor’s degree in Earth Science (geology) from the University of Waterloo, Ontario, in 1994 and a master’s in Hydrogeology from the University of Waterloo, Ontario, in 1997. Suzanne is a Professional Geoscientist in Ontario and a Professional Geologist in New York.

**Elizabeth Rhine** is an Independent Consultant in Greenville, South Carolina. She has more than 25 years of professional experience focused on the characterization and remediation of impacted sites in the chemical, oil and gas, and transportation sectors. She is adept at developing creative and cost-effective remediation strategies for clients to meet the objectives of project stakeholders including responsible parties, regulatory agencies, potential developers, and the public. Her work has focused primarily in groundwater remediation of sites under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA), developing site conceptual models, evaluating site conditions for in situ groundwater remedies, indoor air quality, regulatory compliance, environmental liability valuations, transactional due diligence, and brownfield redevelopment. Elizabeth is the author or co-author of more than a dozen peer-reviewed technical papers and has presented at a number of conferences and universities. Elizabeth earned a bachelor’s degree in biology from Furman University in Greenville, South Carolina in 1989 and a master’s in business administration with an emphasis in data management in 1998.
ITRC's Online Guidance for In Situ Remediation Optimization

Welcome
Optimizing Injection Strategies and In situ Remediation Performance (OIS-ISRP-1)

Free Online Access at: https://ois-isrp-1.itrcweb.org
In Situ Remediation

- A typical in situ remedy includes **delivery** and **dosing of amendments** to enhance abiotic and/or biotic **processes** to treat contaminants in subsurface

- More than thirty years of experience with in situ remedies has greatly improved the state of the science and engineering; though challenges remain
State of Practice

The Problem

- Failing to achieve the objectives or performance requirements
- Unknown variables that influence effectiveness

The Need

- Conceptual Site Model (CSM) more complete
- More efficient and effective remedies
- Framework guidance to facilitate improvements

State regulator survey. ~40% of regulators deemed the first submittal for in situ remediation projects as incomplete
What is Optimization?

- Optimization is the effort (at any clean-up phase) to identify and implement actions that improve effectiveness and cost-efficiency of that phase. *(From ITRC-GRO-1)*

- Optimizing in situ remediation is:
  
  The management of risks and uncertainties through sound science and engineering during different stages of in situ remedy planning and implementation.

- This training and accompanying guidance intended to help transfer “best practices” to benefit all.
ITRC's In Situ Remediation Optimization Toolbox

Guidance Layout

- Remedial Design Characterization
- The Design Wheel
- Performance Monitoring & Feedback Loop
- Stakeholder Considerations

Optimization Process

- Commonly Encountered Challenges
- Amendment Factsheets
- Delivery / Injection Screening Matrix & Factsheets
- Bench / Pilot Testing Considerations for Design
Document Audience and Application

- Intended audience
  - Regulators
  - Responsible Parties
  - Consultants

- Two applications of this document:
  - Improving underperforming remedies
  - Planning, designing and implementing optimized in situ remedies
What are the Technical Challenges?

- Higher contaminant concentrations after injections
- Insufficient amendment distribution and contact
- Contaminants in low permeability zone
- Amendment is "daylighting"/short circuiting
- Using vendor’s dosing default values instead of CSM data
# Commonly Encountered Issues

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Contaminant</th>
<th>Challenges, Lessons Learned, and/or Best Practices</th>
<th>Discussion, Document Section, Links</th>
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</thead>
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<tr>
<td>Bedrock</td>
<td></td>
<td>The sorption of contaminant mass sorbed onto bedrock substrata.</td>
<td>(ITRC 2011).a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limitations of solvent extraction in supercritical mass sorbed into soil.</td>
<td>See Discrete fracture network approach for studying contamination in unsaturated soil.</td>
</tr>
<tr>
<td>Groundwater</td>
<td></td>
<td>Variability of K and velocity in contaminated intervals is needed to estimate ROI delivery approaches and residence time within ROIs.</td>
<td>Higher resolution slug testing, tracer testing, or pilot testing with monitoring to determine contaminant distribution in effective pore space.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mischaracterization of mass flux to be targeted in a mass flux reduction strategy.</td>
<td>Higher resolution sampling to identify transmissive zones for injection based on defined targeted K values, contaminant mass, and heterogeneity within the TTA.</td>
</tr>
<tr>
<td>NAPL or DNAPL</td>
<td></td>
<td>Mischaracterization resulting in misidentifying the presence of LNAPL or DNAPL.</td>
<td>FLAVS (ITRC 2015).b Management of TTZ for presence of LNAPL or DNAPL.</td>
</tr>
</tbody>
</table>

ITRC OIS-ISR-1 Table 1-1 (See Additional Information, Appendix B)

Commonly Encountered Issues with In Situ Remediation
Training Program Learning Objectives

- Identify challenges
- Apply iterative optimization process at each stage of in situ remedy
- Determine amendment, dosing and delivery options
- Monitor performance to make optimization decisions
- Anticipate iterative refinement for remedy design and regulatory approvals
Presentation Road Map

Optimization Process

Remedial Design Characterization

Design: Amendment, Dose & Delivery

Implementation, Monitoring & Interpretation

Regulatory & Stakeholder Considerations

Learning Objective: Identify challenges
ITRC Documents Support Interactive/Iterative Approach

ITRC IDSS Document

ITRC In-Situ Optimization Document

Remedial Design Characterization

Implementation, Feedback and Data Analysis

Optimization process fits into the Site Strategy document during the selection and evaluation of appropriate remedial technologies, and during implementation and assessment of the selected remedy. Application of the Site Strategy document then carries the process through to site closure.
Learning Objective: Apply iterative optimization process at each stage of in situ remedy
RDC = REMEDIAL DESIGN CHARACTERIZATION

It is the collection of additional data, above and beyond general site characterization, necessary to develop a sufficiently detailed CSM.

This enables the design basis for a successful in situ remedy.
RDC – WHY DO IT?

When in situ remedies fail, or produce less than optimal outcomes, it is often due to a lack of detailed data or an insufficiently developed conceptual site model (CSM).

The success of in situ remedies is directly related to a thorough understanding of site and subsurface conditions.
The Impact of Data

HYDROGEOLOGIC DATA:
- Alluvial formation
- 7 borings to ~140 feet
- 3,500-foot alignment
- Soil logged every 5 feet

Figure with permission of Amy Wilson
The Impact of More Data

MORE DATA
► ~40 borings over the 3,500-foot alignment
► Soil logged every 5 feet in vadose zone
► Soil logged continuously below first saturated zone
► Increasing complexity revealed

Figure with permission of Amy Wilson
The Impact of More (and More) Data

EVEN MORE DATA
- ~60 borings over the 3,500-foot alignment
- Soil logged continuously
- Cross-section evolves – even more complex

Figure with permission of Amy Wilson
Remedial Design Characterization (RDC)

WHAT DO WE NEED TO KNOW?

**Geology**
*properties that define flow regimes*

**Hydrogeology**
*properties that influence flow and transport*

**Geochemistry**
*electron acceptors, competitors, metal mobilization*

**Microbiology**
*degradation potential*
RDC - Why Do It? (Redux)

- What is the value of investigation (VOI)? Figure 2-1
- Why spend more money on characterization, when you could be spending it on cleanup?

Remember: when in situ remedies fail, it is often due to a lack of detailed data or an insufficiently developed CSM

ITRC OIS-ISRP-1 Figure 2-1
Value of Investigation (VOI) Case Study

The Setting:
- 20-acre site in California Central Valley
- VOC impacts to soils and groundwater
- Geology - floodplain deposits
- TTZ - sand lens, several feet thick approximately 15 feet below grade

Initial Remedy Attempt:
- Tight redevelopment timeframe
- Enhanced In Situ Bioremediation implemented using sodium lactate

ITRC C15-ISRP-1 Section 2.1.2
Value of Investigation (VOI) Case Study

**The Good**
- Geology well characterized
- Injections properly performed within the sand interval

**The Bad**
- 😞 Hydraulic conductivity not evaluated
- 😞 Injection test not performed
- 😞 Geochemical parameters not used to assess EISB viability
- 😞 No treatability testing
- 😞 Choice of substrate and dosing "based" similar sites
- 😞 Microbial studies not performed
- 😞 Upgradient sources not assessed or removed
The Ugly Outcome

- No reductions in groundwater contamination concentrations
- Site redevelopment was delayed

Site had to be re-characterized (RDC):
- Better definition of source areas
- Better plume definition
- Aquifer testing to estimate K and ROI
- Microbial testing
- Treatability studies to assess various substrates and specify dosing
- Upgradient sources removed
### VOI Case Study
**Cost Outcomes, Table 2-1**

<table>
<thead>
<tr>
<th>Item</th>
<th>VOI Case Study</th>
<th>Hypothetical Using RDC</th>
<th>VOI Case Study</th>
<th>Hypothetical Using RDC</th>
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<td>Initial Site Characterization</td>
<td>$150,000</td>
<td>$130,000</td>
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<td>2</td>
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<td>Upfront RDC (hypothetical)</td>
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<td>$160,000</td>
<td>0</td>
<td>1</td>
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<td>Failed Remedy</td>
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<td>EIS Implementation</td>
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<td>EISB Monitoring</td>
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<td>RDC (as part of Rework)</td>
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<td>1</td>
<td>0</td>
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<td>Re-work (RDC &amp; Remedy)</td>
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<td>Remedy Implementation</td>
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<td>Monitoring and Closure</td>
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<td><strong>Totals</strong></td>
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<td><strong>$580,000</strong></td>
<td><strong>8</strong></td>
<td><strong>5</strong></td>
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<td><strong>Cost Savings and Time Saved with RDC</strong></td>
<td><strong>$380,000</strong></td>
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### What Do We Need To Know?
**“THE TABLE” (2-2)**

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<th>Data Source</th>
<th>Key Parameters</th>
<th>Notes</th>
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<td>Physical Properties</td>
<td>Data Source 1</td>
<td>Parameter 1</td>
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<td>Data Source 2</td>
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<td>Flow Properties</td>
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<td>Note 8</td>
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ITRC OIS-ISRP-1 Table 2-2
and When? (Table 2-2)

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<th>Remediation Phase/Step</th>
<th>Remediation Phase/Step</th>
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<td>Alternatives</td>
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<td>Performance</td>
<td>Monitoring</td>
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<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Abiotic</td>
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<tr>
<td>Biotic</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Legend</th>
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<tbody>
<tr>
<td>More applicable</td>
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<tr>
<td>Less applicable / not applicable</td>
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<table>
<thead>
<tr>
<th>Relative importance of data at the remediation phase indicated</th>
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<tbody>
<tr>
<td>MEDIUM</td>
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ITRC OIS-ISRP-1 Table 2-2
### Physical Properties (Table 2-2)

<table>
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<tr>
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<tr>
<td>Stratigraphy</td>
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<tr>
<td>Degree of Weathering of Geologic Formation</td>
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<td>Fracture Representative Aperture and Length</td>
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<td>Fracture Orientation</td>
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<td>Grain Size Distribution</td>
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<td>Bulk Density</td>
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<tr>
<td>Fraction of Organic Carbon</td>
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<tr>
<td>Primary and Secondary Porosity</td>
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</table>
**THE “HOVER” TABLE (2-3)**

Provenance and mineralogy of a rock or soil matrix are the properties of its physicochemical formation, geologic structure, chemical composition, distribution, and occurrence. They are the governing factors for the physical, flow, and geochemical properties, discussed in Table 2-2, that are necessary to understand and quantify in order to design an optimal in-situ approach.

<table>
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<th>Physical Properties</th>
<th>Phase/Step</th>
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</tbody>
</table>
# Physical Properties

Stratigraphy describes the geologic layering in a formation. Formations with more layers (e.g., gravels, sands, silts) and complex "fingerling" of high permeability units within low permeability media will require detailed characterization so that amendments can be emplaced properly.

| Parameters                                | In Situ Approach | Remediation Phase/Step | | |
|-------------------------------------------|------------------|------------------------|---|---|---|
| Stratigraphy                              | M                | M                      | HIGH | MEDIUM | LOW |
| Degree of Weathering of Geologic formation| M                | M                      | MEDIUM | HIGH | LOW |
| Fracture Representative Aperture and Length| M                | M                      | MEDIUM | HIGH | LOW |
| Fracture Connectivity / Rock Quality Designation| M              | M                      | MEDIUM | HIGH | LOW |
| Fracture Orientation                      | M                | M                      | MEDIUM | HIGH | LOW |
| Grain Size Distribution                   | M                | M                      | LOW | HIGH | LOW |
| Bulk Density                              | M                | M                      | LOW | HIGH | LOW |
| Fraction of Organic Carbon                | M                | M                      | MEDIUM | HIGH | LOW |
| Primary and Secondary Porosity            | M                | M                      | MEDIUM | HIGH | LOW |
## Flow Properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>In Situ Approach</th>
<th>Remediation Phase/Step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fracture</td>
<td>Remedial</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>M</td>
<td>HIGH</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>M</td>
<td>HIGH</td>
</tr>
<tr>
<td>Effective Porosity</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Velocity/Flux</td>
<td>M</td>
<td>M</td>
</tr>
</tbody>
</table>

Heterogeneity refers to the variability in soil types within an aquifer (gravels, sands, silts, clays, bedrock/fortunes). Heterogeneity is related to a unit's provenance and conditions of formation, for example, alluvial units are more heterogeneous than fluvial units. Understanding and mapping the more permeable zones is a critical step in characterization, because these zones are more likely to be saturated with groundwater and contain contaminants. The less permeable units are more likely to have sorbed contaminants that will be slowly released over time via slow diffusion.

ITRC OIS-ISRP-1 Table 2-2
### Flow Properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>In Situ Approach</th>
<th>Remediation Phase/Step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abiotic</td>
<td>Biotic</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Effective velocity</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Velocity/Flux</td>
<td>M</td>
<td>M</td>
</tr>
</tbody>
</table>

Anisotropy refers to the directionality of physical aquifer properties. Layered units are generally anisotropic, with continuity of properties and flow in the lateral direction, limited in the vertical direction by low permeability layers.
Aqueous Geochemistry

<table>
<thead>
<tr>
<th>Parameters</th>
<th>In Situ Approach</th>
<th>Remediation Phase/Step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biotic</td>
<td>Holistic</td>
</tr>
<tr>
<td>Sulphate (SO₄²⁻)</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Chloride (Cl⁻)</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>COD (Chemical oxygen demand)</td>
<td>L</td>
<td>M/L/Medium</td>
</tr>
<tr>
<td>BOD (Biological oxygen demand)</td>
<td>M</td>
<td>M/L/Medium</td>
</tr>
<tr>
<td>NO₃ (Nitrogen oxidant interaction)</td>
<td>M</td>
<td>M/L/Medium</td>
</tr>
<tr>
<td>Metals, elements</td>
<td>Individually Fixed</td>
<td>M/L/Low/Medium/HIGH</td>
</tr>
<tr>
<td>Lead (Pb²⁺)</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Copper (Cu²⁺)</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Chromium (Cr⁶⁺)</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Other Heavy Metals (e.g., lead, copper, silicium)</td>
<td>L</td>
<td>L</td>
</tr>
</tbody>
</table>

Notes: Sulphate is naturally present in many ground waters as a product of geologic formations and their naturally occurring minerals and is often elevated in saline waters. It can also be a manufacturing or agricultural contaminant and a byproduct of persulfate used in some ISCO treatments. Sulphate needs to be carefully considered when selecting a remedial approach, as it can be beneficial and inhibitory, depending on the technology selected. Natural or pre-remediation sulphate at elevated concentrations can inhibit reductive processes such as reductive dechlorination, because sulphate, at elevated concentrations, is a powerful competitor for electrons. Typically, approximately 400 mg/L or greater sulphate at pre-remediation conditions can be a potential cause for concern for reductive dechlorination and special consideration for dosing. On the other hand, sulphate can react in situ with iron or form iron sulphides, which can provide long-term anaerobic chemical reduction. Sulphate reduction is yet another process, where sulphate is used as the primary electron acceptor, that can degrade specific contaminants (e.g., petroleum hydrocarbons).
The Redox Ladder

<table>
<thead>
<tr>
<th>Terminal Electron Acceptors</th>
<th>Associated Metabolic Byproducts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen (O₂)</td>
<td>Water (H₂O)</td>
</tr>
<tr>
<td>Nitrate (NO₃⁻)</td>
<td>Nitrite (NO₂⁻), Nitrogen (N₂)</td>
</tr>
<tr>
<td>Tetrachloroethene (TCE)</td>
<td>Trichloroethene (TCE), Chloride (Cl⁻)</td>
</tr>
<tr>
<td>Manganic Manganese (Mn⁴⁺)</td>
<td>Manganese Manganese (Mn³⁺)</td>
</tr>
<tr>
<td>Ferric Iron (Fe³⁺)</td>
<td>Ferrous Iron (Fe²⁺)</td>
</tr>
<tr>
<td>Trichloroethene (TCE)</td>
<td>Cis- and Trans-Dichloroethene (Cis-, Trans- DCE)</td>
</tr>
<tr>
<td>Vinyl Chloride (VC)</td>
<td>Ethene (C₂H₄), Chloride (Cl⁻)</td>
</tr>
<tr>
<td>Cis- and Trans-Dichloroethene (Cis-, Trans-DCE)</td>
<td>VC, Chloride (Cl⁻)</td>
</tr>
<tr>
<td>Sulfate (SO₄²⁻)</td>
<td>Sulfite (SO₃²⁻) and Sulfit (S²⁻)</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>Methane (CH₄)</td>
</tr>
</tbody>
</table>

ITRC: OIS-ISRP-1 Figure 2-2 Electron acceptors and products in order of reaction preference in progressively reducing groundwater conditions. Select contaminants are included for reference.
Aqueous Geochemistry

<table>
<thead>
<tr>
<th>Parameters</th>
<th>In Situ Approach</th>
<th>remediation phase/step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abiotic</td>
<td>Biotic</td>
</tr>
<tr>
<td>pH</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Temperature</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Redox potential</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Conductivity, Salinity, and Total Dissolved Solids (TDS)</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Chlorine Reduction Potential (CRP)</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Dissolved Oxygen (DO)</td>
<td>M</td>
<td>M</td>
</tr>
</tbody>
</table>

As reductive dechlorination occurs, chloride ions are released and the concentration of chloride may increase. However, naturally and anthropogenic chloride may be present in groundwater at concentrations high enough that this change could be difficult to detect or attribute solely to remediation of the chlorinated solvents. In high chloride environments, such as landfills and aqueous subject to seawater intrusion, chloride can cause toxicity to microbes, typically at concentrations in the thousands of mg/L.

Some chloride ion concentrations are listed in Table 2-2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>In Situ</th>
<th>Remediation</th>
<th>Alternatives</th>
<th>Remedial</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride (Cl⁻)</td>
<td>M</td>
<td>M</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>HIGH</td>
</tr>
<tr>
<td>COD (chemical oxygen demand)</td>
<td>M</td>
<td>L</td>
<td>MEDIUM</td>
<td>HIGH</td>
<td>LOW</td>
</tr>
<tr>
<td>TDS (total oxygen demand)</td>
<td>M</td>
<td>L</td>
<td>MEDIUM</td>
<td>HIGH</td>
<td>LOW</td>
</tr>
<tr>
<td>DOC (non-oxidizable carbon)</td>
<td>M</td>
<td>L</td>
<td>MEDIUM</td>
<td>HIGH</td>
<td>LOW</td>
</tr>
<tr>
<td>Total inorganic carbon</td>
<td>M</td>
<td>L</td>
<td>MEDIUM</td>
<td>HIGH</td>
<td>LOW</td>
</tr>
<tr>
<td>Metals, radionuclides</td>
<td>Individually rated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>M</td>
<td>L</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>HIGH</td>
</tr>
<tr>
<td>Antimony (Sb)</td>
<td>M</td>
<td>M</td>
<td>MEDIUM</td>
<td>HIGH</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>Selenium (Se)</td>
<td>M</td>
<td>M</td>
<td>MEDIUM</td>
<td>HIGH</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>M</td>
<td>L</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>HIGH</td>
</tr>
<tr>
<td>Other Trace Metals (e.g., lead, copper, selenium)</td>
<td>L</td>
<td>L</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
</tr>
</tbody>
</table>
**Microbiology and Degradation Potential**

<table>
<thead>
<tr>
<th>In Situ Approach</th>
<th>Remediation Phase/Step</th>
<th>Performance Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MEDIUM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MEDIUM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MEDIUM</td>
</tr>
<tr>
<td><strong>Dissolved hydrocarbon gases</strong></td>
<td></td>
<td>MEDIUM</td>
</tr>
</tbody>
</table>

- Dissolved hydrocarbon gases are typical degradation products of reductive dechlorination of chlorinated ethenes (e.g., PCE), methanes (e.g., carbon tetrachloride), and propanes (e.g., 1,2-dichloropropane). Acetylene is thought to be primarily a byproduct of the abiotic reduction of chlorinated ethenes by reaction with ZVI or ferrous sulfide. The presence of these dissolved gases generally indicates that some complete reductive dechlorination is occurring. Methane can be produced from the contaminant(s), electron donor, other organics, or carbon dioxide. Methane is also the product of methanogenesis, that is, the reduction of carbon dioxide, and in that case is indicative of a significantly reducing environment. Natural gas contains many of these dissolved gases.

ITRC OIS-ISRIP-1 Table 2-2
Q&A Break

Follow ITRC:
Presentation Road Map

- Optimizing Process
- Remedial Design Characterization
- Design: Amendment, Dose & Delivery
- Implementation, Monitoring & Interpretation
- Regulatory & Stakeholder Considerations

Learning Objective: Determine amendment, dosing and delivery options
Amendment Delivery and Dose Design – The Design Wheel

- Involves consideration of the proposed amendment, delivery method and dose applied simultaneously throughout the in situ RDC design and implementation and monitoring process.

- Any step in the sequence can be repeated as new information becomes available.

Section 3

ITRC OIS-ISRP-1 Modified from Figure 3-1
Iterative Nature of Design

Section 3: Amendment, Delivery and Dose Design

The Design Wheel

Optimization Staircase

- Refinement of design following selection of amendment and delivery strategy may involve various tests, all applying the dose, delivery and amendment design feedback;
  - Results of each test feeding refinements into a subsequent test
Determine Target Treatment Zone

- Target Treatment Zone (TTZ)
  - Definition of TTZ often iterative
  - Considers collateral effects, performance, costs, etc.
  - May be revised as design is developed

- Key Considerations for defining TTZ
  - Cleanup objectives
  - Spatial and temporal relationship to other (combined) remedies
  - Uncontrolled amendment discharge
  - Geological, hydrogeological, and geochemical characteristics
Design Support Elements

- Design elements to support remedial design are an extension of the CSM and RDC data
  - Number one source of failure for amendment injection is lack of adequately detailed characterization of TTZ and reliance on overly simplified CSM
- Design elements used to support design include:
  - Modeling and analytical tools
  - Laboratory bench testing, and
  - Field pilot tests
CSM – Contaminated Industrial Site

- Solvent release
- Sand and Silt
- Underlying Clay

Example Case Study – image prepared using Health Canada CSM Builder Tool 2015
Modeling and Analytical Tools

- Modeling and Analytical Tools
  - Parameter estimation,
  - Groundwater flow and transport
  - Geochemical reactions
- Can range from simple spreadsheet calculations to complex 3D models
- Some of the software is public domain and others are commercially available and require a license

Image used with permission of Geosyntec Consultants.
Laboratory Treatability Bench-scale Testing

- Determine type and dosing of amendments
- Provide data to support remediation technology or series of specific treatments
- Using site-specific materials, confirm that treatment is effective for a specific site’s chemistry

See ITRC OIS-ISRP-1 Table 3-2 for a listing of bench testing objectives and considerations.

Images used with permission of SIREM.
Secondary effects can occur over a wide range of time:
- Transient shifts lasting hours or days
- Long-term changes that may last years

Consider potential secondary effects of the remedy design:
- Evaluate and potentially mitigate secondary effects
- Beginning with bench and field pilot tests

Example: The addition of sodium persulfate can affect the natural or anthropogenic chromium present in the soil or aquifer matrix, which may be oxidized to hexavalent chromium.
Poll Question

- Have you used Bench Tests in your design for an in situ remedy?
  - Yes
  - No

- If you have used Bench Tests in your design for an in situ remedy did the results change your approach?
  - Yes
  - No
Bench Tests Results

- **ISCO**
  - Faster
  - More secondary effects
  - Higher oxidant demand than ideal

- **Bio**
  - Slower
  - Fewer secondary effects
  - Cheaper long term
  - Emulsified vegetable oil (EVO) as donor
  - Chosen option

Example Case Study – Image prepared using Health Canada CSM Builder Tool 2015
Field Pilot Tests Objectives

- Evaluate the impacts of heterogeneities on the performance of the remedial technology
- Evaluate remedy timeframe under real world conditions, combined effects of dilution, advective flow, diffusion, adverse chemical interactions, etc.
- Determine amendment distribution, ROI, injections rates and pressure, volume
- Evaluate secondary effects – metals mobilization, acid production
- Identify locations for sampling/performance evaluation

Used to test the assumptions incorporated into full-scale remedy design
Geologic heterogeneity affects delivery. Geologic heterogeneity results in preferential flow through higher permeability zones. Unconsolidated (sedimentary) geologic deposits are stratified vertically.

The less heterogeneous case (left) results in delivery of amendment in the vicinity of each of the delivery points. The more heterogeneous case (right) results in substantial variability in lateral influence versus depth.

ITRC OIS-ISR-1 Figure 3-4
Graphic used by permission from Trinhydro Corporation
Delivery Strategies - Distribution

Amendment distribution through a porous aquifer media is controlled by:

- The nature of the amendment
  - Soluble,
  - Semi-soluble, or
  - Insoluble

- Permeability of the formation
  - High permeability zones often receive the most fluids, allow broadest radial delivery
  - Back diffusion of contaminant mass storage in low permeability materials can be a significant source that contributes to plume longevity
Delivery Strategies - Pressure

- The pressure at which the fluid is applied to the formation
  - High-pressure emplacement technologies using hydraulic or pneumatic methods are required to deform the aquifer matrix and propagate seams (fractures) within the aquifer matrix
  - Soluble amendments like organic carbon substrates and chemical oxidants can be delivered under gravity flow-low pressure and via high pressure fracturing methods
## Delivery Strategies

*Widely used = ●; Site-specific = ○; and Not applicable = NA*

<table>
<thead>
<tr>
<th>Hydrogeologic Unit</th>
<th>Direct Push Injection (DPI)</th>
<th>Injection Through Wells &amp; Boreholes (B3)</th>
<th>Electrokinesitcs This is Injection through Wells (B2)</th>
<th>Solid Injection (B4)</th>
<th>Hydraulic Delivery Through Wells &amp; Boreholes (B6)</th>
<th>Pneumatic Delivery Through Open Boreholes (B5)</th>
<th>Permeable Reactive Barriers (P2/Ba) (B7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clays (CL, CH, CR)</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Weathered Bedrock</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Compressible/Fractured Bedrock</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>K &lt; 10^3 to 10^4 (Low Perm Soils)</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>K &gt; 10^4 (High Perm Soils)</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Depth &gt; Direct Push Capabilities</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

ITRC OIS-ISRP-1 Table 3-4
Pilot Test – Injection of Emulsified Vegetable Oil

Sand Layer
- Good ROI at low injection pressures
- Good distribution

Clay Layer
- High injection pressure
- Evidence of short circuiting up into sand layer
- Poor distribution
- Uneven and very small ROI

Example Case Study – image prepared using Health Canada CSM Builder Tool 2015
Poll Question

- Have you used Pilot Tests in your design for in situ remedy?
  - Yes
  - No

- If you have used Pilot Tests in your design for in situ remedy, did the results change your design?
  - Yes
  - No
**Full Scale – Injection of Emulsified Vegetable Oil (EVO)**

- **Sand Layer**
  - Direct Injection of EVO
- **Clay Layer**
  - Switch to Electro kinetic (EK) - Bio?
  - Go back to Bench Test

Example Case Study – image prepared using Health Canada CSM Builder Tool 2015
Return to Bench Testing

Clay Layer
- Go back to Bench Test to make sure EK-Bio is an option

Lactate transport rate of 3.2 cm/day

Photo and graphics used with permission from Geosyntec Consultants
Return to Pilot Testing

- Clay Layer
  - Do pilot test to confirm design parameters and applicability
  - Dipole Test
  - Small Scale Test

Photo and graphics used with permission from Geosyntec Consultants.
Clay Layer
- EK-Rin Implementation

Example Case Study – Image prepared using Health Canada CSM Builder Tool 2015; Graphics used with permission of Geosyntec Consultants.

Electro kinetics: OIS-ISRP
Appendix D3
Amendment Delivery Optimization

The refinement of number and spacing of injection points, injection transects, and recirculation wells for minimization of cost or time using one of the delivery strategies:

Grid Pattern  Inject and Drift  Recirculation  Barrier

ITRC OIS-ERP-1 Figure 3-3
Graphic used with permission from Trihydro Corporation
Amendment Behavior and Persistence

Behavior and persistence of the amendment once injected must be understood and estimated:

- Low GW Velocity
- High GW Velocity
- High Persistence
- Low Persistence

GW Flow
Initial Injection
30 Days
60 Days

ITRC OIS-ISRP-1 Figure 3-2
Amendment persistence at natural flow using 4 scenarios.
Graphic used with permission from Trihydro Corporation
Remedial Design is Iterative

- Need to constantly evaluate the data you have
- Refinement of design following selection of amendment and delivery strategy may involve bench and pilot tests
  - Results of each test needs to feed back refinements into a subsequent test or next version of design
- Iterative approach and constant evaluation of new data will provide a strong design and more successful remedial effort

ITRC OIS-ISRP-1 Modified from Figure 3-1
Learning Objective: Using performance monitoring to make optimization decisions.
Implementation and Feedback Monitoring Optimization

- Baseline monitoring
- Monitoring at startup
- Compliance monitoring

- Process monitoring
  - Frequency and parameters vary with amendment
  - Field parameters are inexpensive and have great value

Example of Network Well Locations

- Plume monitor wells
- Injection wells
- Source monitor well
- Sented wells
- Remedy compliance wells
Applying Optimization to Underperforming Remedies

- When should you optimize, select an alternate remedy, or transition to a polishing remedy (e.g., MNA)?
- Have you collected all of the data needed to evaluate progress?
- In what way is the remedy underperforming?
- Which Design Criteria needs to be addressed?
- Can it be optimized?
- Should a supplemental remedy be considered?
Case Study - Background

- Site Info:
  - Total area: ~380 acres
  - Plume extent: 12 acres, including off-site impacts
- Geology: Piedmont, heterogeneous with saprolite of varying thickness overlying transition zone of partially weathered rock and granitic schist
- Contaminants: Chlorinated solvents (carbon tetrachloride, trichloroethene (TCE), and daughter products)
- Existing Remedy: Pump and Treat
  - Ineffective after 13 years

ITRC OIS-ISRP-1 Figure 3-1
Case Study – Multiple Optimizations

- Implemented anaerobic in situ bioremediation
- Optimized bioremediation remedy
  - Evaluate monitoring data monthly – don’t wait for the annual report
  - Know when to anticipate changes in groundwater chemistry and respond early
- Incorporated hydraulic fracturing to improve distribution
Case Study – Remedy Design

- Fixed injection wells on 25-foot centers in grid pattern
- 134 injection wells within 4.1-acre TTZ
- Injections in saprolite only, relying on downward vertical gradient for distribution to deeper zones
- Automated injection system

ITRC OIS-ISRP-1 Figure 3-3 (graphic used by permission from Trihydro Corporation); Cross section Figure with permission of Elizabeth Rhine
Injection Well Network

Legend

- Carbon Tetrachloride Plume
- Injection Well
- Injection Header along Bedrock Trough
- Injection Lateral

Case Study

Figure with permission from Elizabeth Rhine
Good News…

- In the Source Area, MCLs were met within 6 months in performance monitoring wells

Graph with permission of Elizabeth Rhine
...But Not Quite The Expected

- Increase in daughter products
- The pH dropped slightly after 12 months
- Increased methane concentrations
- Ideal redox conditions for biodegradation not generated uniformly across the plume
- Distal end of the plume exhibited no change
  - But it should have been easier to address low concentrations

ITRC OIS-ISRP-1 Figure 3-1
Graph with permission of Elizabeth Rhine
Resulting Plume Configuration

Injection Well Network

Legend
- Carbon Tetrachloride Plume
- Injection Well
- Injection Header along Bedrock Trough
- Injection Lateral

Figure with permission from Elizabeth Rhine
Redox Parameter Evaluation

Figure with permission from Elizabeth Rhine
Given the data just presented, what type of problem do we have? What needs to be optimized for success?

- Delivery
- Dose
- Amendment
- All of the above
Optimization 1

- Downgradient, anaerobic conditions not established
  - COC concentrations and pH stable in this area
- Degradation by-products not observed in the downgradient, low-concentration plume
- What should we do?
  - Revisit RDC
  - Revisit the Design Wheel
  - Increase the radius of influence (ROI) in the downgradient wells

Full-Scale Phase
## Optimization 1 – Operational Changes

<table>
<thead>
<tr>
<th>Problem</th>
<th>Resulting Optimization</th>
</tr>
</thead>
</table>
| **Amendment** | • Address the pH drop  
| | • Lower carbon load from 10% to 5% |
| **Dose** | • Increase the radius of influence (ROI) of downgradient wells  
| | • Decrease the frequency of injection  
| | • Increased the volume from 10 to 25 gal/ft |
| **Delivery** | • Solve the fermentation issue in the holding tank  
| | • Add a clean water flush  
| | • Stir the holding tank |
12 Months after Optimization 1

Figure with permission from Elizabeth Rhine
Poll Question

Given the data just presented, what type of problem do we have? What needs to be optimized for success?

- Delivery
- Dose
- Amendment
- All of the above
Optimization 2 - Concept

- Initial optimization helped in most areas
- Why did COCs persist in this area?
- Revisit RDC and Design Wheel
  - Review boring logs
  - Silts and clay lenses
  - Back-diffusion from clay acting as a long-term source

- Will hydraulic fracturing help?
  - Perhaps
  - Pilot study

ITRC OIS-ISRP-1 Figure 3-4
Graphic used by permission from Trihydro Corporation
Optimization 2 – Fracturing Pilot Test

- Reagent takes path of least resistance, which in this case was the silty sands
- Hydraulic fracturing pilot test to evaluate potential to enhance distribution by creating additional sand layers
Hydraulic Fracture - Prelim Pilot Test

- Installed a single hydraulic fracture using sand suspended in food-grade guar gel using DPT tooling
- Installed piezometers at various depths and equipped with data loggers
- Injected water into fracture
- Influence was observed 3 to 4 feet above and below fracture

Figure with permission of Elizabeth Rhine
Hydraulic Fracture – Stacked Fractures

- Implemented full-scale series of fractures at 7-foot intervals
- Installed a single injection well screened to intercept all 5 fractures
- Installed piezometers to measure ROI
  - 20-foot ROI
  - 40-foot ROI

Figure with permission of Elizabeth Rhine
Hydraulic Fracture – Full Pilot Test

Case Study

Figure with permission of Elizabeth Rhine
Rebound Study Conducted Elsewhere

- Nine months to complete the hydraulic fracture pilot study and install 11 fracture sets
- MNA monitoring during that period
- Nominal rebound in areas where MCLs were achieved
- Back-diffusion (e.g., equilibrium) limited to areas with high clay content per RDC borings
Optimization 2 – Startup

Legend
- Injection Well
- Injection Header
- Injection Lateral
- Hydraulic Fracture Injection Well
- Carbon Tetrachloride Plume

Figure with permission of Elizabeth Rhine
Recap of Hydraulic Fracturing

- ROI of each fracture ~45 feet
- Installed 11 fracture sets and injection wells on 75-foot centers
- Automated injection system
- Injected once a month

- After two injection events, TOC concentrations at optimal levels
- Evidence of reductive dechlorination observed in 6 months

- After 9 months, transitioned to MNA
Redox Parameter Evaluation

Figure with permission from Elizabeth Rhine
Optimization 3 – Transition to MNA

- Know when to stop
- Know when to transition to another technology or MNA
- Consider:
  - Cost/benefit of additional remediation
  - Point of diminishing returns
  - Regulatory framework
  - Final site use
Optimization 3: MNA Phase

- Treating the 4.1-acre TTZ achieved MCLs or close to MCLs throughout
- Natural attenuation in the remaining 8 acres downgradient
- Bedrock aquifer also naturally attenuated
- What's the future use of the property?
- For this site, transitioned to MNA when concentrations were below 5 times the MCL
- Different states may allow MNA at higher concentrations
Closure/Brownfield Redevelopment

- Original Brownfield agreement restricted use to industrial
- Only buyer to express interested wanted to build apartments
  - More stringent criteria
  - Agreed to meet residential criteria because it was cheaper than holding on to the property
- With engineering controls, land use restrictions lifted and residential development allowed
Key Concepts from Case Study

- Including the original P&T remedy, there were 4 cycles of optimization to reach MNA

- Monthly evaluation was critical to maintain schedule for redevelopment

- Evaluate contingency plans up front, and be ready to implement if the data suggest it is needed

Graphic developed by and used with permission from Elizabeth Rhine
Section 4: Five General Strategies

► Anaerobic biostimulation
► Aerobic biostimulation
► Chemical oxidation (ISCO)
► Chemical reduction (ISCR)
► Surfactant/co-flushing
Strategy-Specific Monitoring

▶ Tables and Links to Fact Sheets
  • Monitor parameters appropriate for the remedy
  • Data interpretation guidelines
  • Optimization recommendations

▶ Sample Frequency
  • Dependent on site-specific conditions
  • Varies by reaction time of amendment
  • ISCO monitoring is very different from EISB

▶ Contingency Planning
  • Have one
Presentation Road Map

- Optimization Process
- Remedial Design Characterization
- Design: Amendment, Dose & Delivery
- Implementation, Monitoring & Interpretation
- Regulatory & Stakeholder Considerations

Learning Objective: Anticipate iterative refinement for remedy design and regulatory approvals
Regulatory Considerations

- Statutory Challenges
- Procedural Challenges
- Adaptive Management needs to become part of the regulatory process

Adaptive Management's Application in the Superfund Process

Stakeholder Considerations

▲ Proactive Approach
  • Communicate all relevant information
  • Discuss unknowns and update as information becomes available
  • Regular communication

▲ Media
  • Single official point of contact with a professional, trusted relationship with media
  • Train all communicators and prepare for questions
  • Clear, concise fact sheets
Overall Course Summary – Call to Action

- RDC is key to developing detailed Conceptual Site Model
- Design of amendment, dose and delivery is an iterative process with multiple feedback loops
- Monitoring and data analysis to inform adaptive implementation and feedback optimization

Appendix F Checklist
Performance Evaluation & Optimization of In situ Remediation

Predictable and Optimized Outcome for In Situ Remedies using sound science and engineering
Thank You

- 2nd question and answer break
- Links to additional resources
- Feedback form – please complete

Need confirmation of your participation today?
Fill out the feedback form and check box for confirmation email and certificate.