Oxidant Selection and Activation - Keys to Successful Contaminant Destruction

Presented by Jean Paré, P. Eng.
October 2019
Presentation Outline

• About us
• Chemical Oxidation – Technology Review
• Common Oxidant & Activation Mechanism
• Principle and Applicability
• Design and injection parameters
• Case Study
About us

• Canadian Company founded in 1988
• **Production** and warehouses throughout Canada
  • Quebec
  • Ontario
  • Alberta
  • British Columbia
• **Sectors of activity:**
  • Industrial and Municipal Potable & Waste Water
  • Contaminated Soil and Groundwater
  • Air, Odours and Atmospheric Emissions (Activated Carbon, filtering medias)
  • Process Water & Thermal Exchange Fluids (Glycols)
  • Drilling Fluids (Oil and Gas & Diamond exploration)
  • Aircraft De-icing Fluids
- Chemical Oxidation
- Chemical Reduction
- Co-solvent-Surfactant Washing
- Enhanced Bioremediation

Our product and services
Excellence & Science through proud Suppliers & Partners

ADVANCED OXIDATION TECHNOLOGY (AOT)  Since 2005

PeroxyChem  Since 2005

CARBONE CANADA  Since 2014

CARUS  Since 2014

EthicalChem  Since 2016

EOS Remediation, LLC  Since 2016

ChemBio Formulation  Since 2017

IVEY-SOL®  Since 2017

SiREM  Since 2017

Höganäs  Since 2018
Chemical Oxidation – Technology Review

- Oxidants are introduced or mixed into the soil and groundwater to attack the organic contaminants
- Chemical oxidation treatments are commonly used in potable and wastewater applications
- Oxidants are non-specific and will react with the targeted contaminants AND with the soil organic content called Soil Oxidant Demand - SOD).
- Chemical oxidation reactions involve the transfer of electrons and the breaking of chemical bonds
- Water is the carrier for the oxidants used in chemical oxidation (except for ozone)
- If you have enough oxidant present and sufficient time you will push reaction to FULL mineralization (CO2, H2O, Cl-) of the contaminant of concern
Breaking of chemical bond

Chlorinated ethene destruction using permanganate
Chemical Oxidation – Limitations

- All chemical oxidation reactions occur in the **WATER** or moisture phase (except for ozone)
- Kinetics of the chemical oxidation reaction is thus influence by the **contaminant** of concern **solubility** and **availability** in the groundwater or moisture phase
- Sorbed phase contamination might be challenging to remediate (less available)
- In NAPL containing sites, contamination can persist because of the highly hydrophobic properties of the chemicals that make up the NAPLs
- Injection technique must induce **proper contact** between the contaminant and the oxidant for a proper **duration** for the required reaction to occurs (kinetics)
Additional considerations

- All oxidants can change the oxidation state of metals and thus increase their solubility and mobility.
- Metals of particular concern are: chrome, lead, uranium, selenium, vanadium.
- In most of these cases, the metals will come back in their reduced state once all of the oxidant has been consumed by the environment.
- Impurities contained in the oxidant must be evaluated based on oxidant quality & site specific aquifer characteristics (Manganese, Sulfate, Sodium, etc.)
- In the case of arsenic, oxidation will help immobilizing the metal by reducing its solubility.
Common Chemical Oxidants

- Potassium or sodium permanganate
- Hydrogen Peroxide
  - alone
  - with catalyst
  - with Retarding agents
- Ozone & Per ozone (hydrogen peroxide and ozone mix)
- Potassium or Sodium Persulfate
  - Requires activation to generate free sulfate radicals.
  - Heat, chelated metal, high pH, hydrogen peroxide, surface can be used to activate the persulfate. Activation method can be adapted to site conditions.
- Sodium Percarbonate
### Compounds Degraded by Oxidants

#### Example Contaminants Treated by Oxidation

*not all ISCO reagents treat all compounds listed*

<table>
<thead>
<tr>
<th>Chlorinated Solvents</th>
<th>TPH</th>
<th>Chlorobenzenes</th>
<th>Pesticides</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCE, TCE, DCE</td>
<td>BTEX</td>
<td>Chlorobenzene</td>
<td>DDT</td>
</tr>
<tr>
<td>TCA, DCA</td>
<td>GRO</td>
<td>Dichlorobenzene</td>
<td>Chlordane</td>
</tr>
<tr>
<td>Vinyl chloride</td>
<td>DRO</td>
<td>Trichlorobenzene</td>
<td>Heptachlor</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>ORO</td>
<td></td>
<td>Lindane</td>
</tr>
<tr>
<td>Chloroform</td>
<td>creosote</td>
<td></td>
<td>Toxaphene</td>
</tr>
<tr>
<td>Chloroethane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloromethane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichloropropane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trichloropropane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methylene chloride</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Oxygenates</th>
<th>Phenols</th>
<th>Phenols</th>
<th>Phenols</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBE</td>
<td>Phenol</td>
<td>Chlorophenols</td>
<td>Nitrophenols</td>
</tr>
<tr>
<td>TBA</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Perfluorinated</th>
<th>PAHs</th>
<th>PAHs</th>
<th>PAHs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freon</td>
<td>Anthracene</td>
<td>Benzopyrene</td>
<td>Styrene</td>
</tr>
<tr>
<td>PFOA, PFBA</td>
<td>Styrene</td>
<td>Naphthalene</td>
<td>Naphthalene</td>
</tr>
<tr>
<td></td>
<td>Pyrene</td>
<td>Pyrene</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chrysene</td>
<td>Trimethylbenzene</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Others</th>
<th>Energetics</th>
<th>Energetics</th>
<th>Energetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon disulfide</td>
<td>Trinitrotoluene (TNT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aniline</td>
<td>Dinitrotoluene (DNT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,4-Dioxane</td>
<td>RDX</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Radical Formation Upon Activation

- Kinetically faster reacting radicals that are:
  - More powerful oxidants (SO\textsubscript{4}\textbullet\text{-} and OH\textbullet) than persulfate itself
  - Reductants (O\textsubscript{2}\textbullet\text{-})
  - Nucleophiles (O\textsubscript{2}\textbullet\text{-} and HO\textsubscript{2}\text{-})

<table>
<thead>
<tr>
<th>Oxidant</th>
<th>Standard Reduction Potential (V)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroxyl radical (OH\textbullet)</td>
<td>2.59</td>
<td>Siegrist et al.</td>
</tr>
<tr>
<td>Sulfate radical (SO\textsubscript{4}\textbullet\text{-})</td>
<td>2.43</td>
<td>Siegrist et al.</td>
</tr>
<tr>
<td>Ozone</td>
<td>2.07</td>
<td>Siegrist et al.</td>
</tr>
<tr>
<td>Persulfate anion</td>
<td>2.01</td>
<td>Siegrist et al.</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>1.78</td>
<td>Siegrist et al.</td>
</tr>
<tr>
<td>Permanganate</td>
<td>1.68</td>
<td>Siegrist et al.</td>
</tr>
<tr>
<td>Chlorine (HOCl)</td>
<td>1.48</td>
<td>CRC (76th Ed)</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.23</td>
<td>CRC (76th Ed)</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.82</td>
<td>Eweis (1998)</td>
</tr>
<tr>
<td>Fe (III) reduction</td>
<td>0.77</td>
<td>CRC (76th Ed)</td>
</tr>
<tr>
<td>Nitrate reduction</td>
<td>0.36</td>
<td>Eweis (1998)</td>
</tr>
<tr>
<td>Sulfate reduction</td>
<td>-0.22</td>
<td>Eweis (1998)</td>
</tr>
<tr>
<td>Superoxide (O\textsubscript{2}\textbullet\text{-})</td>
<td>-0.33</td>
<td>Siegrist et al.</td>
</tr>
<tr>
<td>ZVI</td>
<td>-0.45</td>
<td>CRC (76th Ed)</td>
</tr>
</tbody>
</table>
## Conditions for Selecting Chemical Oxidation

<table>
<thead>
<tr>
<th>Chemical Oxidation Applicability</th>
<th>Limitation / Disadvantages</th>
<th>Possible Alternative Options</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mobile NAPL</strong></td>
<td>Probably not the best choice</td>
<td>High oxidant requirement ($)</td>
</tr>
<tr>
<td><strong>Residual NAPL (higher than 10,000’s mg/kg)</strong></td>
<td>Yes, but difficult</td>
<td>High oxidant requirement ($)</td>
</tr>
<tr>
<td><strong>High conc. in soil &amp; groundwater (10’s – 10000’s mg/kg)</strong></td>
<td>Yes, good conditions</td>
<td>Normal considerations</td>
</tr>
<tr>
<td><strong>Dissolved plume (&lt; 1 mg/kg)</strong></td>
<td>Yes, but could be costly</td>
<td>Higher cost due to SOD</td>
</tr>
</tbody>
</table>

Source: Adapted from ITRC 2004  
NAPL: Non-Aqueous Phase Liquid
Before you get to the field

- Validating the qualification and quantification of the selected oxidant or amendment with bench scale lab study

- Soil and Groundwater Oxidant Demand validation and treatability study are ALWAYS recommended

(If it doesn't work in the lab in ideal contact conditions it WON’T work in the field)

- Make sure you have all the necessary data and your injection plan is set properly
Natural Oxidant Demand (NOD) Variability

(adapted from Shaw E & I presentation - 2003)

Source: adapted from Shaw E & I presentation - 2003
Carus Haz Rem Assessment Process

Preliminary Site Assessment

Aquifer Characteristics
- Geology
- Permeability
- Hydraulic conductivity
- Heterogeneity
- Contaminant phase
- Contaminant Distribution

Determine delivery method

Soil Geochemistry
- Porosity
- Particle size distribution
- Soil moisture
- Fe
- pH
- TOC

Determine the number and location of oxidant delivery point

Groundwater Geochemistry
- pH
- Alkalinity
- DO
- COD
- TOC
- Fe$^{+2}$ and Mn$^{+2}$
- Metals

Pilot-scale testing and modeling

Determine oxidant loading rates

Additional Site Characterization (if necessary)

Contaminants of Concern (COCs)
- Soil oxidant demand
- Groundwater oxidant demand
- Contaminant oxidant demand
- Degradation kinetics

Treatability Study

Determine estimated remediation duration

Ozone & Per ozone
Ozone Oxidation

- Ozone (O3) is a gas that is generated On-Site
- Ozone is a very powerful Oxidizer
- Applicable Contaminants:
  - Chlorinated Solvents
  - PAH’s, Chlorinated phenols
  - PCB’s, pesticides
- Ozone is generated from Oxygen and degrades to Oxygen
- Since Ozone is a gas it is most ideal for Vadose Zone treatment vs. liquid oxidants
- Ozone/per ozone persistency is minutes to days
Ozone Oxidation Implementation

- Ozone generation systems
  - Continuous Pressure, output and flow
  - Pulsed Injection
  - Multi-level wells help ozone distribution

- Optimization of biodegradation co-process
  - Improve aerobic conditions
  - Co-metabolic microbial process enhanced by partial ozone oxidation (reducing toxicity)
Hydrogen Peroxide
Hydrogen Peroxide activation methods

Process:
- Hydrogen peroxide and Iron catalyst (or other species) can react to produce OH• (hydroxyl radical)
- Research showing that other radical species produced (superoxide anion, hydro peroxide, etc.) may be more active than the hydroxyl radical.

Basic Fenton reaction:

\[
\text{H}_2\text{O}_2 \rightarrow \text{OH}^\bullet + \text{OH}^- + \text{Fe}^{+3}
\]

- Hydroxyl radical are non-specific oxidizing agents
- Contaminants are converted to H2O, CO2 and halides (Cl-)

Non desired reaction

\[
\text{H}_2\text{O}_2 \rightarrow \text{H}_2\text{O} + \frac{1}{2} \text{O}_2
\]

- This reaction can be induced by temperature, soil organic or mineral species (SOD dependant)
Hydrogen Peroxide activation methods

Variations:

- Hydrogen Peroxide with iron (regular Fenton reagent reaction)
- Need to establish acidic conditions (ideal pH between 4 and 6)
  - Might enhanced metal mobilization
- Modified Fenton Reagent with chelated metals (neutral pH)
- Use of Retarding agent to help minimize heat and oxygen degradation pathway
- Treatability Bench Scale study always recommend

Source: ITRC, 2004
Chemco, 2017
Sodium & Potassium Permanganate
## Sodium and potassium permanganate

<table>
<thead>
<tr>
<th>Sodium Permanganate</th>
<th>Potassium Permanganate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>Powder (dust issue)</td>
</tr>
<tr>
<td>Available up to 40%</td>
<td>Soluble to 3% (field)</td>
</tr>
<tr>
<td>Less complex injection equipment</td>
<td>More complex injection equipment</td>
</tr>
<tr>
<td>Smaller injection volumes</td>
<td>Higher injection volume</td>
</tr>
<tr>
<td>Lower injection time</td>
<td>Longer injection time</td>
</tr>
<tr>
<td>Higher cost than potassium</td>
<td>Less expensive than sodium</td>
</tr>
</tbody>
</table>
Sodium and potassium permanganate

**Single Component Oxidant**
- Complete mineralization of chlorinated ethenes and others
- Complex mixing and distribution of multiple compounds is **not** necessary
- No activation or catalyzing
- Total volume of fluids injected reduced
  - Potential reduction of injection costs and/or short circuiting

**pH**
- No need to adjust pH for application
- Reduced corrosion effects in injection equipment and utilities and structures

**Chemical Persistence**
- Advection and diffusion main transport mechanism
  - Not pressure and reaction dependent
- Long-lasting oxidant
  - Treat compounds desorbing from matrix
  - Diffuse into tight matrices

**Color**
- No tracer required
Permanganate (sodium or potassium) Implementation

- Effective from pH (3 to 12, optimum 7) for desired chemical interaction
- High density (around 1.3) helps distribution and penetration
- Long reaction times allow higher distribution distance and better desorption processes thus low contaminants residual value obtainable
- Applicable in many soil types.
- Possibility to sequester the solid Manganese Dioxide (MnO₂) by pre-mixing polyphosphate & permanganate prior injection.
Permanganate (sodium or potassium) Application

Injection

Hydraulic Slurry Emplacement

Soil Blending
Permanganate Benefits

More Effective
- Low treatment endpoints (e.g. MCLs)
- Rapid treatment (< month)
- High density enhances delivery
- High stability
- Longer transport distances
- Effective in all geological media
- Diffuses into low permeability zones
- Easily scalable
- Reaction not pH sensitive

Safety
- Avoids DNAPL remobilization
- No heat generation
- Non-corrosive
- No hazardous gas generation
- Less intrusive/impact
- Non-hazardous by-products
- Spent solution may be sent to WTP
- Not harmful to bio-systems (non-toxic)
- Color indicator (Un-reacted solution is purple)
Sodium Percarbonate
**Sodium Percarbonate (RegenOx)**

- Requires activation to generate free radicals
- Patented technology using an activated sodium percarbonate
- Applicable to many type of contaminant (petroleum hydrocarbon, chlorinated solvents, ethanes)
- Minimal heat and gas generation
- Extended pH application range (alkaline solutions around pH 10 for initial injection)
- 2 components injection – one of them a slurry
- Low solubility for the sodium percarbonate

Source: Regenesis
Sodium or Potassium Persulfate Portfolio

All Klozur products release the persulfate anion:

Key Characteristics:

- A strong oxidant
- Activation results in the formation of radicals
- Applicable across a broad range of organic contaminants
- Extended subsurface lifetime (weeks to months)
- Little to no heat or gas evolution
- Potential low corrosivity on carbon steel (alkaline activation)
- Applicable in an Oxidative Permeable Reactive Barrier
Persulfate activation methods

- Activation method can be adapted to site conditions. Proper activation for your contaminant vs. site lithology and hydrogeology

- Possible one system injection with the mixing of the activator and oxidant prior to the injection
**Persulfate activation methods**

- **Alkaline Activated Persulfate**
  - Well suited for most applications
  - More compatible with carbon steel
  - Reductants, oxidants and nucleophiles

- **Iron-Chelate Activated Persulfate**
  - Chlorinated ethenes and hydrocarbons
  - Oxidative pathway

- **Heat**
  - Complex sites
  - Polishing step after thermal treatment
  - Reductants, oxidants and nucleophiles

- **Zero Valent Iron**
  - Solid state activator
  - Oxidative pathway

- **Hydrogen Peroxide**
  - Sites that benefit from vigorous reaction with both hydrogen peroxide and sodium persulfate
  - Reductants, oxidants and nucleophiles

- **Surface Activation**
  - Silica Gel matrix
  - Could be injected as a slurry

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*Estimated Activator Usage*

- high pH
- peroxide
- Fe
- heat

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Purchase of Klozur persulfate includes with it the grant of a limited license under Peroxychem's patents covering the use of Klozur persulfate for environmental applications at no additional cost to the buyer.
**Persulfate Heat Activation Mechanism**

**Heat**

\[ \text{S}_2\text{O}_8^{2-} + \text{heat} \rightarrow 2 \text{SO}_4^{\cdot} \]

**Compound with > 90% decomposition treated with persulfate**

<table>
<thead>
<tr>
<th>20 °C</th>
<th>35 °C</th>
<th>45 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>Benzene</td>
<td>1,1,1-TCA</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>Chlorobenzene</td>
<td>Chloroform</td>
</tr>
<tr>
<td>Xylene</td>
<td>1,2-DCE</td>
<td>Methylene Chloride</td>
</tr>
<tr>
<td>1,1-DCE</td>
<td>PCE</td>
<td></td>
</tr>
<tr>
<td>1,2-Dichlorobenzene</td>
<td>TCE</td>
<td></td>
</tr>
<tr>
<td>1,3-Dichlorobenzene</td>
<td>1,1-DCA</td>
<td></td>
</tr>
<tr>
<td>1,2,4-Trichlorobenzene</td>
<td>1,2-DCA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MTBE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vinyl Chloride</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbon Tetrachloride</td>
<td></td>
</tr>
</tbody>
</table>

Aqueous solutions - lab data; 72 hour

**Advantage:**

high oxidation potential with many compound with enough energy supply

**Disavantage:**

might be costly in field application
**Persulfate Alkaline Activation Mechanism**

Alkaline Activation
pH > 10

Degradation of COC Utilizing Alkaline Activation

- pH 10, pH 11, pH 12
- Mol ratio KOH : persulfate
  - Increasing pH

Graph showing ppm VOC vs. Mol ratio KOH : persulfate with various pH levels.
Persulfate activation methods

- Klozur CR (Combined Remedy)
  50 % sodium persulfate with 50 % Perme-Ox Ultra (alkaline activation) with enhanced bioremediation

- PersulfOx
  90 % sodium persulfate with 10 % Silica Gel (surface activation)

- Klozur One
  95 % sodium persulfate with 5 % activator package (multiple activation method)

  *Klozur One is the only fully water soluble all-in-one product*

- Source: Peroxychem / Regenesis
Case Study 1
Combining ISCO with ISS
Case Study: Bolzano, Italy

- Treatment volume:
  - 3,500 m$^3$ (~4,600 yd$^3$)

- Depth:
  - 3 to 8 m bgs (9.8 to 26 ft bgs)

- 556 columns

- Excavation could have caused slope stability issue because or nearby structure

- Reagents
  - 0.7 to 1% Klozur SP
  - 4 to 8 percent Portland cement

- Treatment speed:
  - 37 MT/hr

Courtesy of Ladurner
Remedial Goals

- Contaminant reduction
- Stable (compressive strength)
- Eliminate free product
- Minimize waste generation
  - Normal fluff generation will vary between 6% up to 18% w/w
Auger Based ISCO-ISS

Bolzano, Italy
Courtesy of Ladurner
ISS Remedial Goals:
• UCS:
  • 215 kPa to 470 kPa
  • ~30 psi to ~70 psi
• Permeability:
  • $2.8 \times 10^{-6}$ cm/sec to $7.3 \times 10^{-7}$ cm/sec

Less than 15% bulking of Soils

ISCO Remedial Goals:
• Benzene:
  • 100% sample locations below 2 mg/Kg remedial goal
• TPH (C<12):
  • 100% sample locations below 250 mg/Kg remedial goal
• TPH (C>12):
  • Some free product observed
  • Some TPH (C>12) above goals
Summary

- Remediation and soil stabilization in a single application

- Site was suitable for construction shortly after the application (1-2 weeks)
  - Is now a parking lot with other structures

- ISCO-ISS addresses several issues versus ISS only
  - Less excess soil requiring disposal
  - Carbon footprint decreased
  - Contaminant destruction
  - Contributes to lower leachate concentrations
Case Study 2
Tight Geology Application
Insitu Chemical Oxidation (ISCO) and Bioremediation in the Complex Geologies of the Lower Mainland of B.C.
• Given the yearly variation in water table depth there is often a small amount of contaminated soils that are above the water table.

• Holes are drilled into the excavation area for injection after mixing or the sodium persulfate / calcium peroxide can be mixed and poured directly into an open excavation or pressure injected or mixed into the soil.

• This creates an infiltration gallery effect where water is applied, especially in summer when lower water table conditions prevail.

Source: Ventus Consulting
Pressure injection Application

- Ventus employee makes up a soil watering probe with ½ inch steel threaded pipe.
- Holes are probed into the soils above the glacial till while the pressure jet nozzle of the watering probe mixes the sodium persulfate calcium peroxide with soils.

Source: Ventus Consulting
Open Excavation Soil Mixing Application

- Probe holes close up show additional bubbling where compound has contacted soils contamination.
- Often if we want to speed up the reaction of the compound we add additional water with the watering probe.

Source: Ventus Consulting
Borehole Application

- Injection holes are dug on very narrow spacings and overfilled in sandy conditions.
- In all soils conditions a very narrow spacing of injection holes or application to an underground storage tank (UST) nest before backfilling in preferable.

Source: Ventus Consulting
This $2500 project was completed with injections April 19, 2018 and final samples May 3, 2018 so the project only took some 3 weeks after application. We were able to obtain a further soils sample from the formerly impacted soils area during construction of a garage onsite, allowing collection of the June 22, 2018 sample.

Concentration reductions in soils by late June would be due to both ISCO and bioremediation, dates much later would have predominant bioremediation occurring.

Source: Ventus Consulting
Summary
Chemical Oxidation Applicability

- Using Common Oxidants
  - Source zone treatment
    - Highly soluble
  - Great for GW contamination
  - Oxidative and reductive pathways possible
  - Aqueous Solution Injection
  - Direct Push / Fracking emplacement for slurry
  - Soil Mixing for tight geology or open excavation

- Slow release Oxidant
  - Permeable Reactive Barriers set up and low permeable soil treatment
  - Solid/slurry injectate
  - Oxidative and reductive pathways

- Oxidation/Bioremediation Combination
  - Combined remedy of ISCO followed by bioremediation
  - Solid/slurry injectate
Acknowledgement

- Carus Corporation
- Cascade Drilling
- Ladurner/Bauer
- Peroxychem
- Progressive Engineering
- Regenesis
- Ventus Consulting

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