Evaluating In-Situ Thermal Remediation Technologies: Optimize your Selection Process

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Thermal Treatment – Heat it Up

1. Remove NAPL
2. Polish to target concentrations

[Udell et al. 1999; Alameda Point SEE demonstration]
Vapor Pressure versus Temperature for Selected Chlorinated Alkenes

(Smith et al. 1994)
# Physical Processes/Changes (below 120 °C)

<table>
<thead>
<tr>
<th>Component property</th>
<th>Oil based LNAPL</th>
<th>Chlorinated solvents</th>
<th>Creosote</th>
<th>Coal tar</th>
<th>PCB</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor pressure increase factor</td>
<td>20-80</td>
<td>20-100</td>
<td>20-300</td>
<td>20-300</td>
<td>2000</td>
<td>Abundance of data in literature</td>
</tr>
<tr>
<td>Solubility increase factor</td>
<td>2-100?</td>
<td>1.5-3</td>
<td>10-1000</td>
<td>10-1000</td>
<td>10-1000</td>
<td>Chlorinated solvent less affected than larger hydrocarbons</td>
</tr>
<tr>
<td>Henry's constant increase factors</td>
<td>10-20</td>
<td>0-10</td>
<td>0-10</td>
<td>0-10</td>
<td>0-10</td>
<td>Data absent for most compounds, some decrease?</td>
</tr>
<tr>
<td>Viscosity reduction factor</td>
<td>2 to 100+</td>
<td>1.3-3</td>
<td>5-10</td>
<td>20-100+</td>
<td>3-100</td>
<td>The higher initial viscosity, the more reduction</td>
</tr>
<tr>
<td>Interfacial tension reduction factor</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>2-5</td>
<td>1-5</td>
<td>&lt;5</td>
<td>Typically not dramatic effect (less than factor 2)</td>
</tr>
<tr>
<td>Density reduction (%)</td>
<td>10-20</td>
<td>10-20</td>
<td>10-20</td>
<td>10-20</td>
<td>10-20</td>
<td>Note that DNAPL may become LNAPL</td>
</tr>
<tr>
<td>$K_d$ (reduction factor)</td>
<td>?</td>
<td>1-10</td>
<td>5-100</td>
<td>5-100</td>
<td>NA</td>
<td>Estimates based on limited data</td>
</tr>
</tbody>
</table>

*Note:* Abiotic and biological reactions not listed

- Davis (1997, 1999)
- Imhoff et al. (1997)
- Sleep and Ma (1997)
- Heron et al. (1998, 2000)
- Stegemeier and Vinegar (2001)
Consider In-Situ Thermal Remediation (ISTR):

- For Source Remediation of Organic Contaminants
- To Facilitate a Brownfields Cleanup
- To Achieve Rapid Site Closure
- As part of overall optimization of an existing system, especially where additional source control/removal would significantly shorten the duration of a long-term pump and treat, AS/SVE, Multi-Phase Extraction system.
Steam Enhanced Extraction (SEE)
## Summary of Recent SEE Results

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Contaminants</th>
<th>Depth (ft)</th>
<th>Volume (cy)</th>
<th># wells</th>
<th>Starting contamination level</th>
<th>Post-treatment contaminant levels</th>
<th>Cost ($/cy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portsmouth Gaseous Diffusion Plant, OH</td>
<td>TCE</td>
<td>35</td>
<td>5,000</td>
<td>22</td>
<td>&gt;500 mg/kg, ~ 1,000 lbs</td>
<td>~90% reduction in soils, removed 1,100 lbs</td>
<td>NA</td>
</tr>
<tr>
<td>Alameda Point, CA</td>
<td>TCE+diesel+motor oil</td>
<td>13</td>
<td>3,000</td>
<td>13</td>
<td>&gt;3,000 mg/kg, &gt;10,000 ug/L</td>
<td>99.8 % TCE mass reduction (&lt;5 mg/kg, &lt;50 ug/L)</td>
<td>300</td>
</tr>
<tr>
<td>Beale AFB, Marysville, CA</td>
<td>TCE</td>
<td>40</td>
<td>400</td>
<td>1</td>
<td>1,000 ug/L</td>
<td>80-90% reduction in target zone</td>
<td>NA</td>
</tr>
<tr>
<td>Edwards AFB, CA</td>
<td>TCE+GRO+DRO</td>
<td>60</td>
<td>2,000</td>
<td>5</td>
<td>NAPL in fractures, &gt;2,000 lbs in source zone</td>
<td>ND above water table (&lt;10 ug/kg TCE in rock chips), 50-90% dissolved TCE reduction below water table</td>
<td>150</td>
</tr>
<tr>
<td>Young-Rainey STAR Center Area A, FL</td>
<td>TCE, Toluene, MeCl2, DCE, TPH</td>
<td>34</td>
<td>14,000</td>
<td>51</td>
<td>LNAPL and DNAPL, &gt;500 mg/kg VOCs, &gt;100,000 ug/L TCE</td>
<td>&lt;0.03 mg/kg VOCs, &lt;30 ug/l TCE</td>
<td>265</td>
</tr>
<tr>
<td>Visalia Pole Yard</td>
<td>Creosote</td>
<td>140</td>
<td>400,000</td>
<td>30</td>
<td>NAPL and &gt;1,000 mg/kg</td>
<td>&lt;MCL in compliance wells</td>
<td>65</td>
</tr>
</tbody>
</table>

(Courtesy of G. Heron, 2004)
Six-Phase Heating: Electrical current moves between the 6 electrodes on the outside diameter and the central neutral.

Three-Phase heating is another option.

Horizontal Heated Zone Larger Than Array Diameter

Vertical Heated Zone

Recovery

Courtesy of CES
## Summary of Recent ERH Results

<table>
<thead>
<tr>
<th>Site</th>
<th>Major COC</th>
<th>Depth (ft)</th>
<th>Volume (CY)</th>
<th>Electrode Spacing (ft)</th>
<th>Remedial Goals</th>
<th>% Removal</th>
<th>$/CY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF Plant 4, Ft. Worth, TX</td>
<td>TCE</td>
<td>35</td>
<td>24,000</td>
<td>19</td>
<td>met</td>
<td>97</td>
<td>130-140</td>
</tr>
<tr>
<td>IR Site 5, Alameda Pt., CA</td>
<td>1,1,1-TCA</td>
<td>30</td>
<td>17,000</td>
<td>20</td>
<td>met</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Paducah, KY</td>
<td>TCE</td>
<td>99</td>
<td>5,800</td>
<td></td>
<td>met</td>
<td>99</td>
<td>1200 (pilot)</td>
</tr>
<tr>
<td>Silresim, Lowell, MA</td>
<td>TCE</td>
<td>40</td>
<td>1,250</td>
<td>16.5</td>
<td>not met</td>
<td>96</td>
<td>1280 (pilot)</td>
</tr>
<tr>
<td>Dry Cleaner Chicago, IL</td>
<td>PCE</td>
<td>20</td>
<td>890</td>
<td>8 to 12</td>
<td>met</td>
<td>96</td>
<td>780</td>
</tr>
<tr>
<td>ICN Pharmaceut. Portland, OR</td>
<td>TCE</td>
<td>60</td>
<td></td>
<td></td>
<td>met</td>
<td>99.9</td>
<td>99</td>
</tr>
</tbody>
</table>

(Papers presented at the Fifth Int. Conf. on Remed. of Chlorinated and Recalcitrant Compounds, Monterey, CA: Peacock et al. 2004; Cacciatore et al. 2004; Beyke et al. 2004; Hayes and Borochaner, 2004; Hoenig et al. 2004; Peterson et al. 2004)
Thermal Conduction Heating (TCH) Combined with Vacuum: In-Situ Thermal Desorption (ISTD)
## Representative TCH Results

<table>
<thead>
<tr>
<th>Site</th>
<th>Major COCs</th>
<th>Depth (ft)</th>
<th>Volume (CY)</th>
<th>Initial Max. Concentration (ppm)</th>
<th>Final Concentration (ppm)*</th>
<th>Cost ($/CY)</th>
<th>Major COCs</th>
<th>Depth (ft)</th>
<th>Volume (CY)</th>
<th>Initial Max. Concentration (ppm)</th>
<th>Final Concentration (ppm)*</th>
<th>Cost ($/CY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidential Site, Portland, IN</td>
<td>PCE</td>
<td>20</td>
<td>5,300</td>
<td>3,500</td>
<td>&lt; 0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidential Site, OH</td>
<td>TCE</td>
<td>15</td>
<td>11,500</td>
<td>4,130</td>
<td>&lt; 0.07</td>
<td>140</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell Fuel Terminal, Eugene, OR</td>
<td>Benzene</td>
<td>12</td>
<td>18,000</td>
<td>3.3</td>
<td>&lt; 0.044</td>
<td>200</td>
<td>Gasoline/ Diesel</td>
<td>12</td>
<td>18,000</td>
<td>&lt; 7.9 ft free product</td>
<td>free product removed</td>
<td></td>
</tr>
<tr>
<td>Former Mare Is. Naval Shipyard, Vallejo, CA</td>
<td>PCB</td>
<td>14</td>
<td>175</td>
<td>2,200</td>
<td>&lt; 0.033</td>
<td>6,300 (Pilot)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naval Facility Centerville Beach, Ferndale, CA</td>
<td>PCB</td>
<td>15</td>
<td>1,540</td>
<td>800</td>
<td>&lt; 0.17</td>
<td>420</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southern California Edison, Alhambra, CA</td>
<td>PAH (B[a]P Eq.)</td>
<td>100</td>
<td>16,200</td>
<td>30.6</td>
<td>0.022</td>
<td>425</td>
<td>Dioxins (TEQ)</td>
<td>100</td>
<td>16,200</td>
<td>0.018</td>
<td>0.00048</td>
<td></td>
</tr>
</tbody>
</table>

*(Stegemeier and Vinegar 2001; LaChance et al. 2004; Bierschenk et al. 2004)*

*All remedial goals met*
ISTR Technology Selection: Site-Related Considerations

- ISTR is for Source Areas – Has the Source Area been Delineated?
  - Note: Less characterization is needed within the treatment zone than for non-thermal technologies

- Potential Contraindications:
  - Chemicals that are explosive at elevated temperatures
  - Soil shrinkage, subsidence, foundation stability issues (fairly rare)
  - Limited access for drilling
  - Excessive surface water and/or groundwater flux into remediation area that cannot be economically controlled

Source: ISTR Unified Facilities Criteria (UFC), 2004 (prepared under aegis of US Army Corps of Engineers and USEPA)
## ISTR Technology Selection Considerations (continued)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Preferred Technology*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point &gt;180°C</td>
<td>TCH</td>
</tr>
<tr>
<td>CoC Solid @ STP</td>
<td>TCH</td>
</tr>
<tr>
<td>CoC in fractured crystalline or carbonate rock, or clean indurated sandstone</td>
<td>TCH or SEE</td>
</tr>
<tr>
<td>CoC &lt; 8’ deep</td>
<td>TCH or SEE</td>
</tr>
<tr>
<td>Metal debris or high TDS GW</td>
<td>TCH or SEE</td>
</tr>
</tbody>
</table>

*Based on mass removal, not necessary excluding others

⇒ If none of these conditions apply, continue to screen via cost for each and relative to other options

(ISTR UFC, 2004)
Generalized Approach
(whatever the ISTR technology)

1. Establish hydraulic and pneumatic control.
2. Heat the target volume (area, depth).
3. Optimize mass removal until COC recovery begins to drop off.
4. Optimize treatment and achieve diminishing returns.
5. Controlled cool-down and transition to polishing technique.
Equipment Considerations

- Air compressor
- Water treatment
- Fuel tank
- Water softener
- Clean water discharge
- Heat exchanger
- Contaminated water
- Separation vessels
- Contaminated vapor
- NAPL
- Steam generator stack
- Steam generator feed water
- Clean water discharge
- Recovered liquid
- Biodegradation, hydrolysis
- HPO
- Extraction well
- Steam
- Steam and air injection well
- Water supply

Figure 8.X Schematic of steam enhanced remediation
Equipment Considerations, cont.

• Utilize existing equipment where practical (plant steam, SVE, P&T)

• Materials compatibility important (temperature and chemical)

• Water treatment always for SEE, often necessary during ERH and TCH (groundwater and condensate)

• Off-gas treatment necessary – many different options and approaches (often driven by regulatory approval)
Cost Considerations

- Economies of Scale
- Depth – Deeper is Cheaper (on a unit cost basis)
- Water – Must address groundwater flux
- Off-gas Treatment – Function of regulatory requirements, CoCs, and estimated mass loading
- Contractual Terms – Performance guarantees add to the cost
Target Temperatures

Temperature (C)

Depth

Heat stimulated degradation (SEE, ERH, TCH)

SVOC, dewatered (TCH)

SVOC, partial removal (SEE, ERH, TCH)

VOC (SEE, ERH, TCH)

SVOC, complete removal (TCH)

Heat stimulated degradation (SEE, ERH, TCH)
Dynamic Underground Stripping (DUS) for Complex Sites

Diagram showing the use of electrodes and steam/air for DUS.
DUS or TCH/SER in Complex Stratigraphy
Extraction

Vapor cap
Top soil/clay
Permeable zone
Clay
Extraction
Top soil/clay
Permeable zone
Clay

Power
Vapor cap
Steam

Power
Extraction

Steam
Power

Power
Steam
Several Final Points

It’s not only about saving $ – If you’re optimizing on performance and effectiveness, cost shouldn’t be the only factor – let the chips fall where they may

Consider the life-cycle costs and benefits

- Environmental
- Energy Consumption