LOW-TEMPERATURE THERMAL REMEDIATION

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GRA Remediation Conference – Optimization of Remediation Systems and Long-term Monitoring

November 13, 2019
High-Temperature vs Low-Temperature

• High-Temperature:
  – Range = 70 - 100°C+
  – Primary mass removal mechanism = VOLATILIZATION

• Low-Temperature:
  – Range = 30 - 70°C
  – Primary mass removal mechanism = DEGRADATION
Temperature Effect on Remediation Processes

- Increased temperature = increased energy = increased collisions = increased reactions

- Most enzymes however are fully denatured at 70°C (158 °F)

- Relevant biological reactions have an optimal temperature around 30 - 40°C (86 - 104°F)

- Targeting mesophilic microorganisms for BTEX & petroleum hydrocarbons

**Biological Reactions**

- Enzyme activity
- Optimum
- Increased Collisions \((Q_{10})\)
- Denature

**BTEX Biodegradation Rate**

- Dettmer (2002)
Temperature Effect on Remediation Processes

Abiotic reactions (e.g., hydrolysis, dehydrohalogenation)

10°C change could reduce half lives by approximately 50%

Acceleration of treatment rates for existing enhanced in-situ bioremediation (EISB) systems
Temperature Effect on Remediation Processes
Volatilization, Dissolution, Desorption

(Arcadis, 2018: Adapted from EPA Process Design Manual for Stripping of Organics, 600/2/84/139, 1984.)
Low Temperature Heating Methods

Conventional Heating
• Fuel, electric or gas heaters
• Residential/industrial water boilers in a closed/open-loop system

Geothermal Heating
• Geothermal pumps- extraction/injection heating

Sustainable Heating
• Solar (TISR)
• Waste heat recycling
Thermal In-situ Sustainable Remediation (TISR)

Arcadis Patented Technology

Solar Collectors

Closed-loop heating fluid

Borehole heat exchangers

Circulation pump

Water Level

Contamination

Average Daily Solar Radiation Per Month

ANNUAL

kWh/m²/day

10 to 14
8 to 10
7 to 8
6 to 7
5 to 6
4 to 5
3 to 4
2 to 3
1 to 2
0 to 1
none


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TISR Heat Exchangers

- Corrugated Stainless Steel Coil: Larger Diameter Exchangers
- Copper Loop: Retrofit 2-inch Monitoring Wells
- Combined installation with SVE/AS/HX Wells (existing or newly installed)
TISR Process Components

- Solar collectors consist of a 30 evacuated tube array constructed on an A-frame structure that can be anchored to the ground or building infrastructure (i.e. rooftop)

- Heat transfer fluid comprised of 50% solution of propylene glycol and distilled water

- 120V 0-8gpm heating fluid recirculation pump. Single-phase residential electrical or photovoltaic power connection for the circulation pumps and instrumentation.

- Control panels for power, PLC, alarms and remote monitoring systems
# TISR Performance Monitoring

<table>
<thead>
<tr>
<th>Monitoring Parameter</th>
<th>Performance Assessment</th>
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</table>
| General Groundwater Quality  | - Assess changes in general field parameters indicating processes occurring/stalling  
                                | - Measurement of seasonal groundwater fluctuations                                                                                                                                                                       |
| Temperature Profiling        | - Evaluate Performance and ROI  
                                | - Identification of high GW flux zones creating heat loss within treatment area  
                                | - Evaluate biogenic heat generation                                                                                                                                                                                    |
| COC Groundwater Trends       | - Evaluate compound specific mass degradation over time                                                                                                                                                                |
| Biogeochemical               | - Assess electron-accepting reactions (Denitrification, Oxidation, sulfate reduction, methanogenesis etc.)  
                                | - Measure increases in dissolved gases  
                                | - Passive CO2 flux measurements                                                                                                                                                                                       |
| Microbiological Data         | - Determine if active Eubacterial population is established in subsurface  
                                | - Identified specific degradation pathway is active.                                                                                                                                                                   |
TISR Application - Upstate, NY

- Petroleum hydrocarbon dominated plume spreads 10 acres; 10-15 ppm total BTEX and Trimethylbenzenes
- Fine to medium sand geology, depth to groundwater ~15-17 feet bgs
- Pilot test within small area of plume, minimal measurable NAPL

Fig. S2. Average total volatile organic contaminant baseline concentrations (BTEX and Trimethylbenzenes) compared to contaminant trends observed in a Monitoring Well within the TISR treatment area.
TISR Application - Upstate, NY

Waste Heat from AS/SVE Blowers Pilot:
- Five systems with submerged HX.
- Three systems with shell and tube HX
- 86 heat wells
- Two miles of PEX tubing
TISR Application - Upstate, NY

December 2018

March 2019

TEMPERATURE OF THE WATER

- 10-15°C
- 15-20 °C
- 20-25 °C
- 25-30 °C
- 30-35 °C
- >35 °C
- NO DATA
TISR Application – Denver, CO

- Historically DNAPL present and high (>100 mg/L) concentrations of 1,1,1-TCA, 1,1-DCE, TCE, Methylene Chloride
- Highly fractured and weathered sandstones, siltstones, and claystone
- Low bulk hydraulic conductivity <10^-4 cm/s
- P&T 1997-2011, EISB pilot in source zone 2003, gradually expanded
- TISR pilot in 2017, expanded to 8 BHEs in 2018
- 5-14°F increase maintained in target treatment zone

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Distance from Closest BHE (ft)</th>
<th>Temperature Increase from Ambient (°F)</th>
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<tbody>
<tr>
<td>PZ-04</td>
<td>3</td>
<td>11.8</td>
</tr>
<tr>
<td>IRZ-INJ-S</td>
<td>4</td>
<td>11.4</td>
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<tr>
<td>MW-005</td>
<td>9</td>
<td>14.4</td>
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<tr>
<td>MW-020</td>
<td>9</td>
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<td>MW-017</td>
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<td>6.1</td>
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<tr>
<td>MW-016</td>
<td>20</td>
<td>4.7</td>
</tr>
</tbody>
</table>
TISR Application – Denver, CO

- 1-2 OoM reduction in 1,1-DCE, TCE and 1,1,1-TCA at wells since TISR was installed (October 2017)
- 1,1-DCE and TCE transient increase and then decrease suggests enhancement of other processes
- VC and ethene increases indicate enhanced biotransformation
Summary and Conclusions

- Sustainable technology with negligible operation and maintenance costs
- Abiotic and Biotic degradation rate enhancement – reduced lifecycle costs
- Application in tandem with AS/SVE, MPE, ISB, Bioventing systems
- Effective in complex geology with residual mass
Thank you!

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