RemTech
October 15, 2020

Cost-Effective Destruction of Petroleum Hydrocarbon Contaminants with Expedited Residual Mass Smear Zone (LNAPL) Destruction under Anaerobic Conditions via Biostimulation

Kent C. Armstrong
karmstrong@terrastryke.com
What is Biostimulation

Biostimulation is the modification of the environment to stimulate existing bacteria capable of bioremediation.

This can be done by addition of various forms of rate limiting nutrients and electron acceptors including, but not limited to, phosphorus, nitrogen, oxygen, and/or carbon.

We ask a new approach is needed as to how to view microbial performance and in-situ remediation; changing focus from what individual microbes do and/or produce, to examining and harnessing the ecosystem within which they live.
What is *not* Biostimulation

What *is* Biostimulation
Nitrate (NO$_3$) based additive combined with Proprietary macro-micro inorganic nutrient formulation. Serves as alternative respiratory source for indigenous microbial populations (prokaryotic heterotrophs) under anaerobic conditions. Promotes anaerobic degradation of organic contaminants:

- Petroleum Hydrocarbon (PHC) Compounds
- Polyaromatic-Hydrocarbons (PAHs)
- Non-Chlorinated and Chlorinated Hydrocarbons
- 1,2-DCB; 1,3,5-TMB; Naphthalene; Oils, Sludges
### SITE 1 Chanute Air Force Base

*Enhance Long-Term Compliance*

<table>
<thead>
<tr>
<th>TPHenhanced®</th>
<th>April 4 (µg/L)</th>
<th>April 18 (µg/L)</th>
<th>May 2 (µg/L)</th>
<th>May 21 (µg/L)</th>
<th>%Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>606</td>
<td>1,780</td>
<td>8,350</td>
<td>24.6</td>
<td>99.7%</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>197</td>
<td>178</td>
<td>302</td>
<td>2.02</td>
<td>99.3%</td>
</tr>
<tr>
<td>Toluene</td>
<td>2,360</td>
<td>3,620</td>
<td>8,370</td>
<td>13.4</td>
<td>99.8%</td>
</tr>
<tr>
<td>1,2,4-TMB</td>
<td>282</td>
<td>224</td>
<td>843</td>
<td>4.13</td>
<td>99.5%</td>
</tr>
<tr>
<td>pH</td>
<td>NT</td>
<td>5.7</td>
<td>5.3</td>
<td>6.1</td>
<td>NA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Oxygen Based</th>
<th>April 4 (µg/L)</th>
<th>April 18 (µg/L)</th>
<th>May 2 (µg/L)</th>
<th>May 21 (µg/L)</th>
<th>%Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>1,970</td>
<td>471</td>
<td>362</td>
<td>241</td>
<td>87.8%</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>213</td>
<td>76.7</td>
<td>34.1</td>
<td>8.36</td>
<td>96.1%</td>
</tr>
<tr>
<td>Toluene</td>
<td>6,320</td>
<td>1,130</td>
<td>651</td>
<td>385</td>
<td>93.9%</td>
</tr>
<tr>
<td>1,2,4-TMB</td>
<td>349</td>
<td>80.7</td>
<td>37.8</td>
<td>17.1</td>
<td>95.1%</td>
</tr>
<tr>
<td>pH</td>
<td>NT</td>
<td>9.4</td>
<td>9.8</td>
<td>10.3</td>
<td>11.0</td>
</tr>
</tbody>
</table>
SITE 1 Chanute Air Force Base

Enhanced Solubilization

Enhanced Biotic Degradation
> 99.7% destruction of solubilized mass

Dissolve Phase Destruction
No Solubilization

>9x the molar mass
Benzene destroyed

Enhance Long-Term Compliance
SITE 2

Mineral Oil Bioremediation Demonstration

122-day Change (%) in Soil Concentration from Baseline - OFBC Plot

<table>
<thead>
<tr>
<th>Contaminant Reduction from Baseline (%)</th>
<th>Shallow Soil</th>
<th>Deep Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>-96.6%</td>
<td>-75.6%</td>
</tr>
<tr>
<td>Motor Oil</td>
<td>-97.1%</td>
<td>-80.2%</td>
</tr>
<tr>
<td>TPH</td>
<td>-96.8%</td>
<td>-77.8%</td>
</tr>
</tbody>
</table>

TPEnhanced biostimulated soil plot
Mineral Oil Bioremediation Demo

122-Day Change in Concentrations Diesel Reduction (%)
Mineral Oil Bioremediation Demonstration (soil)
122-day Change in Concentration from Baseline - TPH Reduction (%)

-100%
-90%
-80%
-70%
-60%
-50%
-40%
-30%
-20%
-10%
0%

Average % Change from Baseline

Control Shallow: -84.5%
Control Deep: -57.9%
OFBC Shallow: -96.8%
OFBC Deep: -77.8%
OFCL Deep: -65.2%
PRNA Deep: -60.6%

TPHEnhanced biostimulated soil plot

TPH
Mineral Oil Bioremediation Demonstration

2019 Soil Analytical Results - Diesel Concentrations

Diesel Concentration (mg/kg)


75% reduction

95% reduction

TPHEnhanced biostimulated soil plot
Mineral Oil Bioremediation Demonstration
QuantArray-Petro Results - OFBC Plot

TPHEnhanced biostimulated soil plot

Pre-bioapplication (6/15/19)  7/25/19  9/2/20
Mineral Oil Bioremediation Demonstration
Total Biomass & PLFA Results - OFBC Plot

TPHEnhanced biostimulated soil plot

Research and Development

Battelle®

Exclusive collaboration.
Evaluating the combined effects of TPHenhanced™
Patented enzyme-based technology developed by Battelle.
Enhances breakdown of large chained hydrocarbons;
(TPH), (PAH) and (PCB) contaminants, and others.
Creating greater bioavailability for enhanced microbial
populations to assimilate.
Laboratory evaluations on-going; field Proof-of-Concept
evaluations scheduled.
SITE 3

Former Automobile Fuel-Service Station 1950-1982
Release(s) documented 2003 UST removal program.
2009 groundwater contamination extended off-site.
Contaminants of Concern:

✓ Petroleum Hydrocarbon (PHC) Contaminants
✓ Remedial Driver Benzene, BTEX compounds
✓ Adversely impacting adjacent downgradient properties.
PURPOSE

One-year program – now full-scale
Evaluate biostimulation strategy to destroy residual LNAPL
✓ Expedited Source Zone Depletion
✓ Organically
✓ Sustainably

GOALS

Enhance respiration of indigenous microbial population
Expedite residual Source Mass (LNAPL) Solubilization (flux)
Realize sustainable dissolved-phase contaminant destruction
✓ Expedited Source Zone Depletion
✓ Maintain Anaerobic Conditions
✓ Sustainably
SITE CONDITIONS

No Reported Soil Exceedances

Groundwater exceedances for:

- Benzene
- Total Volatile Petroleum Hydrocarbons (TVPH)
- Xylenes

Low-Plasticity Weathered Silty Claystone; overlying, ‘Stiff’ Weathered Claystone Bedrock

Thin discontinuous sand layers throughout
Acting as preferential pathways for dissolved-phase PHCs

Former UST Basin Source for GW dissolved-phase plume
Extending >500ft downgradient with ≈300ft cross-gradient

GW Elevation 17-27ft bgs (≈6-9m)
Estimated effective porosity $2.11 \times 10^{-2}$ ft/day
BIOSTIMULATION STRATEGY

Seven (7) amending locations amongst network.
Alternated locations per event.
Groundwater amended via;
   Additive-Filled Passive Release Socks (PRS)
   Bulk Additive-Solution (5-18 gallons per node)

Groundwater amended passively every 2-weeks
Utilized existing network of 2-inch monitoring wells
Monitoring locations for each 2-3m downgradient

Deployments maintained for 3-months
Monitoring data discussed covers initial 7-months of program; delayed by COVID-19, restarting Fall 2020?
RESULTS Source Zone Location GP-1

Additive-solution deployed 11/2019 and <2-months later; Realized microbial expedited solubilization of LNAPL contaminants.

Result, [diss.phased] increased = flux of sorbed mass to GW. Specifically:

- Benzene +103% ↑
- Toluene +678% ↑
- Ethyl Benzene +456% ↑
- Xylenes +15,675% ↑

[TVPH] increased +365% ↑
RESULTS Source Zone Location GP-1

As LNAPL removed,
Realize microbial enhanced utilization of dissolved-phase contaminants.
From *peak* bioavailability,
Benzene \(-99.9\% \downarrow\)
Toluene \(-87.1\% \downarrow\)
Ethyl Benzene \(-82.0\% \downarrow\)
Xylenes \(-99.4\% \downarrow\)
Total Volatile Hydrocarbons decreased >99.7% ↓

**TerraStryke®** Safe, Sustainable, Expedited
Source Mass Removal Organically
LNAPL removed by enhanced biosurfactant production from amended microbials

*get the rebound out up-front*

Dissolved-phase reductions due to enhanced microbes utilizing carbon source as electron donor

*realize expedited PHC destruction*

Remove low-perm residual mass organically and *sustainably*

Minimize costs and site impacts

Maximize long-term compliance objectives with biostimulation
As additive is deployed and made available realized expedited solubilization of residual mass by biostimulated microbial populations.

get the rebound out up-front

TOC levels increase as carbon contaminant becomes bioavailable in groundwater. However, microbial populations appear to plummet with increased additive availability; then,

As contaminant levels decrease the TOC rises over time until majority of contaminant has been destroyed/assimilated. Biostimulated change in phenotype to allow biofilm generation and maximum performance.
SITE 4 Former UST Seattle WA

MW-3

3 Injection Events 462-pounds
TPEnhanced
June 26, 2018 (200lbs/400-gallons)
January 23, 2019 (200lbs/400-gallons)
March 28, 2019 (62lbs/120-gallons)

From peak bioavailability:
-93.5% reduction [GRO]
-98.7% reduction [BTEX]
1 Injection Event 198-pounds TPHenhanced
January 22, 2018 (400-gallons additive solution)

2-months post deployment:
-98.9% reduction [GRO]
-99.2% reduction [BTEX]

9-months post deployment:
-85.0% reduction [GRO]
-95.5% reduction [BTEX]

-95.0% reduction in additive availability
OBSERVATIONS

• Heterotrophic plate count densities decreased as contaminant solubilization/destruction performances at peak levels.

• Total Organic Carbon concentrations increased during periods of peak microbial activity; including, the assimilation of carbon-based contaminants.

• Total Volatile Petroleum Hydrocarbon contaminants, including Benzene, decreased >99.7% during 6-month period.

• Overall, 8 of 10 amended wells decreased >99.99% during program after periods of solubilization.

• Degradation and solubilization continue; anticipating 1 more year of amending to complete 18-month project.
HYPOTHESIS

- Additive enhanced microbial populations changed phenotypic characteristics from planktonic to sessile forms as environmental stresses to the subsurface ecosystem were removed.
- This allowed increased communication and establishment of biofilm.
- Within biofilm sessile microbial populations shared information and adapted to current site conditions.
- Were provided protection from predation, adverse conditions, and established 'in-situ bioreactor'.
- Microbes work collectively, as consortium of populations, similar to that of multi-cellular organisms.
CONCLUSIONS

- Prokaryotes are older, more organized and experienced than eukaryotic bacteria.
- Prokaryotes are ubiquitous throughout the Earth.
- Prokaryotes dominate under anaerobic conditions.
- Biofilm necessitates anaerobic conditions and is the most prevalent form of life on the planet.
- By enhancing the ecosystem of prokaryotic bacteria with TPHenhanced we expedite LNAPL solubilization from low-permeable and/or smear zone conditions.
- In doing so we maximize use of organic contaminants as electron donors.
WILL LEAVE YOU WITH THIS

• Many bacteria ferment organic compounds; however,
• Most cannot ‘touch’ Hydrogen (H_2).
• Many Archaea (methanogens) ferment H_2 and CO_2 but can’t ‘touch’ organic compounds.
• TPHenhanced stimulates microbial respiration and enhances the syntrophic destruction of PHCs under anaerobic conditions.
• TPHenhanced maximizes the sustainable destruction of source zone and dissolved-phase contaminants to realize long-term compliance objectives the way Mother Nature intended.
Lots of options out there
Kent C. Armstrong, President
(603) 731-3159
284 Depot Street / P.O. Box 254
Andover, New Hampshire USA

950 Fennell Avenue, Suite 105
Hamilton, Ontario CDN L8V 1X2