In Situ Bioremediation Technologies by Tersus Environmental
Gas inFusion™
• *In Situ* bioremediation
  – Gas delivery
  – Edible oil
  – Achieve site closure
  – Low cost solution

• Soil vapor extraction
## Groundwater Bioremediation

<table>
<thead>
<tr>
<th>Category</th>
<th>Technology</th>
<th>Example Target Contaminants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerobic</strong></td>
<td>Gas inFusion Oxygen Sparge Systems Peroxygens</td>
<td>Petroleum Hydrocarbons</td>
</tr>
<tr>
<td><strong>Anaerobic</strong></td>
<td>Gas inFusion Electron Donors</td>
<td>Chlorinated Solvents</td>
</tr>
<tr>
<td><strong>Cometabolic</strong></td>
<td>Gas inFusion</td>
<td>Dioxane, NDMA, Chloroform, PCE, TCE, MTBE, atrazine</td>
</tr>
</tbody>
</table>
Soil Remediation

• MicroBlower™
  – Remote soil vapor extraction system
  – U. S. Patent 6,971,820
Gas inFusion™ iSOC® Technology

Microporous Hollow Fiber

- Mass transfer device
- Supersaturates treatment well without sparging
- Bioremediation stimulated by delivery of substrates
Complete iSOC System

- Two Stage Low Flow Regulator set at 50psi
- Distribution Header, set for 1 iSOC
- Oxygen Supply, 1cf Usage Per Day
- Polyurethane Tubing
- Reusable Filter w. quick disconnect
- Nitrogen Bubble Release Every 1-7 Seconds
- Down Well Flood Resistant iSOC Unit in 2” Well
Working Demo iSOC System
iSOC® Area of Influence

iSOC® Gas Infusion

Air Sparging
## Dissolved Gas Concentrations

<table>
<thead>
<tr>
<th>Gas Type</th>
<th>Water Column Depth in Feet (Dissolved Gas in ppm)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>5'</td>
</tr>
<tr>
<td>Oxygen</td>
<td>42</td>
</tr>
<tr>
<td>Methane</td>
<td>22</td>
</tr>
<tr>
<td>Propane</td>
<td>66</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2</td>
</tr>
<tr>
<td>Ethane</td>
<td>57</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>1,660</td>
</tr>
</tbody>
</table>
iSOC® Well Schematic

Gas inFusion Well

Water Table

Regulator and Manifold

Gas Supply

Filter

Contaminated Groundwater Treatment Zone

Groundwater Flow

iSOC Unit
Installation Photos
Ground Vault Installation
## Injection Well Concentration Gradient

<table>
<thead>
<tr>
<th>Technology</th>
<th>Dissolved Oxygen (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>iSOC®</td>
<td>40 - 60</td>
</tr>
<tr>
<td>Peroxygens</td>
<td>3</td>
</tr>
<tr>
<td>Oxygen Emitters</td>
<td>10 - 13</td>
</tr>
<tr>
<td>Air Sparging</td>
<td>8 - 11</td>
</tr>
</tbody>
</table>
Gas inFusion™ Technologies

- inVentures
  - iSOC
  - HiSOC
  - BioFlo
  - gPRO
  - CO₂ SWI NAPL Recovery
Cometabolic Bioremediation
Cometabolism

• Fortuitous degradation
  – Bugs derive no energy
  – Contaminants are not carbon source

• Focus
  – Dioxane
  – NDMA
  – Chlorinated compounds
Degradation Pathways

• Aerobic Cometabolic
  TCE → TCE epoxide → CO₂, CL
  DCE → DCE epoxide → CO₂, CL
  VC → VC epoxide → CO₂, CL

• Anaerobic Reductive Dechlorination
  PCE → TCE → DCEs → VC → ETH
Cometabolic Bioremediation Benefits

- Reduces amendment costs
- Applicable to low contaminant concentrations
- Achieve site closure
Gas Management System

Contaminated Groundwater Treatment Zone

Groundwater Flow

Oxygen Gas Supply

Alkane Gas Supply

Nitrogen Connection

Gas inFusion Wells

Filter

iSOC® Unit
Chlorinated Solvent Site Case Study
Former Industrial Facility

Deep Groundwater Contours

Area of aerobic cometabolism treatment
System Design

- Two iSOC units
- Industrial grade oxygen and propane
  – Housed separately in portable garden sheds
cis-1,2-Dichloroethylene
Chlorobenzene

SW-13

DAP application and pure propane infusion commences

Concentration (ug/L)

Chlorobenzene (pre pilot study)

Chlorobenzene (post pilot study)

Jan-93  Jan-95  Jan-97  Jan-99  Jan-01  Jan-03  Jan-05  Jan-07  Jan-09  Jan-11
1,2 Dichloroethane

![Graph showing concentration of 1,2-Dichloroethane over time. The graph indicates a decrease in concentration after the application of DAP and pure propane infusion.]
Chlorobenzene

![Graph showing concentration of Chlorobenzene over time with DAP application and pure propane infusion commencement.]

- **Concentration (ug/L)**
- **SW-20**
- **Jan-93**
- **Jan-95**
- **Jan-97**
- **Jan-99**
- **Jan-01**
- **Jan-03**
- **Jan-05**
- **Jan-07**
- **Jan-09**
- **Jan-11**

- **Chlorobenzene (pre pilot study)**
- **Chlorobenzene (post pilot study)**

DAP application and pure propane infusion commencement.
Results

• DO increased
  – 35 feet north and 50 feet west
• DAP successfully supplied depleted nutrients
• Effectively distributed dissolved propane
Conclusions

• Reduced COCs
  – Allowing approval of MNA and monitoring
• Gained closure for groundwater
Vinyl Chloride Case Study
Vinyl Chloride Case Study

- Old gravel pit site
- PCE release stalled at VC
- Plume 3000’ x 400’ x 30’
- Maximum VC: 30 ppb
- Anoxic groundwater
- High iron & sulfate

(Mapped Plume 2002 > 3000 feet long)
Proof of Concept Microcosm

1 uM methane = 16 ppb; 1 uM ethene = 28 ppb; 1 uM VC = 62.5 ppb
Performance Data (mid-plume)
Performance Data (downgradient)

Monitoring Well RB-581
Vinyl Chloride

Startup Line HST-2

μg/L vs. Months
EDS (Electron Donor Solution)
Advancing the Science of *In Situ* Groundwater Remediation
Target Contaminants

- Chlorinated organics
- Oxidized metals
- Energetic materials
- Nitrate
- Radionuclides
- Acid rock drainage
Self Emulsifying Oil Movie Clip
Hydrogen is What Counts

<table>
<thead>
<tr>
<th>Soybean Oil Based Electron Donor</th>
<th>Pounds of Hydrogen per Pound of Product</th>
<th>Equivalent Pounds for a Pound of EDS-ER</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDS-ER (93% soybean oil)</td>
<td>0.35</td>
<td>1.00</td>
</tr>
<tr>
<td>EVO (45% soybean oil)</td>
<td>0.16</td>
<td>2.14</td>
</tr>
<tr>
<td>EVO (50% soybean oil)</td>
<td>0.18</td>
<td>1.93</td>
</tr>
<tr>
<td>EVO (55% soybean oil)</td>
<td>0.21</td>
<td>1.68</td>
</tr>
<tr>
<td>EVO (60% soybean oil)</td>
<td>0.22</td>
<td>1.61</td>
</tr>
</tbody>
</table>
Soluble Amendment

EDS-QR

• Quick release
• >98% natural seed oils
• No Water
Convergence of Gas inFusion Technology & Electron Donors

- Hydrogen-enriched water reduces demand for electron donor
- Saves money
Supersaturated Water Injection for Enhanced NAPL Recovery in Source Zones
NAPL Source Zone Challenges

- Trapped free-phase LNAPL
- Air channeling / fingering

➢ Poor access of injected air to residual NAPL

Slide courtesy of Marios A. Ioannidis

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Supersaturated Water Injection

- Water is supersaturated with CO$_2$
- Supersaturated water is then injected into the aquifer
- CO$_2$ bubbles nucleate in the aquifer
Conceptual Model

• Rising CO$_2$ bubbles
  – Contact hydrocarbons
  – Cause volatilization

• Groundwater and soil vapor are extracted
Proof of Concept in the Lab

In Situ Gas Saturation Development and Rate of Gas Ebullition

Bubble flow meter

Injection

Supersaturated water, C

Saturated porous medium

Production

Water outlet and level control

\[ V_{g1} \quad V_{g2} \quad V_{g3} \]

\[ V_w \]
In Situ Gas Evolution

Impermeable barriers

SWJ

\[
\begin{align*}
&t = 0 \\
&10 \text{ s} \\
&30 \text{ s} \\
&3 \text{ min} \\
&6 \text{ min} \\
&13 \text{ min}
\end{align*}
\]
Recovery of Residual Hexane
Recovery of Residual Hexane

[t = 0 min]  [13 min]
[t = 30 min]  [65 min]
Modeling of Lab Experiments

Experimental Apparatus

FEMLAB Simulation Domain
Comparison of Simulation to Experiment

\[ k_L\alpha = 0.01S_g \quad s^{-1} \]

\[ v_{in} = 0.078 \text{ cm/s}, \quad C_0 = 5.44 \text{ g/L} \]
Proof of Concept in the Field

- Enclosed cell at CFB Borden, Ontario
- 200 L of hydrocarbon mixture added to saturated zone
  - Pentane
  - Hexane
  - Soltrol

The Test Cell

## NAPL Mass Removal

<table>
<thead>
<tr>
<th></th>
<th>Pentane</th>
<th>Hexane</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (kg)</td>
<td>%</td>
<td>Mass (kg)</td>
</tr>
<tr>
<td>Phase I</td>
<td>24.2</td>
<td>57</td>
<td>15.1</td>
</tr>
<tr>
<td>Phase II</td>
<td>9.3</td>
<td>20</td>
<td>8.3</td>
</tr>
<tr>
<td>Total</td>
<td>33.5</td>
<td>77</td>
<td>23.3</td>
</tr>
</tbody>
</table>

Demonstration Conclusions

• Recovery by volatilization alone
  – 77 % of the Pentane
  – 53 % of the Hexane

• Majority of the NAPL mobilized towards water table
  – Available for liquid phase recovery
Injection Photos

gPRO Gas inFusion System

Carbonated Water Sample

Injection Well
CO₂ Injection Movie Clip
CO$_2$ SWI Benefits

• Significant improvement
• Greater:
  – Zone of influence
  – Recovery rate
  – Percentage removed
• Trapped NAPL mobilized upwards by gas bubbles
• Cost effective
MicroBlower™
Remote Soil Vapor Extraction
U. S. Patent 6,971,820
MicroBlower™

- Solar powered soil vapor extraction
- Enhanced barometric pumping
MicroBlower™ Installations
MicroBlower™ Data
Savannah River Site
Soil Gas VOC Concentrations
234 pounds removed in 10 months
Micro Blower Movie Clip
TersOX

Inorganic Peroxyanogen for Enhanced Aerobic Bioremediation

• TersOx is proprietary formulation of food-grade, calcium hydroxide that produces a controlled-release of molecular oxygen.

• TersOx stimulates natural degradation of petroleum hydrocarbons such as benzene, toluene, ethylbenzene and xylenes (BTEX). This is not a chemical oxidation product.

• The high ratio of O₂ in TersOx (>16% by weight) provides a long-term oxygen source for up to 12 months upon hydration. This sustained release of oxygen stimulates indigenous bacteria, accelerates bioactivity, and promotes increased contaminant removal.
TersOx Specifications

• A white to yellow, powdery material

• Calcium peroxide Releases >16% of its weight as oxygen when hydrated

• Packaged and delivered in 110 lb fiber drums

• Expected shelf-life of material - 2 years

*MSDS for full product specifications available upon request
TersOX

Field Applications

• TersOx and water mixture (slurry) application in excavations

• Dry powder application in soils and excavations

• Injectable slurry for source area and permeable reactive barrier applications
Benefits

• Controlled-release of molecular oxygen to support aerobic microbial biodegradation

• Long-term source of oxygen to the subsurface

• Clean, low-cost, non-disruptive application

• No Operations and Maintenance
Contact Information

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