Purpose

The purpose of this document is to allow the remediation specialist to use parts of this document as a template for their specific remediation action plan (RAP) for the anaerobic bioremediation of chlorinated aliphatic hydrocarbons (CAH) using inVentures Technologies Inc. iSOC® Technology. Specific site information should be used in conjunction with the material provided herein as the specialist sees fit. This document summarizes aspects of the scope or insertions into the scope of work to be performed at a CAH impacted site to remediate groundwater contaminated with various constituents of concern including but not limited to tetrachloroethene (PCE), trichloroethene (TCE), dichloroethene (DCE) and vinyl chloride (VC). This methodology is applicable to any compound that is subject to reductive dechlorination under anaerobic conditions.

Caution of Use

This document does not provide specific recommendations for the site. It is incumbent upon the plan designer to follow all regulatory requirements; federal, state, and local notifications; all jurisdictional permits and laws. The user assumes all responsibility for any consequences resulting from the use of this information or the use of any product described herein.

The blue font in the document represents comments.
The black font in the document is text that can be inserted into the RAP.
The red font identifies information that the remediation designer should insert.

Proposed Remedial Action

Overview of Biological Reductive Dechlorination

The in situ groundwater bioremediation process relies on microorganisms (soil bacteria) that are stimulated by adding electron donors changing, prevailing redox conditions where necessary, and leading to biological contaminant degradation in groundwater. Highly oxidized chlorinated aliphatic hydrocarbons such as tetrachloroethene (PCE) and lower CAHs are used as electron acceptors in the anaerobic process of biologically mediated reductive dechlorination. During the anaerobic biological process, hydrogen substitutes for a chlorine ion on the PCE molecule forming TCE, which can be further reduced to DCE, VC and ethene.

The effect of electron donor addition depends on electron acceptors present. Competing electron acceptors include dissolved oxygen (DO), nitrate, ferric iron (Fe^{3+}) and manganese IV must be reduced to reach favorable conditions for reductive dechlorination.

Reductive Dechlorination Process

Anaerobic reductive dechlorination of CAHs using hydrogen as an electron donor proceeds by the following generalized reaction:

H2 + R-C-Cl => R-C-H + H+ + Cl

Where C-Cl represents a carbon-chloride bond in a chlorinated molecule, C-H represents a carbon-hydrogen bond, and R represents the remainder of the molecule. In these reactions, two electrons are transferred with molecular hydrogen (H2) as the electron donor (which is oxidized) and the chlorinated molecule (R-C-Cl) as the electron acceptor (which is reduced).
(AFCEE 2004)

The reductive dechlorination of CAHs in groundwater is implemented at a site by the infusion of hydrogen as an electron donor with the iSOC® Gas inFusion delivery system. If not already present, anaerobic conditions are generated by the delivery of hydrogen. Sufficient mass of hydrogen must be delivered to satisfy hydrogen demand, calculated from estimates of competing electron acceptors and CAH mass present in the treatment zone. Where appropriate this calculation includes the mass of electron acceptors in the dissolved and solid phase within the treatment area and the mass flux of electron acceptors into the treatment area with groundwater flow. The required mass of hydrogen can then be compared to rates of hydrogen delivery by iSOCs to determine the appropriate number of treatment units necessary for the projected treatment time frame. The design layout and number of treatment wells must also be developed in consideration of site specific hydrogeologic conditions.

On a mass basis, 1.0 gram of molecular hydrogen is sufficient to dechlorinate the following mass of CAHs, assuming 100 percent utilization of molecular hydrogen by the dechlorinating microorganisms:

- 20.6 grams of PCE to ethene
- 21.7 grams of TCE to ethene
- 24.0 grams of DCE to ethene
- 31.0 grams of VC to ethene

Competing electron acceptors may be dissolved in groundwater or present as a solid. One gram of molecular hydrogen is also sufficient to reduce the following mass of competing electron acceptors:

- 7.9 grams of oxygen
- 10.2 grams of nitrate
- 55.9 grams of Iron III (reduced to Fe(II) - aquifer solid demand)
- 27.5 grams of Manganese IV (reduced to Mn(III) - aquifer solid demand)
- 10.6 grams of sulfate
- 5.5 grams of carbon dioxide

(AFCEE 2004)

A detailed procedure for evaluation of hydrogen demand is included in *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents*
Prepared by the Air Force Center for Environmental Excellence (AFCEE), 2004
http://www.afcee.brooks.af.mil/products/techtrans/Bioremediation/BIOREMresources.asp

Delivery of Hydrogen with the iSOC® System for CAH Bioremediation
Enhanced bioremediation stimulated by the infusion of dissolved hydrogen is an effective technology to reduce dissolved CAHs in groundwater. The efficient delivery of dissolved hydrogen into ground water is essential to insure that an abundance of hydrogen is available for the bioremediation process safely and at a reasonable cost.

The iSOC® gas delivery system is based on inVenture's patented Gas inFusion technology - a unique method of infusing supersaturated levels of dissolved gas into liquids. At the heart of iSOC® is a proprietary structured polymer mass transfer device that is filled with micro-porous hollow fiber material that provides an enormous surface area for mass transfer - in excess of 7000 m2/m3. It is hydrophobic and therefore excludes water. The system efficiently delivers gas to liquid by mass transfer without sparging.

In an anaerobic bioremediation applications, the iSOC® supersaturates the treatment well with dissolved hydrogen, typically 2.0 to 4.0 PPM depending on the immersion depth of the iSOC® unit in groundwater. The iSOC® produces a convection current in the well with a designed release bubble from the top of the iSOC® to distribute dissolved hydrogen rich water throughout the screened interval. A curtain of hydrogen rich water disperses around the well into the adjacent groundwater forming a treatment zone and enhanced bioremediation removes target contaminants. Placement of injection wells depends on site-specific conditions and treatment objectives as described further below. Treatment well screens typically span the full thickness of the contaminated groundwater zone. The iSOC® system is installed in a few hours to days depending on the number of treatment wells. iSOC® units are easily moved from well to well to optimize performance and remediation strategies.

iSOC® is constructed of high quality SS316 stainless steel using the latest manufacturing equipment and a proprietary structured polymer mass transfer device. iSOC® is 1.62" (41 mm) in diameter and 12.65" (321 mm) long with a compression fitting for 0.25" Teflon tubing. The housings for the pressure and flow control unit and the drain plug are made from nylon. iSOC® has a lifting ring for connecting to a suspension line for insertion in 2" (50 mm) or larger monitoring wells. The unit is connected to a regulated supply of compressed hydrogen.

The dissolved hydrogen concentration achieved in the treatment well depends on the height of the water column in the well. Each atmosphere of pressure allows for a maximum of approximately 1.6 ppm of dissolved hydrogen. Hydrogen is continuously infused into the aquifer over a period of several months to up to several years, as needed. During this time, a large and continuous supply of hydrogen is infused into the groundwater system to provide significant enhanced degradation of target CAHs. Hydrogen is infused from the iSOC® into the treatment well at a typical rate of 28 standard cubic centimeters/minute.

Treatment Strategy

(Specify treatment strategy)

The right strategy for a particular site will depend on site-specific conditions and site constraints. Strategies for applying the technology include:

- Locating the infusion wells within and immediately upgradient of the source area of the plume to enhance attenuation of contaminants in the source area,
- Creating a dissolved hydrogen biobarrier by locating the infusion wells along a line downgradient of the source of the plume and up gradient of the point of compliance,
- Hotspot treatment by installing treatment wells immediately upgradient and within high concentration areas, and
- A combination of the above three technology deployments.

Treatment areas that exhibit higher hydrogen demand may require tighter spacing of treatment wells. The treatment area developed around an iSOC® treatment well is typically 10 to 15 feet wide and dissolved hydrogen may be distributed over a larger area depending on hydrogen demand, groundwater flow and sediment type. The arrangement of biobarrier wells should consider the potential for seasonal variation in groundwater flow. The use of double rows of treatment wells may be appropriate in high hydrogen demand environments. Were appropriate, existing monitoring wells may be converted to treatment wells to enhance natural attenuation.

iSOC® gas infusion technology works at both high and low permeability sites. Sites dominated by silts and clays may take considerably more time to see results due to the low groundwater flow velocities.

In addition to hydrogen, bioaugmentation with dechlorinating strains of Dehalococcoides species may be required to optimize bioremediation.

Remedial Action Objectives

(Specify remedial objectives including contaminants of concern, target cleanup concentrations, treatment area(s) and time frame)

Scope of Work for Remedial Design and Installation

iSOC® System Design

An iSOC® system does not require electrical power, does not generate any noise and requires little maintenance. The main components of iSOC® systems are:

- iSOC® units (one unit per treatment well)
- Two stage low-flow hydrogen regulator (gauge reading 0-100 PSI)
- Industrial grade hydrogen in cylinders (consumption: 2 cu ft/per day/per iSOC®)
- Stainless steel and Teflon tubing (0.250" OD)
- Conduit for tubing, well head valve boxes and related materials
- An above ground storage area (shed, trailer or security cage for regulator & cylinders)
- A treatment well packer and/or ventilation system

Items supplied by inVentures Technologies per iSOC® include:

- iSOC® unit
- iSOC® tool for use when opening drain plug (1 per distribution header)
- Distribution header complete with regulator connector
- Bleed valve and iSOC® valve connections
- Snoop Liquid Leak Detector (1 per distribution header)
- 1 filter
- 1 iSOC® repair kit: 1 iSOC® flow-control valve, 1 stainless steel snap ring, 1 direction sheet

Pictures of each or these items is available at www.isocinfo.com

Design Plans and Specifications

(Identify iSOC® design plans and drawings)

Necessary plans for installation of an iSOC® system may include:

- Treatment wells layout and construction details and/or selection of properly screened existing monitoring wells for treatment
- Trenching diagram from gas storage location to treatment wells
- Well head iSOC® connection diagram

iSOC® System Installation

Site installations will be installed according to site specific plans prepared by a qualified professional engineer and diagrams and manufacturers specifications. All system components should be leak tested and monitored for hydrogen gas.

iSOC® system installation requirements and guidance are also available at www.isocinfo.com

(Include an installation schedule)

iSOC® System Monitoring

Following startup of the hydrogen infusion system, cylinder gas pressure should be monitored to verify expected usage. Each iSOC® unit uses approximately 2 cubic foot of hydrogen per day. Cylinders are not always 100% full, and flow may vary slightly. Pressure settings on the regulator will be set per the manufacturers specifications. (see www.isocinfo.com website)

During each site visit the remaining cylinder pressure will be recorded along with iSOC® regulator pressure setting. The estimated number of days to cylinder replacement will be calculated based on gas consumption since the last reading.

iSOC® water filters will be inspected at a minimum on a quarterly schedule and drained of accumulated water as necessary.

Remediation Waste Management

The iSOC® system does not produce any wastes.

Performance Monitoring

Groundwater sampling events will be conducted on a quarterly basis. Each of the quarterly sampling events will consist of collecting groundwater samples from performance monitoring wells for analysis of the constituents of concern and indicator parameters. Sampling will be done in accordance with the approved methodology including (specify requirements).

Baseline Sampling

Prior to system implementation, a baseline sampling event will be conducted on a minimum of 2 wells within the plume. A summary of proposed analyses is shown below:

Indicator	Analyses
Contaminant	VOCs
Microbial Activity	Polymerase Chain Reaction (PCR) for detecting the presence of the bacterium Dehalococcoides ethenogenes
Field parameters	Dissolved Oxygen (DO) Oxidation-Reduction Potential (ORP) Temperature, pH, conductivity
Dissolved gases	Hydrogen, ethene, ethane, carbon dioxide and methane
Electron acceptors	Total and dissolved iron and manganese, nitrate, sulfate

This data will be used to assess remedial progress at the site for optimization as necessary.

iSOC® Bioremediation System Costs

(Insert site specific cost information where required)

The system capital costs include groundwater treatment system components and construction engineering. The suggested component headings for the system design include:

- Groundwater Treatment System
  - Infusion Well Installations
  - Hydrogen Infusion Equipment
  - Miscellaneous (Baseline Sampling Event)
- Construction Engineering
  - Construction Labor & Equipment Rental
  - Engineering Oversight
  - Utility Clearance & Mobilization
  - Proposal Preparation

Construction Drawings & Specifications
Bid Package Solicitation & Evaluation
RA Startup Report (Includes As-Builts)
Permitting & Mobilization
Professional Surveying
Oversight

The system O&M costs will consist of

Analytical costs
Quarterly Monitoring Reports
System checks – 2 times first month and then monthly
Gas usage and tank rental
Quarterly Sampling Visit

References and Suggested Reading

The following publications are suggested as references and informative reading for the remediation specialist.

Sutherson, Suthan S. Remediation Engineering; Design Concepts. New York: CRC Lewis Publishers, 1997.

Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents
Prepared by the Air Force Center for Environmental Excellence (AFCEE), 2004
http://www.afcee.brooks.af.mil/products/techtrans/Bioremediation/BIOREMresources.asp