gPRO® Technology

gPRO® Technology Comparison

gPRO Comparisons to Other Technologies

The gPRO is a versatile tool for groundwater treatment that provides high rate gas inFusion into groundwater pumped through microporous hollow fiber cross-current flow modules. The gPRO compliments the capabilities of iSOC and HiSOC systems for gas inFusion applications and extends gas inFusion to new market areas. gPRO systems are targeted on groundwater treatment using primarily biological but also chemical and physical processes depending on the gas infused and the remediation approach. Current applications envisioned for the gPRO include:

• Biological treatment
- Aerobic oxidation (oxygen)
- Cometabolic oxidation (oxygen and alkane gas)
- Cosubstrate oxidation (oxygen and ethene or other co-substrates)
- Anaerobic reductive dechlorination (hydrogen)

• Chemical treatment
- pH adjustment (sulfur dioxide, carbon dioxide, ammonia)
- Geochemical fixation of metals (hydrogen and sulfur dioxide)
- Oxidation of metals (oxygen)

• Physical treatment
- LNAPL and DNAPL recovery enhancement (carbon dioxide
- Specific gas inFusion applications for bioremediation are listed in the following table.

Table 1: Gas inFusion Bioremediation Applications

Contaminant	Gas Delivered	Electron Donor	Carbon Source	Process
Hydrocarbons	O_2	Contaminant	Contaminant	Aerobic Degradation
	O_2+ Alkane	Alkane + Contaminant	Alkane + Contaminant	Aerobic Degradation
MTBE	O_2	Contaminant	Contaminant	Aerobic Degradation
MTBE	O_2 + Alkane	Alkane + Contaminant	Alkane + Contaminant	Aerobic Cometabolism
CAH* (PCE, TCE, DCE)	H_2	H_2	In-Situ Organics	Anaerobic Degradation
	H_2	H_2 + Organic Electron Donor	Added Organic	Anaerobic Degradation
	Alkane	Alkane	Alkane	Anaerobic Degradation
CAH (TCE, DCE, VC)	O_2 + Alkane	Alkane	Alkane	Aerobic Cometabolism
	O_2	Alkane	In-Situ Organics (natural methane)	Aerobic Cometabolism
CAH (Vinyl Chloride)	O_2	Contaminant	Contaminant	Aerobic Degradation
	O_2 + Ethene (Co-Substrate)	Ethene + Contaminant	Ethene + Contaminant	Aerobic Degradation
Ammonia	O_2	Ammonia	In-Situ Organics or CO_2	Nitrification (Aerobic)
Nitrate	H_2 +/- CO_2	H_2	In-Situ Organics or CO_2	Denitrification (Anaerobic)
Perchlorate	H_2 +/- CO2	H_2 Organic or CO_2	In-Situ or Added Organic or CO_2	Dissimilatory Reduction (Anaerobic)
1-4, Dioxane	O_2 + Propane	Propane	In-Situ or Added Organics	Aerobic Cometabolism

* CAH – Chlorinated Aliphatic Hydrocarbons

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Various competing technologies exist for certain applications of the gPRO system. Primary competitors for aerobic biological treatment are air/biosparging and oxygen sparging. Ozone sparging is a physical alternative technology targeted at similar groundwater contamination problems. Each of these methods requires significant electrical power consumed by compressors to inject gas substrates. Chemical oxidation with liquid injections, groundwater pump and treat, and dual phase extraction are technologies that compete with gPRO for groundwater treatment applications but may also be applied in concert with gPRO applications.

Vegetable oil, sugar and carbohydrate injection and hydrogen sparging technologies compete with direct hydrogen inFusion for reductive dechlorination of chlorinated compounds and anaerobic bioremediation and geochemical fixation of other contaminants including nitrate, perchlorate, and metals such as hexavalent chromium. In certain situations these technologies may be applied with a more beneficial effect by combination with direct hydrogen gas inFusion and therefore may be used in concert with gPRO.

Treatments targeted on unsaturated zone soil contamination such as SVE and excavation for off site disposal do not compete with gPRO which is targeted on saturated zone contamination problems. The following table compares gPRO to competing technologies.

Table 2: gPRO Comparison with Competing Technologies:

Technology	Treatment Process	Equipment	Applicable Lithology	Limitations	gPRO® Advantages
gPRO®	**Active gas inFusion into water forming groundwater in situ treatment areas for biological, chemical & physical treatment**	**gPRO® unit, groundwater pumps, pretreatment systems, manifold to injection wells**	**Permeable soil with layered or uniform stratigraphy, high or low heterogeneity and unlimited by well depth**	**gPRO® is not subject to many limitations of competing technologies - only requires sufficient permeability to extract and/or inject sufficient water to deliver substrates to the treatment area**	**N/A**
Air sparging	High flow compressed gas injection designed to physically strip volatile contaminants from groundwater	Compressor, sparge wells, timer, conduit	Permeable soil with uniform stratigraphy generally limited to saturated thickness > 5 ft but < 50 ft	Depth limitations and requirement for SVE. Uneven distribution of gas due to channeling & possible unwanted migration due to water table mounding. Possible vapor intrusion.	gPRO® delivery wells can be used to target substrate delivery where needed with hydraulic control and without mobilizing contaminants to the unsaturated zone
Bio-sparging	Low flow compressed gas injection designed to increase biological degradation	Compressor, sparge wells, timer, conduit	Permeable soil with uniform stratigraphy generally limited to saturated thickness > 5 ft but < 50 ft	Depth limitations and possible requirement for SVE, uneven distribution of gas. Possible vapor intrusion.	gPRO® delivery wells can be used to target substrate delivery where needed and provide larger mass of substrate

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Oxygen sparging	Low flow compressed gas injection designed to increase biological degradation	Oxygen source, oxygen pump, sparge wells, timer, conduit	Permeable soil with uniform stratigraphy generally limited to saturated thickness > 5 ft but < 100 ft	Depth limitations and possible requirement for SVE, uneven distribution of gas. Possible vapor intrusion.	gPRO® delivery wells can be used to target substrate delivery where needed with out moving oxygen to the unsaturated zone
Ozone sparging	Low flow compressed gas injection designed to chemically oxidize contaminants	Oxygen generator, ozone generator, compressor, sparge wells, timer,	Permeable soil with uniform stratigraphy generally limited to saturated thickness > 5 ft but < 100 ft below water table	Depth limitations and possible requirement for SVE, uneven distribution of gas. Possible dangerous effects on subsurface infrastructure. Possible vapor intrusion.	gPRO® delivery wells can be used to target substrate delivery where needed with out moving oxygen to the unsaturated zone
Chemical oxidation	Liquid injection designed to chemically oxidize contaminants	Injection wells, pumps, direct push	Relatively permeable soil and limited competing demand from natural organic compounds	Requires direct contact with contaminant, oxidant rapidly degrades, generally not suited for large area treatment	gPRO® delivery wells can be used to target substrate delivery where needed for biological treatment
Dual phase extraction	Vacuum extraction from multi-phase wells, ex situ treatment	Vacuum blowers, separation and treatment systems	Permeable soil with uniform stratigraphy generally applied to surface of water table	Limited to shallow depths and limitations of NAPL movement under hydrostatic conditions	gPRO® NAPL recovery technology works in conjunction with DPE to mobilize NAPL for removal and bioremediation.
Pump & treat	Groundwater extraction from pumping wells	Pumping and above ground treatment systems	Permeable soil with layered or uniform stratigraphy with low heterogeneity	Ex situ treatment results in long tailing of contaminant concentrations due to poor mass removal.	gPRO® in situ treatment degrades contaminant mass in formation
Hydrogen sparging	Compressed gas injection	Compressed gas supply, injection wells	Permeable soil with uniform stratigraphy generally limited to saturated thickness > 5 ft but < 50 ft	Depth limitations and possible concerns over hydrogen reaching unsaturated zone, vapor intrusion and reaching locations where the lowered explosivity limit may be exceeded..	gPRO® delivery wells can be used to target substrate delivery where needed with hydraulic control without mobilizing contaminants or substrate to the unsaturated zone
Carbon based electron donor Reductive dechlorination	Active or passive injection systems	Pumping systems and/or injection wells	Relatively permeable soil	Viscous liquids and excess biomass required for fermentation reactions reduce formation permeability and result in secondary water quality impacts	gPRO® hydrogen delivery provides electron donor directly without need for fermentation reactions

Application of gPRO at Specific Sites

The selection of a gas inFusion system for a particular site depends on the:

- Hydrogeologic conditions
- Groundwater flow conditions
- Nature of the contaminant

Technology selection should also consider:
• Treatment objectives
• Geochemical conditions

The selection will also have to be made in consideration of other treatment technologies in operation or under consideration for combination at the site. In general the gPRO systems require hydrogeologic conditions suitable for extraction and reinjection of groundwater or the ability to inject large volumes of water from an alternative water supply. Sites where hydrogeologic conditions are suitable for pump and treat system operation are ideal however gPRO applications are not strictly limited to these conditions. Both iSOC and gPRO® may be applicable for different applications at the same site (e.g. gPRO for source area treatment and iSOC for downgradient biobarrier).

Table 3: Site Criteria for Selection of gPRO Technology

Site Criteria	Degree Applicable (least) + → (most)+++++		
Hydrogeologic Conditions			
Stratigraphy	Simple	→	Complex
gPRO®	+++++		+++++
Aquifer material	Course Grained	→	Fine Grained
gPRO®	+++++		+++
Degree of heterogeneity	Low	→	High
gPRO®	+++++		++
Groundwater Flow Parameters			
Hydraulic conductivity (k)	High (> 0.01 cm/s)	→	Low (<0.0001 cm/s)
gPRO®	+++++		++
Hydraulic gradient (i)	Low	→	High
gPRO®	+++++		+++++
Temporal variation in gradient	Little	→	High
gPRO®	+++++		+++
Horizontal flow velocity	Slow (<0.5 ft/day)	→	Fast (>1.5ft/day)
gPRO®	+++++		+++
Vertical flow	Little	→	High downward
gPRO®	+++		++
Mass of contaminant (and competing donors/acceptors)	Low	→	High
gPRO®	+++++		+++++
Volume of contaminated material	Low	→	High
gPRO®	+++++		+++++

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Bioavailability	Low	→	High
gPRO®	+		+++++
Solubility (s)	Low	→	High
gPRO®	+++		+++++
Sorption potential (kd)	Low	→	High
gPRO®	+++++		+++