Biobarrier

Technology description:
General information & application area

Target Audience: Authorities, site owners, consultants, contractors

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1 INTRODUCTION

Permeable reactive biobarriers (biobarriers) are an innovative in-situ remediation technology for contaminated groundwater. This document intends to provide general information about this technology, and its application area and boundary conditions for authorities, consultants and site owners. More detailed information for supporting consultants, authorities and scientists in evaluating the feasibility, designing, implementing and monitoring biobarriers is given in the associated generic guideline.
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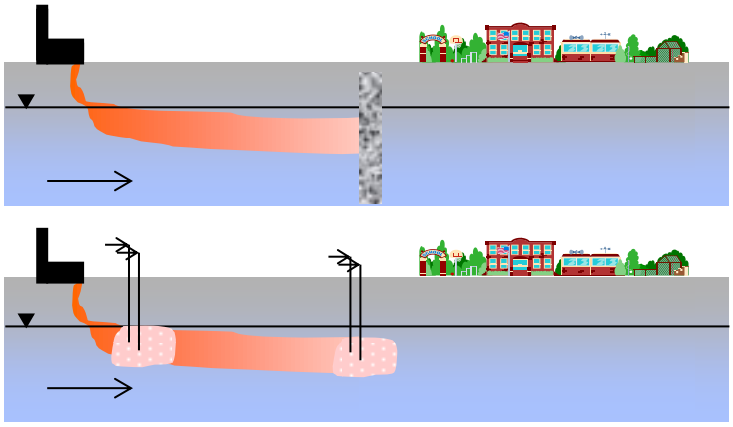
2 GENERAL PRINCIPLES OF THE BIOBARRIER TECHNOLOGY

2.1 CONCEPT

Permeable reactive barriers (PRBs) are installed in the subsurface downstream of a contamination source. In the barrier, pollutant removal processes are activated, which degrade the pollutants in the groundwater while it flows through the barrier. Generally, no pumping is involved and the natural hydraulic gradient is the driving force to move the groundwater through the barrier. Therefore, the PRB technology is a semi-passive to passive technology.



Biobarrier (sensu stricto)

Bioreactive zone (near source zone or in the contamination plume)

Figure 1 Schematic representation of two types of biobarriers.

A permeable reactive biobarrier (biobarriers) is a reactive barrier in which microbial processes are induced to prevent further spreading of the pollutants. The terminology used here, includes biobarriers sensu stricto (excavation & refilling of trench) as well as bioreactive zone (injection of substances that stimulate biodegradation) as indicated in Figure 1. After installation, the system can remain reactive for years when maintained well.

2.2 TARGETED SUBSTANCES & REACTION MECHANISMS

Substances that can be targeted by the biobarrier technology are given in Table 1 as examples, along with their potential emission sources.

Table 1 Overview of substances that can be tackled by biobarrier technology.

Targeted substances			Emission sources
Class	Specific substance	biodegradability	
CAHs (chlorinated aliphatic hydrocarbons)	Tetrachloroethylene (PCE)	Anaerobic: ++ Aerobic: -	Drycleaner activities, degreasing activities, ... Degradation products of other chlorinated compounds
	Trichloroethylene (TCE)	Anaerobic: ++ Aerobic: -	
	Cis-dichloroethylene (cDCE)	Anaerobic: ++ Aerobic: ++	Degradation products of PCE and TCE
	Trans-dichloroethyele (tDCE)		
	Vinylchloride (VC)	Anaerobic: + Aerobic: ++	
	1,1,1-Trichloroethane	Anaerobic : ++ Aerobic : -	Degreasing, chemical industry
	1,1-dichloroethane	Anaerobic : ++ Aerobic : -	Degradation product of 1,1-TCA
	chloroethane	Anaerobic : - Aerobic : +	Degradation product of 1,1-DCA
	1,2-dichloroethane (1,2-DCA)	Anaerobic: + Aerobic : +/-	Chemical industry
	Tetrachloromethane (PCM)	Anaerobic : + Aerobic : -	Chemical industry, dry cleaning
	Trichloromethane (TCM)	Anaerobic : ++ Aerobic : -	Chemical industry
	Dichloromethane (DCM)	Anaerobic : + Aerobic : +/-	Chemical industry, degreasing, paint stripping Degradation product of PCM and TCM
Aromatics	Benzene	Anaerobic: + Aerobic: +++	Petrol gas stations Manufactured gas plants Chemical industry Chemical storage places
	toluene	Anaerobic: + Aerobic: +++	
	ethylbenzene	Anaerobic: + Aerobic: +++	
	xylenes	Anaerobic: + Aerobic: +++	
Fuel oxygenates	Methyl ter-buty ether (MTBE)	Aerobic: + Anaerobic: +/-	
	TBA	Aerobic: ++ Anaerobic: -	
metals	Zn, Copper, ...	In-situ bioprecipitation under sulphate reducing conditions	

+++: Very easy; ++: biodegradable; +: more difficult to biodegrade; +/-: rarely biodegradable; -: not or very slowly biodegradable.

Biodegradation/biotransformation is based on electron transport facilitated by the micro-organisms (bacteria) from an electron donor to an electron accepting component, whereby pollutants are degraded/transformed via oxidation or reduction reactions. Several elements, including carbon, nitrogen, oxygen, sulphur, iron and/or manganese are key components involved in these reactions. The pollutant can act as:

1. **Electron donor**, like in the case of BTEX compounds, where the electron acceptor is oxygen under aerobic conditions. Under anaerobic conditions a set of potential electron acceptors exists comprising nitrate, iron, manganese, sulphate (Table 2).

Table 2: Overview of electron acceptors.

Process	Reaction	Redox potential (E_h in mV)
aerobic:	$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$	600 ~ 400
anaerobic:		
denitrification	$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O$	500 ~ 200
manganese IV reduction	$MnO_2 + 2e^- + 4H^+ \rightarrow Mn^{2+} + 2H_2O$	400 ~ 200
iron III reduction	$Fe(OH)_3 + e^- + 3H^+ \rightarrow Fe^{2+} + 3H_2O$	300 ~ 100
sulfate reduction	$SO_4^{2-} + 8e^- + 10\ H^+ \rightarrow H_2S + 4H_2O$	0 ~ −150
fermentation	$2CH_2O \rightarrow CO_2 + CH_4$	−150 ~ −220

2. **Electron acceptor**, like in case of chlorinated ethenes, nitrate and sulphate under anaerobic conditions. The electron donor can be organic matter in the soil, but is often a limiting factor in groundwater contamination plumes. Therefore, addition of electron donors (carbon source, molecular hydrogen, ...) is often needed to activate the anaerobic biodegradation process.

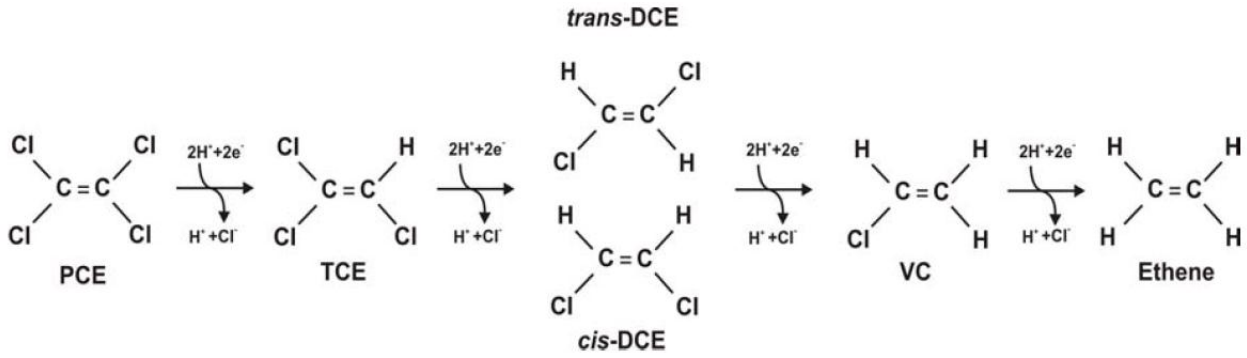


Figure 2. Anaerobic biodegradation mechanism of chloro-ethenes

3. **Electron donor nor electron acceptor**. An example here can be metals. Some metals are removed from groundwater by a secondary reaction, being precipitation with for instance sulphide, that was produced by microbial reduction of sulphate (in-situ bioprecipitation).

Biodegradation reactions are part of the cell metabolism to survive and to multiply. Therefore, also other elements (N, P, ...) and vitamins are needed in trace amount to facilitate the

biodegradation reaction. Most of the trace elements are by nature present in the subsurface. Nitrogen and phosphor, also called nutrients, are needed in a ratio of C:N:P = 100:10:1. In highly polluted areas, (high carbon concentration) addition of nutrients may be needed.

2.3 DEVELOPMENT STAGE OF THE TECHNOLOGY

The biobarrier technology is **available** and **well accepted** for a number of pollutants in many European countries. Biobarriers in the field at pilot scale and full scale have been described in literature from before 1995.

3 APPLICABILITY AND BOUNDARY CONDITIONS OF THE BIOBARRIER TECHNOLOGY

The applicability area of the biobarrier technology is determined by different aspects.

Microbial aspects:

- The pollutants present in the groundwater should be biodegradable, and do not result in accumulation of non-degradable harmful metabolites.
- Pollutants are present in the dissolved phase.
- Environmental conditions (pH, temperature, redox conditions, dissolved oxygen concentration …) at the site could allow biological processes, which exist under natural conditions or which can be created.

Site specific aspects:

- The depth of the groundwater contaminant plume is preferably not located deeper than 40-50 m below ground surface, more preferably not below 20 m below ground surface. For deeper plumes, the installation cost will increase significantly and biobarriers would be restricted to reactive zones (injection of reagents).
- The groundwater flow direction needs to be known and should be relatively stable in time.
- The presence of a shallow impermeable layer sealing the bottom of contamination plume is an advantage for the biobarrier technology as it prevents contaminants passing underneath the biobarrier. Also when no low permeability layer is present, biobarriers can be applicable when this aspect is taken into account during the feasibility and design phase (especially for LNAPL sites).
- In principle, the biobarrier technology is applicable for a wide range of groundwater flow velocities. For higher flow velocity, larger dimensions of the biobarrier are generally needed (to ensure sufficient contact time) resulting in higher costs. The required amounts of amendments such as electron donor or electron acceptor would also be greater.
- The hydraulic conductivity of the barrier should be equal or higher than the permeability of the surrounding aquifer to avoid mounding and by-passing of the groundwater.
- The site is accessible for the installation of the barrier, which may imply the excavation of soil and refilling the trench with reactive media (for barrier sensu stricto) or the installation of injection wells and equipment (for bioreactive zones). After the installation, there may be injection filters that need to remain accessible for repeated injection, or continuous dosing systems. Also accessible monitoring filters are required.

The use of biobarriers is not recommended:

- For pollutants that have not been shown to be biodegradable, or that are transformed in harmful reaction products.
- For sites where free product is expected to migrate into the barrier.
- For sites with groundwater contaminations situated in deep subsurface (> 50 m bgs), due to technical and budget issues.
- When substances (co-pollutants) are present at the site that can inhibit biodegradation.

Positive co-effects linked to the biobarrier technology:

- Micro-organisms and soluble reactive substances can migrate outside the barrier, predominantly in the downstream direction, and enlarge as such the dimensions of the biobarrier.

Negative co-effects linked to the biobarrier technology:

- Changes in redox condition or pH may lead to precipitation of inorganics in the biobarrier, reducing the permeability of the system.
- Stimulation of biodegradation processes implies stimulation of bacterial growth. Over time, the formed biomass or the accumulation of gases such as methane may reduce the permeability of the system, especially of infiltration filter/areas.

4 PERFORMANCE OF THE BIOBARRIER TECHNOLOGY

The **abatement rate** can be defined as the pollutant concentration after the technology implementation divided by the pollutant concentration before implementation of the technology. Biobarriers aim at a reduction of the pollutant below regulatory limits in the downstream area, implying an abatement rate close to 95-100%.

Efficiency drivers: The performance of a biobarrier is for a large part determined by the degradation or fixation rates that are achieved within or downstream of the barrier. These rates depend on multiple factors such as the redox condition, pH, the concentration of the electron donor or acceptor, the microbial community etc. These effects are generally lumped using first order kinetics to describe the degradation rate *in situ*.

The **longevity of the technology** is influenced predominantly by (1) the evolution of the permeability the system, and the (2) the maintenance of good biodegradation conditions.
The evolution of the permeability over time is determined by (1) the initial permeability of the system, (2) the composition of the groundwater, (3) the processes induced in the biobarrier (impacting pH, ORP, bacterial growth, precipitations of metals such as iron hydroxide, ...), (4) the groundwater flow velocity, and (5) potential biofouling controlling actions.
Good biodegradation conditions imply (1) the presence of sufficient electron donor or electron acceptors, nutrients, ... and (2) the absence of inhibiting substances, comprising degradation products.
The lifetime of biobarriers can be in the order of years to decades.

5 COST OF THE BIOBARRIER TECHNOLOGY

Cost drivers for biobarriers comprise (1) the dimensions of the barrier (depth, length and thickness), (2) the price of the reactive material, (3) the local situation on the site (accessibility, surroundings buildings, underground constructions, type of subsurface ...), (4) the local labour costs (country dependent), and (5) amount of maintenance that is needed to keep the biobarrier active and permeable.

The **investment costs** of biobarriers cover a wide range (22- >321 keuro) depending on the barrier concept, but they are usually higher than the investment costs for pump&treat systems. The maintenance cost is generally significantly lower for biobarriers (20 - >70 keuro/year) in comparison with pump&treat.

6 GENERIC APPROACH TO DETERMINE APPLICABILITY OF THE BIOBARRIER TECHNOLOGY FOR A SPECIFIC SITE OR AREA

For a successful application of the biobarrier technology, the following stepped approach is recommended:

Step 1: Site characterisation

A site characterisation is required for checking the application and boundary conditions associated with the technology (see section 3). The site characterisation comprises:

- Identification of the type and concentration of pollution that is present
- Determination of the location of the pollution (unsaturated soil, groundwater, depth, ...)
- Collection of information on the geology (type of layer, permeability, ...)
- Collection of hydrological data (groundwater flow direction and velocity, ...)
- Evaluation of the accessibility of the site.

Step 2 Select removal pathway for the pollutants

Step 1 results in a list of pollutants that should be reduced in concentration. For these pollutants, a biological removal process (electron-donor or electron acceptor …) is to be selected taking into account the in-situ conditions.

Step 3: Feasibility test at lab scale

Lab scale tests can be required (1) to verify the presence of suitable pollutant degrading micro-organisms at a specific site, (2) to verify the degradability of the target components, (3) to select suitable reactive substances (electron-donor, electron-acceptor, micro-organisms, nutrients ...) for the biodegradation process, or more general, to determine the required environmental conditions.

For biobarrier design, degradation rates of the pollutants and other needed input parameters can be deduced from labscale test, preferably column tests. Minimal required contact times of the groundwater and the biobarriers to meet the regulatory limits are calculated. A time period of at least 2 and 6 months should be taken into account for aerobic and anaerobic tests, respectively.

All these test are to be performed with groundwater (and aquifer material) from the site.

Step 4: Design & dimensioning of pilot/full scale biobarriers

Biobarriers can be installed (A) as continuous barriers or funnel-and-gate PRB systems (Figure 3), or (B) as reactive zones where biodegradation enhancing substance are injected into the subsurface (Figure 1).

For continuous barriers and funnel and gate biobarrier concepts, part of the aquifer is removed and replaced by coarse reactive material. Here biodegradation promoting substances are preferably added as slowly releasing solids (like mulch) where after installation no active addition of substances is needed.

In the case of bioreactive zones, the injected substances that promote biodegradation are preferably liquids, but can also be suspensions of small (lower µm range) particles or gasses (air, oxygen, hydrogen, ...). To maintain the required concentrations, repeated injections over time, or even continuous dosing may be necessary.

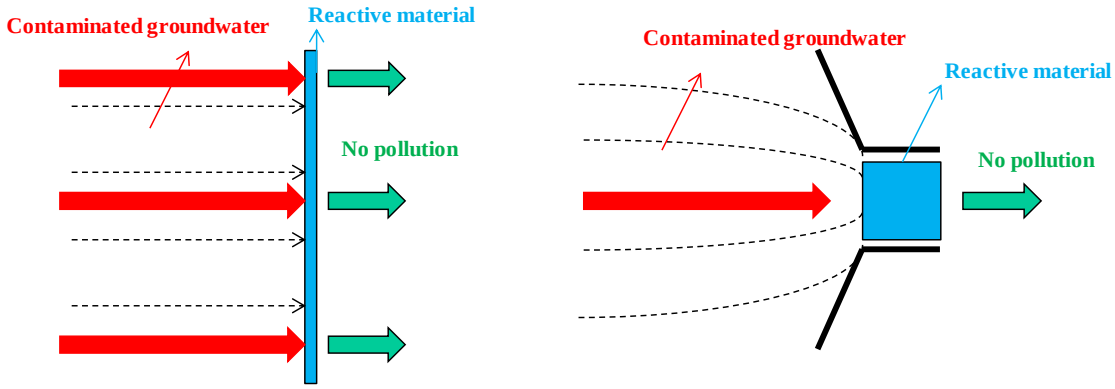


Figure 3 Schematic representation of a continuous (left) and funnel & gate (right) biobarrier concept

For an envisioned installation location at the site and the selected barrier type, the required length and depth of the barrier to catch the groundwater contamination plume are determined based on the collected field information. Based on the expected concentrations of contaminants in the influent of the barrier, the groundwater flow velocity, the design parameters deduced from the laboratory feasibility test and the regulatory limits, a minimal thickness of the biobarrier or width of the reactive zone is deduced.

Step 5: Implementation of a biobarrier

This step comprises the installation of the biobarrier according to the design parameters. Different implementation methods have been described, from which a few are depictured in Figure 4:

- Barrier sensu stricto: continuous trenching, refilling of stabilised (sheet piles, or guar gum) and non-stabilised trenches, soil mixing, funnel & gate system with permeable gates which are filled bioreactive materials that may be replaced periodically
- Injection wells may be installed within a biobarrier trench to inject amendments that can sustain microbial activity for a long time.
- Bioreactive zone: direct push injections, injections via vertical wells, horizontal drains, recirculation wells, ...

Figure 4: Implementation of biobarriers (Left) continuous trencher, (Right)

Step 6: Monitoring of the biobarrier

A post installation monitoring aims at following the performance of the biobarrier, where reduced pollutant concentrations downstream of the biobarrier are envisioned. Generally, permanent groundwater monitoring wells are installed upstream and downstream of the biobarrier at different depths and are sampled during the whole operation time. They may also be installed within a biobarrier trench, vessel or in a reactive zone to monitor the operational conditions. Beside chemical contaminant parameters, process parameters such as the groundwater level, pH, redox conditions are to be followed.

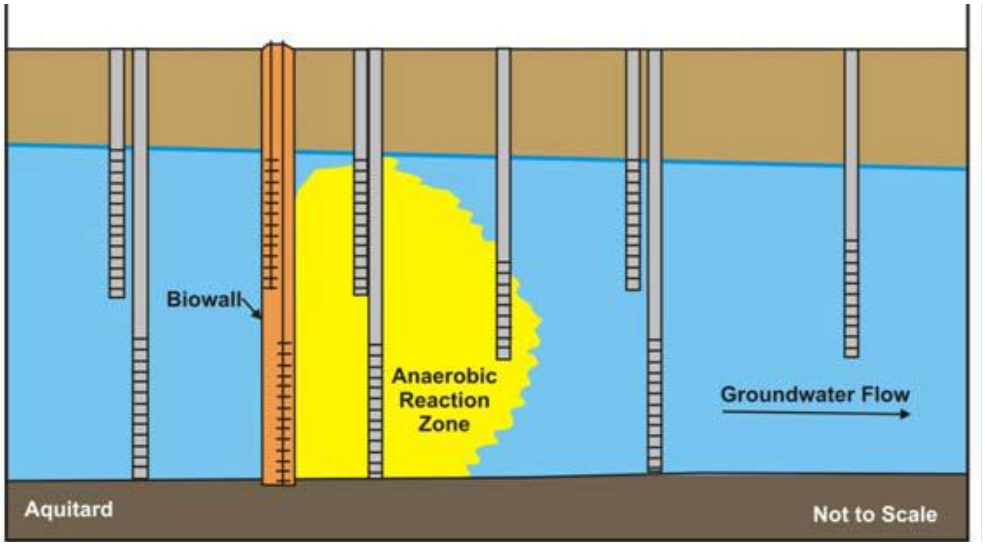


Figure 5: Cross-section of a monitoring well transect for a biobarrier (ITRC, 2011).

Step 7: Closing the site

Generally, biobarriers are expected to remain in the subsurface once the site is closed.

7 CONTACTS

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