

POSSIBILITY OF USING PERMEABLE REACTIVE BARRIER  
IN TWO SELECTED DUMPING SITES

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**Abstract:** In the first part of the paper the most often used processes in PRB technology are presented and described. These processes are: redox reactions, pH control, adsorption and biodegradation. They proceed in the reactive materials listed in the table. In the second part of the paper the procedure used in the assessment of possibilities of using PRB technology is presented. It was suggested to use preliminary assessment during the initial stage of the procedure, as it limits the range of the analysis to several most important factors. Moreover, the conditions of using PRB were described. They can help to decide whether this technology should be accepted or not in the initial stage of the procedure. Such preliminary assessment of possibilities of using PRB was performed for two selected areas of dumping sites located in Upper Silesia, Poland. After accepting the possibilities of using this technology in their area, the types of reactive materials for effective treatment of groundwater were proposed for both of them.

## INTRODUCTION

Groundwater can be polluted by dumping sites among other things. Contaminants from these sources flow downwards in the unsaturated zone reach the groundwater and in the form of diluted solution flow horizontally and can pollute water surface of rivers, lakes, etc. There are many types of such examples in Upper Silesia, Poland. The paper assesses the possibility of using PRB technology (Permeable Reactive Barrier) for two areas of dumping sites located in this region. PRB technology is an interesting method for groundwater remediation and is used when contaminants are in the saturated zone. This novel technique of groundwater remediation is the passive one in which contaminants are removed from an aquifer by the flow through a reactive barrier filled with a reactive material [8, 14]. The illustration of this process is shown in Figure 1.

PRB has several advantages over other methods of groundwater remediation. Reactive barrier can degrade or immobilize contaminants *in situ* without need to bring them up to the surface. It also usually does not require continuous input of energy. Unfortunately, during PRB operation some problems can appear. Seasonal fluctuations in groundwater flow, aquifer and plume heterogeneities, changes in hydraulic parameters over time are the factors that can affect its efficacy.

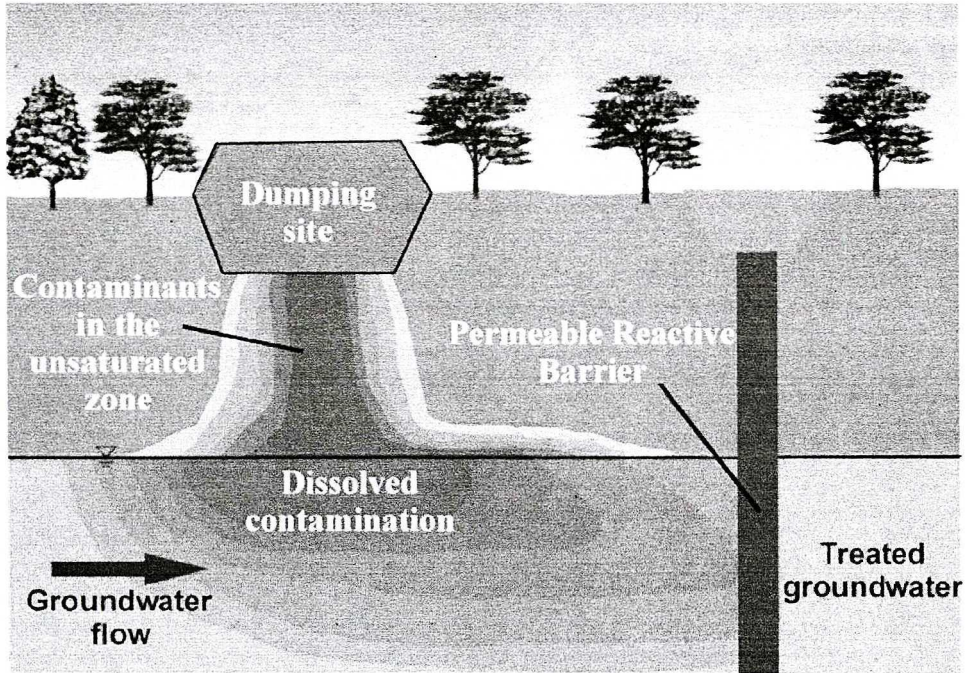


Fig. 1. The rule of groundwater treatment with the use of PRB technology

## TREATMENT PROCESSES

As the contaminated groundwater moves through the reactive barrier, the contaminants are removed by physicochemical, chemical and/or biological processes [7]. Many reactive materials can be used as fillers in PRB. The processes applied here are:

- redox reactions,
- pH control,
- adsorption,
- biodegradation.

### *Redox reactions*

Up till now zero-valent iron  $\text{Fe}(0)$  has been the most common reactive material in the majority of field scale and commercial implementations. First of all it is used for treatment of plumes contaminated with chlorinated hydrocarbons, chromium and arsenic [2, 6]. Scrap iron is not expensive and can be obtained in a granular form in the large quantities needed.

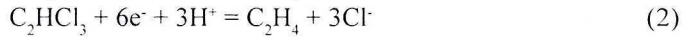
### *Chemical dehalogenation*

Halogenated hydrocarbons, present often in the groundwater, are very toxic, whereas most hydrocarbons (except for benzene among others) are non-toxic or slightly toxic. So, in the reactive material a reaction should change these chemicals into non-toxic hydrocarbons.

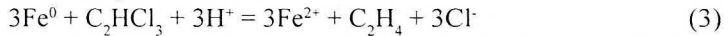
In the reactive material consisting of zero-valent iron  $\text{Fe}(0)$ , it can act as reducing agent and generate ferrous ion by the redox reaction:



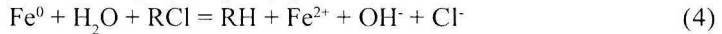
As the zero-valent metal in the reactive cell corrodes, the resulting electron activity is believed to reduce the halogenated compounds to potentially non-toxic products, e.g. the degradation of trichloroethylene to ethene can be presented as:



The overall reaction can be presented as:

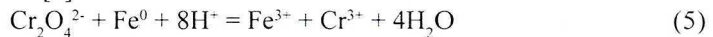


Hence, it may be said that the reduction proceeds primarily by the removal of the halogen atom and its replacement by hydrogen [2].



*Precipitation*

Chromium(VI) can be also removed from groundwater by chemical reduction with iron (iron promotes reduction). Chromium in the oxidation states 6+ is very toxic, whereas chromium(III) is slightly toxic and is easy to precipitate. Hence, reduction of chromium(VI) into chromium(III) is the reaction which allows to remove it from groundwater. The overall reaction for the hexavalent chromium, which occurs in water (under typical ground water pH and Eh conditions) as an oxyanion in the form of  $\text{CrO}_4^{2-}$  or as  $\text{Cr}_2\text{O}_7^{2-}$  can be presented as [6]:



Such reaction is important due to negative charge of these anions which are not attracted by negatively charged mineral surfaces [9]. That is why other anions and oxyanions containing Se(VI), As(III), As(V), Tc(VII) are also important groundwater contaminants.

Reaction 5 occurs spontaneously. Couples with a lower standard electrode potential reduce couples with a higher potential (Fig. 2) [6].

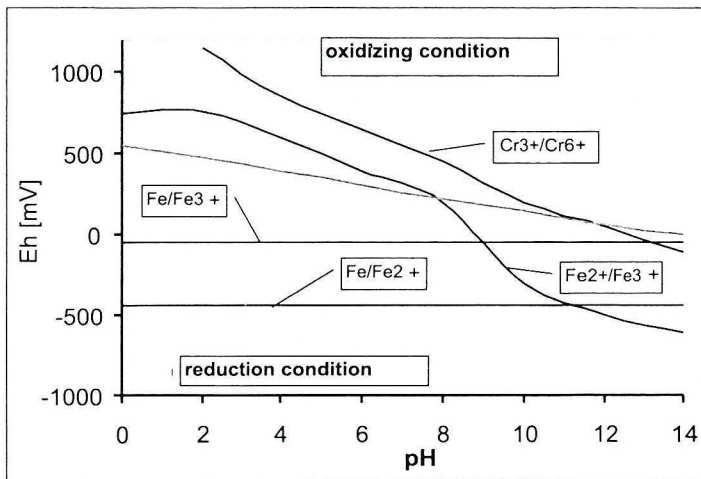
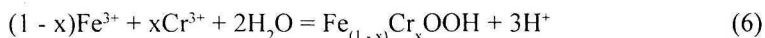


Fig. 2. pH-Eh diagram showing the stability fields for water and some iron and chromium species [6]

In a further step, iron and chromium are precipitated as chromium(III) hydroxides or chromium-iron hydroxide solid solutions [9].





It needs to be said that both reduction of chromium(VI) into chromium(III) and precipitation of chromium(III) hydroxides or chromium-iron hydroxide are sensitive to pH.

In the case of groundwater flowing through the industrial, mine and nuclear disposal sites it may bear positively charged inorganic cations such as  $\text{Cd}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Pb}^{2+}$ , and complex cations such as  $\text{UO}_2^{2+}$ . All these cations are characterized by higher standard electrode potential than zero-valent iron. So it displaces hazard cations from groundwater:



$$U_{\text{Fe}/\text{Fe}^{2+}} < U_{\text{Cu}/\text{Cu}^{2+}}$$

where:  $U_{\text{Fe}/\text{Fe}^{2+}}$  – standard electrode potential V.

### *pH control (precipitation)*

Contaminants precipitation can also be conducted without changing redox conditions. The solubility of metals is dependent on (apart from reduction potential) pH conditions, aqueous concentrations of reacting species, and reaction kinetics. Hence, it was found that contaminants precipitation can be performed in reactive material by changing pH conditions. The effect of pH on the mobility of many inorganic constituents is shown in Figure 3 [17].

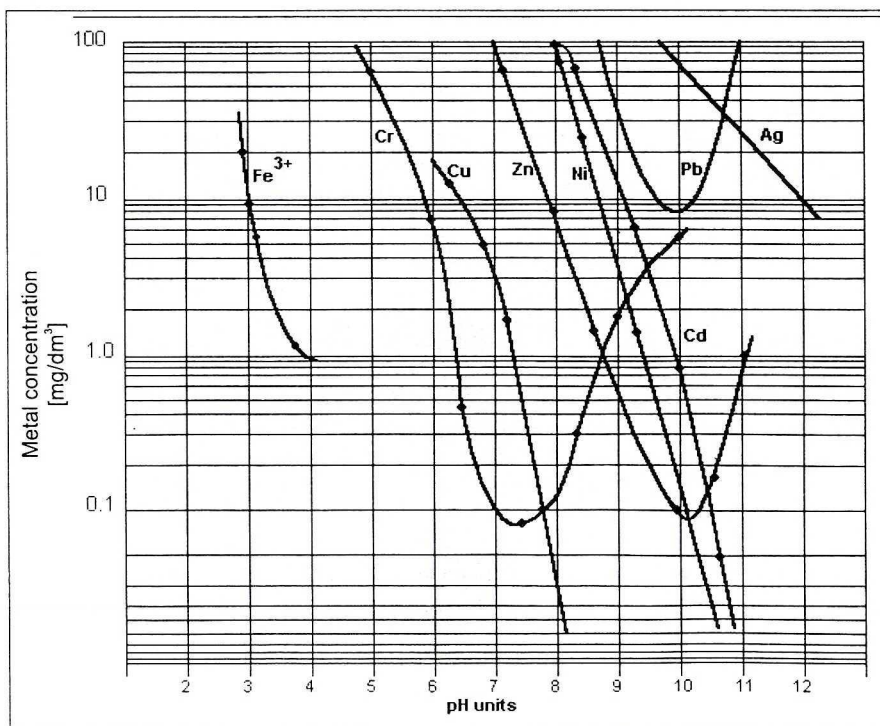


Fig. 3. Metals hydroxide solubility as a function of their concentration and pH [17]

As one can see, the solubility, and thus mobility, of many inorganic compounds is reduced in a range of neutral to slightly basic pH (in this case sparingly soluble metal hydroxides arise), while the solubility and mobility of them can increase in either very acidic or, in the case of amphoteric hydroxides, very basic pH solutions (then dangerous metal anions e.g. chromate arise).

### **Adsorption**

Contaminants adsorption (including ion exchange) on a different kind of materials is a well known process used in sewage and water treatment technology. Adsorption is a process that occurs when a liquid solute accumulates on the surface of a solid adsorbent, forming a molecular or atomic film (the adsorbate) [16]. As regards the strength of fixation between adsorbent and adsorbate the adsorption process can be divided into [1]:

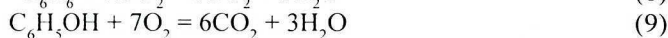
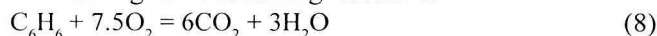
- physical adsorption – the adsorbate adheres to the surface only through van der Waals interactions (weak fixation of molecules or atoms);
- chemisorption – the adsorbate adheres to the surface through the formation of a chemical bond (higher strength of fixation than physical adsorption).

The manner and strength of fixation is of great importance in relation to the possibility of remobilization, and is strongly influenced by parameters such as concentration, solubility, and speciation of the contaminants and co-solvents, and the prevalent pH, Eh and temperature conditions [10].

To select proper and effective sorption material for PRB, it must meet the following conditions: high sorption capacity, high selectivity for the target contaminants, fast reaction kinetics, high hydraulic permeability, long-term effectiveness, it needs to be non-harmful to the environment, available at reasonable costs [10], insoluble, not biodegraded, and easy to apply. Unfortunately, sorption material should be replaced and regenerated frequently due to effects of potential desorption or reversed ion-exchange [3]. This aspect makes adsorption barrier rather expensive and not attractive comparing to other types.

### **Biodegradation**

In the groundwater there are microorganisms which can decay hazardous hydrocarbons using them as a source of carbon and/or energy. Biodegradation of organic compound is a molecule alteration of hydrocarbons due to enzymes, leading to a formation of less or non-toxic compounds such as CO<sub>2</sub>, H<sub>2</sub>O, inorganic compounds and biomass. Benzene and phenol can be biodegraded according to the following reactions:



Sustained conditioning of the aquifer system generally is important for biological processes in PRB. Biodegradation process runs slowly, and in order to accelerate it a favorable condition should be created in reactive barrier. The most important factors that the biodegradation is dependent on are:





- concentration of oxygen in water ( $> 0.2 \text{ g O}_2/\text{m}^3$ ),
- concentration of nutrients in water (C:N:P = 100:10:1),
- temperature (15–45°C),
- redox potential (Eh  $> 50 \text{ mV}$ ),
- pH (6.5–8.0).

## METHODOLOGY FOR ASSESSMENT OF POSSIBILITIES OF USING PRB TECHNOLOGY

The crucial question in the case of contaminated groundwater is whether it is possible to use PRB technology in an effective way. Due to complexity of contaminants migration process in groundwater and treatment process in reactive material, PRB technology can be used in specific conditions and require (Tab. 1) [13]:

- identification of hydrogeological, geological and site conditions;
- characterization of contaminated groundwater;
- determination of PRB parameters, which cover: reactive material parameters, groundwater treatment parameters and geometrical PRB parameters.

Table 1. The procedure in the assessment of possibilities of using PRB technology [12]

Procedure stages	Hydrogeological, geological and site characteristics	Contaminated groundwater characteristic
Preliminary assessment of possibilities of using PRB technology	surface conditions: <ul style="list-style-type: none"> <li>- aboveground building and construction;</li> <li>- slope of ground;</li> </ul> ground and groundwater conditions: <ul style="list-style-type: none"> <li>- groundwater velocity;</li> <li>- underground building and construction;</li> <li>- aquitard characteristics* (homogeneity, continuity, thickness, depth, hydraulic conductivity);</li> </ul>	<ul style="list-style-type: none"> <li>- type and concentration of contaminants (possibility of using reactive material for the contaminants and necessity of use PRB);</li> <li>- spread of plume (depth);</li> </ul>
	condition of preliminary assessment (Tab. 3)	
	<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="text-align: center;">             decision of using PRB technology            acceptance         </div> <div style="text-align: center;">           resignation  </div> </div>	
Detailed assessment of possibilities of using PRB technology	<ul style="list-style-type: none"> <li>- precipitation quantity;</li> <li>- area, shape and volume of dumping site;</li> <li>- property of groundwater protection (e.g. cut-off wall, draining system);</li> <li>- hydrogeological property of aquifer and waste material (bulk density, hydraulic conductivity, porosity, dispersion parameters);</li> <li>- homogeneity, continuity, thickness and depth of aquifer and aquitard;</li> <li>- groundwater direction and velocity;</li> <li>- height of groundwater level;</li> <li>- property of surface water reservoir and other hydrological objects;</li> </ul>	<ul style="list-style-type: none"> <li>- type and property of waste material (according to acts of legislation);</li> <li>- hydrogeochemical background of groundwater;</li> <li>- physicochemical indicators of groundwater (e.g. pH, Eh, electrolytic conductivity);</li> <li>- type and concentration of contaminants in groundwater - selection the most hazardous chemical/s as a indicator for remediation (due to concentration, toxicity, etc.);</li> <li>- property of selected chemicals;</li> <li>- spread of plume of selected chemicals (width, depth);</li> <li>- allowable concentration of chemicals in according to acts of legislation;</li> <li>- emission time of contaminants into the ground;</li> <li>- presents of microorganisms;</li> </ul>
	assessment on the basis of groundwater filtration model and contaminants migration model	
	<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="text-align: center;">             decision of using PRB technology            acceptance         </div> <div style="text-align: center;">           resignation  </div> </div>	
Optimization of the PRB parameters	reactive material parameters	
	groundwater treatment parameters	
	geometrical PRB parameters	

\* - not assessed in case of LNAPI.



For this reason PRB technology can not be used for each groundwater area. There are some limitations which depend on many factors. Proper identification of those factors can help to decide whether this technology should be accepted or not. Complete assessment of possibilities of using PRB is expensive. Hence, it is suggested to use preliminary assessment during the initial stage of the procedure (Tab. 1), as it limits the range of the analysis to several most important elements.

To evaluate the technical possibilities of using PRB technology in selected groundwater areas, such preliminary assessment was performed in this study. Below are discussed preliminary assessment factors used in the initial stage of the procedure, which can help to decide whether this technology should be accepted or not (Tab. 1) [12].

The type and concentration of contaminants is the most important factor during the assessment of possibilities of using PRB technology. In this stage, on the basis of field and laboratory tests, it is evaluated whether effective, cheap and environmentally friendly reactive material for identified chemicals exists. There are reactive materials for both organic and inorganic chemicals. A compilation of laboratory and field research into chemicals treated with reactive material is provided in Table 2 [2, 14, 15]. It is divided into the contaminant groups (inorganic and organic), into the reactive material type, and finally into the type of the principal reaction which allows to remove contaminants.

The second important factor evaluated in the preliminary assessment is the depth of contamination. It depends on property of chemicals, hydrogeological and geological conditions and time when contaminants started migrate to the groundwater. The depth of aquitard and its homogeneity and thickness can allow to estimate vertical migration of contaminants, hence, it is a very important factor. Because of the cost and technical problem, the depth of aquitard should not be more than 15 m. LNAPL phase is an exception to this rule. This phase flows on the surface of groundwater, so reactive barrier can be "hanged" in aquifer [12, 13].

As one can see from Table 1 groundwater velocity is a next important factor evaluated during the preliminary assessment. Slow as well as high groundwater velocity can be unfavorable [13]. High groundwater velocity can require a thick treating zone to achieve allowable concentration of contaminants. It can cause PRB cost increase, as contaminants have to have enough residence time in reactive material to be removed below the allowable limits. Slow groundwater velocity can cause PRB not viable to use compared with other remediation methods. When possibility of using PRB is evaluated in the case of high groundwater velocity, the assessment depends on type and concentration of contaminants and type of groundwater treatment processes.

There are more other factors which can make PRB location difficult. Surface condition like above- and underground building and construction and slope of ground can disturb or make earth workings impossible, and in this way application of PRB technology can be unfeasible [5].

Table 3 presents the conditions for assessment of possibilities of using PRB technology in the initial stage of the procedure shown in Table 1. They may be helpful to decide whether this technology should be accepted or not for selected areas of contaminated groundwater located in Upper Silesia, Poland.

Table 2. The reactive materials used in laboratory or field test for different kind of contaminants [2, 14, 15]

	Contaminants	Reactive material	Type of reaction
Inorganic chemicals	arsenic (As)	activated alumina, bauxite	sorption or substitution barriers
	molybdenum (Mo), uranium (U), technetium (Tc), cesium (Cs)	activated carbon	
	uranium (U), technetium (Tc)	exchange resins	
	molybdenum (Mo), mercury (Hg), uranium (U), arsenic (As), phosphorus (P), selenium (Se), copper (Cu)	ferric oxides and oxyhydroxides	
	molybdenum (Mo), uranium (U), aluminum (Al), barium (Ba), cadmium (Cd), manganese (Mn), mercury (Hg), nickel (Ni), uranium (U)	magnetite	
	molybdenum (Mo), uranium (U), chromium (Cr), arsenic (As), lead (Pb), sulfate	peat, lignite, coal	
	molybdenum (Mo), uranium (U), technetium (Tc), lead (Pb), cadmium (Cd), zinc (Zn)	phosphates	
	aluminum (Al), barium (Ba), cadmium (Cd), manganese (Mn), mercury (Hg), nickel (Ni), uranium (U), strontium-90 (Sr), Arsenic (As), chromium (Cr), lead (Pb), selenium (Se)	zeolite	precipitation barriers
	chromium (Cr), Arsenic (As), sulfate, uranium (U), vanadium (V)	biota	
	molybdenum (Mo), uranium (U), technetium (Tc), arsenic (As), chromium (Cr)	ferrous hydroxide, ferrous carbonate, ferrous sulfide	
	molybdenum (Mo), uranium (U)	lime, fly ash	
	molybdenum (Mo), uranium (U), arsenic (As), cadmium (Cd), selenium (Se), sulfate	limestone	
	molybdenum (Mo), uranium (U), arsenic (As)	Mg(OH) <sub>2</sub> , MgCO <sub>3</sub> , CaCl <sub>2</sub> , CaSO <sub>4</sub> , BaCl <sub>2</sub>	
arsenic (As), manganese (Mn), molybdenum (Mo), selenium (Se), uranium (U), technetium (Tc), aluminum (Al), barium (Ba), cadmium (Cd), lead (Pb), nickel (Ni), technetium (Tc), strontium-90 (Sr), sulfate, nitrate, chromium (CrVI)	zero-valent metals	degradation barriers	
nitrate	biota		
nitrate	zero-valent metals		
Organic chemicals	cVOC	ferrous minerals	degradation barriers
	fuel hydrocarbons	ORC® compound	
	TCE	ultramicrobacteria	
	TCE, DCE, cVOC, PCB, nitroaromatics, VC, PCE, TCA, chlorophenols, CT, TCM, DCM, TCP, feron, DCA, CHCl <sub>3</sub>	zero-valent metals	sorption barriers
	TCE	zeolite activated carbon clays	
	BTEX, phenols, VOC, PAH	activated carbon	



Table 3. Preliminary assessment conditions for using PRB technology in effective way [5]

The group of factors	Factors	The conditions of using PRB technology	
Contaminant	type of contaminants <sup>1</sup>	possibility of treating contaminants (Tab. 2)	
	concentration of contaminants <sup>1</sup>	allowable concentration of chemical is exceeded (act of legislation) [11]	
Surface conditions	aboveground objects	absence of aboveground objects	
	shape of ground	shape of ground is even. Slope ground < 10°	
Ground and groundwater conditions	groundwater velocity - horizontal filtration (average seepage velocity)	velocity from 10 m/year to 500 m/year	
	underground objects	absence of underground objects	
	aquitard located under contaminated area <sup>2</sup>	depth	< 15 m
		thickness	> 1 m
		homogeneity and continuity	homogeneity and continuity of aquitard - well identified
hydraulic conductivity k		≤ 1,0 E-10 m/s	

<sup>1</sup> - conditions that exclude the possibility of using PRB technology,

<sup>2</sup> - not assessed in the case of LNAPL

Negative assessment in the case of the first two conditions related with contaminants (Tab. 3) exclude the possibility of using PRB technology. It can happen when it is not possible to remove contaminants from groundwater using known and available reactive material or when the allowable concentration of chemicals is not exceeded in accordance with the law regulation [11]. The first condition should be explained more. In the groundwater polluted by dumping sites there are often many types of chemicals. It can happen that for some of them there is not reactive material in PRB that could allow to remove them from groundwater in the effective way. So in some areas of contaminated groundwater, especially when there are no other decontamination methods and when these chemicals are non-toxic or slightly toxic, the designer can decide arbitrarily that PRB technology may be used in spite of its incomplete efficacy. The most important in this case is that using this technology toxic chemicals may be removed from groundwater and thus achieve better level of the environment quality. So lack of the possibilities of removing one or a few contaminants from groundwater does not mean PRB technology should be finally excluded.

If there were negative assessment in the case of other conditions presented in Table 3 it would not mean that PRB technology should be neglected, it could just increase expenses during the construction and/or could make this execution difficult. Thus, effective groundwater remediation using PRB technology means reaching a compromise on environmental requirements and financial and technical factors during execution of PRB construction.

After accepting of possibilities of using PRB technology as a result of preliminary assessment, the next steps in the procedure are (Tab. 1):

- I. detailed assessment of the possibilities of using PRB technology - by careful identification of area and contaminants,
- II. optimization of the PRB parameters [4].

Careful identification of contaminants and hydrogeological, geological and site conditions allows to create numerical models of groundwater filtration and contaminants

migration. The detailed assessment of the possibilities of using PRB technology is conducted on the basis of these models (they allow to visualize the results) and conditions presented in the paper [12]. The models are also the basis for geometrical PRB parameters optimization (Tab. 1) [4].

### ASSESSMENT OF POSSIBILITIES OF USING PRB TECHNOLOGY IN THE SELECTED AREAS OF DUMPING SITES LOCATED IN UPPER SILESIA, POLAND

In the study, the possibility of using PRB technology in two areas of dumping sites located in Upper Silesia, Poland was assessed on the basis of conditions presented in Table 3. Main types of wastes which were stored on the dumping sites are presented in Table 4. All the information's required for the assessment came from their technical documentation. Since the information about the name of the dumping sites and technical documentation are confidential the dumping sites were called by their numbers used in the study.

Table 4. Types of wastes stored on the selected dumping sites

No. of dumping site	Wastes
1	fly-ash and furnace slag, waste from treating sewage, used ion-exchange resins
2	toxic chemical wastes in a form of fluid and semi-fluid (main fluid waste contains phenols), fly-ash and furnace slag

In Table 5 for each assessed dumping sites were described:

- types of contaminants in groundwater,
- above- and underground conditions.

Table 5. Surface, ground and groundwater conditions and contaminants list for selected dumping sites areas

No.	Identified dumping sites factors	decision	
		P*	F*
1	contaminants: chromium(VI), cadmium, sulfate, zinc, potassium; allowable concentration of all presented chemicals is exceeded in accordance with law regulation [11]	yes	yes
	absence of above- and underground objects; shape of ground is uniform; slope ground < 10°	yes	
	aquitard located under contaminated area: depth – ca. 4.5 m, thickness – more than 10 m, homogeneity and continuity – well identified, hydraulic conductivity – ca. 5E-9 m/s	yes	
	average seepage velocity – ca. 70 m/year	yes	
2	contaminants: phenols, BTEX, zinc, lead, chromium(VI), nickel, arsenic, sulfate, magnesium, calcium, chloride; allowable concentration of all presented chemicals (except for magnesium and calcium) is exceeded in accordance with the law regulation [11]	yes	yes
	absence of above- and underground objects; shape of ground is uniform; slope ground < 10°	yes	
	aquitard located under contaminated area: depth – from 8 to 10 m, thickness – from 1 to 2 m, homogeneity and continuity – poor identified, hydraulic conductivity – ca. 8E-11 m/s	yes	
	average seepage velocity – ca. 20 m/year	yes	

\* P – partial assessment, F – final assessment

In that table the partial assessment of using PRB technology for each factor was given. The decision whether this technology might be accepted or not was given in a form of a final assessment in the last column of the table.

On the basis of the assessment presented in Table 5 it was affirmed that both areas of dumping sites are suitable for using PRB technology for treating contaminated groundwater. Unfortunately, in both cases, in the groundwater there are chemicals that are not possible to be removed using typical reactive material in PRB. These chemicals are presented in Table 5 in the form of underlined and bold text. However, potassium as well as calcium, magnesium and chloride are rather neutral to animals and human health and thus do not affect the environment.

In the case of dumping site no. 2 a bigger problem is connected with homogeneity and continuity of aquitard located under contaminated area. In spite of the decision that PRB technology can be used in the groundwater area of dumping site no. 2, there has to be measured continuity of that layer. If that aquitard was discontinuous or inhomogeneity it should be sealed by using e.g. injection technology.

In order to remove chromium(VI), cadmium, sulfate from groundwater located under dumping site no. 1 the zero-valent metals may be used in PRB as a material that cause precipitation of ions by redox reactions (Tab. 2). Granulated zero-valent iron is characterized by reduction property; hence, it may be used in the first segment of reactive barrier. As regards zinc it can adsorb on the surface of phosphates (Tab. 2). Thus this material may be used as a second segment in reactive barrier.

In the case of dumping site no. 2 a similar situation occurs. To remove lead, chromium(VI), nickel, arsenic, sulfate and zinc from groundwater situated under this object, there may be used granulated zero-valent iron and phosphates as well. But the biggest problem connected with this water is presence in it of phenols and BTEX. Allowable concentration of these chemicals is exceeded a few thousand times in accordance with law regulations [11]. The biochemical process is very effective for removing these chemicals from groundwater. But due to such a concentration it can not be used in PRB – phenols and BTEX in large concentrations are toxic to microorganisms. Therefore, granulated activated carbon is proposed to be used as a reactive material in PRB for removing of these contaminants from groundwater. This material is expensive but very effective (it may also stop other chemicals on its surface).

Because of the limited adsorbing capacity of the granulated activated carbon, it must be replaced and regenerated. In order to facilitate the temporary replacement of the activated carbon, the reactive barrier should be made of prefabricated units or filter columns.

## CONCLUSIONS

1. There are four types of processes which can be used in the reactive material. The processes are:
  - redox reaction – using that reaction the changing of toxic halogenated hydrocarbons into non-toxic hydrocarbons follows or the precipitation of a toxic ions takes place;
  - pH control – by changing pH conditions into neutral or slightly basic the precipitation of the toxic ion can appear;



- adsorption – using adsorbent material in aquifer the contaminants accumulate on the surface of it and are retarded with reference to groundwater flow;
  - biodegradation – molecule alteration of hydrocarbons due to enzymes, leading to formation of less or non-toxic compounds such as CO<sub>2</sub>, H<sub>2</sub>O, inorganic compounds and biomass.
2. As a result of the research it was found that PRB technology can be used in both areas of dumping sites. Zero-valent iron and phosphates are proposed to be used as a reactive material to treat groundwater in PRB for dumping site no. 1 and no. 2 as well. Moreover, due to the presence of phenols and BTEX in groundwater of dumping site no. 2 the granulated activated carbon is proposed to be used in its area as an additional (third) reactive material in PRB. Unfortunately, this material should be replaced and regenerated frequently due to effects of potential desorption or reversed ion-exchange. This aspect causes that adsorption barrier is rather expensive and difficult to execute. In order to facilitate the temporary replacement of the activated carbon, the reactive barrier should be made of prefabricated units or filter columns.
  3. The methodology presented in this paper was created for determining the technical feasibility of PRB construction. It is divided into: preliminary and detailed assessment of the possibilities of using PRB technology and optimization of the PRB parameters. The preliminary assessment is separated because it can be achieved with limited input of money.
  4. The conditions presented in Table 3 can be used as a basis for taking a decision whether PRB might be accepted or not in the initial stage of the assessment of possibilities of using PRB technology. The data needed for that assessment can be obtained from technical documentation of dumping site area and from the monitoring of groundwater. To sum up: the methodology presented in the article is a convenient and easy to use way for assessing the possibilities of using PRB technology.

#### LIST OF ABBREVIATIONS

BTEX	– benzene, toluene, ethylbenzene, xylene;
CT	– carbon tetrachloride;
DCA	– dichloroethane;
DCE	– dichloroethene;
DCM	– dichloromethane;
LNAPL	– light non-aqueous phase liquid;
ORC®	– oxygen release compound;
PCB	– polychlorinated biphenyl;
PCE	– perchloroethylene;
PAH	– polycyclic aromatic hydrocarbon;
PRB	– permeable reactive barriers;
TCA	– trichloroethane;
TCE	– trichloroethylene;
TCM	– trichloromethane;
TCP	– trichloropropane;
VC	– vinyl chloride;
VOC	– volatile organic compound;
cVOC	– chlorinated volatile organic compound.

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#### MOŻLIWOŚĆ ZASTOSOWANIA TECHNOLOGII PRB W OBSZARACH DWÓCH WYBRANYCH SKŁADOWISK ODPADÓW

W pierwszej części artykułu przedstawiono i opisano najczęściej stosowane procesy w barierze aktywnej technologii PRB. Do procesów tych należą: reakcje redox, wytrącanie przez regulację pH, adsorpcja oraz biodegradacja. Procesy te przebiegają w zestawionych w tabeli materiałach aktywnych. W drugiej części artykułu przedstawiono procedurę postępowania w ocenie możliwości zastosowania technologii PRB. Zaproponowano by w pierwszym etapie procedury przeprowadzać ocenę wstępną, która ogranicza zakres analizy do niezbędnych i najistotniejszych czynników. Przedstawiono warunki stosowania technologii PRB, które mogą być pomocne w podjęciu decyzji o akceptacji bądź rezygnacji z jej stosowania w początkowym etapie procedury. W artykule

wstępnie oceniono możliwości zastosowania technologii PRB dla dwóch wybranych obszarów składowisk odpadów zlokalizowanych na terenie województwa śląskiego w Polsce. Po zaakceptowaniu w ich obszarze możliwości stosowania technologii, zaproponowano dla obu z nich odpowiedni materiał aktywny pozwalający na skuteczne oczyszczanie wód gruntowych.