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PERMEABLE REACTIVE BARRIERS (PRBS) IN EUROPE: POTENTIALS AND EXPECTATIONS

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ABSTRACT

For European PRBs, which have been operated between 10 and at least 2 years now, an overall analysis has been implemented in order to come to a more accurate prediction of the actual general performance and reliability in their long-term run. Predominantly, German, Austrian, Suisse, French, UK and Danish PRB projects were appraised in order to come to reliable conclusions. Major overall results from the work of the German PRB research and development (R&D) network "RUBIN", funded by the Federal Government (BMBF), and from the works at the recently published French, UK and German PRB handbooks and guidelines, resp., are included/were taken into account.

INTRODUCTION

In Europe "efficiently controllable" PRBs (EC-PRBs) such as in situ vessels (ISV), Drain-and-Gate PRBs or significantly modified F&G technologies ("non-classical" F&G) are the preferred solutions in comparison to continuous reactive barriers (CRBs) in the U.S. The criteria supporting the first technological option are that the PRB can be configured to suit site-specific features and that monitoring and maintenance can be controlled more effectively. Some companies propose a maintenance strategy based on annual operations that can range from simple clearing of clogged sections to replacement of the reactive medium (particularly recommended for barriers based on the adsorption principle). This approach can only be considered if the design of the barrier allows easy access to the treatment reactor. This optimized maintenance strategy is sometimes backed up with guarantees on the performance of the barrier, usually over periods of 10 or 30 years.

PRBs in Germany, Austria and Switzerland

Five of the ten F&G-related systems are characterized by specially positioned or designed funnels and/or gates, e.g., relatively flat gates installed closely below ground level, or reactors receiving passively or even actively diverted/lifted ground water. Designers have provided versatile, partly highly sophisticated elements for actual and/or potential active measures in order to be able to exert extended control over the PRB during its operation, for instance by direct intervention into the installation. There are only two, relatively short CRBs in Germany so far, namely Reichenbach and Rheine (both do not exceed 25 meters in length, resp.), of which the Rheine PRB is a pilot installation that was placed inside a significantly broader plume. At Willisau, Switzerland, a full scale hanging CRB applying zero valent iron (ZVI) to treat a chromium(VI) contamination has been installed in early 2004.

Three different ZVI types ("Gotthart-Maier", "iron sponge" (ReSponge®), and "Hartgussstrahlmittel") or activated carbon have been the exclusively applied reactive materials in the field to treat chlorinated cVOCs and/or polycyclic aromatic hydrocarbons (PAH) in German PRBs so far. A full scale F&G provided with a biological treatment zone inside three gates for degradation of PAHs is scheduled to be set up at a contaminated site in Offenbach in 2007/2008. Despite the fact that the single Austrian PRB has performed apparently well and reliably over the first six years of its operational term, the interest in this technique seems to be still lukewarm in Austria. In Germany, however, PRBs have been recognized as potentially attractive alternatives to common active *in situ* ground water remediation techniques. Depending on their overall performance in meeting German clean-up goal standards, especially in the long-term, PRBs have the potential to gain broad acceptance that is still lacking. Hence, a German "capstone report" on PRBs as an established technology cannot be issued yet, because the development is currently in a transition state towards more applications (BURMEIER *et alii*, 2002; BIRKE *et alii*, 2002, 2003a, 2003b, 2004a, 2004b; RUBIN, 2006; SAFIRA, 2004). Extensive data are scheduled to be published in a comprehensive manner in the German compendium and guidance on PRBs in 2006, which is currently compiled by the "RUBIN" network/consortium in its final version, a PRB network of more than nine projects nationwide, funded by the Federal Government (BMBF).

GERMAN, AUSTRIAN AND SWISS PRBs: PERFORMANCE IN 2006 – AT A GLANCE

Bernau. Set up in 2001, partly actively working EC-PRB (reactor elements) (lifting of ground water by pumping), hence a sophisticated design (pilot scale, one reactor cell adjacent to ground surface, equipped with 18 oversized concrete columns), for addressing very high cVOC concentrations in two aquifers (> 100 mg/L TCE), ZVI;

clogging of ZVI by high amounts of $FeS_{(x)}$ and H_2, effects are scheduled to be scrutinized within the RUBIN PRB network until 2006 (potential impact for further sites with similar problems expected!) (BIRKE *et alii*, 2003a; RUBIN, 2006). TCE is efficiently degraded, however, cis-DCE is encountered at elevated concentration levels.

Bitterfeld. Set up in 1999, "SAFIRA" test site, EC-PRB, special Drain-and-Gate system/ISV (pilot scale), different reactive materials/processes (for testing); cVOCs and chlorinated aromatics (complex scenario), partly successful degradation of main contaminants (system is not designed for actually remediating the megasite Bitterfeld) (SAFIRA, 2004).

Denkendorf. Set up in 2001, Drain-and-Gate, shaft reactor/in situ vessel (ISV) (full scale, 90 m long gravel/filter pipe drainage), GAC; cVOCs, appr. 10 µg/L cVOCs left, i.e., clean up goal (< 10 µg/L cVOCs) accomplished (BIRKE *et alii*, 2003a; RUBIN 2006).

Edenkoben. Set up in 1998 (pilot scale), expanded to full scale in 2000, F&G (six gates), ZVI; cVOCs, no performance data available yet (BIRKE *et alii*, 2003a; RUBIN 2006).

Karlsruhe. A F&G system was installed in 2000 at the former manufactured gas plant site in Karlsruhe, Germany, for long-term remediation of a groundwater contamination by PAHs, Benzene and Vinylchloride (SCHAD *et alii*, 2000; BIRKE *et alii*, 2003a). The system consists of a 240 m long and 17 m deep funnel and eight gates. Approximately 10 l/s contaminated groundwater have to be treated with about 150 tons of activated carbon, for which regenerations cycles between 5 and 15 years, depending on the concentration of the contaminants, are expected.

Already a few months after setting up the Karlsruhe PRB, it was found that considerable amounts of ground water were constantly bypassing the system at its northern edge, resulting in an increase of PAH concentrations in some monitoring wells up to 100 µg/l. Since April 2003, PAH concentrations at the northern edge have been decreasing and have reached the remediation target value in the beginning of 2005. A theoretical study, which was conducted in 2004 and covered sophisticated modeling methods, revealed that the bypassing ground water was caused by pumping off ground water northward of the system in the inner city of Karlsruhe (due to independent sewer construction works over approximately two years). The same explanation applies to the observed PAH-increase in early 2005 (BIRKE *et alii*, 2004a, 2004b). Since the active pumping measure has ceased, bypassing ground water has never been observed any longer. Another effect had to be held responsible for the feigned malfunction of the system in the first three years of operation: In 2003, it was furthermore realized that several gates had been overflowed under normal conditions. It could be found out that this unexpected effect was due to missing seals at the top of these gates. In summer and fall 2003, due to very hot and dry weather conditions, a very low water table in Rhine valley, where the Karlsruhe is located, was encountered. Throughout this period, it could be verified that – as soon as the water level fell below the top of the activated carbon bed inside the gates – contaminant values downstream dropped significantly as originally expected. Therefore, until April 2004, all gates were slightly modified, hence the potential for further overflowing in the future could be eliminated entirely. Since April 2004, the clean-up efficacy of the entire system is close to 100%.

Kraichgau. Set up in 2001, "DHR" (combined cut-off wall and siphon system), GAC; cVOCs, working effectively (after shutdown of an insufficient P&T measure), i.e., removing more cVOCs than using before P&T), however, clean up goals are not accomplished yet.

Munich. Set up in winter/spring 2004, EC-PRB, ISVs (full scale, four gates), GAC; PAHs (former gas works plant) (BIRKE *et alii*, 2004a), performance data available in 2005 show a performance as expected.

Oberursel. Set up in early 2002, F&G (full scale, one gate), ZVI; cVOCs, no performance data have been made available or published at all so far (RUBIN, 2006).

Reichenbach. Set up in 2000, CRB (full scale, appr. 20 m long inside a manufacturing hall), GAC; mainly PCE, partly achieving remediation goal (cVOCs < 10 µg/L) (BIRKE *et alii*, 2003a).

Rheine. Set up in 1998, CRB (pilot scale, 23 m long inside a broader plume (plume is appr. 200 m wide)), two ZVI types packed apart into two segments: iron sponge (ReSponge®) and "Gotthart-Maier" iron mixed with pea gravel; main contaminant PCE, > 99 % PCE degradation a few meters inside the ReSponge® segment, i.e., German clean up goals (< 10 µg/L cVOCs) achieved, 70-90 % PCE degradation downstream of the "Gotthart-Maier"-segment (BIRKE *et alii*, 2004a, 2004b; RUBIN, 2006).

Tübingen. Set up in 1998, F&G (full scale, three gates), ZVI; cVOCs, malfunction, bypassing ground water verified, gates partly clogged and/or preferential flow paths, reasons not unambiguously understood yet (relevant work is underway/ongoing) (PARBS *et alii*, 2003). Potential gas clogging accompanied by mineral precipitation is being under intense scrutiny.

Brunn am Gebirge, AUSTRIA. 1999, EC-PRB, „AR&B"(= "Adsorptive Reactor and Barrier" system/ISV (full scale, four ISVs in accessible shafts), GAC; PAHs, BTEX, cVOCs, phenols, all contaminants below detection limits/remediation goals achieved since 1999 (Niederbacher 2001, Niederbacher 2004, PEREBAR 2003, Birke et al. 2004a, 2004b).

Willisau, SWITZERLAND. Set up in early 2004, hanging CRB (full scale, non-overlapping boreholes in two rows), ZVI; Cr(VI) (BIRKE *et alii*, 2004b), first results from spring 2005 verifiy good performance.

According to the national as well as the international development and the analyses of overall findings at various PRB sites worldwide, some general conclusions have temporarily been drawn in Germany so far: PRBs with a specifically directed ground water flow such as "Drain-and-Gate" or "Trench-and-Gate" look promising, because the hydrology is passively manipulated and controlled, therefore, regarding the flow towards the reactor, it is well understood in principle. Furthermore, PRBs equipped with ISV (EC-PRBs) which were inserted into accessible shafts look promising, because control/maintenance concerning the reactive material can be relatively readily exerted, if needed. Finally, PRBs employing activated carbon (AC) look promising, because it is a well-established reactive (sorptive) material, deployed in a variety of other clean-up processes. It can be advantageously combined with other materials like ZVI in PRBs, and it can treat a variety of different ground water contaminants, even when encountered in complex mixtures and in difficult ground water environments (high hardness, high sulfate etc), both successfully and economically. Moreover, positive findings at several CRB sites worldwide, especially at the Rheine PRB (CRB = *no* ground water control) and re ISV/Shaft Reactors plus Drainage (EC-PRBs = *very high* ground water control), equipped with GAC or particularly effective ZVI such as ReSponge®, imply that both these systems seem to have a promising future. However, "classical" F&G systems are apparently losing ground, because they may exert unpredictable influence on the ground water flow regime, even if a thorough modeling was implemented. If a malfunction occurs, e.g., by clogging of the reactive material or bypassing ground water, they often permit neither extended nor cheap investigation, control and/or intervention/repair regarding the particular damage, due to intrinsic hindrance re "active repair" related to their special design. EVERY PRB System that ensures a PLUG FLOW of the contaminated ground water towards its reactor(s)/reactive zones may be successful (JEFFERIS 2002, BIRKE *et alii*, 2004). We ought to be not allowed to hold any planning/engineering failure entirely responsible for every malfunctioning PRB (although they do occur). Actual scientific or other unambiguous evidence is needed. Chemical processing engineers and hydrogeologists ought to be consulted to a greater extend than until today in order to clarify current PRB issues.

EUROPE´s FIRST ZVI PRB AND IN-GROUND REACTOR

In 1994, Europe's first ZVI PRB and the first PRB to use an in-ground reaction chamber (in-ground reactor) was erected at an operational industrial site in Belfast which was used for the manufacture of electronic components. Although the design has been widely adopted and developed, it should be recognised that the initial concept was advanced to meet specific constraints of the original site setting. Historic spillages of chlorinated solvents had led to an intense though localised contaminant source. Details of the site setting and initial performance of the reactor are given in JEFFERIS *et alii* (1997). The principal contaminant at the site was trichloroethene (TCE) and the highest identified concentration was 390 mg/litre. Other chlorinated solvents were present but at much lower concentrations

The iron filings technology seemed to have potential for the Belfast site and samples of the site groundwater obtained from sampling wells were shipped to EnviroMetal Technologies Inc., Waterloo, Canada for column treatability studies (reported in THOMAS *et alii*, 1995). The tests suggested that a residence time of about 12 hours was necessary to ensure that vinyl chloride, a degradation by-product did not leave the reactor above regulatory limits (the TCE could be degraded to below detection limits in one tenth of this time). Significant questions were the flow rate through the reactor and the factor of safety should be allowed to convert from laboratory estimated residence time to field values.

Design of the Reactive System. In Belfast, the site geology and location placed a number of restraints on the reactor design:

- the contaminant source extended to within a few metres of the site boundary, outside the boundary there was a public road and it was not practicable to extend the reactive zone into the road. The reactive treatment zone therefore needed to be very compact.
- the solvent source was underlain by a thin layer of clay which had prevented its migration to greater depth. If this layer were penetrated by a reactive gate the free solvents would sink and pollute a lower aquifer stratum. Though ultimately they would be retained by a thick clay layer at about 10 m depth which underlay the site and dipped towards the proposed funnel.
- the groundwater perched on the thin clay layer was shallow and showed seasonal variations in depth. It would be difficult to achieve any significant depth of horizontal flow in a reactive treatment zone without deepening the gate and thus penetrating the underlying thin clay layer.
- a perched water table also existed in the fill covering the surface of the site. In wet seasons, if allowed to enter the reactive treatment zone, this water could dominate flow through it and unacceptably reduce the residence time. It therefore had to be prevented from entering the reactive zone.
- proximity to buildings and cost prevented the use of sheetpiles to form the reaction chamber and the funnel of the funnel and gate system (at the time all previous reactors had been formed within sheetpile boxes).
- if a slurry trench cut-off were used to form the funnel then it was imperative that the iron filings should not be inundated and blocked by slurry. The iron would have to be contained or slurry wall constructed first.
- excavation next to a slurry wall, to install a reactive treatment zone, could cause local collapse of the cement-bentonite and/or a poor seal between the wall and the iron filings. It would be undesirable to have the possibility of a preferential flow path at this interface.
- the clean-up was being undertaken voluntarily and was not driven by regulatory requirements. It was therefore particularly important that those working on or adjacent to the project should not be exposed to contamination and early in the design study it was decided that there should be no hand excavation of contaminated soil or work near it, for example to form or fill the reactor. Personal protective equipment could have enabled hand excavation but the risks were deemed inappropriate for a voluntary remediation.

After consideration and rejection of many reactive treatment zone designs the in-situ reactor configuration shown in Figure 1 was developed as best fitting the site constraints. In place of the previously used horizontal flow reactive treatment zones the flow was arranged to be vertical, in a 12 m tall by 1.2 m diameter steel reactor shell which was filled with iron filings as shown in the figure. This design enabled the reactor to be placed between the contamination and the site boundary. This could not have been achieved with a horizontal flow regime as the design calculations had shown that the flow path length needed to be at least 5 m plus entry and exist zones to collect and disperse the flow.

The reactor was placed in an enlargement in a cement-bentonite cut-off wall which was used to funnel the flow to the reactor (see Figure 2). This wall was toed into the deep aquiclude layer and the enlargement was taken to a depth of slightly over 12 m to accommodate the reactor shell. The cut-off and enlargement penetrated through the clay layer on which the chlorinated solvents were retained. However, as the cut-off material was designed to have a permeability of $<10^{-9}$ m/s minimal downward migration of solvents will occur. The vertical flow direction within the reactor ensured that the full depth of the iron filings was saturated whatever the seasonal variation in groundwater level. The piping of the flow into the reactor and the change of direction from horizontal to vertical flow will tend to homogenise the flow both in terms of concentration and across the cross-sectional area of the reactor. Flow heterogeneity across a reactor can seriously comprise its performance (JEFFERIS, 2002).

- Because of the relatively low permeability and heterogeneity of the adjacent soil it was decided that the flow to the reactor should be collected via an upstream, high permeability, collector and that downstream of the reactor there should be a similar distributor. The collector and distributor were formed from gravel filled piles taken down to the top surface of the thin clay layer and capped with clay to prevent surface water ingress. A polymer supported, gravel backfilled, slurry trench was the preferred construction expedient to form the collector and distributor but in 1994 there were still concerns about the effect of polymer remaining on the iron filings and as there was insufficient time to carry out the necessary research augered piles were used.
- The reactor was fitted with sampling points at 1.5 m intervals throughout the iron filings bed depth so that its performance could be monitored. Monitoring points were also installed in the collector and distributor piles.
- Iron filings in contact with water in an oxygen free environment produce hydrogen. This hydrogen was vented from the reactor via a vent tube fitted with a spark arrester and mounted in a tall lighting standard.
- Finally the internal geometry of the reactor was arranged so that the pipework connections to the gravel filled collector and distributor piles could be made from within the clean environment of the reactor shell without the need for any hand excavation or for anyone to enter the excavations all of which were undertaken with a backhoe under cement-bentonite slurry so as to minimise the escape of solvent vapours or in open hole with an auger. During the works airborne solvent concentrations were monitored and found to be undetectable.

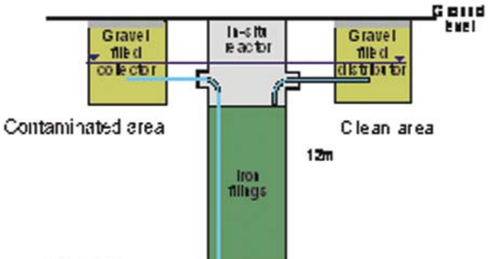

Figure 1

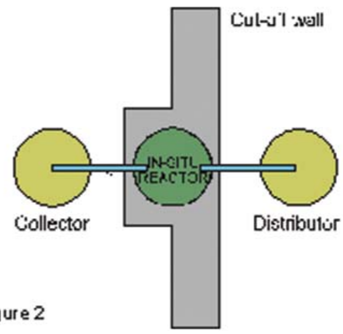

Figure 2

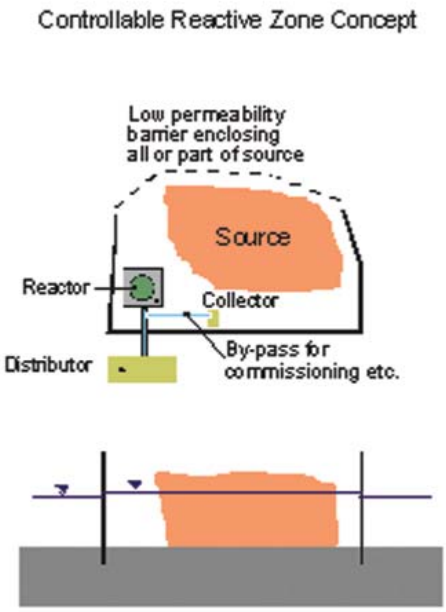

Figure 3

Figg. 1, 2 and 3 - Cross sectional view and overview of the Belfast PRB

Performance. The reactor has performed as designed and there has been substantial reduction in the source and the downstream plume. A major uncertainty at the design stage was the flow through the reactor and field measurement proved difficult. Tests were undertaken with several tracers materials. When successful, these showed that there was spare flow capacity in the reactor – the first in-ground reactor had been designed with a reasonable factor of safety. However, this spare capacity was not wasted, rather it was exploited to treat water pumped from the plume downstream of the reactor – a plume of contaminant had developed prior to installation of the PRB. This proved very effective and significantly reduced the extent of the plume.

Lessons Learned. The in-ground reactor installed in a slurry cut-ff wall was the best solution to meet the constraints of the land ownership, pollution source and geology of the particular site. Those working on potential future PRB sites need carefully to consider the constraints of their sites. PRBs are not a 'one design fits all technology'. However, adoption of the in-ground reactor concept brings many engineering benefits and the design has been widely used elsewhere. No doubt, others were thinking along similar lines in 1994 but have the benefits and problems of the-ground reactor been fully recognised? These include:

- The in-ground reactor provides a controlled reactor zone – a basic tenet of chemical engineering is that there should be a controlled/controllable zone.
- Homogenisation of the flow to provide a more uniform concentration – achieved by collecting the flow and piping it to the reactor – i.e. separating the flow collector and the reactor. Achieving uniform flow across the full cross-section of a reactor is extremely difficult at low bed velocities. Homogenisation also is helped by the change of flow direction from horizontal to vertical.
- The vertical orientation allows the use of greater flow path length to cross-sectional area ratio thus reducing the potential for short circuiting – flow concentrating in high flow pathways due to slight heterogeneities in the bed. However, it must be accepted that, short-circuiting remains a serious issue in PRB design because of the very flow rates (long residence times) required for many PRB reactive materials.
- Estimation of the input flow to PRBs is a major problem – especially for in-ground reactors as the reactor volume is likely to be constrained. The author's experience with Belfast and several other PRBs is that the present modelling techniques although good at providing flow directions and groundwater contours are soft when it comes to predicting flow rates. The PRB designer has still to accept a wide range of credible flowrates from the modeller – and design for this range.
- As the cost of a PRB is directly influenced by the flow rate better prediction procedures are required. Also site pumping test protocols must be refined.
- In-ground reactors are good for sites where the flow is expected to be low to moderate. A present challenge is to design in-ground reactor system for sites where the groundwater flow may be large – or large for part of a year.
- however, it should not be assumed that better modelling and testing will provide all the answers. The flow through a PRB will vary seasonally and over longer timescales because of changes to the groundwater regime resulting from developments around the site and in the watershed and climatic changes. The risk assessment for a PRB must consider these factors.
- a PRB may accumulate contaminants as well as destroy them. Decommissioning must be considered in the design at the outset (CAREY *et alii*, 2002).
- In Belfast the reactor was installed in an enlargement in a cement-bentonite cut-off wall. This was necessary because the source of the contamination was very close to the site boundary. For later projects, the reactor has been placed inside the cut-off wall with only a pipe taken through the wall. This can be significantly cheaper and ensures that the contamination remains within the funnel.
- On some sites it may be advantageous to pump the flow to the reactor. This can ensure a more uniform flow rate but it has to be demonstrated that there will be effective plume capture under all seasonal groundwater conditions.

Conclusions. The concept of an in-ground reactor adds further flexibility to the design of reactive treatment zones, allowing more precise control of the reaction environment and easy chemical recharging or recovery and replacement of the active material should this be required. Also several reactors may be linked in series to treat mixed contaminants.

The use of in-ground reactors allows the full armoury of chemical engineering reactor technology to be applied to what is often regarded as a civil engineering / environmental science problem. This will bring many new ideas.

Significant remaining problems are: the design of in-ground reactors for high flow situations and the monitoring of PRB performance. If costs are to be kept to the minimum, monitoring intervals must be as long as possible – this requires confidence in PRB performance and proactive design for long monitoring intervals. In steady state, PRB performance can be modelled and sampling within a reactor system may allow confidence that performance will remain satisfactory for months / years to come. However, there can be complicating factors such as desorption of contaminants as a result of competitive sorption between contaminant species leading to release of sorbed contaminants as rather short spikes at concentrations higher than their original input concentrations. Procedures need to be developed to identify impending changes.

STILL EXISTING BARRIERS FOR A BROADER IMPLEMENTATION OF PRBs IN EUROPE

Although the first North American PRB installations were mainly of the funnel & gate type, the continuous wall is now the preferred solution here. One of the main arguments in its favour is its lower sensitivity to design flaws. This means less risk in complex sites with heterogeneous pollutant pathways and distribution (which in turn simplifies the characterisation phase). In Europe, however, modified F&G and EC-PRBs are the preferred solutions. The criteria supporting this technological option are that the PRB can be configured to suit site-specific features and that monitoring and maintenance can be controlled more effectively. Some companies propose a maintenance strategy based on annual operations that can range from simple clearing of clogged sections to replacement of the reactive medium (particularly recommended for barriers based on the adsorption principle). This approach can only be considered if the design of the barrier allows easy access to the treatment reactor. This optimised maintenance strategy is sometimes backed up with guarantees on the performance of the barrier, usually over periods of 10 or 30 years.

Sequential treatment of pollutants. In principle, PRBs can be used to treat different pollutants, by means of sequential processes involving different reactive media (multi-barrier concept). Europe-wide results show that sequential treatments are mainly in the pilot stage or emerging (such as performed by the SEREBAR network in the UK). However, several PRBs are being used to treat a combination of pollutants by means of a single reactive medium, the one constraint being that the reactive mechanism involved has to be adapted to the pollutants concerned. Fe treatment can be applied both to degrade chlorinated solvents (reductive dehalogenation) and to reduce Cr^{VI} in Cr^{III} (as in the example of the Kolding barrier in Denmark). Working on the same principle, an active carbon filter based on the adsorption principle can be used to treat organic pollutants in combination (hydrocarbons, PCB, PAH, etc.). These examples show that treating a given combination of pollutants does not raise any major problems when only a single type of reactive medium is used. However, the situation is very different when several reactive media are used in sequence. It then becomes difficult to design and manage the hydraulics of the system (head loss) and its reactive behaviour (kinetics). Although it is possible, in theory, to combine several reactive media (especially with F&G configurations), the analysis of industrial projects shows that the multi-barrier solution is still in the laboratory concept stage, with no industrial-scale transfer occurring as yet.

Maintenance and longevity. Although the PRB concept itself can be validated in view of past experience, its longevity and long term performance cannot yet be fully assessed, nor is it possible to identify an exact maintenance strategy. This is undoubtedly a barrier to further development of the technique. Ten years of experience are still clearly inadequate in view of the lifetimes under consideration (30, 40 or 50 years). The problem of lack of hindsight is compounded by the difficulty of capitalizing on experience with existing projects (lack of communication on failures, problems with keeping up monitoring procedures after several years of operation, etc.).

Economic aspects. The total cost of a barrier (capital investment plus operational and maintenance costs) is not the only criterion at issue. A comparative analysis of different solutions will also depend on the financial situation of the organization responsible for the site and its management strategy (transfer or upkeep, use for industrial purposes or not, etc.). Initial investment capacities and available cash flow for the years ahead can also be important factors in the choice of technology. Some may give preference to a technology with high initial investment costs and low operational costs, while others may prefer the reverse.

It is generally agreed that PRB treatments involve higher investment costs than active systems (P&T), but lower operating and maintenance (O&M) costs. Consequently, the ultimate cost of a PRB system can be lower than for a P&T system after a few years. Where the profitability threshold actually lies depends directly on O&M costs, and especially on the service life of the barrier, both in terms of the chemical reactivity of the medium and its hydraulic performance. When determining the cost of a barrier and assessing the profitability threshold, the critical variable is the barrier's longevity, or in other words the scale and frequency of maintenance on the reactive medium.

An indepth analysis performed by French researchers of North American and European PRB projects shows the importance of factors of scale in determining capital investment costs (site characterization, design of the PRB, purchase of the reactive medium and construction of the barrier, plus any licence fees). Standard investment costs, calculated according to the barrier's surface area (length x depth) usually amount to less than 3000 □/m². Where the surface area is very large (>1000 m²), costs drop to less than 1000 □/m². In projects with a surface area of more than 1000 m² (15 altogether), average investment costs amounted to 780 □/m². The lowest costs were around 150 to 200 □/m².

Regulation. European approaches to the question of polluted sites and soils are highly diverse. Only a few countries have developed specific legislation to address the issue, and no country in Europe has any specific approach or regulations concerning PRBs. French regulations on polluted sites are set out under the overall framework provided for under the 19 July 1976 ICPE Act (no. 76-663) on designated installations requiring environmental protection measures, the 21 September 1977 decree (no. 77- 1133) bringing the Act into effect, and the Water Act of 1999. These fundamental items of legislation (and their links with the legislation on water) therefore govern the various statutory provisions applying to the installation of a PRB, especially with regard to prescribing and defining rehabilitation objectives.

Characteristics specific to Europe. Although the PRB concept first emerged in North America, our study shows that European projects have also played a part in the development of this technology.

After two early projects in 1994/1995 (full scale ZVI EC-PRB in Belfast, UK, and A22 motorway, France), the technique was developed in 1996 and began to take off in 1998 (first German full scale PRBs). The total number of European projects is estimated at 35, including just over 20 on an industrial scale. A number of European companies are offering sophisticated and proven technical solutions, and numerous R&D projects are under way, ranging in scale from laboratory tests to pilot installations.

The main weakness at European level is undoubtedly a lower level of communication and exchange, especially in the organization of R&D efforts as they do not produce sufficient communication on operational projects. This lack of communication gives rise to:

- difficulties in building on experience;
- a lack of information among the various parties involved (including site owners, decision makers, technology developers, contractors, regulators). This may result in the implementation of inappropriate and ineffective processes at sites that may be particularly suited to PRB technology (P&T treatment of chlorinated solvent plumes whose sources are diffuse and not accurately located) or, conversely, in choosing a PRB option for sites where this is inappropriate;
- a lack of co-ordination at the national and European level which do not permit rationalizing both R&D efforts (including demonstration projects) and development of innovative industrial solutions.

The most active and most efficiently organized networks are SEREBAR in the UK and RUBIN in Germany. RUBIN is scheduled to be extended into 2009-2010, i.e., additional funding from the Federal Government will be provided in Germany for some new PRB projects and for further investigations at old installations showing problems in oder to clarify last open issues.

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