CL:AIRE

SAB 1
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sabre bulletin

CL:AIRE SABRE bulletins describe specific, practical aspects of research from the LINK Bioremediation Project SABRE, which aimed to develop and demonstrate the effectiveness of *in situ* enhanced anaerobic bioremediation for the treatment of chlorinated solvent DNAPL source areas. This bulletin describes an overview of the SABRE project, with key project topics presented in more detail in previous and forthcoming CL:AIRE publications.

Project SABRE (Source Area BioRemediation) – an Overview

1. INTRODUCTION

Project SABRE was a five-year collaborative project undertaken by a multidisciplinary team from the UK, USA, and Canada, supported through the DTI Bioremediation LINK programme. Its objectives were to demonstrate that *in situ* enhanced anaerobic bioremediation can result in effective treatment of chlorinated solvent dense non-aqueous phase liquid (DNAPL) source areas and to improve related site investigation tools and process understanding. An important feature of the SABRE programme was the field application of DNAPL partitioning electron donor to the source zone to provide a source of electron donor at the DNAPL:water interface. The SABRE project is one of the most detailed demonstrations of its kind, and the first scientifically robust development of *in situ* bioremediation of a chlorinated solvent source zone in the UK.

This document presents an overview of the SABRE project. Key project topics are described in previous and forthcoming CL:AIRE publications (Table 1). The CL:AIRE and Environment Agency-funded Streamtube project (CL:AIRE Research Project 14) ran in parallel with SABRE, at the same site, and results from that study are reported in part in CL:AIRE SABRE Bulletin 5 and in CL:AIRE Research Bulletin 11.

Table 1. SABRE-related publications from CL:AIRE.

Bulletin Type	Title
Research Bulletin 6	Results of a laboratory microcosm study to determine the potential for bioremediation of chlorinated solvent DNAPL source areas
SABRE Bulletin 1	Project SABRE (Source Area BioRemediation) – an overview (this document)
SABRE Bulletin 2	Site investigation techniques for DNAPL source and plume zone characterisation
SABRE Bulletin 3	Results of laboratory column studies to determine the potential for bioremediation of chlorinated solvent DNAPL source areas
SABRE Bulletin 4	Insights and modelling tools for designing and improving chlorinated solvent bioremediation applications
SABRE Bulletin 5	Overview of the SABRE field tests
SABRE Bulletin 6	Source area DNAPL bioremediation: Performance monitoring and assessment
Research Bulletin 11	Streamtube project overview: Longitudinal transect assessment of the SABRE site DNAPL source zone

2. THE CHLORINATED SOLVENT DNAPL PROBLEM

Tetrachloroethene (PCE) and trichloroethene (TCE) are chlorinated solvents that have been used extensively in industry and are common groundwater contaminants (Environment Agency, 2003). Their limited aqueous solubility often leads to the presence of DNAPL source zones at contaminated sites that can be a long term source of groundwater contamination. DNAPL releases may result in persistent contaminant source areas due to mass transfer limitations from the organic phase, and therefore low risk-based targets.

Under anaerobic conditions, PCE and TCE may be biodegraded via reductive dechlorination (biologically-mediated step-wise replacement of chlorine with hydrogen) to form ethene, which poses no unacceptable risks at the concentrations arising. This microbial activity is commonly used in the treatment of dissolved-phase TCE plumes. However, reductive dechlorination has also been observed at concentrations associated with the presence of DNAPL (typically >10% of aqueous solubility), indicating that reductive dechlorination may be a viable *in situ* treatment in TCE DNAPL source zones (Harkness et al., 1999). In contrast to treatment of a dissolved phase, the primary goal of bioenhanced DNAPL treatment is to achieve and maintain a high flux of contaminant from the DNAPL and sorbed phases to the aqueous phase and couple this to dechlorination near the DNAPL:water interface and within the plume (Aulenta et al., 2006). This is achieved by increasing the aqueous phase TCE concentration gradient close to the interface through enhanced biodegradation of the dissolved compounds. The flux is further enhanced because the aqueous phase solubilities of the reductive dechlorination intermediates (cis-1,2-dichloroethene (cDCE) and vinyl chloride (VC)) are higher than that of the parent PCE and TCE (ITRC, 2005). Use of electron donors that partition into the DNAPL phase and then slowly dissolve back into the water phase have been shown in laboratory studies to provide optimum conditions for dechlorination to occur at the DNAPL:water interface and thereby enhance dissolution (Yang and McCarty, 2002).

3. PROJECT BACKGROUND

Project SABRE was a logical incremental development from the work performed by the US-based RTDF (Remediation Technologies Development Forum) Bioremediation of Chlorinated Solvents Consortium (see: http://www.rtdf.org). The consortium's demonstration of the effectiveness of biostimulation in treating PCE and TCE plumes at Dover Air Force Base, Delaware (Ellis et al., 2000) and at Kelly Air Force Base, Texas (Major et al., 2002) has led to wide uptake of those technologies inside and outside the US. The Project SABRE team included a number of core members of that consortium, therefore the project benefited from the circa $15M investment in earlier applied research. Wider UK membership, including the British Geological Survey and several UK universities and consultancies, ensured maximum transfer of learning to the UK and clear exploitation paths.

The LINK Bioremediation programme was founded following the Joint Research Council Review of Bioremediation Research in the UK (1999). One of the recommendations was the development of a "fully integrated multidisciplinary research initiative" and in April 2001 it was launched with the vision to "help provide UK industry with the multidisciplinary capability necessary to enable the commercial application of bioscience for the clean up of contaminated land, air and water". Over 50 outline proposals and 14 full proposals were reviewed to arrive at a diverse portfolio of 12 projects with topics including sequenced reactive barriers, phytoremediation, laboratory methods for assessing bioavailability and of course both *ex situ* and *in situ* bioremediation technologies. These projects received over £5M of funding towards total project costs in excess of £11M over the period 2001-2009 having contributed 8 years of knowledge and experience to the benefit of UK plc. Programme sponsors included BBSRC, BERR, Environment Agency, EPSRC, NERC and the Scottish Government. DTI's LINK Bioremediation funding scheme therefore offered the SABRE project team an opportunity to undertake a project in the UK, with match-funding from the UK government.

The focus of the SABRE project has been the field demonstration of enhanced bioremediation of the source zone by application of DNAPL-partitioning electron donors. A former chemical manufacturing plant in the East Midlands hosted the project, where a DNAPL source zone, comprising mostly TCE, is present. Use of TCE began in 1963 and ceased during the late 1980s.

Near-surface geology at the site, beneath Made Ground, comprises Alluvium (1 to 2.5 m thick) overlying River Terrace Gravels (3 to 5 m thick) over Mercia Mudstone Formation (>60 m, weathered near the surface) (Lelliott et al., 2009). A DNAPL phase comprising approximately 71% trichloroethene (TCE) (with minor pentachloroethane, 1,2 dichloroethene and tetrachloroethene) had penetrated both of the superficial formations and approximately the uppermost metre of the Mercia Mudstone. Concentrations in the sediment approached 80 g/kg (about 20% of residual saturation for this formation). Total source mass estimates ranged from 5 to 16 tonnes. DNAPL was observed to be heterogeneously distributed within both the Alluvium and River Terrace Gravels. In some areas, high DNAPL saturations were observed at the base of the River Terrace Gravels, suggesting previous migration along the interface with the Mercia Mudstone. A plume of TCE contamination was identified in groundwater downgradient from the source zone. Plumes of cDCE, VC, and ethene were also observed, demonstrating spatially variable degradation of TCE migrating from the source.

To achieve the objectives of the project, the 15 industrial and research partners were coordinated into seven multidisciplinary work packages. These included (1) site investigation (characterise the field site before and after treatment), (2) laboratory research (microcosm and column tests to determine the optimal conditions for the bioremediation process), (3) field engineering (test cell design, installation and operation), (4) performance assessment (traditional and novel techniques for evaluating success), (5) flow and process numerical modelling (development of tools to aid in design, results interpretation, and assist future technology implementation), as well as a project management team and dissemination committee. A Scientific Advisory Group – consisting of three leading academics in the field – was also appointed to help guide the project and ensure the highest scientific standards were maintained.

4. OVERALL CONCLUSIONS

4.1 Demonstration of the Technology in the Laboratory

Microcosm experiments were performed in triplicate by four laboratories (DuPont, GE, SiREM and Terra Systems) to select the most appropriate electron donor (energy source for the bacteria) and to determine if nutrient addition and bioaugmentation with a TCE-degrading bacterial culture would enhance reductive dechlorination (Figure 1). Results showed that, in groundwater from the site, reductive dechlorination of TCE to ethene was possible at high TCE concentrations (above 500 mg/L in the aqueous phase) associated with a DNAPL source zone (CL:AIRE Research Bulletin 6). Addition of an electron donor, bioaugmentation with KB-1™ culture and addition of nutrients (diammonium phosphate and yeast extract) all increased the rate of reductive dechlorination, and increased the likelihood that the process would reach the ethene end-point. Emulsified soya oil, methanol and lactate were found to be the most effective electron donors. However, emulsified soya oil is both a partitioning donor and has substantial practical benefits when used in the field. Its chief practical benefit is that it can be delivered to a target treatment zone, where it becomes immobilised and serves as a long term source of electron donor due to its low solubility. Properly applied, it can substantially reduce operational and maintenance costs relative to a soluble/mobile donor. Therefore, emulsified soya oil was carried forward to the field application.

Figure 1. Subset of the more than 130 microcosm experiments conducted with site soil and groundwater (CL:AIRE Research Bulletin 6).

Soil column experiments were performed by three laboratories (GE, SiREM and DuPont). Their aims were to: understand the physical-chemical behaviour of partitioning donors in flow systems, estimate the extent of DNAPL dissolution enhancement created by the bioremediation process, determine the effects of sulphate from the Mercia Mudstone on dechlorination, and develop kinetic data to support the modelling efforts.

The column experiments demonstrated that the emulsified soya oil effectively partitioned into the TCE DNAPL and persisted in promoting long-term dechlorination without causing clogging (CL:AIRE SABRE Bulletin 3). Enhanced dissolution of the DNAPL source was observed and DNAPL depletion rate was enhanced by a factor of approximately two. Addition of the emulsified soya oil to columns that did not contain TCE DNPL but that were fed high concentrations (e.g. 250 mg/L) of aqueous phase TCE demonstrated that TCE could be completely dechlorinated to ethene at residence times of around six days. Finally, the column experiments demonstrated that detrimental pH shifts were possible during very high rate reductive dechlorination but that these shifts could be mitigated with bicarbonate addition. Results from the column experiments also allowed the development and calibration of numerical models used to develop new quantitative understanding of the dechlorination process (see Section 4.5 below).

4.2 Source Zone Characterisation

The innovative "Triad" approach to site investigation was used to rapidly assess the site condition and the locations of DNAPL sources, to facilitate accurate detailed investigation and cell design. A three-week long dynamic work strategy for DNAPL characterisation was established using the following methods.

- Electrical resistivity tomography (ERT) supplied qualitative spatial data on the topography of geological surfaces and the locations of underground structures.
- Combined membrane interface probe (MIP) and electrical conductivity (EC) profiling supplied qualitative data on the spatial and vertical distribution of contamination and depths of geological interfaces.
- Core sampling supplied quantitative data on the spatial and vertical distribution of contamination, organic carbon, residual porosity and the locations of geological interfaces. Sudan IV tests on cores supplied qualitative data on the spatial and vertical distribution of DNAPL.

CL:AIRE SABRE Bulletin 2 fully describes how qualitative and quantitative data were used in combination to assess spatial heterogeneity and inform the siting of the SABRE cell. To summarise, ERT, MIP and EC data were used to guide and inform the ongoing site investigation process as they are rapidly-deployable techniques which do not require laboratory analyses yet still provide decision-quality data. This allowed a potential cell location to be identified rapidly, so that coring could be guided to the optimum locations for gathering relevant information.

4.3 Test Cell Construction, Monitoring, and Testing

For the field pilot test, a rectangular cell was constructed 30 m long by 3 m wide, with its long axis approximately aligned with the prevailing hydraulic gradient (CL:AIRE SABRE Bulletin 5). The cell intersected a DNAPL source area. Plastic sheet piles were used to construct the cell and were keyed into the top of the Mercia Mudstone to effect containment (this was the first time that plastic sheet piles were used in the UK). The cell was open at the upgradient end and closed at the downgradient end. At the influent end of the cell, a system of abstraction and injection wells were used to homogenise, and control the rate of, influent groundwater. At the effluent end, abstraction wells removed the groundwater: in this way the residence time within the cell (nominally 45 days) could be controlled. Containment of the cell permitted hydraulic control to be established over the source area so that accurate contaminant mass balances could be computed for dissolved contaminants.

A dense monitoring network was installed in the cell, including two multi-level sampling fences oriented perpendicular to flow (Figure 2), results from which were used in conjunction with point hydraulic conductivity measurements to compute contaminant mass discharges, decay rates and mass flux distributions (CL:AIRE SABRE Bulletin 6). Standard fully screened monitoring wells were installed so that "traditional" concentration and mass flux monitoring results could be compared. Two grids of electrodes were incorporated into the multi-level devices to allow comparison of chemical and geophysical (ERT) monitoring techniques (Wilkinson et al., 2008). Boreholes constructed for injection of electron donor and bioaugmentation at the source zone were also monitored. In addition, the Streamtube monitoring network provided further information on 2D distribution of contaminants parallel and perpendicular to flow.

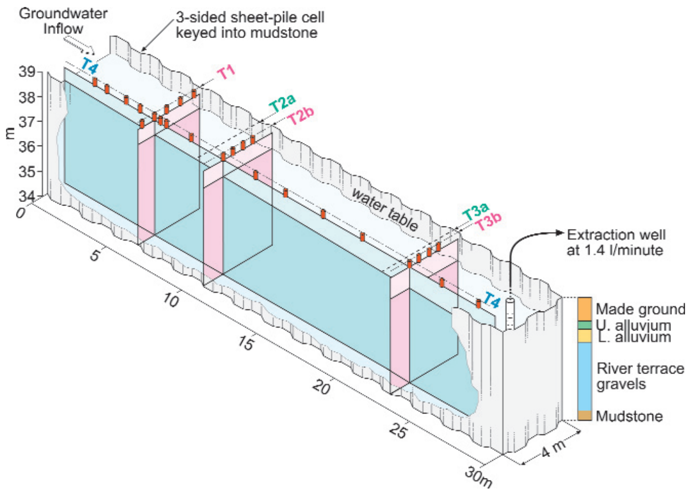

Figure 2. Schematic of the SABRE experimental test cell, showing location of conventional monitoring wells and multilevel sample transects. Figure courtesy of the Streamtube project.

Hydraulic characterisation of the cell was performed with a combination of tracer testing, falling head tests on each of the ports in the flux fences, and by qualitative assessment of contaminant distribution. Hydraulic property contrasts between the Alluvium and River Terrace Gravels were identified early on in the programme. Some areas of the River Terrace Gravels contained lower dissolved chlorinated solvent species concentrations (presumably a result of enhanced flushing due to higher permeability), and the distribution of injected electron donor was found to vary across the test cell, suggesting that delivery was influenced by permeability.

Even within the River Terrace Gravels, hydraulic properties showed a highly heterogeneous 3D distribution: in the test cell hydraulic regime, the residence time for individual flow paths varied from less than 3 days to greater than 100 days (average 45 days). Preferential flow paths that had been identified by the combined hydraulic characterisation programme showed enhanced turnover of contaminants, but also hosted more reductive dechlorination activity.

4.4 Test Cell Operation and Performance

Cell operation commenced in January 2007 with a baseline monitoring period that lasted approximately 100 days. The purpose of the baseline period was to allow contaminant concentrations in the cell to come to equilibrium under pumping conditions. Injection of SRS™ (a commercial soya oil emulsion provided by Terra Systems Inc.) was completed in April 2007 and bio-augmentation with KB-1™ culture (provided by SiREM) was completed in May 2007. Pumps in the cell were turned off in January 2009 for post-remediation characterisation of the source zone. Indications that enhanced *in situ* bioremediation was occurring were identified immediately post-injection. Complete conversion of TCE to cDCE was observed immediately down-gradient of the primary DNAPL zone in the cell. Down-gradient concentrations of total ethenes (TCE+cDCE+VC+ethene) began to increase after about 2.5 cell volumes had been flushed through the cell: at this time the relative concentration of VC increased (Figure 3). Significant increases in ethene concentration were first reliably detected in the cell after about 3.5 cell volumes had been flushed. SRS™ (as indicated by total organic carbon (TOC) measurements) appears to have become depleted near the DNAPL source after about 5 pore volumes: this was accompanied by a decrease in dechlorination. For future implementations careful monitoring of TOC concentrations would indicate appropriate times for re-dosing.

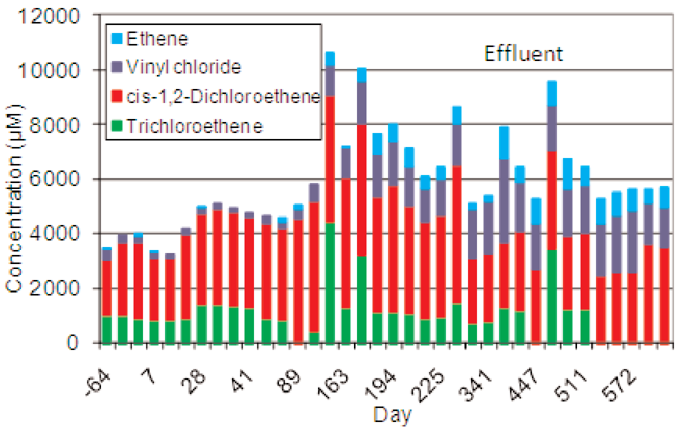

Figure 3. Chlorinated ethenes in test cell effluent.

Pre-and post-treatment soil data were evaluated in detail to produce estimates of DNAPL mass removal and quantify the uncertainty in those estimates. Upper confidence limit DNAPL mass estimates are consistent with the removal of 875 kg ethenes in the test cell effluent and suggest that, pre-treatment, the test cell contained in excess of 1 tonne of TCE, of which 60-75% was removed and/or completely dechlorinated to ethene during the field test (Figure 4).

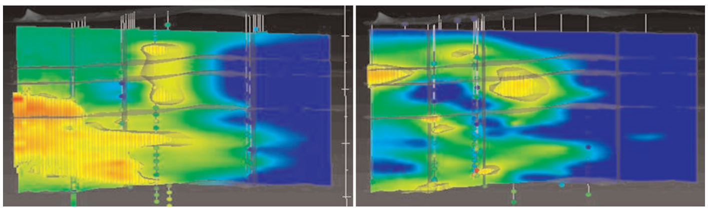

Figure 4. Pre- and post-treatment DNAPL distribution in the test cell. Reds and yellows represent higher residual saturation (CL:AIRE SABRE bulletin 5).

To summarise the gains of implementing the technology over and above natural attenuation (as monitored during the baseline period), these were as follows (CL:AIRE SABRE Bulletin 5):

- Chlorinated ethene flux enhancement of approximately 1.6: averaged over the life of the field test, this represented a potential decrease in DNAPL source lifetime of 40%.
- Elimination of TCE in the treated cell effluent, and the full conversion of 15 to 25% of the TCE to ethene or beyond in the cell.

Outside the cell, further pilot tests were undertaken to investigate alternative implementations of the technology that might be used in the full-scale site remediation (CL:AIRE SABRE bulletin 5). SRS™ was compared against cheese whey, a relatively inexpensive alternative electron donor. In terms of performance as electron donors, they were comparable, with both causing complete dechlorination to ethene (although SRS™ proved marginally better). However, SRS™ was found to be economically preferable to cheese whey because the latter was considerably more expensive to deliver to the formation and caused formation damage by clogging (for more details see CL:AIRE SABRE Bulletin 5).

The project developed and used five numerical models ranging from practical tools for engineering design to research codes (Figure 5). These numerical models have proved valuable in interpreting and understanding laboratory and field data by providing insight into processes (and their interactions) that are difficult to observe. In addition, they are valuable for designing bioremediation schemes and optimising their performance. At all scales and degrees of complexity, models are particularly useful for evaluating what-if scenarios and examining the sensitivity of bioremediation performance to the natural and engineered site conditions. A summary of the modelling tools developed, including their potential to support and optimise future remediation scheme design, is outlined below.

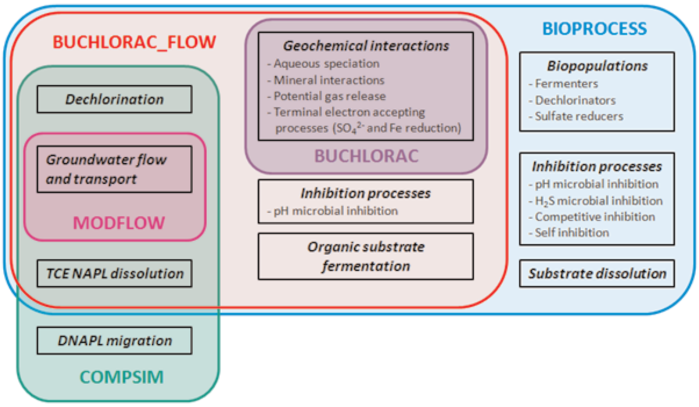

Figure 5. Five numerical models created/modified within SABRE for addressing aspects of *in situ* enhanced bioremediation (CL:AIRE SABRE bulletin 4).

A groundwater flow model was developed in MODFLOW to analyse the hydraulic conditions in the SABRE field test cell and to evaluate different electron donor injection strategies with the objective of maximising its distribution while minimising the on-site application cost.

COMPSIM is a comprehensive numerical groundwater fate and transport model capable of simulating multi-phase, multi-dimensional and multi-component systems (Sleep and Sykes, 1993). This model provides a practical and computationally efficient modelling platform for simulating dechlorination at the field scale. For situations where complex hydraulic or geochemical field conditions prevail, this model may be a useful design tool for engineers that, once calibrated for those field conditions, may be applied by the developers for interested parties.

BUCHLORAC was created as a practical and easy-to-use software tool that can provide detailed buffer dosage estimates for field dechlorination projects. With many remediation sites prone to groundwater acidification as dechlorination proceeds, implementation of pH control strategies may be crucial to the design of successful treatment schemes. The program is available as free supplementary material with Robinson and Barry (2009) or from http://infoscience.epfl.ch/record/135054.

BUCHLORAC_FLOW, an extension of BUCHLORAC that includes flow and reactive transport in multiple dimensions, was able to demonstrate how the acidity build up is influenced by the field-scale flow system, including *in situ* heterogeneity (Brovelli et al., 2010). This model is primarily a research tool, but could be readily applied to field sites by the developers on behalf of interested parties.

BIOPROCESS is a comprehensive model designed to simulate the complex suite of physical, biological, and geochemical processes interacting in bioremediation (Kouznetsova et al., 2010). This model was able to provide significant insight into the feedbacks between processes controlling effective bioremediation design, including sensitivity to potential inhibition factors. It also assisted in analysis of the column experimental data and the understanding gained from this model will help direct future remediation scheme design. However, due to the model's complexity, high computational demand and input requirements, its primary use is further research.

The SABRE modelling program is described in detail in CL:AIRE SABRE Bulletin 4.

5. APPLICATION OF THE TECHNOLOGY

Two sets of issues should be considered when considering the application of this technology in the field: environmental (applicability of the technology given differing geochemical and hydrogeological conditions) and management (likely acceptability to regulators and site management, including factors such as cost, project time constraints, reliability and sustainability).

5.1 Environmental Issues: Geochemistry

Numerous processes competed for the injected organic substrate. Sulphate reduction, iron reduction and methanogenesis all consumed a proportion that could not contribute to dechlorination. In the test cell, methanogenesis was largely inhibited due to the high TCE concentrations, making the dechlorination process much more efficient. Sulphate reduction was more important because of in-flow of sulphate-rich groundwater from the Mercia Mudstone beneath the cell. Slow fermentation of the SRS™ organic substrate provided a long term source of carbon for the most efficient dechlorination.

As in the column studies, pH excursions were observed in the field after about one pore volume had been pumped through the test cell: where pH values began dropping towards pH 6 as the reductive dechlorination reaction accelerated. Due to concerns that microbial activity would be compromised, influent groundwater was dosed with potassium and sodium bicarbonate and the pH quickly stabilised to more neutral values. Some aquifer plugging was noted but could not be explicitly tied to the bicarbonate addition.

Competitive and toxic inhibition of the dechlorination process is important. For example, at TCE concentrations approaching 500 mg/l the dechlorination reaction rate is reduced by 85% due to the high concentration. However, consistent (but slow) dechlorination is predicted at concentrations up to 750 mg/l TCE (CL:AIRE Research Bulletin 6).

5.2 Environmental Issues: Hydrogeology

The SABRE project has demonstrated that this technology is likely to be suitable for use in many geological and hydrogeological conditions but with some important qualifications. Groundwater flow rate (i.e. residence time in the active treatment zone) is an important factor in controlling the process. Higher flow rates decrease the overall time available for conversion of TCE to ethene and can result in incomplete dechlorination.

The technology is most suitable for use in sandy aquifer settings. It may be applied at relatively high groundwater velocities through careful selection of electron donor and donor delivery method. For example, where emulsified vegetable oil (and similar products) adsorbs to the aquifer matrix (porous media and fracture walls) and partitions into the DNAPL. This allows the technology to function effectively, even in highly permeable environments where soluble electron donors, such as molasses and lactate, would be rapidly flushed out of the treatment zone. However, the dominance of preferential flow paths in fractured aquifers suggests that the technology may be less suitable under such conditions. The technology is unlikely to be effective in low-permeability strata, where amendment delivery would be problematic.

Although the average residence time in the SABRE test cell was 45 days, the residence time for individual flow paths varied over two orders of magnitude. Complete dechlorination occurred within the longer flow paths, but not along the shorter ones, resulting in test cell effluent that contained a mixture of TCE and its daughter products including ethene. In full-scale application, similar behaviour is expected although there could, of course, be a larger total span in residence time; and the longest residence times would typically be associated with the smallest flux. Adequate residence time must therefore be provided for complete dechlorination.

5.3 Management Issues

Under many circumstances *in situ* bioremediation may be the lowest cost and most sustainable remedial option, making it the preferred technology. Its extended treatment times may not be a disadvantage at operational sites, while reduced infrastructure may also be highly favourable. The technology can also be safely applied near or under existing buildings, although man-made preferential flow paths may lead to complicated flow patterns.

Although this technology has the potential to decrease remediation timeframes relative to natural attenuation or pump and treat, mass transfer limitations out of DNAPL source zones can still result in extended timeframes, depending on remedial targets. The relatively long treatment timescales and potential cost uncertainties associated with *in situ* bioremediation could result in it being unsuitable (when used alone) for redevelopment projects or in other circumstances where completion of remediation within a short time-frame may be required.

Table 2 summarises part of a comparative technology evaluation carried out for full-scale remediation at the SABRE research site. This illustrates the relatively lower cost and high sustainability of *in situ* bioremediation for treatment of DNAPL source zones under site conditions. While this is a site-specific assessment, the results may be generalised.

5.4 Application of the Technology in the UK

For PCE and TCE source zone remediation the use of *in situ* bioremediation can be considered as part of the CLR11 options appraisal process (Environment Agency, 2004). Its use is likely to be preferable on sites where the efficacy and benefits through more sustainable remediation can be demonstrated. The aim of the Environment Agency in sponsoring the SABRE research has always been to promote improved remedial methods.

In situ enhanced bioremediation for DNAPL source areas using emulsified vegetable oil has already been implemented successfully at full-scale at a site in the UK, winning the Brownfield Briefing Award 2009 for best use of a single remediation treatment technique.

A second phase of emulsified vegetable oil injection in the test cell was carried out in March 2010. Full-scale treatment at the SABRE research site is scheduled to start in late 2010.

Table 2. Comparison of technology options for full-scale remediation of DNAPL source area at the SABRE research site.

Technology	SABRE approach *in situ* bioremediation	Excavation and off-site disposal	High temperature *in situ* thermal treatment	*In situ* chemical oxidation
Description of technology	*In situ* bioremediation using reductive dechlorination enhanced by amendment with emulsified vegetable oil (EVO), soluble electron donor, nutrients, together with bioaugmentation if appropriate	Excavation of source to 7 m depth inside a tent with full air containment and off gas treatment. Excavation requires dewatering and treatment of abstracted groundwater. Off-site disposal to landfill including UK Landfill Tax	*In situ* high temperature thermal treatment using steam injection	*In situ* chemical oxidation using potassium permanganate or Fenton's Reagent
Total cost[a]	£1.5 million	£2.5 million	£2.85 million	£3.0 million
Unit cost of soil treatment, £ per m3	£300 per m^3	£500 per m^3	£570 per m^3	£600 per m^3
Confidence in cost estimate	Moderate: estimate based on site-specific treatability data, pilot trials and unit rates	High: market-tested cost based on competitive tender against defined contractual terms	Moderate to High: market-tested quotation from contractor but contract terms not fully defined	Moderate to High: market-tested quotation from contractor but contract terms not fully defined
Timescale	3 to 5 years	6 months	15 months	1.5 to 2 years
Confidence in timescale	Low	High	Moderate	Moderate
Major advantages	Most sustainable solution Potentially lowest cost Can be used safely close to and beneath site infrastructure[b]	Rapid Moderate cost Cost certainty	Short treatment time	Short treatment time May be safe to use close to and beneath buildings and other site infrastructure
Major disadvantages	Cost uncertainty Long timescale	Poor sustainability[c] Risk of fugitive emissions[e] Not suitable for remediation beneath site infrastructure[b] unless these can be removed prior to treatment	Poor sustainability score due to large energy use Risk of fugitive emissions of VOCs Risk of ground heave causing damage to site infrastructure[b]	Likely higher cost. Moderate sustainability[c] due to chemical use Aquifer fouling[d] Use of hazardous chemicals[f]

a Independent supervision and 12 month validation monitoring included in all options.
b Infrastructure includes buildings, site roads, car parks and underground services.
c Sustainability: Excavation and off-site disposal scored low due to (i) transport impacts from large-scale transportation of soil and (ii) contaminants are transferred to contained landfill not treated.
d Associated with potassium permanganate due to precipitation of manganese dioxide.
e From excavations, stockpiles and vehicle movements.
f Fenton's Reagent requires use of hazardous chemicals (acid and hydrogen peroxide).

Acknowledgments

The SABRE project team comprises (in no particular order): Acetate Products, Akzo Nobel, Archon Environmental, British Geological Survey, Chevron, DuPont, ESI, General Electric, Geosyntec Consultants, Golder Associates, Honeywell, Scientifics, Shell Global Solutions, Terra Systems, University of Edinburgh, University of Sheffield and CL:AIRE.

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