TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP13

PASSIVE TREATMENT OF SEVERELY CONTAMINATED COLLIERY SPOIL LEACHATE USING A PERMEABLE REACTIVE BARRIER

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

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CL:AIRE was established as a public/private partnership in March 1999, to facilitate the field demonstration of remediation research and technology, including innovative methods for site characterisation and monitoring, on contaminated sites throughout the UK. The results of project demonstrations are published as research or technology demonstration reports and disseminated throughout the contaminated land community.

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Adam P. Jarvis PhD
Paul L. Younger PhD C.Geol C.Eng

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CL:AIRE
7th Floor
1 Great Cumberland Place
London
W1H 7AL

Tel 020 7258 5321
Fax 020 7258 5322
Web site: www.claire.co.uk

PASSIVE TREATMENT OF SEVERELY CONTAMINATED COLLIERY SPOIL LEACHATE USING A PERMEABLE REACTIVE BARRIER

Adam P. Jarvis and Paul L. Younger

Hydrogeochemical Engineering Research and Outreach (HERO), Institute for Research on the Environment and Sustainability, Newcastle University, Newcastle upon Tyne, NE1 7RU

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This is a CL:AIRE technology demonstration project report. Publication of this report fulfils CL:AIRE's objective of disseminating and reporting on remediation technology demonstrations. This report is a detailed case study of the application of a passive treatment system of severely contaminated colliery spoil leachate using a Permeable Reactive Barrier. CL:AIRE strongly recommends that individuals/organisations interested in this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

The Environment Agency recently concluded, as part of its River Basin Characterisation exercise, that some 1,800 km of England and Wales' watercourses were "at risk" from mining-related pollution. Many of the worst quality waters arise as drainage from spoil heaps, wherein the processes of sulphide mineral oxidation and dissolution which are the root cause of mining-related pollution, are particularly vigorous. The major pollutants associated with discharges from coal spoil heaps are acidity, iron, manganese, aluminium and sulphate. Mine and spoil heap drainage is a persistent form of contamination, with discharges remaining polluted for centuries or even millennia. For this reason the preferred option for remediation of such discharges is passive treatment. Such technologies rely on naturally-occurring chemical and biological reactions to effect treatment, and therefore do not require ongoing inputs of energy and / or chemicals. Consequently long-term costs are kept to a minimum, and such systems may also offer amenity benefits.

At Shilbottle, Northumberland, the spoil heap of the former Shilbottle Grange Colliery was a source of very severe contamination of the adjacent Tyelaw Burn. Staff and students at Newcastle University first began evaluating the problem in the late 1990s. These investigations led to the design, by the Newcastle team, of a full-scale Permeable Reactive Barrier (PRB), settlement lagoons and aerobic wetland, for treatment of the spoil heap drainage. In July 2002 Northumberland County Council commenced construction of the system, which was completed in September 2002.

Although a number of technologies exist for the passive remediation of acidic, metal-rich, spoil drainage, without installation of water pumping facilities, none of them are appropriate for the interception and treatment of diffuse, subsurface leachate. This was precisely the problem at Shilbottle, where subsurface drainage, arising from a perched aquifer within the spoil heap, was causing diffuse contamination of the Tyelaw Burn along approximately 150 – 200 m of its length. This report describes the highly successful application of PRB technology to this problem. The 180 m long PRB intercepts the drainage and, through a combination of calcite dissolution and bacterial sulphate reduction, generates sufficient alkalinity to both neutralise a large proportion of the acidity and allow the subsequent retention of the contaminant metals within the settlement lagoons and aerobic wetland. The successful performance of the system is demonstrated in this report with analytical data spanning two years.

Continued intensive monitoring of the site is being made possible by past and current logistical and financial support from CL:AIRE, Newcastle University's Science Research Investment Fund – second round (SRIF2) Earth Systems Laboratories project, the LINK sponsored Bioremediation of acidic mine waters by sulphate reduction in novel, compost-based field-scale bioreactors (ASURE) project, and the European Commission Framework Programme 6 (FP6) Coal Mine Sites for Targeted Remediation Research (CoSTaR) project. The latter funding stream in particular is ensuring that the site is a significant focus of national and international research, the outcomes of which it is hoped will yield substantial benefits to many other owners of such contaminated sites, both in the UK and worldwide.

ACKNOWLEDGEMENTS

Many organisations and individuals have contributed to the Shilbottle PRB. Most notably, we are indebted to Northumberland County Council, and particularly Mr Aln Elliott (Team Leader, Environmental Projects). CL:AIRE continue to support the work of the Hydrogeochemical Engineering Research & Outreach (HERO) Group at Newcastle. For their contributions to the Shilbottle PRB we are especially grateful to Paul Beck (former CEO), Nicola Harries and Dr Rob Sweeney. Mr Chris Bullen of Unipure Europe Ltd kindly provided cost estimates for an equivalent active treatment system (Section 8 of this report).

We would also like to acknowledge the funders of the PRB at Shilbottle: Northumberland County Council, Newcastle University, ONE North East, SITA Environmental Trust (under the Landfill Tax Credit Scheme), Northumberland Environmental Partnership, and the European Regional Development Fund (North East of England RECHAR II Programme 1994 – 1999). Construction of the treatment system was undertaken by Hellen (Contracts) Ltd, Hetton-le-Hole, County Durham and W L Straughan & Son Ltd, Bedlington, Northumberland. Boreholes were installed by Drilcorp Ltd, County Durham.

Continuing research at the site has been made possible by various funding bodies: DTI/BBSRC/EPSRC 'ASURE' Biorem LINK project (EPSRC ref no GR/S07247/01), supported also by Scottish Coal, Rio Tinto and White Young Green; EU FP6 Project Passive *In Situ* Remediation of Acidic Mine / Industrial Drainage 'PIRAMID' (EVK1-CT-1999-000021); EU FP7 CoSTaR-ARI, (RITA-0CT-2003-506069); HSBC Partnership for Environmental Innovation (which allows deployment of research technicians to the site); Newcastle University's SRIF2 funding stream ('Earth Systems Laboratories'); the Egyptian Government, funding from which supported the PhD research of Dr Mahmoud Moustafa; the Engineering and Physical Sciences Research Council, which has funded many of the MSc students that have conducted projects at the site.

The Environment Agency has been particularly constructive and accommodating in their support of the development of this novel treatment system, and we are especially grateful to Mr Dave Edwardson of the Tyneside office.

Finally, we are of course indebted to the many current and former students and staff at Newcastle University who have contributed to this project. Former MSc students who have worked at the site are Phil Amos, Lawrence Bowden, Andrew Daugherty and Alec Martin. Dr Mahmoud Moustafa was instrumental in developing our understanding of the hydrology of the spoil heap and barrier during his PhD study. Past and present staff to who we owe thanks are Professor Andy Aplin, Dr Selina Bamforth, Dr Lesley Batty, Dr Daniel Fabian, Dr Catherine Gandy, Dr Karen Johnson, Dr Will Mayes and Dr Charlotte Nuttall. Ongoing sampling and analysis at the site is facilitated by the tireless work of the HERO Group research technicians, Jane Davis and Patrick Orme.

CL:AIRE would like to thank Dr Brian Bone of Environment Agency and Professor Phil Morgan of ESI for reviewing this report.

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ABBREVIATIONS

ALD	Anoxic Limestone Drain
BSR	Bacterial Sulphate Reduction
CoSTaR	Coal Mine Sites for Targeted Remediation Research
FP6	Framework Programme 6
HERO	Hydrogeochemical Engineering Research & Outreach
ICP-OES	Inductively Coupled Plasma-Optical Emission Spectroscopy
NCC	Northumberland County Council
OLD	Oxic Limestone Drain
PE	Polyethylene
PIRAMID	Passive *In Situ* Remediation of Acidic Mine / Industrial Drainage
PRB	Permeable Reactive Barrier
QA/QC	Quality Assurance/Quality Control
RAPS	Reducing and Alkalinity Producing System
SD	Standard Deviation
SRB	Sulphate Reducing Bacteria
SRIF2	Science Research Investment Fund – second round
WFD	Water Framework Directive

1. INTRODUCTION

1.1 BACKGROUND, PURPOSE AND OBJECTIVES

This Technology Demonstration Report has been prepared by the Hydrogeochemical Engineering Research & Outreach (HERO) group at Newcastle University as part of CL:AIRE's initiative to disseminate good practice in the effective remediation and management of contaminated land.

This particular report focuses on the demonstration of Permeable Reactive Barriers (PRBs) as a technology for effective and low cost remediation of coal spoil heap leachate pollution. The following paragraphs briefly outline the context of this particular technology demonstration project, generally in terms of the scale of mine and spoil pollution in the UK, and more specifically in respect of the HERO group's ongoing collaboration with CL:AIRE in the development of novel technologies for mine water and spoil heap leachate remediation. The remainder of the report discusses in detail the outcomes of the project.

Mining-related pollution is a major source of aquatic pollution in the UK. The Environment Agency (England & Wales), in its recent assessment of the pressures and impacts on surface waters and groundwaters (a preliminary requirement of the EU Water Framework Directive (2000/60/EC)), estimated that 1,800 km of streams and rivers in England and Wales were "at risk" from mine water pollution. In addition some 9,000 km^2 of groundwater bodies were also estimated to be "at risk" (http://www.environment-agency.gov.uk). Estimates of streams and rivers currently impacted by mining-related pollution are in the region of 300 – 600 km. In coal mining regions the pollutant of principal concern is iron, but aluminium, manganese, sulphate and acidity are also important co-contaminants in many cases. Where pollution arises from metals mines, a host of other metals may also be of concern; within UK shores zinc, lead and copper are the most significant. The causes of mine water pollution are briefly outlined in Section 2.1, but two key points are worth highlighting here:

1. The metal contaminants associated with mine water pollution will persist in the environment if not removed and, even in those mine waters with the very highest metal concentrations, recovery and re-use has not proven economically feasible to date (personal communication, Dr Kirk Nordstrom, United States Geological Survey, 2004)[1].

2. Mine and spoil heap pollution may persist for timescales measurable in decades and centuries where source control is not possible.

Because of these issues, research and development in the field of mining-related pollution remediation has focused on solutions that are (a) reliably able to prevent pollutants entering the aquatic environment and (b) can do so in the most sustainable and economically efficient way. The purpose of this report is to demonstrate the utility of PRBs as a technology that can meet these criteria.

The Shilbottle PRB forms part of a larger passive system including oxidation ponds and a wetland. The Shilbottle system is one of a network of six passive mine and spoil heap leachate treatment systems in the north-east of England which together comprise the CoSTaR facility (Coal Mine Sites for Targeted Remediation Research). CL:AIRE designated CoSTaR as the second of its National Research Infrastructure facilities. The facility is managed jointly by Newcastle University, the Coal Authority, Durham and Northumberland County Councils and CL:AIRE. Research at the CoSTaR sites has also been funded by the EU Framework 5 PIRAMID project (Contract EVK1-CT-1999-000021) and the DTI/BBSRC/EPSRC Biorem 4 LINK project 'ASURE' (EPSRC GR/S07247/01) led by

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[1] "...the very highest metal concentrations…" is a reference to Iron Mountain, California, where concentrations of iron, copper and zinc of 111,000 mg/L, 4,760 mg/L and 23,500 mg/L respectively have been recorded (together with a pH of -2.5). See Nordstrom (2004) for further details.

Newcastle and Bangor Universities, and co-funded by Rio Tinto, Scottish Coal and White Young Green. All six CoSTaR sites lie within a 30 mile radius of Newcastle upon Tyne, as shown in Figure 1.1. Further details of each system can be found in CL:AIRE (2006a) and at http://www.ncl.ac.uk/environment/research/HEROGroup.htm/.

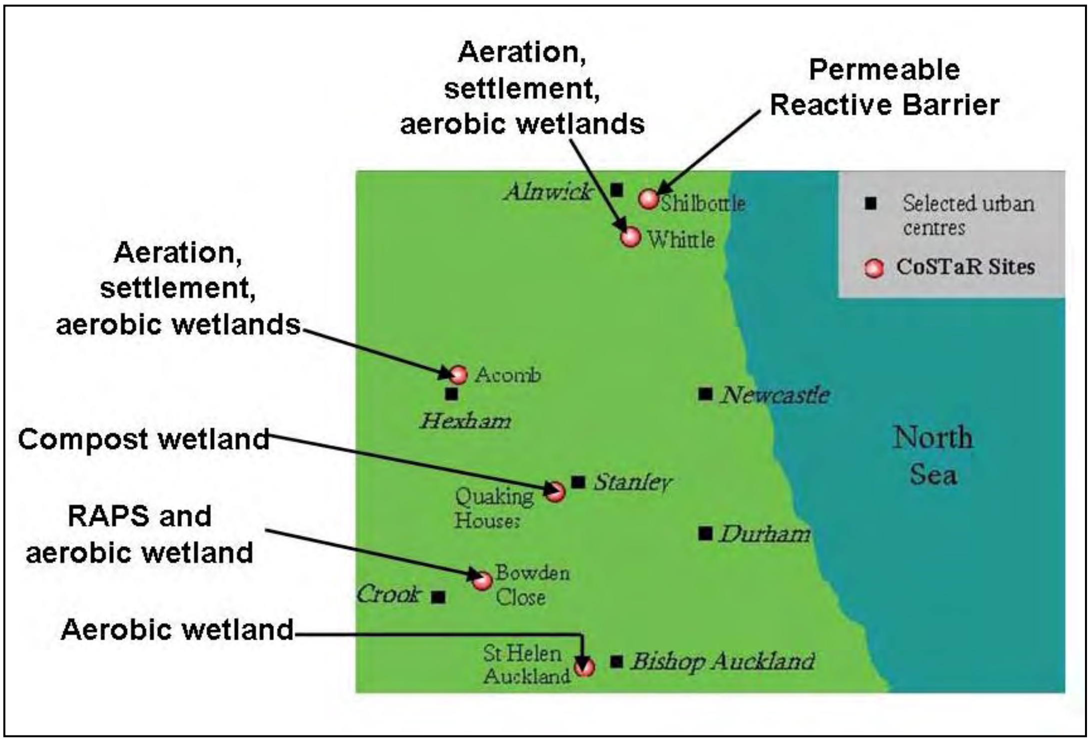

Figure 1.1. Location of the CoSTaR sites, and summary of passive treatment units at each.

The purpose of the CoSTaR facility is to enable researchers from across Europe to visit the sites to conduct their own research investigations. Staff at Newcastle University provide the detailed background in which the context of such research can be set i.e. site history, results of routine monitoring.

The overall aim of this network of sites, and the monitoring and research that continues at each of them, is to demonstrate the benefits and applications of passive treatment technology for mine water remediation, to encourage more widespread use of these treatment approaches in the future, not only in the UK but also throughout Europe. Funding to support International Access to Research Infrastructure has been allocated to CoSTaR by the European Commission (EU FP7 Contract RITA-0CT-2003-506069), greatly facilitating dissemination of the technology throughout the EU, as well as bringing broader research perspectives to bear on the systems. A number of specific research objectives are being pursued on all CoSTaR sites, the most important of which are as follows:

- Determine the relative importance of the various mechanisms that effect pollutant attenuation e.g. calcite dissolution, bacterial sulphate reduction.
- Investigate how hydraulic conditions influence treatment performance.
- Move towards more accurate prediction of the longevity of such systems.

Investigation of such issues will enable optimisation of treatment design and performance and, ultimately, improved cost effectiveness of passive mine water treatment. In addition, the processes harnessed in such systems may well have application to the resolution of other forms of inorganic pollution streams.

The Shilbottle PRB, and associated treatment facility, is unique among the CoSTaR sites insofar as the system treats a diffuse source of spoil heap drainage – all the other sites address point sources of pollution. This in itself is an important element of the uniqueness of the Shilbottle PRB, since this is the first system in the UK specifically targeted at treating a diffuse mine or spoil heap leachate. However, the diffuse nature of the drainage also presents its own particular challenges, which are not limited to the obvious difficulty of effectively intercepting the leachate. Direct measurement of flow-rates into and out of the PRB is not feasible, not only because the drainage is diffuse, but also because it is a subsurface leachate. Equally, collection of water samples from the precise interface between spoil heap and PRB, and PRB and settlement lagoons, is not possible. Therefore detailed interpretation of the performance of the system is not as straightforward as would be the case for a unit with well defined, measurable inlet and outlet points.

This is mentioned in this introductory section as the reader should be mindful of this issue during the subsequent chapters. Notwithstanding this difficulty, it is also worth emphasising at this stage that the PRB at Shilbottle is the only unit within the entire treatment system that is capable of affecting neutralisation of acidity and generation of alkalinity, which is the primary objective of remediation of this highly acidic leachate.

1.2 REPORT ORGANISATION

This report is organised into eight main sections beyond this introduction, addressing issues related to the construction and the operation of the PRB at Shilbottle.

The background to spoil heap leachate generation and treatment options is provided in Chapter 2, and this is followed by an overview of the study site itself in Chapter 3. Chapter 4 covers technology demonstration support issues, such as contract agreements, health and safety, and sampling and analysis protocols. A detailed section is devoted to the design process, covering issues from the treatment philosophy, through detailed laboratory trials, and concluding with design and construction details for the full-scale system (Chapter 5). Chapter 6 provides an overview of the performance of the system to date (and full data are provided in Appendix 1 of the report). Technology close out issues are discussed in Chapter 7, and an economic evaluation of the system compared to other technologies is provided in Chapter 8. Report conclusions are provided in Chapter 9. There is a full list of references.

2. BACKGROUND TO SPOIL HEAP LEACHATE GENERATION AND TREATMENT

2.1 EVOLUTION OF POLLUTED SPOIL HEAP LEACHATE

The root cause of pollution from mining facilities is the oxidative dissolution of sulphide minerals, which promotes the mobilisation, and in many cases subsequent release to surface and ground-waters, of metals, acidity and sulphate. Although there are a host of sulphide minerals that may be subject to this oxidative dissolution process (e.g. ZnS, NiS, PbS, CdS etc), the principal mineral of concern in coal mining districts is pyrite (FeS_2). That this latter mineral is a disulphide, as opposed to the previous examples which are monosulphides, only serves to enhance the acid-generating potential of the key chemical reactions, which are as follows:

$$2FeS_2(s) + 7O_2(aq) + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (1)$$
$$2Fe^{2+} + ½O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O \quad (2)$$
$$2Fe^{3+} + 6H_2O \leftrightarrow 2Fe(OH)_3(s) + 6H^+ \quad (3)$$
$$14Fe^{3+} + FeS_2 + 8H_2O \rightarrow 2SO_4^{2-} + 15Fe^{2+} + 16H^+ \quad (4)$$

Reaction (1) illustrates the release of ferrous iron (Fe^{2+}), sulphate and acidity (represented by protons, H^+) from pyrite in the presence of aqueous oxygen and water. This reaction is bacterially catalysed, by such organisms as *Acidithiobacillus ferrooxidans*. Subsequent oxidation of ferrous iron to ferric iron (Fe^{3+}) consumes acidity (Reaction (2)). However, subsequent hydrolysis of ferric iron (Reaction (3)), and further oxidation of pyrite by ferric iron (Reaction (4)), both release acidity. The formation of solid ferric hydroxide ($Fe(OH)_3$) in Reaction (3) occurs rapidly in surface watercourses, and it is the deposition of this bright orange-red precipitate (known as “ochre”) on streambeds that is a typical feature of watercourses affected by mine water pollution.

When they emerge at the surface not all mine waters are in fact acidic, despite the oxidative dissolution of pyrite being one of the most acid-generating reactions in nature. This is principally because neutralising reactions may occur during the passage of mine water from the site of pyrite oxidation and dissolution to the surface environment. Dissolution of calcite-containing materials is a principal source of neutralisation. However, mine waste on the surface rarely contains a substantial limestone component. Furthermore, the oxidative dissolution of pyrite can be particularly vigorous in the more open structure of spoil heaps (which allow more rapid ingress of water and oxygen for pyrite oxidation and dissolution). As a consequence spoil heap leachate is commonly net-acidic. Since most metals are more soluble under low pH conditions, other contaminants may also be released in spoil heap leachate. Aluminium is a particularly common co-pollutant in spoil heap discharges, as it can be mobilised from aluminosilicate minerals (e.g. clays) at low pH. Some UK examples of the quality of spoil heap leachate are given in Table 2.1.

Table 2.1. Some examples of spoil heap leachate quality from around the United Kingdom.

Name	**Flow [l/s]**	**Fe [mg/l]**	**Al [mg/l]**	**Mn [mg/l]**	**Acidity [mg/l] as $CaCO_3$**	**SO_4 [mg/l]**	**pH**
Aspatria, Cumbria(a)	-	198	9.2	14.5	495	2034	2.9
East Cramlington, Nortumberland(b)	0.0-6.3	85.4	61.6	13.5	564	2715	4.5
Nailstone #5, Leicestershire(a)	0.03-20	47.7	29.4	7.0	293	757	3.2
Quaking Houses, Co Durham(a)	0.7	6.1	8.6	4.3	66	774	5.8
Baads Bing, West Lothian(c)	-	550	80	6.3	2420	3077	2.8

Sources: (a)Jarvis and Younger (2000); (b)Palmer *et al.* (2005); (c)Younger (2001)

What is the source of water that generates spoil heap leachate? Direct surface runoff during and after rainfall events can be a cause of water pollution from exposed (un-capped) spoil heaps, due to rapid dissolution of metal salts on the surface and direct entrainment of sediment to watercourses. Engineering solutions for such sources of spoil heap pollution can be very problematic due to the highly variable flow-rates and contaminant concentrations encountered (see Nailstone #5 in Table 2.1, for example). In other cases perched water tables may develop within spoil heaps, with recharge derived from the surface (infiltration of rainfall) and / or from subsurface flow of water from adjacent land (at Shilbottle it appears that both sources contribute to the total volume of spoil leachate). In these cases contaminated waters may emerge in a diffuse manner from the toe of the spoil heap, or even directly to a receiving watercourse via the stream bank or bed (though also typically as diffuse pollution). The implementation of an engineered solution for spoil heap leachate remediation arising from a perched aquifer is a central topic of this document.

2.2 PASSIVE TREATMENT OPTIONS FOR SPOIL LEACHATE

It may be apparent from the discussion above that one obvious intervention to prevent, or at least limit, generation of polluted spoil tip leachate is to restrict the supply of oxygen and water entering such heaps. Such engineering works, which have been termed *passive prevention of pollutant release* (PIRAMID Consortium, 2003), are not uncommon. Placement of an impermeable ‘dry cover’ or ‘cap’ on spoil heaps, which both restrict ingress of oxygen and water, and forms a medium suitable for the establishment of a vegetative sward on the heap, has been successfully accomplished at many sites. However, such interventions have a very high capital cost, and in many cases do not entirely prevent seepages of polluted leachate. Indeed, where recharge is predominantly via groundwater flow from adjacent land such interventions may result in only limited reductions in the overall volume of leachate. Because of their high capital cost, placement of dry covers on spoil heaps, in the UK at least, is usually not just for purposes of water quality improvement, but also for wider amenity development benefits. Further discussion of engineering design considerations for dry cover design can be found in PIRAMID Consortium (2003).

Notwithstanding the potential benefits of passive prevention of pollutant release technologies, in many cases treatment of contaminated waters is still a requirement. In such instances, passive treatment is generally the favoured approach to remediation. Passive treatment has been defined by PIRAMID Consortium (2003) as “*…the deliberate improvement of water quality using only naturally-available energy sources (e.g. gravity, microbial metabolic energy, photosynthesis), in systems which require only infrequent (albeit regular) maintenance in order to operate effectively over the entire system design* life”. The dual objectives of passive treatment of acidic mine and spoil discharges are the generation of alkalinity (and therefore elevation of pH), and immobilisation of contaminant metals. The elevation of pH is a prerequisite of metal immobilisation, at least if metal attenuation is to occur at a rate that gives a realistic chance of accomplishing effective treatment within a reasonable footprint of land. With the exception of PRBs, which are introduced in Section 2.3, Table 2.2 provides a brief typology of passive treatment units applicable to the remediation of acidic spoil and mine water discharges, giving a brief description, reference to an example paper, the overall objective of each, and their advantages and limitations. Further details of the design of each type of unit can be found in Hedin *et al.* (1994a), PIRAMID Consortium (2003) and Younger *et al.* (2002).

Table 2.2. A brief typology of passive treatment units other than PRBs which have been used or proposed for the remediation of acidic spoil leachate.

Name	**Overall aims**	**Brief description and example reference**	**Advantages**	**Limitations**
Anoxic Limestone Drain (ALD)	- Generation of alkalinity	- A buried, limestone-filled, trench which is inundated with through-flowing mine water. - Hedin *et al.* (1994b)	- Limited intrusion on land use. - Simple construction.	- Potential clogging with Al and Fe precipitates limits use to waters with < 2 mg/L of each, or dissolved oxygen < 1 mg/L. - Composition of limestone potentially a problem (dolomite slow to dissolve).
Oxic Limestone Drain (OLD)	- Generation of alkalinity - Attenuation of metals	- As ALD, but metals also retained. Flow velocity > 0.1 m/min to prevent armouring by Fe and Al under the oxic conditions. - Cravotta and Trahan (1999)	- Overcome limitations of ALD. - Limited intrusion on land use. - Simple construction.	- Composition of limestone potentially a problem (dolomite slow to dissolve). - Long-term viability not certain.
Compost wetland	- Generation of alkalinity - Attenuation of metals	- Simple surface flow wetland but with compost (and sometimes limestone) substrate; depth of water above substrate kept to a minimum. - Jarvis and Younger (1999)	- Low hydraulic head requirement. - Simpler engineering than RAPS.	- Large land area requirement compared to RAPS.
Reducing and Alkalinity Producing System (RAPS)	- Generation of alkalinity - Attenuation of metals	- Compost and limestone in a downward flow configuration, and completely inundated; overall depth of substrate 0.5 – 1.0 m. - CL:AIRE (2006b)	- Hydraulically more efficient than compost wetlands. - Less land area required than compost wetlands.	- Substantial hydraulic head required (≥ 1.5 m minimum).

2.3 THE ROLE OF PERMEABLE REACTIVE BARRIER (PRB) TECHNOLOGY IN SPOIL HEAP LEACHATE REMEDIATION

Although the passive treatment technologies listed in Table 2.2 have been successfully employed in the remediation of acidic mine waters, the engineering of all of them is predicated on the mine water emerging as a point source and at the surface. However, as noted in the last paragraph of Section 2.1, leachate from spoil heaps rarely emerges as a point source, and is not always evident as surface water at all. Diffuse surface runoff from spoil heaps may lend itself to collection via drainage networks, for subsequent treatment as a ‘point’ source by one of the technologies listed in Table 2.2. However, subsurface flows are not readily treatable with such systems. In short, it is difficult to conceive of any realistic option other than a pump-and-treat scheme in such circumstances. This of course contravenes the passive treatment definition (above), and installing such a pump-and-treat system, with subsequent treatment using one of the technologies in Table 2.2, would have serious implications for the long-term operating costs of such a scheme.

PRBs fill this technology gap. They are specifically designed to intercept diffuse subsurface flows of contaminated water. There are currently some 110 pilot- and full-scale PRBs across the USA and Europe (Smith *et al.*, 2003), but uptake of PRB technology has been slow in the UK (Bone *et al.*, 2005). The road to more widespread implementation of PRBs in England & Wales has become easier with the introduction of a design guidance document for PRBs, produced by the Environment Agency (England & Wales) (Environment Agency, 2002). In addition, the introduction of the EU Water Framework Directive (WFD) (2000/60/EC) has served to concentrate attention on diffuse sources of pollution, which are perceived as a potentially serious barrier to the achievement of WFD objectives. Thus, it might be anticipated that PRB uptake will increase in the future, with increasing pressure to address diffuse pollution, and a clearer understanding of the regulatory conditions that have to be met in designing such systems.

Although there are now a number of PRBs in the UK using a range of reactive materials (Smith *et al.*, 2003), the Shilbottle PRB is the only one that addresses spoil heap leachate remediation (or, indeed, any form of inorganic pollution).

3. STUDY SITE

3.1 SITE DESCRIPTION AND HISTORY

The 15 hectare Shilbottle spoil heap lies at National Grid Reference NU 217086, 2.5 km east southeast of the village of Shilbottle and some 8 km from Alnwick. The Tyelaw Burn runs approximately north-south along the western flank of the tip. It enters the River Coquet approximately 2 km to the south-east of the spoil heap (Figure 3.1).

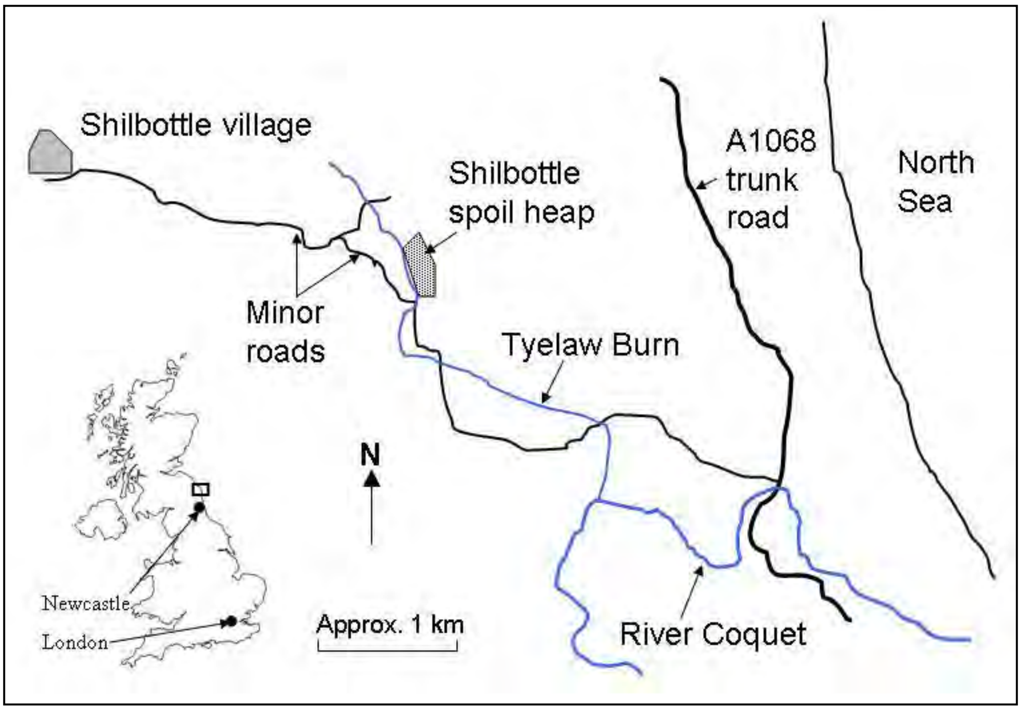

Figure 3.1. Location of the Shilbottle spoil heap and surrounding features.

The Shilbottle coal seam occurs in a Carboniferous Limestone Series. A single seam was worked at Shilbottle Colliery up until 1982 when the pit closed. However, despite the occurrence of the seam in a limestone series, the spoil heap at Shilbottle largely comprises highly pyrite-rich roof strata from the mine. As a consequence there is very little neutralising capacity in the material, and the leachate emanating from the tip is therefore highly acidic (see below). This is in contrast to the adjacent Whittle colliery, where deep mine water is pumped and treated by the Coal Authority. At this site limestone in the workings serves to neutralise the mine water, and therefore the Whittle CoSTaR site (see CL:AIRE, 2006a) treats net-alkaline water.

3.2 QUALITY OF LEACHATE EMANATING FROM THE SHILBOTTLE SPOIL HEAP

Table 3.1 illustrates the nature of the highly acidic and metal-rich leachate generated by the Shilbottle spoil heap (by the processes outlined in Section 2.1). The locations of the sampling points GW9 – GW11 are not indicated on Figure 5.2 but, prior to construction of the PRB, lay along the line of the PRB sampling points B1 – B4. Although these points represented the most visually significant, seepages along the toe of the spoil heap prior to remediation were very much diffuse in nature. Measurement of flow-rate was therefore difficult, but estimates suggested that the total volume of leachate was in the order of ≤ 10 L/s. Further discussion on the range of flow-rates encountered, and the influence of rainfall on flow-rate, is provided in subsequent sections of this report.

Table 3.1. Chemical characteristics of leachate from the Shilbottle spoil heap (from Younger *et al.,* 2003).

	GW9	**GW10**	**GW11**
pH	4.17	3.55	3.29
Acidity (mg/L as $CaCO_3$)	3322	2534	1360
Fe (mg/L)	688	452	278
Mn (mg/L)	238	181	165
Al (mg/L)	298	249	97
SO_4^{2-} (mg/L)	11176	9288	6334

As well as being highly acidic, the leachate had concentrations of iron, manganese and aluminium that were among the highest ever recorded for a mine or spoil discharge in the UK. The Tyelaw Burn was severely contaminated as a consequence of these discharges. The Tyelaw Burn is a relatively minor tributary of the River Coquet (Figure 3.1). Nevertheless, since the River Coquet is one of the most important Salmonid fisheries in the UK, and has a major drinking water abstraction point downstream of the confluence with the Tyelaw Burn, this spoil heap leachate was a major cause of concern to Northumberland County Council and the Environment Agency.

4. TECHNOLOGY DEMONSTRATION SUPPORT ISSUES

4.1 CONTRACT AGREEMENTS AND REGULATORY APPROVAL

Northumberland County Council (NCC) own the Shilbottle Grange Colliery site, including the spoil heap. The site was originally acquired from the former National Coal Board in the 1980s, with a view to implementing land restoration to create a woodland habitat. Much surface reclamation had already occurred under the management of NCC before the PRB project commenced. Earlier reclamation had included the construction of three reedbeds as amenity / habitat features, the lowermost of which received a proportion of the toe drainage from the spoil heap. It was the poor quality of the outflow from this wetland which aroused the interest of local Environment Agency officers, who opened up a dialogue with NCC over options for improving the chemical nature of the site discharge, especially as regards iron (which typically exceeded 250 mg/L, and sometimes reached 500 mg/L, at the final outfall) and pH (usually 3 or less).

After consultations with the authors and other colleagues at Newcastle University, the system design detailed in this report was arrived at. Construction of the Shilbottle PRB and associated ponds was contractually managed by NCC, with technical advice from Newcastle University. The relationship between these two principal project partners was subject to a Memorandum of Understanding.

At the time the Shilbottle PRB was conceived, the Environment Agency did not have a mechanism in place to review the detailed design of the system (this has since changed, at least with regard to PRBs installed within recognised aquifers; Environment Agency 2002). However, Environment Agency staff in the region are particularly familiar with passive remediation technologies for mine waters, due to their experience on the other CoSTaR sites. There were therefore no objections to the plans put forward by NCC. The mixture of funding sources used to support the development (see ‘Acknowledgements’) did not require any particular approval. Detailed design drawings were issued by NCC without further ado, and tenders invited from any interested contractors. Construction supervision was provided by NCC in line with well-established procedures.

4.2 HEALTH AND SAFETY

Besides the usual site safety issues associated with earth-moving operations on construction sites (e.g. hazards from moving plant; falling hazards associated with open excavations; hazards associated with possible slope failures during cut-and-fill operations), no particular health and safety issues arose requiring special planning. Prior sampling of site leachates had already established the absence of List I metals (Cd, Hg) which are potentially hazardous to human health. The abundant List II metals (Zn, Al and, due to its potential as a silt-forming agent, Fe) present in the site drainage, though severely ecotoxic at the concentrations encountered, are not believed to be hazardous to humans via skin contact. Deliberate ingestion of such waters is instinctively avoided due to the alarming colour of the water (burgundy red), and risks of accidental ingestion (e.g. if someone were to fall into the water) were effectively eliminated by ensuring no bodies of standing water were present in the areas of active operations.

4.3 DEMONSTRATION WORK AND SAMPLING PLAN

At the launch of the CL:AIRE Technology Demonstration Project at Shilbottle in 2002, the following proposed outcomes were specified:

1. The restoration of the Tyelaw Burn to the 'good status' which it has not known to have enjoyed since the onset of large-scale mining more than 100 years ago.
2. Demonstration of the applicability of PRB technology for acidic leachates.
3. Development of a highly-characterised PRB which can be used to address hydrodynamic and solute transport issues which are common to many such systems.

4. Provision of high-quality data for the 2003 EU PIRAMID guidelines on passive treatment system design and construction (for EU-wide use thereafter).
5. Making available a complex biogeochemical reactor, which will have multiple possible educational uses for science and engineering students.

Every one of these outcomes has been met, as documented throughout this report, but especially in sections 2.3, 5.1, 5.4, 6, 8 and Appendix 1. Of particular note are the following:

1. The chemical quality of the Tyelaw Burn has improved dramatically (see Appendix 1); it is now completely free of the vivid red ochre staining which once afflicted its entire length, and it carries significantly less manganese than hitherto, thus improving the sustainability of the ongoing public water supply abstraction from the River Coquet opposite its confluence with the Burn.
2. As described in the text below, the PRB is successfully treating one of the worst examples of acidic leachate in the UK.
3. The PRB is indeed highly-characterised, with multiple boreholes and multi-level samplers providing detailed information on leachate evolution within the structure. As mentioned, these data are now being used to support innovative system dynamics modelling of long-term engineering performance.
4. The PIRAMID Guidelines (PIRAMID Consortium 2003) did indeed benefit from inclusion of advice arising from the experience of constructing the Shilbottle PRB, and from early performance data obtained from the system.
5. There have to date been five MSc theses and one PhD thesis on the system, produced by Newcastle environmental engineering students; the EU FP7 international access funding has greatly extended the benefits of the system to students and postdoctoral researchers throughout Europe.

With regard to routine sampling in support of these demonstration activities, Table 4.1 illustrates the original proposals (in 2002) and what has actually been achieved.

Table 4.1. Original proposals for the Shilbottle PRB, and actual achievements

Sampling proposed …	**Sampling achieved …**
Hydraulic head measurements of influent, effluent and intermediate points, with data logging at hourly intervals in selected monitoring wells (weekly / monthly dips in others)	Accomplished as specified, with the addition of a number of boreholes located throughout the spoil heap (the pollutant source zone), which allowed modelling of particular groundwater ‘flow tubes’ feeding specific parts of the PRB
Stage measurements in ponds and channels on the site, and in the Tyelaw Burn	Very low surface hydraulic gradients across the site meant that this was not as necessary as first anticipated.
Collection of routine hydrochemical samples of surface and subsurface waters at the site	Achieved, data included in Appendix 1
Tracer testing of the PRB under a range of seasonal conditions.	Achieved, principally using drift-and-pump-back tests from boreholes. Results were not as illuminating as had been hoped (see Moustafa, 2006).
Periodic removal and destructive analysis of pre-packaged substrate elements and dialysis tubes, to reveal the state of compost diagenesis at different depths over time	Not yet undertaken, as it proved far easier for logistical reasons (site access for appropriate equipment; safe deployment on a fairly level surface) to undertake this work at Bowden Close (CL:AIRE, 2006b).
Rainfall and air temperature logging at or near site	Met Office date were used during most of the period to date, but a secure site has now been established at Whittle (a closely-adjoining CoSTaR site), which will provide more site-specific data in future.

4.4 ANALYTICAL METHODS AND QUALITY ASSURANCE/QUALITY CONTROL

Measurements of pH, redox potential, electric conductivity and temperature were taken in the field with a Myron 6P Ultrameter. Alkalinity was titrated directly with 1.6 N sulphuric acid and Bromcresol-Green Methyl-Red indicator, using a Hach AL-DT test kit. Flow-rate was measured using the bucket and stopwatch method at the end point of the system.

Water samples of the full-scale system were taken in acid-rinsed polyethylene (PE) bottles and analysed by ion chromatography (anions) and Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) (cations) at the geochemistry laboratories at Newcastle University, applying standard analytical protocols and standard chemicals for calibration and Quality Assurance/Quality Control (QA/QC) (APHA, 1998).

Sampling of boreholes and piezometers was achieved using a suitable length of 'Waterra' tubing (flexible plastic tubing of approximately 10 mm internal diameter). Water rises up the tube with repeated upward and downward movement within the water column in the borehole, due to the presence of a ball valve on the submerged end of the tubing. The tubing was purged with approximately 3 volumes of the tubing before collecting a sample, in order to ensure that any standing water in the piezometer was evacuated before collection of a sample.

5. REMEDIATION DESIGN AND PROCESSES

5.1 PROCESS AND DESIGN PHILOSOPHY FOR THE SHILBOTTLE PRB

The spoil heap leachate at Shilbottle arises as diffuse subsurface flow. Previous efforts to remediate the pollution had been undertaken by installing an aerobic wetland, located at the southern end of the tip (Figure 5.2). However, this system failed to treat the water effectively for two reasons:

1. Approximately 60% of the leachate bypassed the wetland, and therefore continued to pollute the Tyelaw Burn, and

2. Because this is an aerobic wetland, there is no capacity to generate alkalinity within it. As a consequence pH remained low, and the degree of attenuation of metals was limited. Even at low pH some removal of iron and aluminium may occur, via hydrolysis and precipitation, albeit very slowly. However, these reactions release protons, and therefore further depress pH in the absence of alkalinity to buffer such reactions.

This is shown in Equation (3) for ferric iron, and for aluminium precipitation is represented as follows:

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3(s) + 3H^+ \qquad (5)$$

The reason a large volume of the leachate bypassed the system was because of its subsurface nature. In many areas along the toe of the spoil heap the leachate's first appearance at the surface was immediately adjacent to the Tyelaw Burn, and therefore in the lowest lying part of the site.

Because the leachate was only manifest at the surface very close to, or within, the Tyelaw Burn, it would not have been possible to have employed any of the technologies listed in Table 2.2 without the installation also of a pumping arrangement to transfer the water to the inlet of the system. Therefore an alternative technology was required which could intercept and treat the water on its passage through the subsurface (i.e. without the need for energy inputs for pumping operations). Therefore PRB technology was the preferred approach.

The specific objectives for treatment of this waste stream were to generate alkalinity (raise pH) and immobilise metals within the treatment system. Biogeochemically, the mechanisms harnessed to effect these changes in water quality are similar to those operative at the Quaking Houses compost wetland and Bowden Close Reducing and Alkalinity Producing System (CL:AIRE, 2002; CL:AIRE, 2006b). The first process is the simple dissolution of calcite-rich materials (of which carboniferous limestone is the principal one used), which will neutralise acidity at pH < ~5, and generate alkalinity at pH > ~5, as illustrated in Equations (6) and (7) respectively (Blowes *et al.*, 2004).

$$CaCO_3 + 2H^+ \leftrightarrow Ca^{2+} + H_2O + CO_2 \qquad (6)$$
$$CaCO_3 + H^+ \leftrightarrow Ca^{2+} + HCO_3^- \qquad (7)$$

However, intimate contact between a leachate of this quality (Table 3.1) with limestone alone would likely result in rapid coating of the limestone with iron and aluminium hydroxide precipitates (a process referred to as "armouring") and, ultimately, clogging of the system (as noted in Table 2.2). By promoting conditions of anoxia armouring can be limited without inhibiting the rate of calcite dissolution. Therefore the limestone is mixed with an organic substrate[2], which results in rapid consumption of dissolved oxygen via microbial respiration.

These anoxic conditions, in a carbon-rich substrate, also encourage a process known as dissimilatory sulphate reduction, which is a key mechanism of pollutant attenuation in

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[2] "Substrate" in this context, and throughout this document, refers to the organic media used in passive treatment systems.

compost-based passive systems for mine and spoil leachate remediation. It will be noted from Equations (1) - (4) that a typical characteristic of all mine waters arising from the oxidative dissolution of sulphide minerals is an elevated sulphate concentration. In a carbon-rich substrate, where aqueous sulphate concentration is greater than 100 mg/L, and ferric iron is absent (ensured by the anoxic conditions), Sulphate Reducing Bacteria (SRB) are likely to colonise. SRB utilise low-carbon number compounds in the organic substrate, resulting in the reduction of sulphate and, crucially, the generation of bicarbonate alkalinity. This reaction is illustrated, in very simplified form, by Equation (8), in which CH_2O represents a low-carbon number compound (typically acetate in reality) (Younger *et al.*, 2002).

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^- \qquad (8)$$

The reduced sulphur compounds generated during dissimilatory sulphate reduction may react with divalent metals ions (such as Fe^{2+}), immobilising these metals as monosulphide precipitates within the organic substrate (Equation (9)).

$$Fe^{2+} + H_2S + 2HCO_3^- \rightarrow FeS(s) + 2H_2O + 2CO_2 \qquad (9)$$

Although sulphate reduction processes are known to immobilise divalent metals in this manner, and such attenuation is clearly beneficial, it is not currently possible to make *a priori* predictions of the extent to which metals will be removed as monosulphides. Indeed, the overriding design philosophy of the PRB was maximisation of attenuation of acidity and generation of alkalinity. To ensure that metal concentrations were reduced to acceptable levels prior to discharge back to the Tyelaw Burn further treatment units were also required. Therefore settlement lagoons and an aerobic wetland were built into the treatment system design. In order for effluent from the PRB to enter settlement lagoons, water had to be brought to the surface. Therefore the system was designed such that the PRB would be keyed into the underlying boulder clay at the site. Spoil heap leachate from the perched water table within the heap would flow through the barrier, but would then be forced upwards, to flow through a brick rubble fill layer on the downstream face of the PRB, and enter the settlement lagoon. This layout is illustrated conceptually in Figure 5.1.

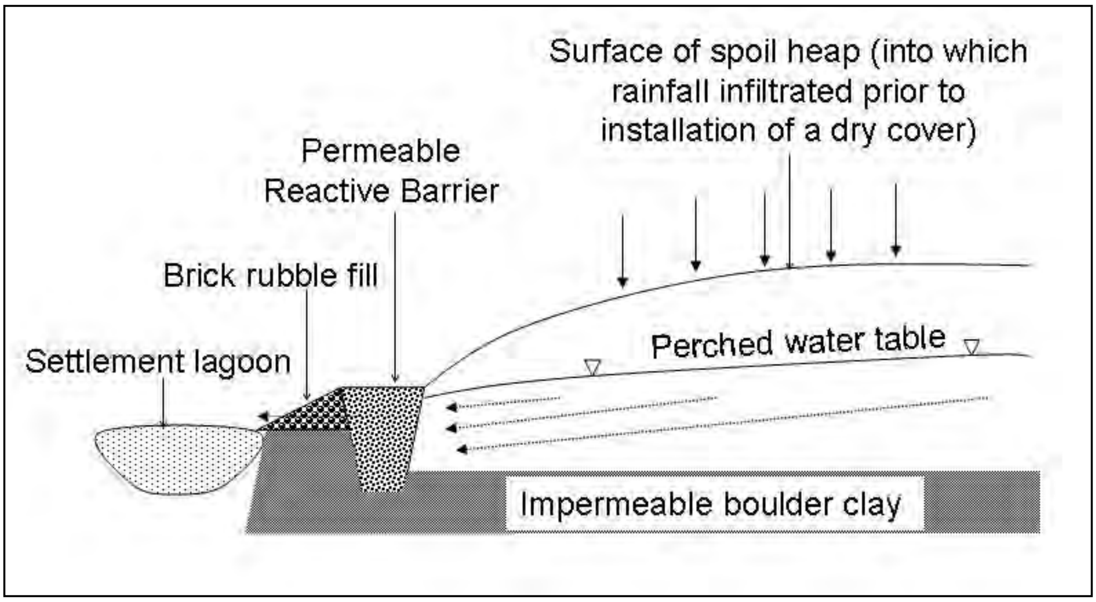

Figure 5.1. Conceptual cross-section of the PRB and settlement lagoon layout at Shilbottle (from Jarvis *et al.*, 2006).

Following treatment in the PRB the leachate would be net-alkaline, and therefore under aerobic conditions within the settlement lagoons iron and aluminium would be removed as hydroxide precipitates, via Equations (3) and (5). It should be noted that an *excess* of alkalinity was essential here, since release of protons during hydrolysis of Fe^{3+} and Al^{3+} would need to be buffered.

A final step of treatment in the design was to make use of the existing wetland at the site for ‘polishing’ of the effluent from the settlement lagoons. Although this aerobic wetland had not previously functioned efficiently (see above) generation of alkalinity within the PRB would ensure that further iron and aluminium attenuation would occur within the confines of this wetland.

Settlement lagoons and aerobic wetland treatment of net-alkaline mine water and spoil heap leachate are now widely applied, with a high rate of success (assuming they are designed correctly), and in this sense they are largely considered ‘proven technology’. However, the efficient functioning of these units at Shilbottle was predicated on them consistently receiving net-alkaline water from the PRB. The effective operation of the PRB was therefore essential. For this reason laboratory experimentation was undertaken prior to full-scale development of the PRB. The objectives of this preliminary work were twofold:

1. Select a substrate mix that would encourage the dual processes of calcite dissolution and dissimilatory sulphate reduction.
2. Select a substrate that would be both permeable enough to allow passage of water through the PRB, taking into account likely decreases in permeability due to sedimentation processes and compaction, but would also have a structure that was not so open as to prevent the development of anoxic conditions. This objective was particularly challenging given the conflicting nature of these requirements.

The following section briefly describes the laboratory work that underpinned selection of such a substrate.

5.2 LABORATORY AND FIELD WORK UNDERPINNING DESIGN

Determination of the principal hydrological flow-routing through the spoil heap was an essential step in determining the location and dimensions of a PRB required to intercept all of the polluted subsurface drainage from the spoil heap (i.e. elevation relative to surface of spoil heap, depth, and lateral extent). A network of boreholes, the locations of which are illustrated on Figure 5.2 (prefixed ‘U’), were installed across the spoil heap to investigate these subsurface flow pathways. A perched water table exists within the spoil heap, which has a hydraulic gradient falling from east to west. Subsurface water flowing along this gradient becomes polluted as it passes through the spoil material, ultimately emerging along the western flank of the tip. Evidence from borehole monitoring, and from visual observations at the surface, illustrated that polluted leachate was emanating from a substantial lateral portion of this western toe of the spoil heap, with the conclusion that the PRB would need to mirror this lateral extent if it was to intercept all of the polluted leachate.

The permeability of the colliery spoil at Shilbottle was also determined during this site investigation phase. A constant discharge pumping test was conducted near the toe of the spoil heap to calculate the maximum permeability of the spoil. The result of this exercise indicated a permeability of 5.5×10^{-5} m/s (4.76 m/d). This permeability test was undertaken because Benner *et al.* (1997), following experiences of installation of a PRB at Nickel Rim, Canada, recommended that the permeability (K) of the PRB substrate should be an order of magnitude higher than that of the surrounding mine waste (i.e. $K_{\text{substrate}} \geq 5.5 \times 10^{-4}$ m/s in the Shilbottle case).

Amos and Younger (2003) report the results of an investigation specifically aimed at identifying a substrate with the appropriate permeability and reactivity for use in the Shilbottle PRB. Table 5.1 shows the various combinations of media that were used during these investigations. The selection of these particular materials was based in part on the outcomes of previous tests (e.g. Jarvis and Younger, 1999), and in part on their availability and cost.

The permeability of the various combinations of substrates was determined using constant head permeameters in an upflow configuration. The experiments were designed in such a way as to allow the surface of the substrate column to be loaded with weights (surcharged), to simulate the effects of compression of substrate under its own weight. The density and porosity of the substrates were subsequently determined by mass-volume measurements and water displacement respectively (Amos and Younger, 2003).

Table 5.1. Combinations of materials used during evaluation of the most appropriate substrate for use in the Shilbottle PRB (adapted from Amos and Younger, 2003).

Designation	Description
#1	50% limestone chips 25% slurry screenings[1] 25% compost[2]
#2	75% limestone chips 12.5% slurry screenings 12.5% compost
#3	50% pea gravel 25% slurry screenings 25% compost
#4	50% limestone chips 50% compost

[1]A solid by-product of the mechanical screening of cattle slurry and [2]from the composting of organic municipal waste

Alongside the physical tests of substrate permeability, Amos and Younger (2003) also conducted reactivity tests on these media. For these batch experiments an artificial mine water, closely analogous in chemical composition to the actual spoil heap leachate quality shown in Table 3.1, was introduced to the substrates. Samples of this water were then drawn off at daily intervals for a period of 7 days, and then again after periods of 10 days and 36 days (to reflect the wide variation in PRB residence times reported in previous literature (Younger *et al.,* 2002)). Analyses of concentrations of key variables (pH, acidity, alkalinity, Fe, SO_4) were the basis of subsequent interpretation of the reactivity of the various substrate mixes.

The conclusion drawn by Amos and Younger (2003) was that the best overall substrate mix for the PRB at Shilbottle was #1 in Table 5.1, comprising 50% limestone chips, 25% slurry screenings, and 25% compost. This substrate showed the best combination of characteristics in terms of permeability (7.2×10^{-3} m/s without surcharge mass, decreasing to 6.6×10^{-3} m/s with a surcharge mass of 39 kg), and reactivity (i.e. attenuation of key contaminants). It was on the basis of these experiments that the substrate for the full-scale PRB was selected.

5.3 MOVING TO FULL-SCALE

Results of groundwater monitoring at the Shilbottle spoil heap made it apparent that the PRB would have to have a substantial lateral extent, parallel to the western toe of the spoil heap, if it were to intercept all of the drainage effectively. Two generic options are available for the configuration of a PRB:

1. a ‘funnel and gate’ system, in which two impermeable limbs of the barrier (the ‘funnel’) channel groundwater towards a permeable reactive ‘gate’, through which all leachate must pass, and
2. a ‘continuous wall’ arrangement, in which the entire length of the barrier comprises permeable reactive media.

In this case a continuous wall system was selected because:

- there was very little land available between the toe of the spoil and the line of the Tyelaw Burn (even after it had been re-routed – see below), given the necessity to construct settlement lagoons in this area (Figure 5.2). To achieve the necessary residence time for effective treatment the reactive gate of a funnel and gate system would have been prohibitively wide given these land restrictions.
- because 50% of the reactive media were composted materials they were available at very low cost, and therefore the overall cost per unit length of the reactive substrate was

less than that of an impermeable material (e.g. clay) required for the funnel and gate configuration.

Sufficient residence time within the PRB was vitally important if successful treatment was to be effected. Various methods were employed to derive flow-rate estimates, including constant discharge pumping tests, and discharge measurement in the Tyelaw Burn upstream and downstream of the area of diffuse seepage. Daugherty (1998) estimated that mean total flow-rate was approximately 2.5 L/s, with a maximum in the order of 10 L/s. In determining the design residence time for the PRB, which in turn would dictate its overall dimensions, a number of issues were considered:

- the optimum period for generation of alkalinity via calcite dissolution has been shown to be approximately 14 hours (Hedin *et al.*, 1994b).
- whilst the highest possible residence time would be desirable, this had to be tempered by cost and land availability considerations.
- previous PRB systems have had residence times in the range 2 – 60 days (Younger *et al.*, 2002). Given this variation, it is arguably best to determine the most appropriate residence time on a case-by-case basis.

The final design of the PRB at Shilbottle was of a system approximately 180 m long, up to 3 m deep, and 2 m wide. Assuming homogenous flow into the PRB along its length, and substrate porosity of approximately 30% (as previously determined by Amos and Younger (2003)), this would provide for a nominal residence time of 10 – 40 hours for flow-rates of 2.5 to 10 L/s.

Following the selection of a suitable substrate composition for the PRB at Shilbottle (substrate #1 in Table 5.1) the UK suffered a major epidemic of Foot & Mouth disease (FMD) in 2001[3]. Because of this outbreak the use of cattle slurry screenings in the full-scale PRB, not long after the epidemic, was not considered appropriate. This material was therefore substituted with horse manure and straw, which had already proven an effective medium for other compost-based passive spoil heap leachate treatment systems (e.g. Jarvis and Younger, 1999). A second modification to the design was the use of blast furnace slag in a short section of the PRB (at the southern end), as a lower cost alternative to limestone as a source of alkalinity.

5.4 THE FULL-SCALE PASSIVE SYSTEM

5.4.1 CONSTRUCTION, LAYOUT AND FLOW PATHWAYS

Figure 5.2 illustrates the overall plan layout of the treatment system at Shilbottle, which was completed at the end of 2002. The main section of PRB runs for approximately 140 m north-south along the western flank of the spoil heap. In addition there is a 40 m section of PRB (installed at a later stage) that runs approximately east-west, and intercepts leachate from the southern flank of the spoil heap. Effluent from the main section of the PRB discharges to a series of 3 settlement lagoons. It should be noted that effluent from the PRB directly enters all of these lagoons, and therefore no improvement in water quality was anticipated from Lagoon 1 to Lagoon 3. The waters from all 3 lagoons overspill to the pre-existing aerobic wetland at the southern end of the site. Effluent from the 40 m section of PRB directly enters the aerobic wetland. The final discharge point from the aerobic wetland to the Tyelaw Burn (marked as 'End point' on Figure 5.2) is some 200 m to the south of Lagoon 3. The Tyelaw Burn itself was re-routed as part of the construction works, in order to accommodate the settlement lagoons. The original line of the Burn was some 30 m to the east of that indicated on Figure 5.2, approximately along the line of the lagoons as shown.

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[3] It should be noted that, although the reference to the article by Amos and Younger is dated 2003, the laboratory work reported in the paper was conducted prior to the outbreak of FMD, and the paper itself was also submitted for publication before the epidemic.

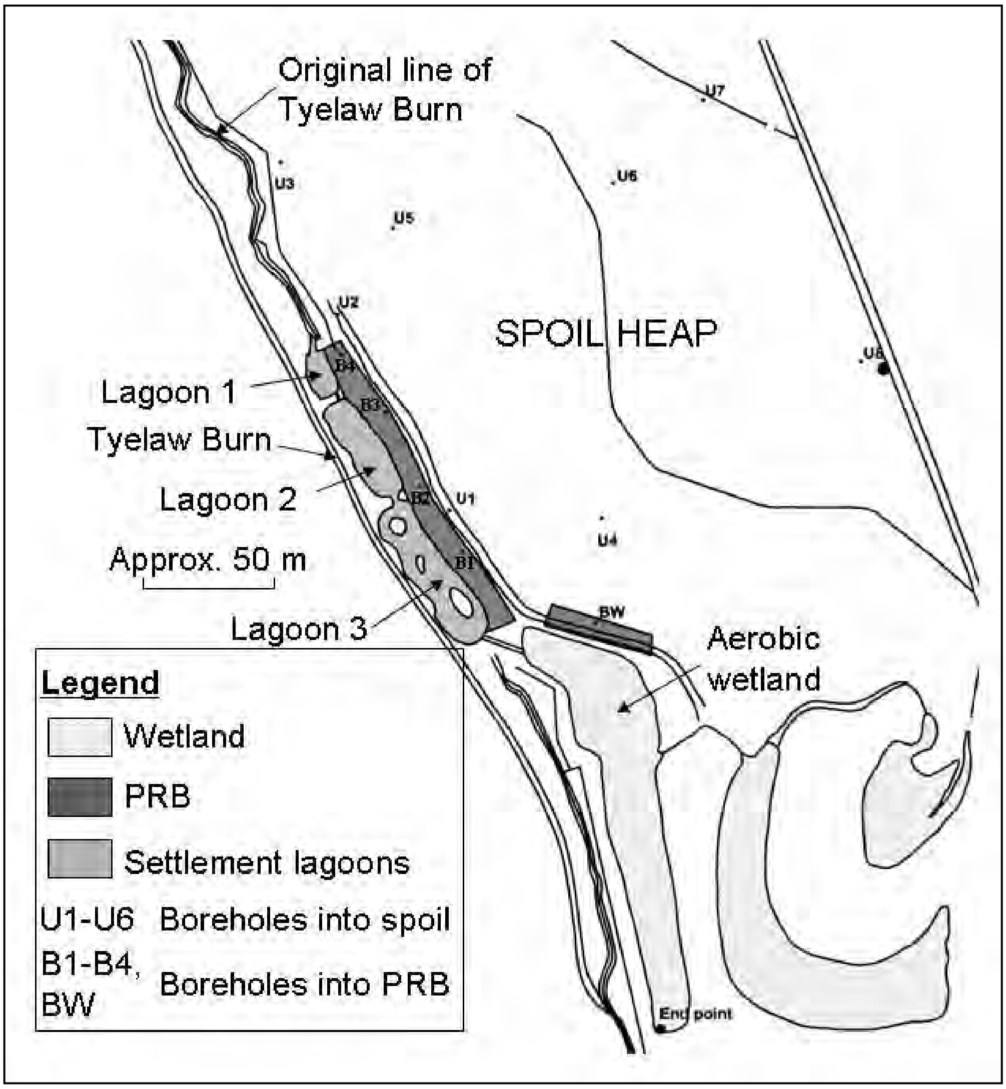

Figure 5.2. Layout of the PRB, settlement lagoons and aerobic wetland on the western flank of the Shilbottle spoil heap, Northumberland.

Construction works at the Shilbottle site commenced in July 2002, and were completed in September 2002. Construction work began with diversion of the Tyelaw Burn, which was initially too close to the toe of the heap to allow excavation of both PRB and settlement lagoons. The original and new lines of the Burn are illustrated on Figure 5.2. Construction of the PRB itself began with excavation of the 140 m long trench (following completion of an access track). Figure 5.3 illustrates that the trench effectively involved excavation of the toe of the spoil heap. Since the toe of the heap slopes from east to west, the eastern wall is higher than the western face. Figure 5.3 also clearly illustrates the boundary between the spoil and the underlying boulder clay, and seepage of leachate was principally from this boundary. Since the excavation cut at least 0.5 m down into the clay, the PRB was effectively keyed into this impermeable layer. With the exception of one small area (see below) an artificial liner was therefore not required. At intervals along the base of the trench 0.5 m high bunds were emplaced to prevent rapid migration of water down its length.

Cut material from the trench excavation was either used for landscaping works on other parts of the site or, in the case of spoil material that may have been a source of secondary contamination, was disposed of to a licensed waste disposal facility that had been retained at the site during earlier phases of restoration.

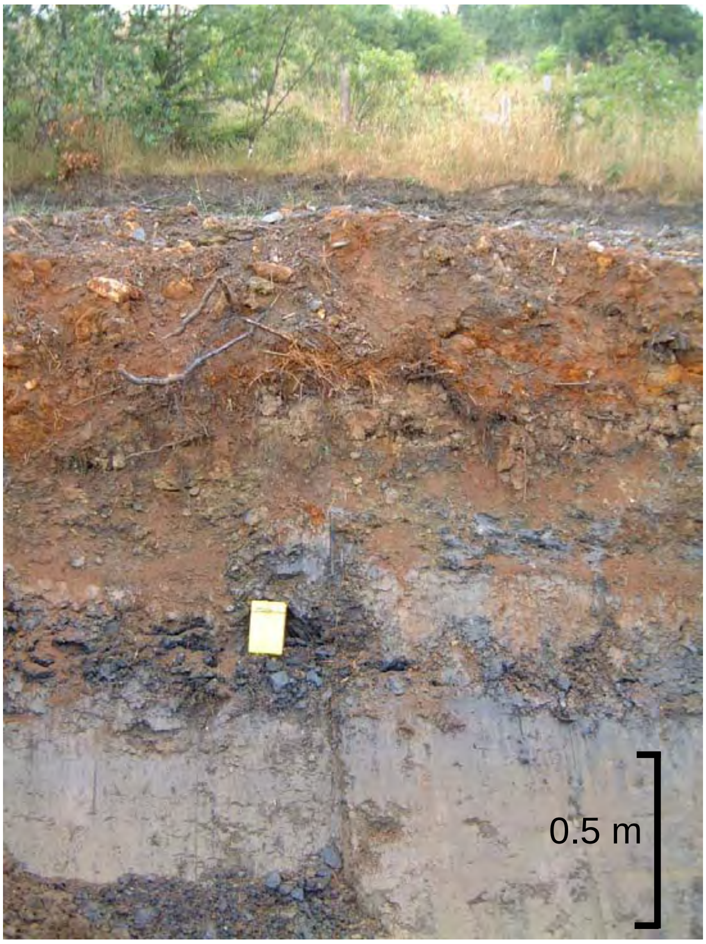

Figure 5.3. Excavation of the trench for the PRB underway, clearly indicating the contact between the (relatively permeable) oxidised colliery spoil (orange in colour) and the underlying, low-permeability boulder clay (dark grey in colour). The contact lies immediately below the notebook (there is minimal seepage of leachate at this particular point).

A permeable brick rubble berm was placed along the western bank of the trench, to facilitate the passage of water from the PRB into the settlement lagoons (Figure 5.4). In one area, where there was a particularly large seepage of leachate, an impermeable geotextile liner was wrapped around the rubble berm. This was done as there was some concern that the high flow-rate of this seepage may cause piping through the barrier at this point. The geotextile liner ensured that water from this seepage would be forced along the length of the barrier, thus ensuring sufficient contact time with the reactive substrate.

The compost and limestone substrate (Figure 5.5) was combined in an agricultural mixer before being backfilled into the trench from north to south along its length (Figure 5.6). During backfilling of the substrate the piezometers, labelled B1-B4 on Figure 5.2, were positioned at intervals along the length of the PRB, at three depths in each location, to allow subsequent sampling of spoil leachate as it passed through the substrate (Figure 5.6). Unlike many other PRBs, the surface of the unit at Shilbottle was not capped with a clay layer. Infiltration of small volumes of rainwater, or surface runoff from the spoil heap, was not a concern, since it would rapidly become stripped of oxygen as it passed downwards through the substrate. The surface of the PRB rapidly developed a grass sward, and after several years of operation it is difficult to distinguish the surface of the PRB from the adjacent ground.

Figure 5.4. PRB construction: the first load of reactive media to be tipped into the trench, abutting the spoil on the right, and the demolition-rubble berm on the left (upon which Professor Andy Aplin is standing); the demolition rubble provides a permeable interface through which water can flow from the PRB into the settlement lagoons (being formed in the background).

Figure 5.5. Stockpiles of manure and limestone, ready for mixing prior to placement in the PRB trench.

Figure 5.6. Mixed substrate being placed into the PRB trench. In the foreground a cluster of multi-level piezometers have been installed.

The settlement lagoons (Figure 5.2 and Figure 5.7) were excavated along the original line of the Tyelaw Burn, to a depth of 1 – 2 m. An open channel connection facilitates transfer of water from lagoon 3 to the pre-existing aerobic wetland (Figure 5.8).

Figure 5.7. The settlement lagoons after completion and commissioning of the Shilbottle passive treatment system. The water flowing out of the lagoons is bright orange in colour due to the rapid hydrolysis and precipitation of iron in the presence of the alkalinity generated in the PRB.

Figure 5.8. The pre-existing aerobic wetland at the site, which effects polishing treatment of the effluent from the settlement lagoons.

5.4.2 DESIGN NOVELTIES

5.4.2.1 A unique combination of substrates to tackle a grossly polluted water

An earlier small-scale trial of PRB technology for spoil leachate treatment was reported from Renishaw Park, Derbyshire, by David Laine (*personal communication*, 2001). However, subsequent site works led to the loss of the system (at least as regards access for sampling to quantify performance) before any data could be collected from it. The Shilbottle system is thus the only PRB in the UK treating spoil heap leachate. So far as we are aware (after extensive discussions with PRB specialists in Canada), no other PRB like that at Shilbottle (i.e. installed in the toe of a spoil heap, rather than in a natural aquifer) yet exists anywhere else in the world. It is also believed that the Shilbottle PRB is the largest continuous-wall PRB of any type, anywhere in the world, and it is certainly the largest mine drainage treatment PRB in the world. The quality of the spoil leachate treated by the Shilbottle PRB is the worst recorded in England, and may only be exceeded in the entire UK by one or two spoil leachates in Scotland (see Table 3.1 and Younger 2001).

The overall construction cost of the system, discussed in detail in Section 8, was kept to a minimum by the use of a unique combination of locally available materials for the PRB substrate. The novel laboratory-based experiments that led to the selection of this particular combination of substrates are described in detail by Amos and Younger (2003).

PRBs are typically stand-alone treatment units, with the treated water remaining in the subsurface following passage through the reactive media (Boshoff and Bone, 2005). In contrast, at Shilbottle subsurface leachate is forced to the surface following initial treatment by the PRB (principally generation of alkalinity and immobilisation of metals), for subsequent further attenuation of metals using settlement lagoons and an aerobic wetland.

5.4.2.2 Monitoring and sampling facilities

Figure 5.2 illustrates the locations of the networks of boreholes and piezometers in the spoil heap and PRB at Shilbottle. The four clusters of piezometers in the main section of the PRB

(B1 – B4), and the piezometer cluster in the 40 m section of the PRB (BW) comprise three multi-level sampling tubes. The three piezometers in each cluster allow sampling of water 0.3 m, 1.0 m and 1.9 m from the base of the PRB trench. Each piezometer tip is packed in gravel to prevent blockage due to fine sediments associated with the PRB substrate. There are eight boreholes in the spoil heap itself (marked U1 – U8 on Figure 5.2), which allow assessment of spatial and temporal heterogeneities in spoil heap water quality. In addition to these subsurface sampling points, water samples are routinely collected from each of the three settlement lagoons, from the outlet of the aerobic wetland (the point at which water returns to the Tyelaw Burn, marked ‘End point’ on Figure 5.2), and from the Tyelaw Burn itself downstream of the effluent from the treatment system.

Within the constraints of available resources (financial, staff), water samples are collected monthly from Borehole U1, the piezometers in the PRB, and the surface waters in the settlement lagoons, wetland outlet, and Tyelaw Burn. The entire network of boreholes in the spoil heap are now sampled at quarterly intervals. Much of the cost of the sampling and analysis programme for the Shilbottle system in recent years has been met by funding from the DTI/BBSRC/EPSRC Biorem 4 LINK funded project, 'ASURE' (GR/S07247/01), supported by funds from the HSBC Partnership for Environmental Innovation.

6. PERFORMANCE OF THE FULL-SCALE SYSTEM

6.1 OVERVIEW

Complete listings of concentrations of all major contaminants, at all sampling points, are provided in Appendix 1. The purpose of this section of the report is to highlight the overall performance of the system, with an emphasis on attenuation of acidity and metals. Comments are also made about the key mechanisms of attenuation, and on actual and potential current and future issues regarding treatment performance.

Table 6.1 provides summary performance data for the system. For clarity, only selected points through the treatment system are shown. What is clear from Table 6.1 is that concentrations of all the main contaminants are substantially reduced between the spoil heap and the end point of the treatment system. Within the barrier (B1 Med, B2 Med and B3) concentrations of metals and sulphate are higher than within the spoil heap, which is indicative of the retention of these contaminants (as metal monosulphides) within the PRB. At the effluent point from Lagoon 3 iron and aluminium concentrations are > 65% less than within the spoil heap, indicating the rapid hydrolysis and precipitation of these metals within the settlement lagoons. Note also, however, that the pH in Lagoon 3 is very low (mean of 3.91), a consequence of the release of protons during the hydrolysis reactions shown in Equations (3) and (5).

Table 6.1. Summary data showing the treatment system performance at Shilbottle (all concentrations are in mg/L, and mg/L as $CaCO_3$ in the case of alkalinity and acidity; S.D. is standard deviation; n is the number of measurements; see Figure 5.2 for locations).

Location		pH	Fe	Mn	Al	Alkalinity	Acidity[1]	SO_4
	mean	4.11	383.8	110.0	274.8	0	1727	7306
U1	S.D.	0.23	281.8	78.9	215.1	0	2196	3673
	n	12	29	29	29	29	12	29
	mean	5.07	874.3	177.2	116.6	309	2752	9476
B1 Med	S.D.	0.86	263.9	40.8	118.6	226	1099	1615
	n	6	21	21	21	20	6	21
	mean	4.42	538.4	191.4	327.5	17	4205	9757
B2 Med	S.D.	0.30	90.5	33.2	243.6	35	1595	2174
	n	6	21	21	21	21	6	21
	mean	5.15	465.7	206.0	119.3	156	2461	9165
B3	S.D.	1.12	91.3	40.1	133.6	171	1063	1956
	n	6	23	23	23	22	6	23
	mean	3.91	109.2	95.3	92.1	9	1383	5654
Lag 3	S.D.	1.08	73.2	35.1	94.0	32	728	2210
	n	12	27	27	27	27	12	27
End point	mean	5.13	20.8	54.6	42.9	30	470	3149
	S.D.	1.50	20.2	38.1	49.7	51	464	2136
	n	12	27	27	27	27	12	27
Tyelaw Burn	mean	6.90	2.4	3.4	3.9	140	32	278
	S.D.	0.42	2.4	1.4	2.5	49	18	86
	n	9	9	9	9	9	9	9

[1] Acidity is calculated according to the equation of Hedin *et al.* (1994a): Acidity (mg/L as $CaCO_3$) = $50[2(Fe^{2+}/56) + 3(Fe^{3+}/56) + 2(Mn/55) + 3(Al/27) + 1000(10^{-pH})]$ where concentrations are in mg/L.

Mean iron concentration of the effluent from the aerobic wetland is 20.8 mg/L, and the mean removal efficiency for iron since commissioning is in excess of 90%, as illustrated in Figure 6.1. It should be noted that ordinarily system performance is reported in terms of contaminant *load* attenuation (i.e. flow-rate x concentration), as this is a far more robust metric than removal efficiency. However, it is not currently possible to measure influent flow-rate (since it is both diffuse and in the subsurface), and therefore contaminant load removal cannot be calculated.

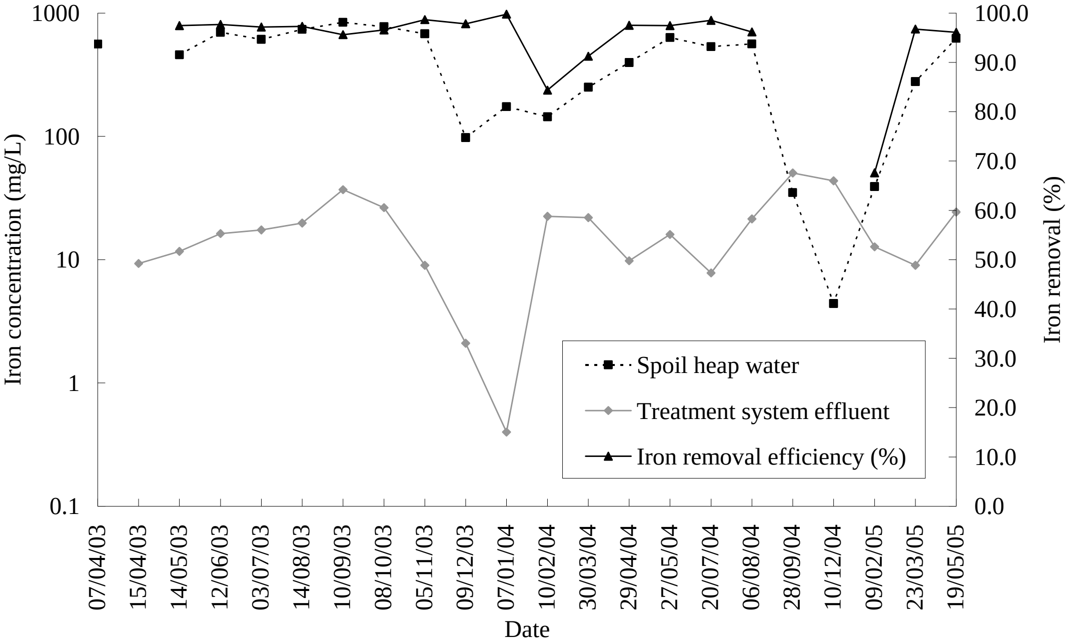

Figure 6.1. Concentrations of iron within the spoil heap (Borehole ‘U1’, Figure 5.2) and at the effluent point from the treatment system (‘End Point’, Figure 5.2), together with removal efficiency (%) for iron (from Jarvis *et al.*, 2006).

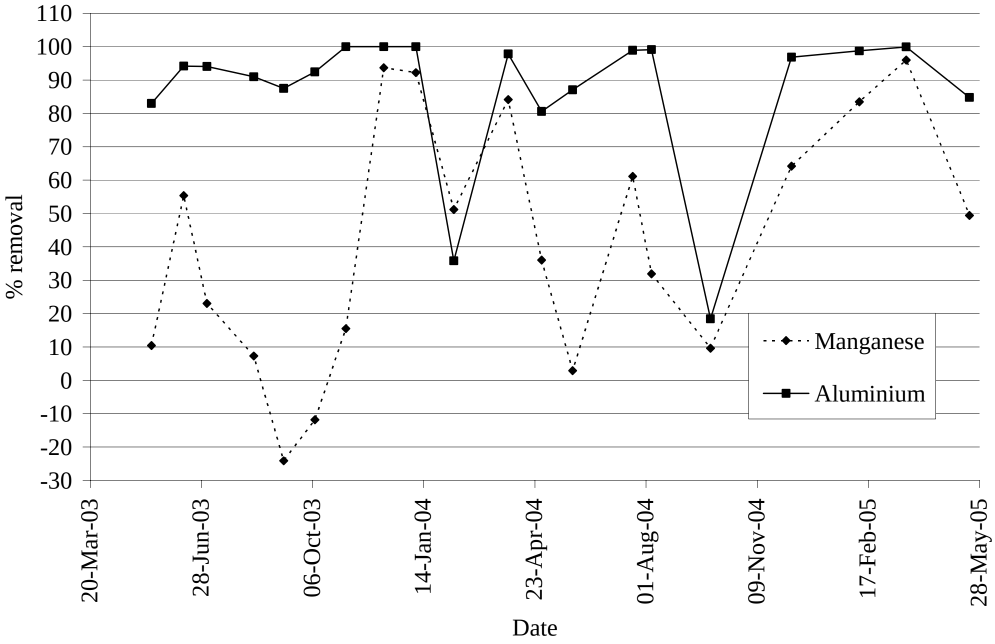

Figure 6.2. Removal efficiencies (%) for manganese and aluminium at the Shilbottle treatment system (raw water is represented by sample point ‘U1’, and treated water by ‘End Point’; See Figure 5.2) (from Jarvis *et al.*, 2006).

Aluminium removal is also highly efficient (a mean of 87% over the monitoring period; Figure 6.2). In the case of both iron and aluminium occasional drops in efficiency appear to relate to occasions on which metal flocs, in suspension, are carried over the effluent weir. To prevent this occurring in the future plans are in hand to create deeper areas of water within the aerobic wetland, and install baffles to increase residence time for settling.

Interpretation of changes in pH, acidity and alkalinity through the treatment system is complex. Alkalinity concentration within the PRB ranges from 0 – 600 mg/L as $CaCO_3$, implying spatially heterogeneous production, possibly related to development of preferential flow-paths through the barrier.

Inspection of Figure 6.3 illustrates that pH is variable at each of the sample locations, for the period of monitoring reported here. This variation in fact increases with progress through the treatment system (i.e. greatest variation in pH is apparent at the End Point), and lowest recorded pH values are also evident at the End Point. The low pH values at the end point imply poor treatment performance. The reason this occurs is that the concentrations of iron and aluminium are so high in the Shilbottle spoil drainage that subsequent release of protons during hydrolysis of these metals in the settlement lagoons and aerobic wetland (Equations (3) and (5)) results in rapid consumption of the alkalinity produced in the PRB, and then excess release of protons, hence causing a reduction in pH. It appears that the high variation in pH, particularly at the outlet end of the system, relates to dilution by direct precipitation; during low flow conditions release of protons due to metal hydrolysis is especially vigorous, whilst the greatest potential for dilution during storm events is at the end of the system, which receives the maximum volume of diluting inputs.

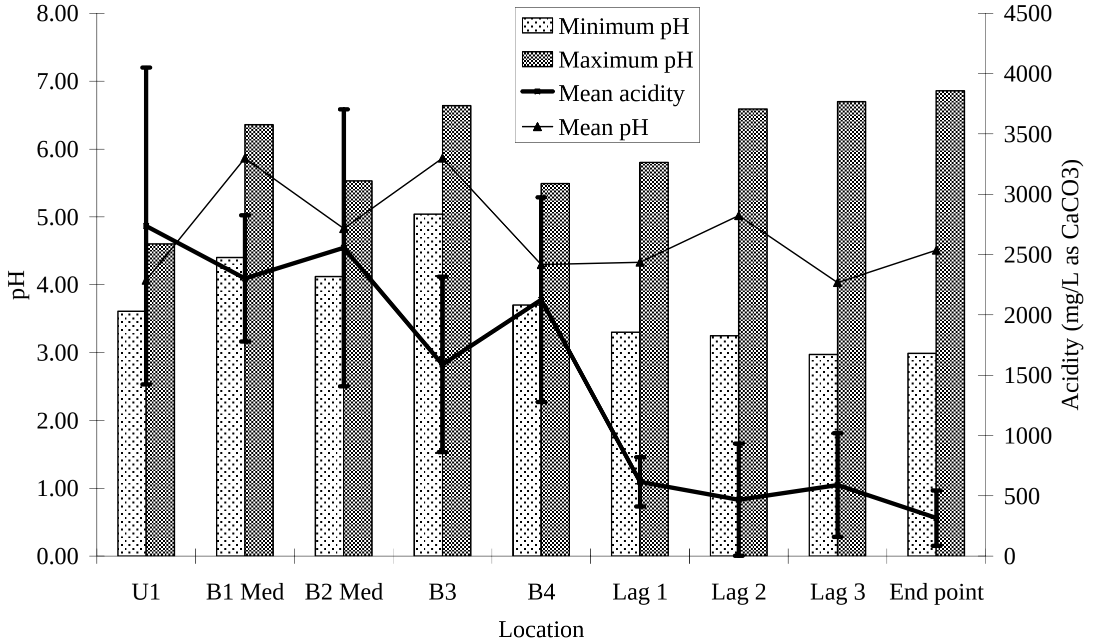

Figure 6.3. Summary statistics for pH, together with mean acidity concentration, through the treatment system at Shilbottle (all points are illustrated in Figure 5.2) (error bars show standard deviation from the mean acidity concentration; *n* = 16 except Lag 1 where *n* = 9) (from Jarvis *et al.*, 2006).

The low pH of the effluent water is not the serious issue that it may at first appear. This is because the acidity concentration of the spoil heap decreases significantly through the treatment system (from approximately 2,500 mg/L as $CaCO_3$ to < 500 mg/L as $CaCO_3$; Figure 6.3). Acidity concentration is not just a function of proton concentration (or ‘activity’ more accurately), but also of metal ion concentration. Acidity is a much more pervasive problem in receiving watercourses, since its attenuation is manifest principally by deposition of metals (an ecological and aesthetic problem in its own right) for considerable distances downstream of the outfall. pH, on the other hand, is rapidly corrected by simple dilution. Indeed measurements in the receiving watercourse (the Tyelaw Burn) 5 – 10 m below the outfall indicate circum-neutral pH values. Notwithstanding this rapid attenuation of pH, the intention is to install permeable limestone berms across sections of the aerobic wetland in the near future, to elevate pH prior to final discharge to the Tyelaw Burn.

6.2 REMOVAL MECHANISMS FOR METALS, ACIDITY AND SULPHATE

Concentrations of metals are elevated within the PRB itself (see data in Appendix 1), illustrating that this is a major sink for these contaminants. Sulphate concentrations also decrease across the PRB (from approximately 8,700 mg/L to 5,000 mg/L), and therefore dissimilatory bacterial sulphate reduction (BSR) appears to be a key process of metal attenuation and alkalinity generation (see Equations (8) and (9)). This process has been widely cited elsewhere as an important treatment process (e.g. Walton-Day, 1999; Blowes *et al.*, 2004; Fabian *et al.*, 2005).

Within the settlement lagoons and wetland the immobilisation of iron as a solid ferric hydroxide precipitate is clearly evident by the bright orange colour of these sections of the treatment system (see Figure 5.7, for example). The relevant reactions are shown in equations (3) and (5) for iron and aluminium respectively. However, water quality analyses also indicate that sulphate concentration decreases across the wetland (from approximately 5,000 to 2,900 mg/L). Inspection of magnesium concentration data across the wetland suggest that dilution may be influential on some occasions, but is not sufficient to account for all of the decrease in sulphate concentration (magnesium is present in low concentrations in rainfall, and is therefore a useful indicator of dilution). Therefore the precipitation of iron hydroxyl-sulphate minerals may be an important sink for both iron and sulphate. Mineralogical analyses (e.g. X-Ray Diffraction) have not yet been undertaken to confirm that these minerals are indeed present, but are certainly an item for future work.

It is worth referring back to the comments made at the end of Section 1.1 at this stage, which relate to the difficulty of collecting samples from the upstream and downstream interfaces of the PRB with the spoil heap and settlement lagoons respectively. This renders determination of the exact changes in water quality, specifically through the PRB, difficult. However, it is clear that the PRB serves the purpose for which it was designed - neutralisation of acidity and generation of alkalinity. At the pH of the water in the spoil heap the rapid hydrolysis and precipitation of iron within the settlement lagoons would simply not be seen without the correct functioning of the PRB. It would be possible to determine the form in which metals and sulphate are retained within the PRB by sampling the reactive media within the PRB and conducting mineralogical analysis upon these samples. However, this would necessitate invasive (and therefore destructive) sampling of the PRB, which is clearly not desirable while the PRB is in operation. Alternative means of elucidating the relative importance of BSR in the generation of alkalinity may utilise carbon and sulphur isotope geochemical analysis, and this is certainly an avenue of enquiry on the HERO Group's research agenda.

7. PERSPECTIVES FOR TECHNOLOGY DEMONSTRATION CLOSE OUT

7.1 THE LONGEVITY OF SPOIL HEAP LEACHATE CONTAMINATION

Observations alone demonstrate that spoil heaps have the potential to serve as pollutant sources for centuries (abundant examples in the UK) or even millennia (e.g. spoil heaps dating back to the Bronze Age in the Iberian Pyrite Belt). Whether a particular spoil heap will continue to release pollutants over such an extended time-scale depends on three principal factors:

(i) The relative proportions of pollutant source minerals (especially sulphides, but also some ferrous-iron bearing carbonates such as siderite and ankerite) and minerals which neutralise acidity, thus favouring precipitation and or sorption of pollutant metals onto mineral surfaces.

(ii) The degree of water saturation of the spoil, since the availability of oxygen to weather the sulphide minerals is highly restricted where pores are filled with water. The most prolific of pollutant-releasing spoil heaps are those in which grain sizes are such that freely-draining pores are present, containing a mixture of air and water. Water saturation rises with increasing mud content, due to the smaller sizes of pores, which will drain less readily under gravity. The mud content of many spoil heaps actually increases over time due to weathering of mudstone clasts.

(iii) The extent and efficacy of any reclamation measures (such as clay capping, revegetation etc) which serve to limit the ingress of oxygen and / or water to parts of the heap containing pollutant source minerals.

Relatively few systematic studies have been made of the longevity of pollutant release from spoil heaps. However, all such studies indicate that pollution can typically be expected to continue for many centuries in the absence of remedial measures (e.g. Evans *et al.*, 2003; Gandy, 2005).

7.2 THE LIFETIME OF PASSIVE TREATMENT SYSTEMS

One of the principal attractions of passive treatment technologies is their potential to provide effective remediation for extended periods of time without the need for ongoing inputs of reactants, and with only minimal maintenance. However, as passive mine water treatment systems have only existed since the late 1980s (and few of the original systems were retained in operation, due to changes in site conditions, such as re-mining by opencast) the experience base in relation to the effective length of passive system lifetimes is still insufficient to categorically demonstrate sustained performance over decades as opposed to years. Most estimates of passive system longevity to date are necessarily forecasts, typically based on rather simplistic assumptions over relative rates of clogging with new precipitates and creation of new pore-space by dissolution of minerals and / or hydrolysis of organic matter. To date, the majority of estimates suggest that passive systems designed in accordance with scientific principles (see PIRAMID Consortium 2003) can be expected to operate for two to three decades before their substrates will require wholesale replacement.

The ASURE project, which looked in some detail at biogeochemical processes in three CoSTaR sites including Shilbottle, included some innovative predictive modelling of the likely longevity of subsurface flow bioreactors such as the Shilbottle PRB. Longevity was in this case examined in physical terms, by looking at the balance between porosity creation by dissolution of limestone/hydrolysis of organic matter, and occlusion of pore space by precipitation of new mineral solids. A system dynamics model was used to assess these processes, which effectively compete for creation/destruction of permeability, with system failure being reached when the permeability can no longer accommodate the design flow.

Permeability in such systems is a function of intergranular porosity, which is continually being consumed by accumulation of sulphide and hydroxide minerals, and simultaneously enhanced by carbonate dissolution and metabolisation of solid organic matter by bacterial consortia. At the time of writing this model, which is being implemented as a ‘systems dynamics’ model using the VENSIM™ modelling platform, is still undergoing generic testing and sensitivity analyses, the results of which will be reported in detail in future journal papers. However, initial indications of simulations run using data similar to the mean inflow / outflow data for the Shilbottle PRB suggest that total extinction of porosity is unlikely over any time-scale, and that final failure of the system will actually come when all organic matter is finally exhausted in more than four decades time.

7.3 MEETING THE REQUIREMENTS OF WATER AND WASTE LEGISLATION

Clearly this report is not the forum for detailed discussion of regulatory matters which are the legal province of the Environment Agency and Northumberland County Council, as site owners. However, in general terms, the construction of the Shilbottle PRB has been a success from the point of view of environmental regulation. The complete elimination of ochre staining from the Tyelaw Burn, which had previously been subject to such pollution for many decades, has switched the focus of Environment Agency attention from the Shilbottle leachate to other issues in the area.

During the early years of operation of the new PRB and associated ponds at Shilbottle, the Environment Agency were concerned that the pH of the final effluent from the reedbed was still often rather low. However, Figure 6.3 illustrates that whilst pH is periodically low in the final discharge, acidity concentration is consistently reduced, by in excess of 80%. This is critical, as it illustrates the effective removal of mineral acidity (i.e. that caused by hydrolysable metals such as Fe and Al). The attenuation of this mineral acidity is vital, since mineral acidity is pervasive in receiving watercourses, principally because metals hydrolyse and precipitate to form ecologically damaging coatings of metal solids on stream beds. The presence of low pH alone is not of such great concern, since dilution alone is sufficient to remedy the problem, without any pervasive effects. Nevertheless, plans are in place to address final pH correction before discharge to the Tyelaw Burn, and these measures have been outlined in Section 6.2; the regulatory authorities have indicated no objection to this approach.

In terms of waste legislation, a particular long-term issue relates to the eventual safe disposal of spent substrate from the PRB, which can be expected to be rich in sulphides, and hydroxides / hydroxysulphates of iron and aluminium which will at some point in future be dredged from the oxidation ponds and reedbed. Fortunately, this long-term prospect was anticipated during system design, and NCC retained part of the spoil heap site as a licensed waste site, on which it is intended to construct a dry entombment for the sulphide wastes (and other appropriate, less stringent, disposal for the hydroxides / hydroxysulphates) at some point in the future. Provisions of the new European Mine Waste Directive are consistent with this long-term strategy for treatment wastes derived from mineral wastes on a former mine site.

8. ECONOMIC CONSIDERATIONS AND A COMPARISON WITH COSTS FOR ACTIVE TREATMENT

8.1 CAPITAL COSTS

Table 8.1 summarises actual or estimated construction and operational costs for the Shilbottle PRB system, compared to estimated costs for an active treatment system. The data for the cost estimates for the active treatment system have been kindly provided by Chris Bullen of Unipure Europe Ltd, Monmouth, Wales. Because passive treatment systems rely on naturally-occurring chemical and biological processes, which generally occur more slowly than reactions taking place in active treatment, overall treatment scheme dimensions are typically greater. The capital cost of a passive treatment system may consequently be high, particularly due to the potentially high costs of earth moving operations (see, for example, cost estimate for the aerobic wetland in Table 8.1) and land acquisition.

The Shilbottle scheme was constructed immediately adjacent to the spoil heap on the site, but on land in the ownership of Northumberland County Council. Since the treatment initiative was driven by Northumberland County Council there were consequently no land acquisition costs. However, an indicative cost for land of this sort, for which there is unlikely to be any other use, is £500 / acre (personal communication, Mr Stuart Rolley, UK Coal Authority). Since the overall footprint occupied by the Shilbottle scheme is approximately 9,000 m^2, estimated land purchase costs would have been in the order of £1,100, and therefore a minimal part of the overall capital cost indicated in Table 8.1.

As noted earlier in this report, the treatment system makes use of the substantial aerobic wetland (approximately 4,000 m^2) that already existed on the site. To ensure a realistic comparison, a cost estimate for construction of the wetland is given in Table 8.1.

Table 8.1. Actual or estimated costs of the Shilbottle PRB system compared to an equivalent active treatment system.

	Passive system	**Active system**
Capital expenditure – PRB and lagoons	£78,000[a]	£200,000[b]
Capital expenditure – wetland[c]	£200,000	-
Operational expenditure[d]	£7,500 / year[e]	£44,500 /year[f]

[a] Actual construction costs of PRB, settlement lagoons and ancillary works

[b] Cost estimate provided by Unipure Europe Ltd., and based on a containerised High Density Sludge (HDS) plant, including polymer dosing equipment, reactor mixers, clarifier rake, recycle and excess sludge pumps, potable and process water pump systems, calcium hydroxide silo, make up and dosing system, air blower, discharge monitoring tank, control panel and suitable control and monitoring equipment. Does not include planning and enabling works.

[c] Estimated using a typical unit cost for wetland construction of £50 / m^2 (Jarvis and Younger, 1999)

[d] Does not include waste sludge disposal

[e] Based on historic and planned operational expenditure since system commissioning.

[f] Includes calcium hydroxide supply, manpower, maintenance, flocculant / polymer supply and electricity

8.2 PROJECTED LIFE-CYCLE COSTS FOR FULL-SCALE PASSIVE AND ACTIVE TREATMENT

For reasons outlined in Section 7.2 accurate prediction of passive treatment system lifetime is very difficult, and therefore projecting life-cycle costs with confidence is also difficult. Early indications from the modelling work, discussed in Section 7.2, suggest that the Shilbottle PRB life will be governed by the availability of organic carbon, resulting in a predicted lifetime of some 40 years. However, the Quaking Houses compost wetland (the first passive system for the remediation of acidic spoil drainage in the UK; see Jarvis and Younger, 1999) required complete renovation after 8 years. However, the principal factor that determined the lifetime of the Quaking Houses system was in fact the accumulation of dead plant material within the system. The Shilbottle PRB and lagoons are not planted, and therefore this is not anticipated to be an issue. Nevertheless, to provide a conservative comparison of projected life-cycle costs for passive versus active treatment at Shilbottle, and to be consistent with the similar evaluation recently reported in CL:AIRE (2006b), it has been calculated on the basis of a 10 year lifetime for the purposes of Table 8.2.

Table 8.2. Estimated life-cycle costs for the existing full-scale passive treatment system and an active system designed by Unipure Europe Ltd.

	Passive system	**Active system**
First life-cycle (10 years)[a]	£353,000	£645,000
Two life-cycles (20 years)[b]	£428,000	£1,090,000
Each additional life-cycle[b]	£75,000	£445,000

[a] Excluding site investigation, planning and enabling works

[b] Excluding substrate / sludge disposal costs. Substrate and sludge disposal costs may be a significant proportion of overall operational costs. However, designers of active treatment systems will rarely make *a priori* judgements about the costs of disposal of treatment sludge, since even trace quantities of certain elements may increase disposal costs by an order of magnitude (lab and pilot studies would usually precede any such estimate). For comparative purposes, it is currently estimated that disposal cost of the substrate from the Shilbottle system would be in the order of £50,000, which is most unlikely to be any greater than sludge disposal costs for an equivalent active treatment system (based on costs from the Coal Authority's Horden treatment system).

Although the absolute capital costs for construction of the passive system at Shilbottle are higher than an equivalent active system Table 8.2 illustrates that the substantially higher operational costs of the active system mean that over the longer term the cost of the passive system becomes substantially lower. It should be noted that the active treatment system design is based on achieving final contaminant metal ion concentrations of < 1 mg/L. The passive system at Shilbottle does not achieve such low residual metal concentrations, and it is certainly the case that much closer process control would be achievable with an active treatment system. Therefore in situations where very strict regulatory conditions must be met, or indeed where land availability is restricted and / or land cost is very high, active treatment may become the preferred (or perhaps only) option.

Nevertheless, these numbers clearly demonstrate the economic advantage of passive treatment over longer time scales, quite apart from potential amenity benefits associated with passive units. However, it should be noted that the costs in Table 8.2 are based on rough estimations and therefore are to be used with caution. Again, it should be stressed that one of the objectives of the Shilbottle project is to learn more about long-term performance and lifetimes of passive treatment systems.

9. CONCLUSIONS

9.1 GENERAL CONCLUSIONS

Monitoring of the Shilbottle PRB since its installation has demonstrated the successful application of this novel passive treatment technology to the remediation of highly acidic and metal-rich spoil heap leachate. Concentrations of both iron and aluminium are typically reduced by in excess of 90% (approximately 500 mg/L to < 20 mg/L in the case of iron), and acidity concentration through the treatment system decreases from a mean of 2,500 mg/L as $CaCO_3$ to < 500 mg/L as $CaCO_3$.

Not only is the treatment system a demonstrable success in its own right, but this report has outlined how the partnership of landowners, regulators, research scientists and engineers has effectively worked to develop and implement a unique technology to improve the quality of a local stream, with marked benefits for downstream users.

The Shilbottle PRB continues to be a site at which there is vigorous research activity. The site is a particular attraction for research visitors from across Europe, visiting Newcastle University under the auspices of our EU Access to Research Infrastructure CoSTaR programme (Coal mine Sites for Targeted Remediation research). Notwithstanding research by these visitors, specific areas of interest include determining the precise roles of bacterial sulphate reduction (BSR) and calcite dissolution in the generation of alkalinity, investigating the hydraulics of the PRB to establish why some sections of the PRB work more effectively than others, and examining carbon and sulphur cycling within the system with the ultimate objective of predicting PRB longevity (Jarvis *et al.*, 2006).

9.2 LIMITATIONS OF THE TECHNOLOGY

The Shilbottle PRB Technology Demonstration Project has illustrated many of the strengths of this approach to the remediation of acidic and metalliferous leachates. It nevertheless also has its limitations. There are limits to the levels to which alkalinity can be raised in a single flow-through system before kinetics become sluggish and further increments in alkalinity could only be gained at the expense of far longer residence times. In this case, total alkalinity never rises much above 300 mg/L as $CaCO_3$ (see Table 6.1) and never exceeds 600 mg/L (see Appendix 1), even in those parts of the PRB which are inferred to have the highest residence times (on the grounds of relatively low permeabilities as measured by slug tests; Moustafa 2006). Even when alkalinity is at a maximum, the total acidity tends to remain in excess of 2,000 mg/L as $CaCO_3$ (often far more; Table 6.1), so that the water leaving the PRB is still markedly net-acidic. Only a system of sequential anaerobic / aerobic reactors (adopting the principle of 'successive alkalinity producing systems' first proposed by Kepler and McCleary 1994) could completely overcome this constraint, but such a strategy would require far more land area and site relief (i.e. exploitable hydraulic head) than are available on this site.

As with all treatment systems (active or passive) PRBs generate large quantities of waste solids which will eventually have to be dealt with. At present, effective disposal options are restricted to permanent submergence (to prevent oxidation by limiting diffusional access by oxygen) or dry entombment. In this particular case, there is no problem with the latter, given the availability of a licensed waste disposal facility on site. At other sites, conditions may not be so favourable and more careful planning for long-term disposal (*in situ* or to another site) will be required during project design.

9.3 APPLICABILITY AND POTENTIAL FUTURE DEVELOPMENTS

It is clearly feasible to propose the straightforward transfer of the technology demonstrated at the Shilbottle site to other sites with similar problems, without any need for further process development. Nevertheless, it may well be that higher performance efficiencies could be gained by improvements in the specification of the reactive substrate. There is so little difference in performance between the blast furnace slag and limestone gravel sections of the PRB to render the choice between those two inorganic components of the substrate a non-issue: a simple comparison of costs will be the deciding factor in each case. With regard to the organic fraction of the substrate, it is now clear (in the wake of the ASURE project and similar work recently completed in South Africa and the USA) that there is some scope for improving reactivity by specifying more refined sources of carbon, which will require less prior attack by ligno-cellulose degraders before they release the short-chain acids which are the preferred metabolites of iron- and sulphur-reducing bacteria. This is an area of active, ongoing research at HERO and elsewhere. The possibility of obtaining large quantities of cellulose fibre at modest cost, from steam autoclave treatment of municipal wastes, has recently emerged due to the development by Graphite Resource Ltd of the first industrial-scale plant in the UK to use this process (scheduled for construction during 2006-07 at Derwenthaugh, Gateshead). Although subject to future experimentation, this type of development offers the possibility of specifying carbon fractions which are far better characterised than the typical horse manure / straw / compost mixtures used to date.

There remains the intriguing possibility of applying technology along the lines of that demonstrated at Shilbottle to the treatment of other metalliferous effluents, such as those associated with various branches of manufacturing. As head limitations are unlikely to be a constraint in active industrial plants where pumping is routinely practised, it is unlikely that this particular form of a PRB would be required; a configuration akin to that described from the Bowden Close RAPS system (CL:AIRE TDP5) is more likely for such applications; however, most of the lessons about reactivity learned at Shilbottle will still be applicable.

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APPENDIX 1: BASIC MONITORING DATA

Borehole U1

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
12-Feb-03		210	38	122	0		6237
6-Mar-03		466	120	355	0		6780
7-Apr-03		560	161	419	0		9208
14-May-03		459	149	354	0		8246
12-Jun-03		699	164	390	0		9185
3-Jul-03		611	162	380	0		8949
14-Aug-03		738	179	333	0		9479
10-Sep-03		842	170	272	0		10449
8-Oct-03		775	177	280	0		10658
5-Nov-03		680	179	309	0		10556
9-Dec-03		98	37	68	0		4709
7-Jan-04	3.77	174	48	93	0	922	4910
10-Feb-04	4.60	144	46	134	0	1087	3270
30-Mar-04		250	84	266	0		5811
29-Apr-04		397	122	380	0		8270
27-May-04		633	227	581	0		10920
20-Jul-04		535	217	413	0		9267
6-Aug-04		562	188	415	0		7405
28-Sep-04	4.03	35	15	39	0	311	4542
10-Dec-04		4	5	16	0		2153
9-Feb-05	4.00	39	13	32	0	274	2883
23-Mar-05	3.96	278	82	246	0	2018	8367
19-May-05	4.17	624	221	862	0	6308	13968
6-Jul-05	3.84	724	220	705	0	5617	15655
23-Aug-05	4.22	500	132	391	0	3308	10694
27-Oct-05	4.15	59	17	54	0	437	2156
30-Nov-05	3.99	29	8	31	0	245	2926
9-Jan-06	4.19	6	4	16	0	113	2004
7-Feb-06	4.37	1	5	12	0	78	2205

Borehole U2

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
12-Feb-03		467	138	168	0		10000
6-Mar-03		440	149	205	0		6800
7-Apr-03		355	125	143	0		6906
14-May-03		278	93	136	0		6202
12-Jun-03		311	94	138	0		6879
3-Jul-03		280	83	118	0		6422
14-Aug-03		274	90	112	0		6901
10-Sep-03		278	80	88	0		5725
8-Oct-03		250	85	98	0		7423
5-Nov-03		316	103	87	0		7591

Borehole U3

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
12-Feb-03		172	69	121	0		8280
6-Mar-03		176	73	136	0		5600
7-Apr-03		116	50	92	0		6257
14-May-03		74	46	61	0		5691
12-Jun-03		58	48	50	0		5844
3-Jul-03		43	44	38	0		5252
14-Aug-03		34	51	21	0		5864
10-Sep-03		30	49	11	0		5761
8-Oct-03		23	53	11	0		5928
5-Nov-03		21	58	8	0		6420
30-Nov-05	3.60	94	59	194	0	1365	7600
7-Feb-06	3.77	65	39	87	0	676	5875

Borehole U4

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
12-Feb-03		5.4	6.4	1.8	690		4260
18-Mar-03		9.7	9.2	3.6	696		3387
15-Apr-03		24.9	9.7	22	808		3476
14-May-03		0.2	5.8	0.5	712		3277
12-Jun-03		11.9	9.6	6.8	670		3613
3-Jul-03		4.1	6.3	0.8	808		3008
14-Aug-03		5.8	8.8	1.1	740		3350
10-Sep-03		1.8	7.5	0.5	780		3363
8-Oct-03		2.3	7.9	0.5	760		3426
5-Nov-03		2.1	8.6	0.5	760		3460
30-Nov-05	6.41	15.9	12.2	31.8	750	227	3472

Borehole U5

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
12-Feb-03		23.0	7.7	47.8	501		3622
18-Mar-03		30.9	7.5	34.3	552		3056
15-Apr-03		22.5	5.1	15.5	516		3156
14-May-03		17.0	4.8	4.6	600		2981
12-Jun-03		21.5	5.5	20.6	544		3049
3-Jul-03		25.9	4.5	17.9	570		2954
14-Aug-03		38.6	6.1	60.2	512		3348
10-Sep-03		15.4	3.6	3.5	586		3208
8-Oct-03		13.1	3.9	3.7	606		3061
5-Nov-03		14.4	4.4	3.9	580		3103

Borehole U6

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
12-Feb-03		5692	1520	1181	0		44180
15-Apr-03		6041	1533	1698	0		61389
14-May-03		6646	1594	1421	0		56920
12-Jun-03		5638	1297	1352	0		55437
3-Jul-03		4307	990	917	0		38883
14-Aug-03		3908	1057	898	0		38696
10-Sep-03		3367	814	667	0		33532
8-Oct-03							
5-Nov-03							
30-Nov-05	3.31	718	761	326	0	4501	18370

Borehole U7

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
12-Feb-03		52.0	54.7	19.8	263		3400
18-Mar-03		69.7	65.5	38.5	234		3015
15-Apr-03		62.5	61.8	41.9	328		3258
14-May-03		98.7	72.8	22.5	500		3060
12-Jun-03		98.5	81.9	44.1	200		3789
3-Jul-03		115.0	77.0	30.8	224		3112
14-Aug-03		121.0	95.0	27.7	256		3377
10-Sep-03		158.0	86.1	107.0	156		3620
8-Oct-03		127.0	93.9	71.2	140		3549
5-Nov-03		103.0	97.8	28.7	48		3505
30-Nov-05	4.51	299.0	59.2	700.0	0	4532	4337
7-Feb-06	4.50	143.0	63.0	129.0	0	1088	4121

Borehole U8

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
12-Feb-03		10.0	21.3	4.5	372		1780
18-Mar-03		2.0	23.2	0.9	350		1695
15-Apr-03		5.8	18.0	3.5	446		1752
14-May-03		5.7	17.2	2.9	750		1637
12-Jun-03		7.2	18.6	2.1	350		1714
3-Jul-03		4.8	14.6	2.0	376		1599
14-Aug-03		1.5	15.3	0.0	346		1539
10-Sep-03		4.9	14.9	1.5	350		1535
8-Oct-03							
5-Nov-03							
30-Nov-05	6.64	34.4	36.7	22.5	440	253	1564
7-Feb-06	6.88	2.5	8.2	1.2	353	26	1502

PRB piezometer B1 lower

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
12-Feb-03		1356	213	102	275		16566
6-Mar-03		1494	250	163	114		11730
7-Apr-03		1275	202	156	66		11852
14-May-03		888	168	27	582		9413
12-Jun-03		898	172	34	528		9514
3-Jul-03		720	155	23	554		9185
14-Aug-03		745	170	8	546		8857
10-Sep-03		845	159	6	576		7928
8-Oct-03		724	169	5	586		8878
5-Nov-03		775	181	5	540		8931
9-Dec-03		794	188	7	506		9777
7-Jan-04	6.00	989	174	6	480	2117	10728
10-Feb-04	6.14	1373	236	71	128	3276	11465
30-Mar-04		1080	173	54	240		10550
29-Apr-04		1194	165	91	29		10351
27-May-04		1026	204	57	260		10574
20-Jul-04		925	249	38	220		9256
6-Aug-04		964	187	38	321		9161
28-Sep-04	4.71	582	169	171		2298	9757
10-Dec-04		583	171	382	0		9948
9-Feb-05	4.42	823	169	245	0	3140	10562
23-Aug-05	4.73	841	181	310	7	3554	12033
27-Oct-05	5.26	483	94	60	69	1367	7425
30-Nov-05	4.98	408	79	96	45	1404	6730
9-Jan-06	4.62	532	108	176	2	2125	8007
7-Feb-06	4.64	838	159	362	0	3798	10986

PRB piezometer B1 medium

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
6-Mar-03		1282	224	102	526		10645
7-Apr-03		1221	193	291	162		11017
14-May-03		898	168	161	600		8869
12-Jun-03		899	173	68	450		8347
3-Jul-03		744	159	28	534		9181
14-Aug-03		791	173	15	500		8675
10-Sep-03		844	160	14	568		7900
8-Oct-03		745	170	11	532		8899
5-Nov-03		749	183	8	520		8666
9-Dec-03		737	182	8	508		8836
7-Jan-04	6.09	831	161	5	460	1807	9420
10-Feb-04	6.26	1303	230	65	152	3107	11109
30-Mar-04		1079	174	102	140		10929
29-Apr-04		1173	165	106	22		10375
27-May-04		1010	204	66	208		10134
20-Jul-04		889	255	73	120		9111
6-Aug-04		896	193	149	164		8994
28-Sep-04	4.40	482	170	273		2688	9601
23-Aug-05	4.56	828	187	338	0	3698	12415
30-Nov-05	4.58	144	39	153	8	1178	4592
7-Feb-06	4.55	815	158	412	0	4033	11278

PRB piezometer B1 upper

Date	pH	Iron mg/l	Manganese mg/l	Aluminium mg/l	Alkalinity mg/l	Acidity mg/l	Sulphate mg/l
23-Aug-05	4.47	859	188	424	0	4233	12519
30-Nov-05	4.60	154	35	136	10	1095	4276
7-Feb-06	4.58	816	161	422	0	4096	11362

PRB piezometer B2 lower

Date	pH	Iron mg/l	Manganese mg/l	Aluminium mg/l	Alkalinity mg/l	Acidity mg/l	Sulphate mg/l
12-Feb-03		698	170	370	0		11580
6-Mar-03		749	214	538	0		9240
7-Apr-03		585	181	393	0		9763
14-May-03		568	167	351	0		8676
12-Jun-03		581	168	200	0		7953
3-Jul-03		505	152	141	0		8173
14-Aug-03		476	160	30	0		7384
10-Sep-03		542	156	72	0		7992
8-Oct-03		475	164	95	20		8677
5-Nov-03		469	171	94	0		8078
9-Dec-03		425	181	88	25		8279
7-Jan-04	4.72	507	165	173	10	2167	8853
10-Feb-04	5.10	592	208	498	20	4202	10001
30-Mar-04		543	197	540	0		11433
29-Apr-04		524	204	474	0		10486
27-May-04		539	247	418	0		10957
20-Jul-04		508	280	298	0		9617
6-Aug-04		492	206	281	0		8502
28-Sep-04	4.08	533	199	419	0	3646	11716
10-Dec-04		509	220	425	0		12106
23-Mar-05	4.22	646	211	461	0	4101	11999
19-May-05	4.33	557	236	848	0	6137	14312
6-Jul-05	4.06	604	231	660	0	5170	27857
23-Aug-05	4.34	597	228	484	0	4172	14310
27-Oct-05	4.38	647	213	557	0	4639	13950
30-Nov-05	4.16	666	204	773	0	5858	13740
9-Jan-06	4.19	648	199	778	0	5844	13188
7-Feb-06	4.36	711	205	748	0	5800	13078

PRB piezometer B2 medium

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
6-Mar-03		740	211	683	0		9105
7-Apr-03		587	183	379	0		9558
14-May-03		579	168	303	0		8558
12-Jun-03		578	170	171	0		7776
3-Jul-03		492	148	99	0		8172
14-Aug-03		425	151	21	0		7322
10-Sep-03		515	152	38	40		7837
8-Oct-03		420	157	41	110		7800
5-Nov-03		461	169	84	74		7340
9-Dec-03		429	186	63	102		7924
7-Jan-04	4.70	438	158	95	10	1598	8384
10-Feb-04	4.87	590	205	520	20	4316	10200
30-Mar-04		551	202	551	0		11640
29-Apr-04		515	203	469	0		11432
27-May-04		538	246	415	0		10850
20-Jul-04		506	279	285	0		9906
6-Aug-04		506	207	238	0		8322
28-Sep-04	4.12	462	195	413	0	3478	11457
23-Aug-05	4.32	600	224	482	0	4159	14223
30-Nov-05	4.15	677	203	785	0	5943	13890
7-Feb-06	4.37	698	203	742	0	5740	13207

PRB piezometer B2 upper

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
6-Mar-03		649	212	334	0		7560
7-Apr-03		560	182	392	0		8660
14-May-03		552	167	175	0		7943
12-Jun-03		576	168	263	0		7749
3-Jul-03		496	147	162	0		7086
14-Aug-03							
10-Sep-03							
8-Oct-03							
5-Nov-03							
9-Dec-03		354	162	40	300		6787
7-Jan-04							
10-Feb-04							
30-Mar-04		570	199	543	0		11279
29-Apr-04		544	202	426	0		10402
27-May-04		560	244	357	0		10249
20-Jul-04		502	277	242	10		9328
6-Aug-04							
28-Sep-04							
23-Aug-05	4.32	622	222	451	0	4022	13988
30-Nov-05	4.26	593	182	674	0	5137	12700
7-Feb-06	4.36	665	204	720	0	5561	13353

PRB piezometer B3

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
12-Feb-03		507	168	69	240		9663
6-Mar-03		676	226	82	0		7690
7-Apr-03		543	194	42	100		8586
14-May-03		609	183	84	400		8066
12-Jun-03		424	167	5	300		7837
3-Jul-03		374	158	5	380		7284
14-Aug-03		336	164	6	392		7511
10-Sep-03		371	156	7	442		6969
8-Oct-03		366	169	15	402		7696
5-Nov-03		388	179	5	320		8448
9-Dec-03		342	185	11	20		8260
7-Jan-04	6.42	346	154	8	55	942	7602
10-Feb-04	6.64	509	213	30	110	1463	8203
30-Mar-04		541	235	357	0		10078
29-Apr-04		536	218	178	10		9154
27-May-04		513	246	74	240		9653
20-Jul-04		494	305	155	10		9428
6-Aug-04		504	225	91	0		8362
28-Sep-04	5.04	481	208	215		2432	9662
10-Dec-04		533	247	184	0		10808
23-Aug-05	4.08	499	251	416	0	3663	15076
30-Nov-05	4.36	417	252	340	0	3094	12200
7-Feb-06	4.33	402	235	364	0	3170	12567

PRB piezometer B4

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
12-Feb-03		503	146	201	0		7569
6-Mar-03		567	183	210	0		7560
7-Apr-03		382	132	151	0		7120
14-May-03		399	117	143	0		6798
12-Jun-03		446	120	192	0		7586
3-Jul-03		397	115	142	0		7113
14-Aug-03		396	122	124	0		7300
10-Sep-03		427	113	106	0		7566
8-Oct-03		362	116	113	0		8358
5-Nov-03		386	118	116	0		8215
9-Dec-03		356	135	120	0		8174
7-Jan-04	4.08	259	136	185	0	1742	6424
10-Feb-04	4.68	265	224	695	0	4743	11958
30-Mar-04		499	170	358	0		9109
29-Apr-04		391	118	198	0		7021
27-May-04		513	172	211	0		8537
20-Jul-04		422	179	154	0		7089
6-Aug-04		411	137	159	0		6401
28-Sep-04	3.83	482	171	296	0	2823	10179
10-Dec-04		406	150	208	0		8651
23-Aug-05	4.05	502	183	317	0	2995	11615
30-Nov-05	3.66	438	208	742	0	5293	14230
7-Feb-06	4.04	556	182	325	0	3134	10545

Settlement lagoon 1

Date	pH	Iron mg/l	Manganese mg/l	Aluminium mg/l	Alkalinity mg/l	Acidity mg/l	Sulphate mg/l
15-Apr-03		149	108	65	0		5809
14-May-03		217	120	65	0		6235
12-Jun-03		223	121	50	0		5897
3-Jul-03		100	75	32	0		3965
14-Aug-03		187	115	5	0		6787
10-Sep-03		85	90	3	0		6288
8-Oct-03		170	101	3	0		6896
5-Nov-03		178	97	3	40		5942
9-Dec-03		145	129	16	0		6072
7-Jan-04	3.87	149	91	33	0	619	4593
10-Feb-04							
30-Mar-04							
29-Apr-04							
27-May-04							
20-Jul-04							
6-Aug-04							
28-Sep-04							
23-Aug-05	3.15	260	113	103	0	1277	8061
27-Oct-05	4.19	70	59	97	0	776	6143
30-Nov-05	3.65	158	83	179	0	1439	7040
9-Jan-06	3.41	324	116	179	0	1803	8082
7-Feb-06	3.26	338	114	125	0	1533	7610

Settlement lagoon 2

Date	pH	Iron mg/l	Manganese mg/l	Aluminium mg/l	Alkalinity mg/l	Acidity mg/l	Sulphate mg/l
15-Apr-03		125	116	65	0		6042
14-May-03		124	109	42	0		5678
12-Jun-03		130	85	18	0		5205
3-Jul-03		125	86	33	0		4613
14-Aug-03		167	115	7	0		6649
10-Sep-03		26	68	5	0		4500
8-Oct-03		68	81	9	0		5076
5-Nov-03		5	5	0	130		373
9-Dec-03		24	29	2	77		1564
7-Jan-04	6.08	52	41	7	40	205	2417
10-Feb-04	4.46	176	127	201	0	1664	7078
30-Mar-04		56	39	15	0		3068
29-Apr-04		190	124	125	0		6702
27-May-04		6	20	5	59		1376
20-Jul-04		18	61	4	35		3384
6-Aug-04		15	16	4	156		890
28-Sep-04	3.36	79	95	94	0	854	6392
10-Dec-04		34	44	27	50		2442
9-Feb-05	3.26	66	81	45	0	545	4704
23-Mar-05	3.17	101	89	82	0	832	5187
19-May-05	3.31	223	127	163	0	1559	7159
6-Jul-05	3.04	142	109	113	0	1125	8139
23-Aug-05	2.97	189	125	110	0	1229	8526
27-Oct-05	4.58	49	39	55	0	463	3518
30-Nov-05	4.59	90	52	124	2	946	4990
9-Jan-06	3.51	221	96	139	0	1357	6991
7-Feb-06	3.09	310	142	254	0	2264	9256

Settlement lagoon 3

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
15-Apr-03		124	119	65	0		6241
14-May-03		122	109	42	0		5793
12-Jun-03		128	106	32	0		5410
3-Jul-03		40	80	28	0		4620
14-Aug-03		108	104	5	0		5916
10-Sep-03		18	76	6	0		4471
8-Oct-03		52	69	5	0		4419
5-Nov-03		10	14	1	125		771
9-Dec-03		10	17	1	117		1191
7-Jan-04	5.07	93	81	30	10	482	3818
10-Feb-04	4.57	161	123	190	0	1568	6706
30-Mar-04		182	111	112	0		6043
29-Apr-04		142	109	104	0		6095
27-May-04		46	104	65	0		5404
20-Jul-04		16	98	29	0		4450
6-Aug-04		42	71	22	0		3897
28-Sep-04	2.97	105	105	113	0	1060	6968
10-Dec-04		103	80	45	0		4451
9-Feb-05	4.84	26	39	19	2	224	2625
23-Mar-05	3.04	164	112	105	0	1125	6165
19-May-05	3.25	172	153	256	0	2036	8971
6-Jul-05	3.06	98	98	102	0	963	7707
23-Aug-05	2.87	179	135	128	0	1344	9027
27-Oct-05	3.87	132	89	170	0	1348	6315
30-Nov-05	4.07	125	74	171	0	1311	6227
9-Jan-06	6.25	262	149	358	0	2728	9623
7-Feb-06	3.04	290	150	283	0	2408	9342

End point

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
15-Apr-03		9.3	99.9	86.4	0		5168
14-May-03		11.7	97.6	60.2	0		5070
12-Jun-03		16.3	47.3	22.7	0		2694
3-Jul-03		17.4	61.5	22.6	0		3563
14-Aug-03		19.8	96.4	30.1	0		5168
10-Sep-03		36.9	94.6	34.0	0		5972
8-Oct-03		26.4	76.6	21.1	0		4791
5-Nov-03		9.0	12.0	0.0	93		844
9-Dec-03		2.1	1.1	0.0	82		331
7-Jan-04	6.81	0.4	6.3	0.0	91	12	528
10-Feb-04	5.67	22.5	60.0	86.0	10	627	3202
30-Mar-04		21.9	17.6	5.8	72		930
29-Apr-04		9.8	69.7	73.7	0		3924
27-May-04		16.0	101.0	75.0	0		5093
20-Jul-04		7.8	38.0	4.5	0		1629
6-Aug-04		21.4	48.5	3.5	0		2330
28-Sep-04	3.69	50.4	94.9	31.9	0	450	5005
10-Dec-04		43.6	28.7	0.5	48		1670
9-Feb-05	7.03	12.7	6.4	0.4	176	37	512
23-Mar-05	7.03	9.0	4.5	0.1	152	25	496
19-May-05	4.44	24.4	77.4	131.0	0	914	4323
6-Jul-05	3.21	65.6	117.0	171.0	0	1311	7125
23-Aug-05	3.70	85.6	92.2	94.6	0	856	6015
27-Oct-05	6.74	1.3	6.4	1.0	76	20	466
30-Nov-05	5.02	6.1	15.3	26.1	12	184	1262
9-Jan-06	4.89	4.2	20.2	23.0	5	173	1531
7-Feb-06	3.31	9.9	83.3	152.0	0	1038	5373

Tyelaw Burn downstream of treatment system

Date	pH	Iron	Manganese	Aluminium	Alkalinity	Acidity	Sulphate
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
9-Feb-05	7.54	1.8	2.5	1.1	189	14	223
23-Mar-05	7.01	2.2	2.8	2.0	160	20	267
19-May-05	6.65	2.0	4.1	5.0	171	39	374
6-Jul-05	6.20	8.6	5.0	6.0	33	58	309
23-Aug-05	6.86	2.7	4.5	4.5	98	38	355
27-Oct-05	7.38	1.0	1.4	1.2	164	11	158
30-Nov-05	7.16	1.5	2.6	4.3	132	31	231
9-Jan-06	6.60	1.0	2.1	2.5	178	20	184
7-Feb-06	6.69	1.1	5.2	8.7	136	60	397