IMPLEMENTING THE DEGRADING PACKED BED REACTOR TECHNOLOGY AND VERIFYING THE LONGTERM PERFORMANCE OF PASSIVE TREATMENT PLANTS AT VRYHEID CORONATION COLLIERY

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Water Research Commission

IMPLEMENTING THE DEGRADING PACKED BED REACTOR TECHNOLOGY AND VERIFYING THE LONG-TERM PERFORMANCE OF PASSIVE TREATMENT PLANTS AT VRYHEID CORONATION COLLIERY

Report to the
WATER RESEARCH COMMISSION

by

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on the project entitled :
"Monitoring, evaluation and verification of the long-term performance of passive treatment plants at Vryheid Coronation Colliery"

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EXECUTIVE SUMMARY

Background

The South African mining industry is facing major problems with regard to the management and treatment of contaminated mine water. These problems exist with regard to operational mines and, importantly, they also exist for mines which have ceased operations and which have long-term water quality problems.

Currently available mine water effluent treatment technology is primarily of a chemical or physical nature. Although this technology is generally effective, it typically has very high capital and operating costs and requires intensive, ongoing, long-term maintenance. This is a particular problem for those mines that have ceased operations and where it is neither practical, nor cost-effective, to construct an active treatment plant.

An urgent need was, therefore, identified to develop low cost, self-sustaining, low maintenance passive treatment systems to address the problems of acidification and salinisation (in terms of sulphate) at operating, defunct and closed mines in South Africa. For this purpose, passive treatment is defined as follows:

"A water treatment system that utilises naturally available energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and requires regular but infrequent maintenance to operate successfully over its design life."

Pulles Howard and de Lange Inc. (PHD) has been responsible for a major research effort in developing an Integrated Managed Passive Treatment system better known as IMPI over the last eight years. This patented South African technology can reliably remove sulphates, acidity and metals from acid mine drainage (AMD). The essence of the IMPI process is the subdivision of the overall treatment process into individual units, each designed and optimized to perform a key function.

A key feature in this technology is that it will generally be required to operate for a number of years, typically decades, and continue to perform in accordance with its specified design capability. However, research undertaken to date has shown that passive treatment plants do undergo a change in performance with time. Specifically, the plants operate at a high efficiency for the first 6 – 9 months before settling down to a lower but more sustainable efficiency over the long-term.

A pilot plant for the passive treatment of AMD was designed, constructed and operated at Vryheid Coronation Colliery (VCC) by PHD. This plant has been operational since 1996 and contributed to major breakthroughs in passive treatment development. Based on discussions with researchers in the USA and UK, the VCC pilot plant reactors are believed to be the longest running, most closely monitored passive sulphate removal reactors in the world. These reactors (four small sulphate reducing units (SSRU) and two large sulphate reducing units (LSRUS)), which have been monitored on a daily basis for 7 years, followed typical trends with regards to sulphate reduction where initial sulphate reduction rates are high, coinciding with the availability of readily degradable carbon, and thereafter declining as only the more recalcitrant carbon is left.

New methods for sustaining successful long-term operation of passive treatment systems therefore had to be developed. A descriptive model of events occurring in the mobilisation of lignocellulose as a carbon and electron source in experimental wood chip packed columns and the development of the patented Degrading Packed Bed Reactor (DPBR) under the auspices of the Department of Art, culture, Science and Technology (DACST) led to a breakthrough in passive treatment. Readily available carbon is supplied to the influent of the sulphate reducing unit (SRU) which initiates the removal of oxygen from the system through microbial metabolic processes. This leads to the establishing of anaerobic conditions and negative redox potential essential for sulphate reduction. As

sulphate reduction commences, sulphide and alkalinity concentrations increase. More sulphate reduction occurs leading to higher sulphide and alkalinity production. Lignocellulose degradation is enhanced in the presence of high alkalinity and high sulphide concentrations. Alkalinity assist with the swelling of the lignocellulose while sulphide prevents the repolimerasation of lignocellulose after microbial cleavage.

Objectives

The objectives of this study, how it was achieved (implementation) and the success of achieving these objectives are summarised in Table *i*.

Table *i*: Objectives, implementation and success of the different tasks

Objective	Implementation	Success
Monitor, evaluate and verify long-term performance of the VCC Pilot Plant	-Daily pH, flow rate, electrical conductivity and temperature measurements were performed -Monthly sampling of the different units where performed evaluating pH neutralisation, sulphate reduction, sulphide production, alkalinity production and metal removal (manganese, aluminium and iron)	-Daily and monthly sampling of the VCC Pilot Plant improved the understanding of the long-term performance of the passive treatment plant
Implement enhancement strategies to improve the long-term performance of the plant	-SSRU 3 was decommissioned and recommissioned as a DPBR -SSRU 2 and SSRU 4 were supplemented with molasses	-The DPBR was commissioned successfully and operated, monitored and evaluated for a period of 18 months -Molasses supplementation was implemented successfully in a passive mode using the mariotte siphoning concept
Improve the long-term performance of the existing passive treatment plant by a factor of 60-80 % (average)	Enhancement strategies were implemented as patented	-The performance of SSRU 2 improved with 116 % -The performance of SSRU 4 improved with 783 % -The DPBR achieved the target sulphate load removed of 60 g/m^3 carbon /d
Develop operational and maintenance guidelines for full-scale passive sulphate removal systems	The available maintenance history of the VCC Pilot Plant was used to develop and evaluate a preliminary maintenance schedule	-Problem areas were identified, an activity list for maintenance was compiled and an preliminary maintenance programme developed
Develop guidelines for design parameters	Experience obtained from operating the VCC Pilot Plant and previous studies performed at VCC Pilot Plant and through DACST were used to develop design guidelines	-Preliminary design criteria was developed

Results and discussion

The performance of the pilot plant was measured against a target sulphate removal rate of 60 g sulphate/m^3 of carbon/day required to render the passive treatment process economically viable. The performance of the different SRUs varied over time and in the long-term none of the SRUs achieved the target sulphate load removed. During the start-up period, when there was an abundance of readily degradable carbon, driving sulphate reduction, there was a higher rate of sulphate reduction. Sulphate reduction decreased as the readily degradable was depleted and only the recalcitrant carbon remained.

Various detailed studies where performed at the VCC Pilot Plant in an attempt to determine causes for system malfunction. One of the short-comings of the SRUs was the hydraulic design of the SRUs as inverted truncated pyramids which led to the short-circuiting of water through the system and only the centre core of the reactor was hydraulically active.

The most important parameter preventing sulphate reduction found was the prevailing oxic conditions in the bulk of the units. In the presence of significant microbial activity, oxygen present in the system would have been consumed during biodegradation of organic matter. System malfunction was therefore ascribed to the lack of carbon biodegradation and thus the unavailability of readily biodegradable carbon to drive sulphate reduction.

The enhancement strategies developed during the DACST funded project were successfully implemented at the VCC Pilot Plant *i.e.* SSRU 3 was decommissioned and recommissioned as a DPBR and SSRU 2 and SSRU 4 were supplemented with molasses. The DPBR achieved the target sulphate load removed of 60 g/m^3 carbon /d. It must be noted that the sulphate loads obtained with the DPBR were lower than the sulphate loads reduced during the DACST project (averaging 400 g/m^3 carbon /d). This could be attributed to the fact that kinetic column studies were not performed to optimise passive treatment systems for site specific scenarios as well as scale-up. The DPBR was packed with similar carbon sources to that used in the standard SRUs for comparison reasons. The DPBR outperformed SSRU1, which had similar packing and operational conditions for the same period of operation.

Although the DPBR achieved the target sulphate load removed of 60 g/m^3 carbon /d, the effluent sulphate concentrations were still high averaging 816 mg/ℓ after 24 % reduction. It must be kept in mind that the optimum conditions for sulphate reduction did not exist for the DPBR and that sulphate reduction would be higher if the right operating conditions were selected through kinetic column studies. Also the Integrated Managed Passive (IMPI) treatment system consist of more than one sulphate reducing unit and that more SRUs will be incorporated into the system to achieve the discharge water quality objectives.

The supplementation of molasses to SSRU 2 and SSRU 4 led to increased sulphate loads removed and SSRU 2 had an average increase of 16.5 g/m^3 carbon /d (126 % increase) while SSRU 4 had an average increase of 32.1 g/m^3 carbon /d (783 % increase).

PHD has developed a preliminary maintenance guideline which have been implemented and monitored at the VCC Passive Treatment Plant. It was found that maintenance could be performed fortnightly and will include the replenishment of the readily available carbon, setting of flow rates of splitter boxes, sampling of the passive treatment plant, checking for blocked pipes and general maintenance at the plant.

Kinetic column studies form the basis of developing the design criteria of a passive treatment plant. Optimal operating conditions for sulphate reduction is determined using site specific carbon sources and the actual mine water. Various other design criteria need to be taken into consideration including hydraulics, topographical gradient *etc.* PHD has developed preliminary design criteria for the construction of full-scale passive treatment plants.

Conclusions

The implementation of the IMPI process, as patented after the Innovation Fund project (Department of Art, Culture, Science and Technology), resulted in the desired result of enhanced sulphate reduction at the VCC pilot plant. When comparing the older VCC sulphate reduction units with the DPBR results it is clear that the new DPBR technology has moved the sulphate reduction process to a higher level. The use of the rapid breakdown kick start carbon source (molasses) has also indicated that it is effective in increasing sulphate reduction for the older sulphate reduction units that were no longer achieving the required performance.

Recommendations

Following the successful demonstration of the IMPI Technology at the VCC pilot plant, it is recommended that the DPBR principles should be integrated into the design criteria of a full-scale passive treatment system. The design of a full-scale passive treatment system should also allow for a post-treatment system and a sulphide oxidation reactor to remove excess sulphides. Maintenance needs to form an integral part of the operation of a full-scale passive treatment plant.

The results of the DPBR and the kick-start carbon supplementation at VCC have shown encouraging results that need to be monitored for at least another year.

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Mr HM du Plessis	Water Research Commission (Chairman)
Mr GN Steenveld	Water Research Commission
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LIST OF ABBREVIATIONS

AMD	Acid Mine Drainage
COD	*Chemical Oxygen Demand*
DPBR	Degrading Packed Bed Reactor
HSRU	Hydrogen Sulphide Removal Unit
IMPI	Integrated Managed Passive Treatment System
LSRU	Large Sulphate Reducing Unit
PHD	Pulles Howard & de Lange
PSOB	Primary Sulphide Oxidising Bioreactor
SOBR	Sulphide Oxidation Bioreactor
SRB	Sulphate Reducing Bacteria
SRU	Sulphate Reducing Unit
SSOB	Secondary Sulphide Oxidising Bioreactor
SSRR	Secondary Sulphate Reducing Reactor
SSRU	Small Sulphate Reducing Unit
USA	United States of America
UK	United Kingdom
VCC	Vryheid Coronation Colliery
VFA	Volatile Fatty Acids

CHAPTER 1

INTRODUCTION AND BACKGROUND

Many industries, especially mining companies, are faced with serious problems caused by effluents containing high amounts of sulphate, heavy metals and low pH. Discharging effluents containing such sulphate concentrations into surface waters contributes directly to the salinisation and the corrosion potential of the receiving waters (Dill *et al.*, 1994). The heavy metal concentrations present in the effluent are toxic to all biota while the acidic pH disturbs the ecological systems maintained in the receiving waters (Gray, 1997). Acid mine drainage (AMD) is a term used to describe leachate, seepage, or drainage that has been affected by natural oxidation of sulphide minerals contained in rock that is expose to air and water (Atlas and Bartha, 1993). AMD is therefore categorized as a multi-factor pollutant (Gray, 1997).

Currently available effluent treatment technology for dealing with water quality problems is primarily of a chemical or physical nature (Coetser, 2003). Although this technology is generally effective, it typically has very high capital and operating costs and requires intensive ongoing, long-term maintenance. This is a particular problem for those mines that have ceased operations and where it is not practical or cost-effective to construct an active treatment plant that requires constant supervision and maintenance.

There is an increasing demand for inexpensive, environmentally friendly technologies to remediate AMD. The use of Sulphate Reducing Bacteria (SRB) in the biological removal of sulphates is such an alternative. SRB can oxidize organic compounds like lactate and acetate, if a suitable electron donor is available (Dill *et al.*, 1994). During this process, sulphate is used as an electron acceptor and reduced to sulphide. Various experiments using different bioreactor set-ups have been studied for potential use in the biological removal of sulphate by SRB (Tuttle *et al.*, 1969; Maree and Strydom, 1985; 1991; Van Houten *et al.*, 1994).

The overall reaction carried out by SRB during sulphate reduction is as follows:

$$2CH_2O + SO_4^{2-} \leftrightarrow 2CHO_3^- + H_2S \qquad (1)$$

Under anaerobic conditions, SRB oxidize simple organic compounds with sulphate as the terminal electron acceptor, and this results in the generation of hydrogen sulphide and bicarbonate ions. The hydrogen sulphide reacts with heavy metals in the AMD to precipitate them from solution as metal sulphides. This can be illustrated in equation 2:

$$H_2S + M^{2+} \rightarrow MS\ (s) + 2H^+ \qquad (2)$$

Where M represents metals including Cd, Fe, Pb and Zn. As a result, the bicarbonate ions react with protons to form CO_2 and water, thereby neutralising the acidity in solution. This is illustrated in equation 3:

$$HCO_3^- + H^+ \rightarrow CO_2\ (g) + H_2O \qquad (3)$$

Pulles Howard and de Lange Inc. (PHD) was responsible for a major research effort in developing an Integrated Managed Passive Treatment system better known as IMPI over the last eight years. This patented, South African technology can reliably remove sulphates, acidity and metals from AMD. The essence of the IMPI process is the subdivision of the overall treatment process into individual units, each designed and optimized to perform a key function. This integrated process is shown in Figure 1.1.

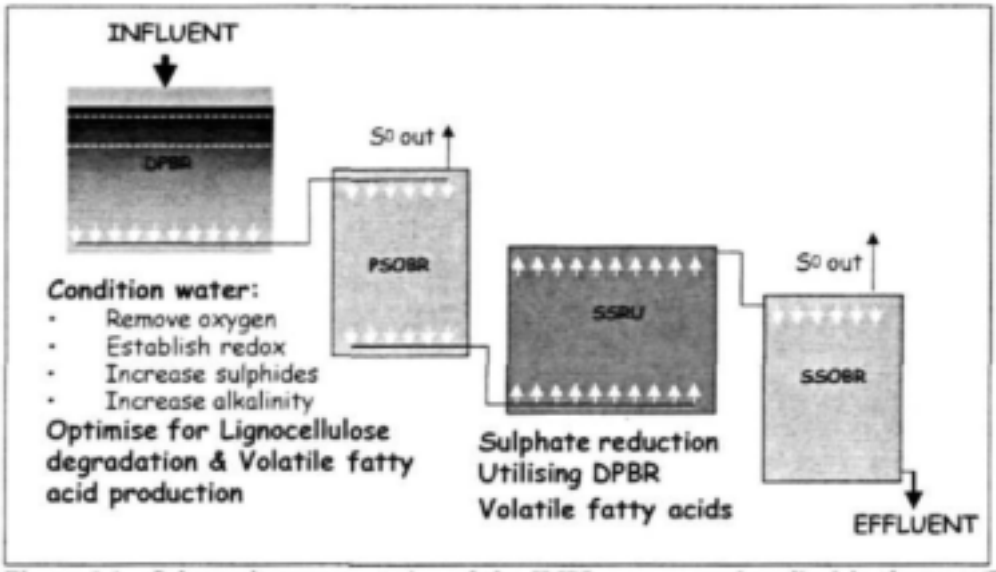

Figure 1.1 : Schematic representation of the IMPI process as described in the text (DPBR = degrading packed bed reactor; PSOBR = primary sulphide oxidizing bioreactor; SSRU = secondary sulphate reduction unit; SSOBR = secondary sulphide oxidizing bioreactor)

The purpose and essential features of the 4 different stages can be summarised as follows:

Reactor 1: Degrading Packed Bed Reactor (DPBR): This reactor is packed with multiple layers of specially selected carbon sources (electron donors) and also receives regular inputs of readily available carbon. The primary functions of this unit are to rapidly condition the influent by removing dissolved oxygen, establishing the desired redox conditions and producing elevated levels of sulphides and alkalinity in the first portion of the reactor. The remainder of the reactor is devoted to the optimized hydrolysis of lignocellulose material and the production of volatile fatty acids (VFA). The effluent from this reactor will contain reduced levels of metals and sulphate and elevated levels of sulphides, alkalinity, (VFAs) and nutrients (Pulles *et al.*, 2002; Pulles *et al.*, 2003).

Reactor 2: Primary Sulphide Oxidising Bioreactor (PSOBR): This reactor contains very little carbon source material and has the primary function of oxidizing sulphides to elemental sulphur for removal from the reactor while minimizing changes to the VFAs, nutrients and redox conditions (Pulles *et al.*, 2002: Pulles *et al.*, 2003).

Reactor 3: Secondary Sulphate Reducing Reactor (SSRU): This reactor contains a specially selected single carbon source rather than a multiple layer, multi-carbon source. The primary function of this reactor is to utilize the VFAs produced in the DPBR and to remove additional sulphate down to the design level. The effluent from this reactor would contain reduced levels of metals, sulphate, VFAs and nutrients and elevated levels of sulphides, and alkalinity (Pulles *et al.*, 2002; Pulles *et al.*, 2003).

Reactor 4: Secondary Sulphide Oxidising Bioreactor (SSOBR): This reactor contains very little carbon source material and has the primary function of oxidizing sulphides to elemental sulphur for removal from the reactor (Pulles *et al.*, 2002; Pulles *et al.*, 2003).

If required, a final aerobic polishing stage could be added, primarily to remove residual levels of VFAs and nutrients. The individual units could be combined in a tapered–up or tapered-down configuration, *i.e.* one DPBR to many SSRUs or vice-versa, depending on the design duty of the reactors (Pulles *et al.*, 2002; Pulles *et al.*, 2003).

The performance of the IMPI systems can best be evaluated by studying the effective removal of sulphates and the addition of alkalinity and sulphides. The average sulphate removal rate for the DPBR reactors was 400g sulphate removed/m^3 of carbon/day with a range of between 170 and 925,

depending on the loading rate applied to the reactor (Pulles *et al.*, 2002; Pulles *et al.*, 2003). These values exceed the original target set of 60 g sulphate removed/ m^3 of carbon/day.

To date, three primary phases of research on this topic have been commissioned:

1. PHASE 1: A project funded by the Water Research Commission, Chamber of Mines, Eskom and Sasol and undertaken at Arnot Colliery and Western Areas Gold Mine (Pulles *et al.*, 2001).
2. PHASE 2: A project funded by Anglo Coal and undertaken at Vryheid Coronation Colliery (PHD, 1999).
3. PHASE 3: A project funded by the Department of Arts Culture Science and Technology's Innovation Fund undertaken at Vryheid Coronation Colliery and various laboratories around the country.

Comparative performance for the different phases of the research project is shown in Figure 1.2.

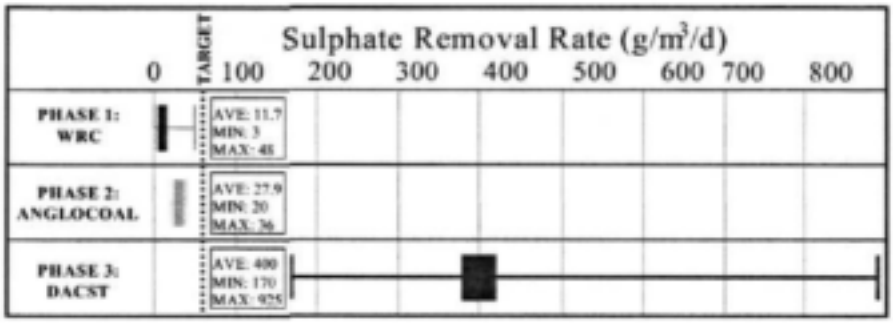

Figure 1.2 : Summary of sulphate removal performance for all project phases to date

The IMPI technology is designed in accordance to a definition of passive treatment where ***passive treatment is defined as a water treatment system that utilises naturally occurring energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and requires regular but infrequent maintenance to operate successfully over its design life.*** It is our belief that one of the primary reasons why passive treatment technology has previously so often failed to perform over the long-term, is the lack of a maintenance programme.

A key feature in the IMPI technology is that it will generally be required to operate for a number of years, typically decades, and continue to perform in accordance with its specified design criteria. However, research undertaken to date has shown that passive treatment plants do undergo a change in performance with time. Specifically, the plants operate at a high efficiency of sulphate for the first 6 – 9 months before settling down to a lower but more sustainable efficiency over the long-term (Coetser, 2003).

A pilot plant for the passive treatment of acid mine drainage (AMD) was designed, constructed and operated at Vryheid Coronation Colliery (VCC) by PHD (Figure 1.3). The plant consisted of four small sulphate reducing units (SSRUs), two large sulphate reducing units (LSRUs), a wetland and an oxidation cascade for treatment of South and West Discharges. Details of the passive treatment plant and its operation are given in Chapter 2. This plant has been operational since 1996 and contributed to major breakthroughs in passive treatment development (PHD, 1999). The objectives of evaluating the VCC pilot plant is to determine the long term feasibility of passive treatment systems for bioremediation focussing on sulphate reduction, pH neutralisation and metals removal.

Figure 1.3 : Location of Pilot Plant Site at Vryheid Coronation Colliery

Based on discussions with researchers in the USA and UK, the VCC pilot plant reactors are believed to be the longest running, most closely monitored passive sulphate removal reactors in the world. These reactors, which have been monitored on a daily basis for 7 years, followed typical trends with regards to sulphate reduction where initial sulphate reduction rates are high (coinciding with the availability of readily degradable carbon) and thereafter declining as only the more recalcitrant carbon is left. The actual performance is somewhat erratic and needs to be confirmed and explained, in order to properly understand the long-term stability of the technology to remove sulphates (PHD, 1999). However, as there is a requirement to raise the long-term efficiency of these reactors, the intent is to apply the enhancement strategies developed during a project supported by an Innovation Fund Project (Pulles *et al.*, 2002; Pulles *et al.*, 2003) to reactors that have already been in operation for several years. The express aim of obtaining at least a 60-80 % improvement in their performance with regards to sulphate removal.

The objectives of this study were to:

- Monitor, evaluate and verify the long-term performance of the VCC pilot passive treatment plant.
- Implement performance enhancement strategies to already existing pilot scale reactors that have been in operation at VCC since 1996.
- Improve the long-term performance of the existing passive treatment plant by a factor of 60-80%.
- Develop operational and maintenance guidelines for passive treatment systems.
- Develop design parameters that should be used when designing passive treatment plants.

The successful completion of this research will enable the verification of the long-term performance of passive treatment reactors and will also enable the validation of the Innovation Fund-developed strategies to increase the efficiency of plants that have been operating for a number of years.

Whilst this study was only for two years (2002 – 2004), when analysing the data and determining trends, the whole database was used (1996 – 2004). The monitoring of the success of the DPBR and molasses supplementation is also continuing for an extra year (April 2004 to March 2005) as funded by the WRC (K8/578).

CHAPTER 2

MATERIALS AND METHODS

2.1 LAYOUT AND CONFIGURATION OF THE VCC PILOT PLANT

Figure 2.1 illustrates the configuration of the VCC Pilot Plant as operated from November 1996 to August 2002. The insert illustrates the plant modifications where SSRU 3 was decommissioned and re-commissioned as a Degrading Packed Bed Reactor (DPBR) in August 2002. Details of the plant modifications are described in Section 2.2. The pilot plant consisted of four Small Sulphate Reducing Units (SSRUs), two Large Sulphate Reducing Units (LSRUs) and a post treatment facility comprising of the aerobic wetland and oxidation cascade. All units receive their feed water from the splitter boxes where the South Discharge and West Discharge water are mixed in a theoretical ratio of 1:1. Treated water from the SRUs was then "polished" in a post-treatment facility, consisting of a wetland and an oxidation cascade to remove residual nutrients added to the system (Figure 2.1). Effluent from the oxidation cascade was then discharged into a natural stream flowing outside the pilot plant (Figure 2.1).

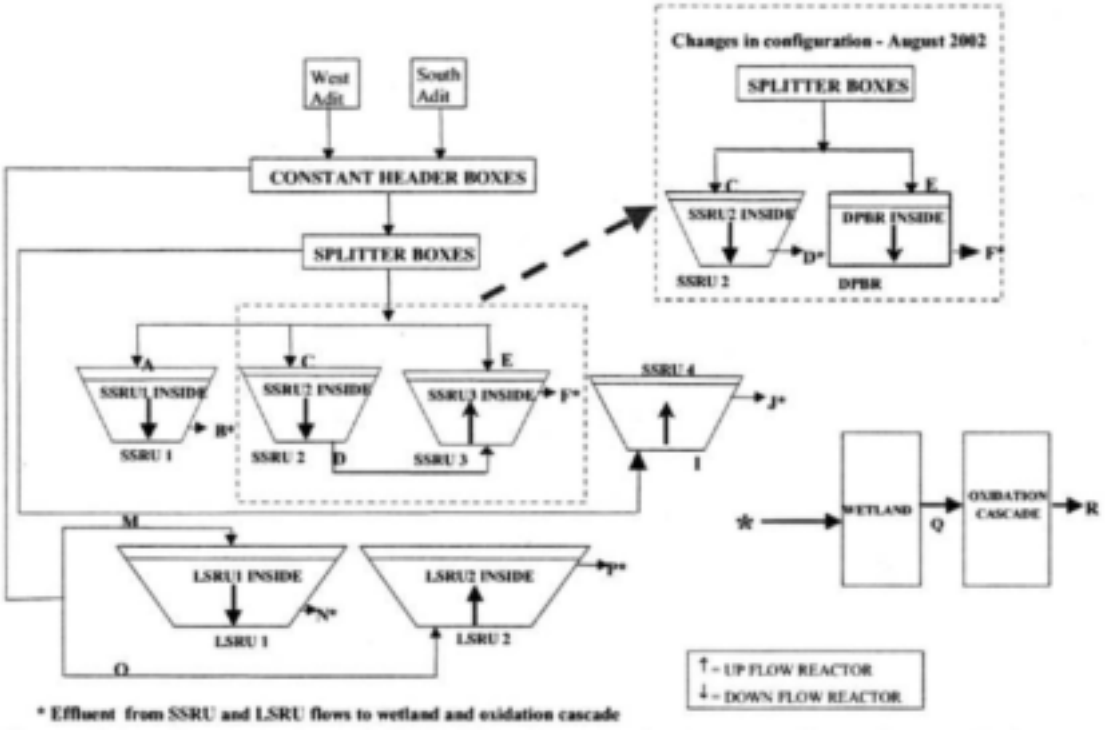

Figure 2.1 : Configuration of VCC Pilot Plant indicating sampling points and direction of flow (November 1996 – August 2002). Changes in configuration are depicted in the insert (August 2002) (A description of sampling points is given in Table 2.6)

2.1.1 Small Sulphate Reducing Units (SSRUs)

The SSRUs were constructed as inverted truncated pyramids (1200 m^2 (bottom) x 6600 m^2 (top) x 1800m (Height)), filled with layers of the various organic substrates (Table 2.1). In order to increase the permeability of the carbon substrate in SSRU 3 and SSRU 4, 50 % inert dolerite layers were incorporated in between the carbon layers (Table 2.1). The inert dolerite however seemed to decrease the permeability and although originally designed as downflow units, SSRU 3 and SSRU 4 were changed to upflow units due to headloss problems experienced . SSRU 3 were operated in series *i.e.* the effluent from SSRU 2 was fed anaerobically to SSRU 3 (Figure 2.1). This configuration however changed in November 2002 when SSRU 3 was decommissioned and re-commissioned as a DPBR (Section 2.2). SSRU 4 was the only unit sealed on top using plastic sheeting to ensure anaerobic

conditions. Effluent from the SSRUs was then gravity fed to the post-treatment facility (Figure 2.1). Table 2.1 summarises the different carbon substrate layers used to pack the SSRUs.

Table 2.1 : SSRUs Carbon Substrate Layers (m^3)

Carbon Substrate	SSRU 1		SSRU 2		SSRU 3		SSRU 4	
	Volume of carbon (m^3)	Number of layers	Volume of carbon (m^3)	Number of layers	Volume of carbon (m^3)	Number of layers	Volume of carbon (m^3)	Number of layers
Hay	2	2	None	None	6	2	4	2
Wood chips	6	3	6	3	None	None	None	None
Sawdust	2	2	2	2	2	2	6	2
Sewage Sludge	2	2	2	2	2	2	4	2
Manure	4	3	1	1	4	2	2	2
Chicken litter	2	2	None	None	4	2	4	2
Silage	None	None	7	3	None	None	None	None
Bulking agent	None	None	None	None	8	3	8	3
Total volume of carbon (m^3)	***18***		***18***		***18***		***20***	

Changes made to the layout and configuration of the SSRUs will be discussed under plant modifications (Section 2.2).

2.1.2 Large Sulphate Reducing Units (LSRUs)

The LSRUs were constructed similar to the SSRUs, *i.e.* as inverted truncated pyramids pyramids (6000 m^2 (bottom) x 12000 m^2 (top) x 2200m (Height)), filled with layers of the various carbon substrates (Table 2.2). The two LSRUs running in parallel were designed to remove sulphates in a single stage reactor (Figure 2.1). LSRU 1 was operated as a down flow unit, while LSRU 2 was operated as an up flow unit (Figure 2.1). Effluent from the LSRUs was then gravity fed to the post-treatment facility (Figure 2.1).

Table 2.2 : LSRUs Carbon Substrate Layers (m^3)

Carbon Substrate	LSRU1		LSRU2	
	Volume of carbon (m^3)	Number of layers	Volume of carbon (m^3)	Number of layers
Hay	46	6	50	6
Wood chips	12	2	20	3
Sawdust	30	2	20	3
Sewage Sludge	12	2	12	2
Manure	30	2	22	3
Chicken litter	5	1	10	2
Bulking agent	121	8	None	None
Total volume of carbon (m^3)	***135***		***134***	

2.1.3 Hydrogen Sulphide Removal Units (HSRU)

The HSRUs were constructed with a horizontal flow along a tortuous path. A 100 mm thick layer of inert dolerite stone was placed on the bottom of the units to act as a growth medium for the anaerobic photosynthetic sulphur oxidising bacteria.

2.1.4 Acid Mine Drainage (AMD) Feed

West Discharge and South Discharge seepage from the former VCC mine are mixed in equal volumes before sending it through the SRUs for treatment. Acid mine drainage (AMD) from the West Discharge is fed to a constant header box via a pipeline while seepage from the South Discharge is pumped to a storage tank from where it is gravity fed to a constant header box (Figure 2.2). A detailed description of the chemical changes over time for the West Discharge and South Discharge is given in Chapter 3.

The South Discharge and West Discharge water are gravity fed into two constant header boxes from where the AMD flows into separate compartments of the splitter boxes (Figure 2.2). Each of the SRUs is equipped with a splitter box to enable passive control of flow rates. Each splitter box consists of two water collection compartments (South Discharge and West Discharge) equipped with a V-notch in front and an overflow plate. Excess water flows over the overflow plate and a constant flow is obtained going through the V-notch. South Discharge and West Discharge water are then mixed in the mixing chamber where after it is gravity fed through pipelines to the sulphate reducing units (Figure 2.2).

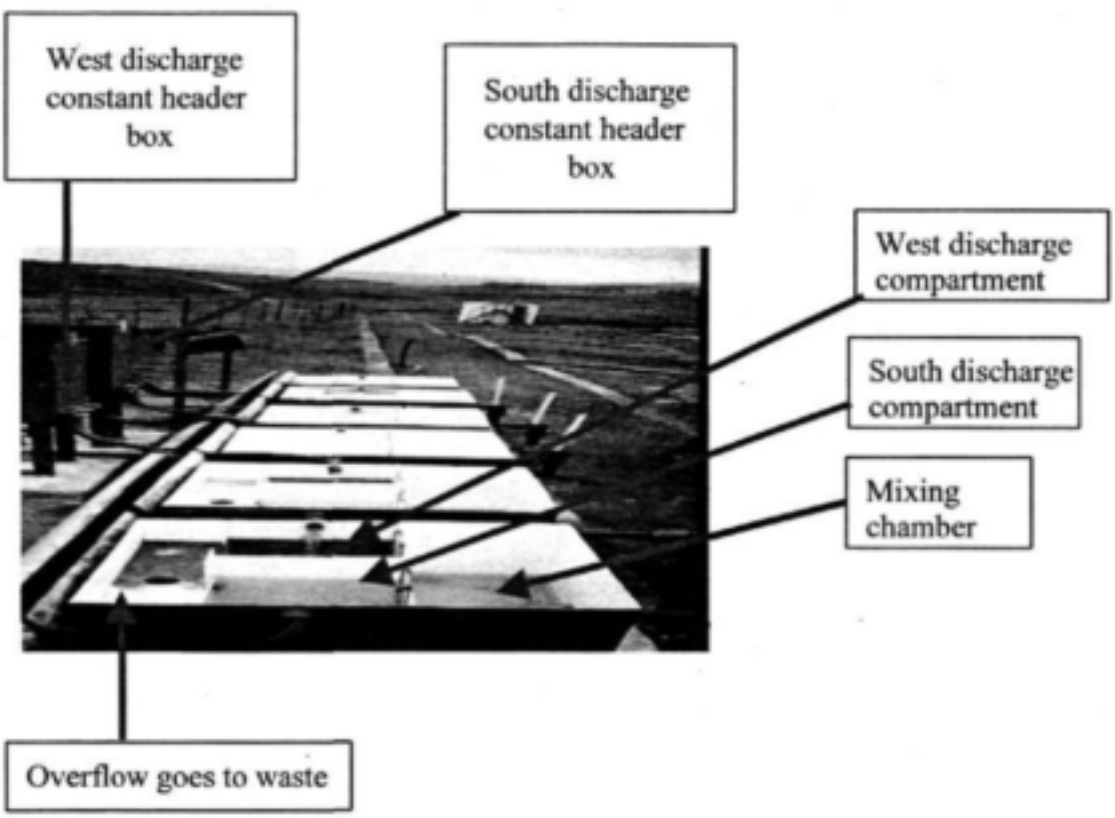

Figure 2.2 : Photograph of splitter boxes at the VCC Pilot Plant showing the different compartments

2.1.5 Post Treatment Units

The SRUs are responsible for an addition of nutrients and organic loading to the treated water, making it unsuitable for discharge without any form of post-treatment. The post-treatment facility consisted of an aerobic wetland and an oxidation cascade (Figure 2.1). The aerobic wetland was constructed as a shallow reedbed with a zigzag flow configuration with the objection of removing organic nutrient loads. The oxidation cascade is responsible for the oxygenation of the treated water and the possible removal of manganese not removed in the upstream SRUs.

2.1.6 Operation of the VCC Pilot Plant

The pilot plant was commissioned in November 1996 and operated until December 1998. Due to a lack of funding, the VCC Pilot Plant was not operational nor was it monitored during the period December 1998 to August 1999. Funding from the Department of Arts, Culture, Science and Technology (DACST) and the Water Research Commission (WRC) made it possible to operate and monitor the VCC Pilot Plant during the period August 1999 and March 2004. For the purpose of this report, the operation and monitoring of the VCC Pilot Plant will be discussed in two sections, namely Phase 1 and Phase 2. Phase 1 refers to the period November 1996 to December 1998 and was characterised by the availability of readily available carbon while Phase 2 refers to the period August 1999 to March 2004 which was characterised by a lack of readily available carbon *i.e.* only recalcitrant carbon left in the system. Table 2.3 summarises the different modes of operation during the different phases of operation for the various SRUs.

Table 2.3 : Summary of the units at the VCC Pilot Plant showing phases and mode of operation

Date	**Phase**	**Component**	**Description**
Nov 1996 to Dec 1998	1	SSRU 1 SSRU 2 SSRU 3 SSRU 4	Small units running in series with all other units
Nov 1996 to April 2002	1 & 2	LSRU 1 LSRU 2	Large units operated in single step and in parallel
Nov 1996 to Dec 1998	1	HSRU 1 HSRU 2	Units connected in series to SSRU 3 and SSRU 4
Aug 1999 to April 2002	2	SSRU 1 SSRU 4	Units connected in parallel to SSRU 2 and SSRU 3
Aug 1999 to April 2002	1 & 2	SSRU 2 SSRU 3	Units connected in series with outflow from SSRU 2 feeding SSRU 3
Aug 1999 to April 2002	2	HSRU 1 HSRU 2	Units decommissioned and not operational
August 2002	3	SSRU 3	Decommissioned and recommissioned as a degrading packed bed reactor (DPBR)
October 2002	2	DPBR	Molasses supplementation into the feed water line
May 2003	2	SSRU 2	Molasses supplementation into the feed water line
November 2003	2	SSRU 4	Molasses supplementation into the feed water line

2.1.7 Hydraulic Loading Rates

The pilot plant units were operated at a range of different flow rates. The target and actual average influent and effluent flow rates are summarised in Figure 2.3 and 2.4.

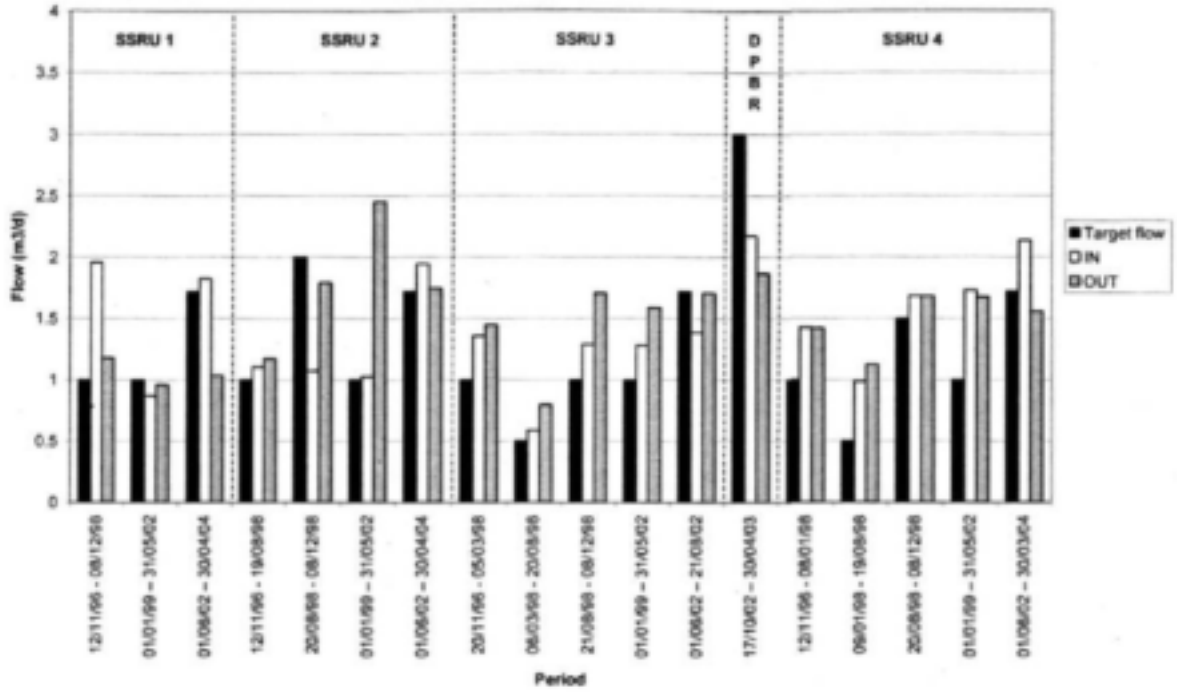

Figure 2.3 : Target flow, measured influent and effluent flow of the SSRUs and the DPBR

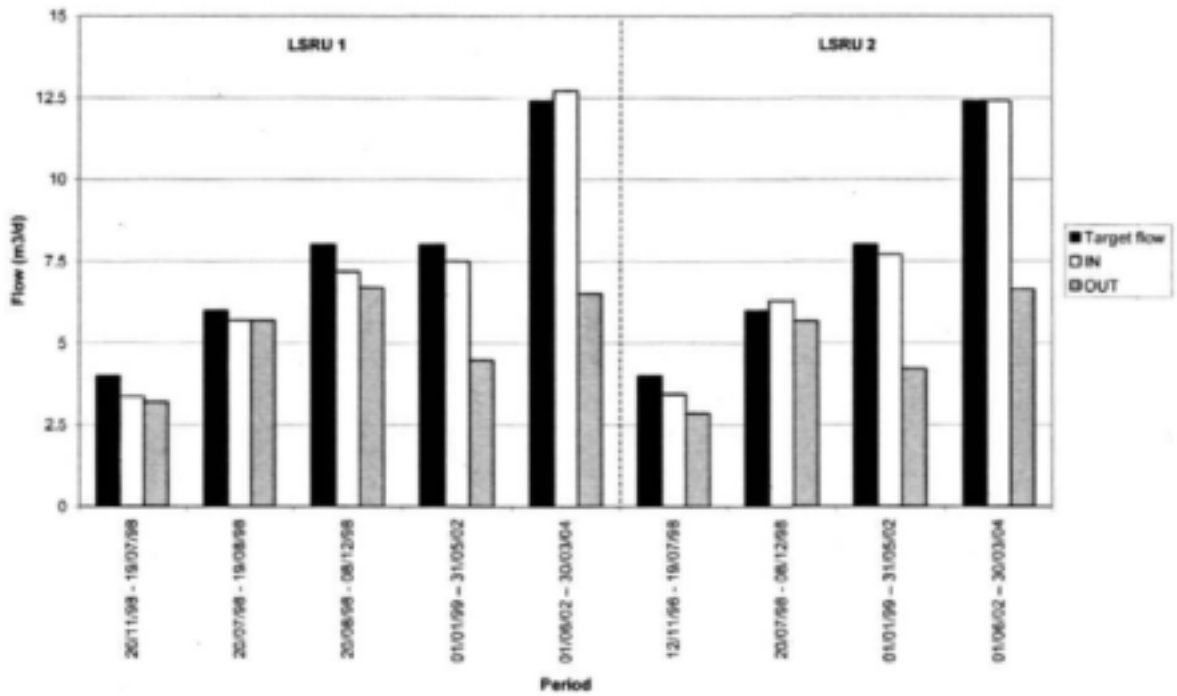

Figure 2.4 : Target flow, measured influent and effluent flow of the LSRUs

2.1.8 Sampling regime and data acquisition

2.1.8.1 Daily Collection of Data

The pilot plant at VCC is maintained and operated by an operator appointed by PHD. Flow rate, temperature, conductivity and pH are measured Monday to Friday and recorded. Evaporation and rainfall data are also recorded.

2.1.8.2 Monthly and Fortnightly collection of Data

The sampling frequency and analysis done during the different phases of operation at the pilot plant are outlined in Table 2.4.

Table 2.4 : Summary of sampling frequency and analysis done at VCC Pilot Plant

Period	Phase	Frequency	Acidity	Alkalinity	Aluminium	Ammonia as N	Biological oxygen demand	Calcium	Chemical oxygen demand	Chloride	Electrical	*Escherichia coli*	Iron	Kjeldahl nitrogen	Magnesium	Manganese	Nitrate	Nitrite	Ortho-phosphate	pH	Redox potential	Sodium	Sulphate	Sulphide	Total dissolved	Total Phosphate	Volatile fatty acids
December 1996-November 1997	1	Fortnightly			√	√		√	√			√	√		√	√							√		√	√	
December 1997-December 1998	1	Fortnightly	√	√	√	√	√	√	√	√	√		√	√	√	√	√	√	√	√		√	√		√	√	√
January 1999-November 2001	2	Monthly		√	√	√			√		√		√			√			√	√			√	√	√		
December 2001-April 2002	2	Monthly		√	√	√			√		√		√			√			√	√			√	√			
May 2002-March 2004	2	Monthly		√	√				√		√		√			√				√	√		√	√			

A description of the various samples taken at different locations in the VCC Pilot Plant is given in Table 2.5.

Table 2.5 : Descriptions of samples taken at different locations in the pilot plant (See Figure 2.1)

SAMPLING POINT	DESCRIPTION
A	SSRU 1 IN
B	SSRU 1 OUT
C	SSRU 2 IN
D	SSRU 2 OUT
E	SSRU 3 IN
F	SSRU 3 OUT
I	SSRU 4 IN
J	SSRU 4 OUT
M	LSRU 1 IN
N	LSRU 1 OUT
O	LSRU 2 IN
P	LSRU 2 OUT
Q	Oxidation Cascade IN
R	Oxidation Cascade OUT
WEST DISCHARGE	Acid Influent AMD
SOUTH DISCHARGE	Neutral Influent AMD
SSRU 1 – Inside	Samples for SSRU 3 and LSRU 2 (upflow units) were collected just below carbon layer of each unit in order to obtain a true representation of the sulphate/sulphide concentration before re-oxidisation of sulphide back to sulphate occurs at the surface. These samples represent the effluent of the reactors Samples for SSRU 1, 2 and LSRU 2 (down flow units) are collected just above the carbon layer, representing the influent of these reactors
SSRU 2 – Inside	
SSRU 3 – Inside	
LSRU 1- Inside	
LSRU 2 – Inside	

Current sampling regime (July 2001 – March 2004)

- Once a month, two sets of samples are collected at the pilot plant. One set is collected at 16 sampling points and the other set is collected as just above or below the carbon bed as described in Table 2.5 and Figure 2.1 (inside samples) at SSRU 1, SSRU 2, SSRU 3 and the LSRUs. The dates on which sampling for this project were performed are summarised in Appendix J:

The sampling procedure for the influent and effluent samples of the sulphate reducing units and post treatment facility is as follows:

- **Sulphate Concentration:**
  A volume of 20 mℓ sample is preserved with 10 mℓ (1M) HCl.

- **Sulphide Concentration**
  A volume of 50mℓ sample is preserved with 4 drops zinc acetate (APHA, 1998).

- **Other Analyses**
  A 1 ℓ unpreserved sample filled to the brim is collected for the analysis of redox potential, pH, alkalinity and metal concentrations.

Inside samples (as described in Table 2.5) were collected as a 1 ℓ composite sample for each of the SRUs. Five sub-samples were taken at different points in the SSRUs to make up the 1ℓ composite sample, while sub-samples were collected at nine different sampling points in the LSRUs to make up the 1 ℓ composite sample. In the up flow reactors (SSRU 3 and LSRU 2), the inside samples were collected just below the carbon layer in order to measure loss due to re-oxidation of sulphide to

sulphate (Figure 2.1). In the down flow reactors (SSRU 1, SSRU 2 and LSRU 1), inside samples were collected just above the carbon layer to measure the effect of evaporation and rainfall on sulphate and sulphide concentrations (Figure 2.1).

2.1.8.3 Specialist Studies

Tracer studies were performed on SSRU 2 and the DPBR in order to determine if hydraulic short-circuiting is taking place within the SRUs (2003). Previous tracer studies performed at VCC using sodium fluorescene were not successful due to possible interference with sulphur precipitates in the water and physical adsorption onto the carbon source.

Sodium bromide was however successfully used as tracer during laboratory scale studies performed at PHD (Fourie, 2002). This method was used to perform tracer studies on SSRU 2 and DPBR.

A mass of 1.37 kg of sodium bromide was dissolved in 13.3 ℓ of AMD. The tracer solution was then poured into the splitter boxes flowing into SSRU 2 and the DPBR, respectively. The theoretical retention time per SRU was 2.73 days. Numerous samples were taken from the effluent from SSRU 2 and the DPBR and bromide concentrations determined. Bromide concentrations were plotted against time to determine when breakthrough of the tracer occurred.

2.1.9 Data reporting

2.1.9.1 Sulphate load

An economic feasibility study performed by PHD indicated that in order for a passive treatment system to be economically viable, 60g of sulphate must be removed per cubic metre of carbon per day (g/m3 carbon /d^3 carbon/d) (PHD, 1999). Sulphate load removed is calculated using the monthly influent and effluent sulphate concentrations and measured influent flow taking the effect of rainfall and evaporation into account according to the following equations:

Sulphate load in (g/m3 carbon /d^3 carbon/d) =

$$\frac{[SO_4^{2-} \text{ concentration IN (mg/ℓ) x influent flow } (m^3/d)] + [SO_4^{2-} \text{ concentration in rain (mg/ℓ) x rainfall } (m^3/d)]}{\text{volume of carbon } (m^3)}$$

Sulphate load out (g/m3 carbon /d^3 carbon/d) =

$$\frac{SO_4^{2-} \text{ concentration OUT (mg/ℓ) x [influent flow } (m^3/d) + \text{rainfall } (m^3/d) - \text{evaporation } (m^3/d)]}{\text{volume of carbon } (m^3)}$$

Sulphate load removed (g/m3 carbon /d^3 carbon/d) =

Sulphate load in (g/m3 carbon /d^3 carbon/d) – Sulphate load out (g/m3 carbon /d^3 carbon/d)

2.1.9.2 Average pH

The following calculations were used to determine the average pH:

1. Convert pH values to the activity of hydrogen (H^+) *e.g.* 10^(-pH)
2. Average the activity of the H^+ for the period investigated.
3. Convert the average activity to pH *e.g.* –log(average activity)

2.2 PLANT MODIFICATIONS

2.2.1 Decommissioning of SSRU 3

In order to implement the findings of the Innovation Fund project (Pulles *et al.*, 2002: Pulles *et al.*, 2003) and to enhance future performance of the reactors, one of the SRUs was decommissioned. SSRU 3 was selected to be decommissioned based on the lack of long term performance of the unit as well as the fact that it was the only SSRU which was operated in series with another SSRU. The series configuration of SSRU 3 with SSRU 2 resulted in high influent sulphide concentrations to SSRU 3 resulting in low sulphate reduction due to the inhibitory effect of hydrogen sulphide to sulphate reducing bacteria. Decommissioning of SSRU 3 was done between the 19th and 21st August 2002. Various samples were taken during the decommissioning of SSRU 3 in an attempt to explain the low sulphate removal efficiencies obtained. Prior to draining SSRU 3, liquid samples were taken from the water column above the carbon surface. SSRU 3 was then emptied, using a pump. Solid samples were taken at each of the visible carbon layers before removing the carbon layer to reach the next visible carbon layer using manual labour. Sampling and removal of the different carbon layers were repeated until the bottom of the unit was reached.

Although 10 different layers of waste carbon were packed into the reactor at commissioning in 1996, compaction of the carbon sources occurred, making identification of all of the initial carbon layers impossible.

2.2.2 Recommissioning of SSRU 3

Design and operational changes between the old SSRU 3 and the DPBR SSRU 3 are summarised in Table 2.6.

Table 2.6 : Design and operational changes between the old SSRU 3 and the DPBR SSRU 3

Variable	Old SSRU 3	DPBR SSRU 3
Configuration	Inverted truncated pyramid	Rectangle
Waterproofing	Unit sealed with a manure layer followed by lining with plastic sheeting	Unit built with a double brick wall and plastered with cement containing waterproofing material and painted with two layers of Bitumen
Reactor size	23.3 m^3	25.9 m^3
Volume of carbon packed	18 m^3	18 m^3
Type of carbon packed	Layers of sawdust, sewage sludge, chicken litter, manure, hay	Layers of sewage sludge, pine wood chips, hay, chicken litter, sawdust, manure
Bulking agent	Dolerite stone layers were inserted	No bulking agent
Flow configuration	Up flow	Down flow
Molasses supplementation	No	Yes
Influent	SSRU 2 effluent	Mixture of West Discharge and South Discharge water

2.2.2.1 Configuration

The University of the Witwatersrand conducted hydraulic studies on the SRUs constructed as inverted truncated pyramids (Figure 2.5) (Fourie, 2002). Of particular note was the observation of differences in vertical velocity of two orders of magnitude between the axis of the reactor and the outer zone. There was indeed a large volume of substrate that was not being exposed to much flow and therefore the only hydraulically active zone was the centre core of the unit (PHD, 2002). As a result, the existing reactor configuration of an inverted pyramid (Figure 2.5) was changed to a rectangular shape (Figure 2.6) in order to maximise hydraulic activity in the SRU.

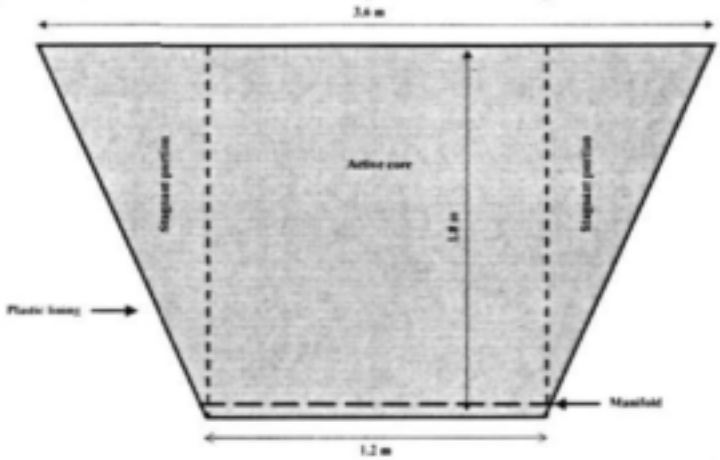

Figure 2.5 : The inverted pyramid configuration of SSRU 3 prior to decommissioning (not to scale)

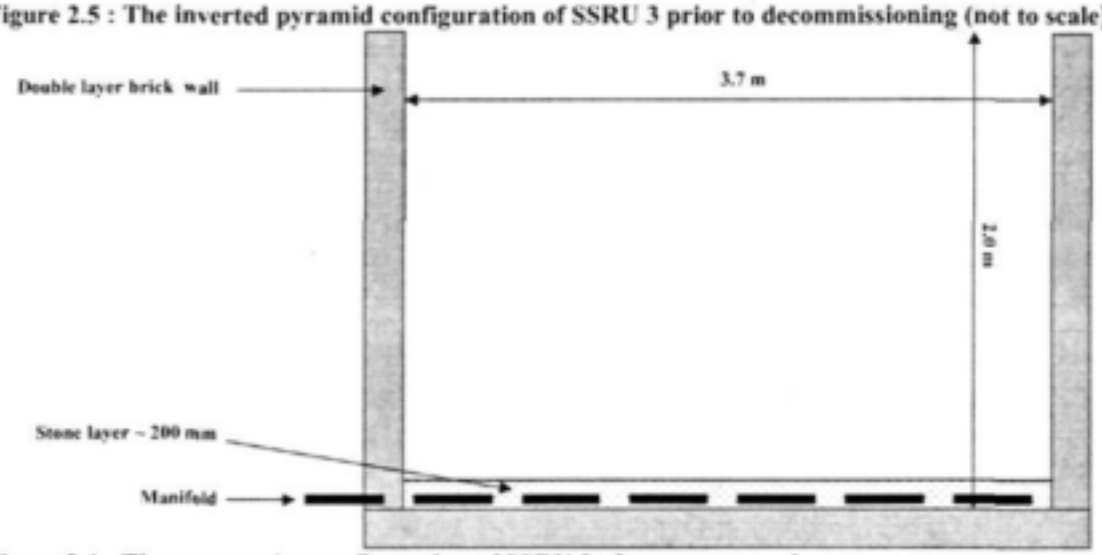

Figure 2.6 : The rectangular configuration of SSRU 3 after reconstruction

Figure 2.6 illustrates the new rectangular configuration of SSRU 3 while Figures 2.7 and 2.8 demonstrate the inlet manifold.

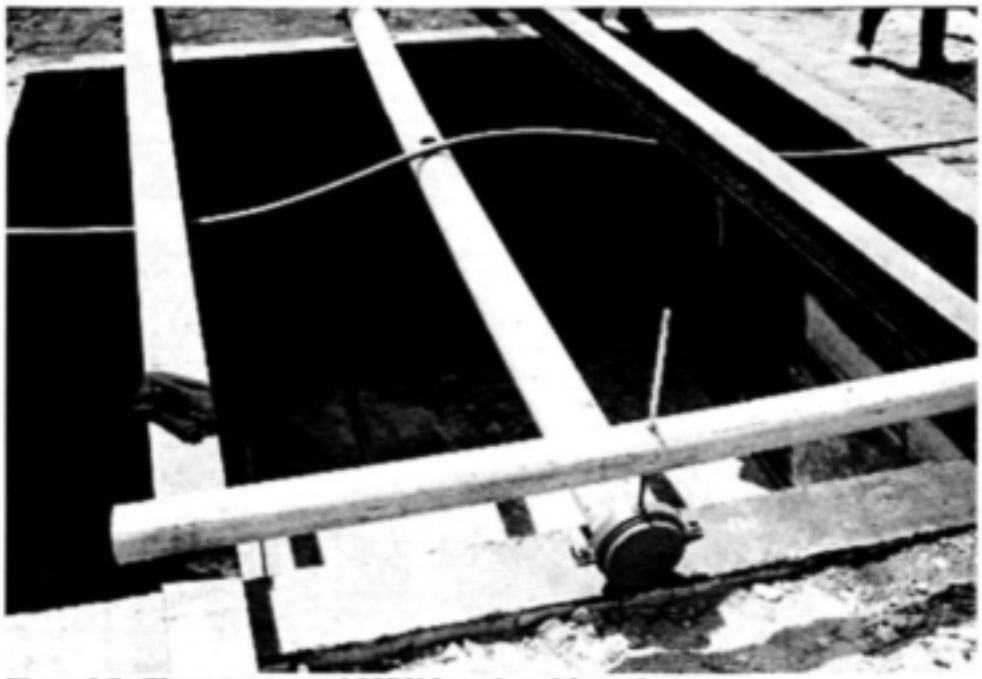

Figure 2.7 : The reconstructed SSRU 2 as viewed from the top

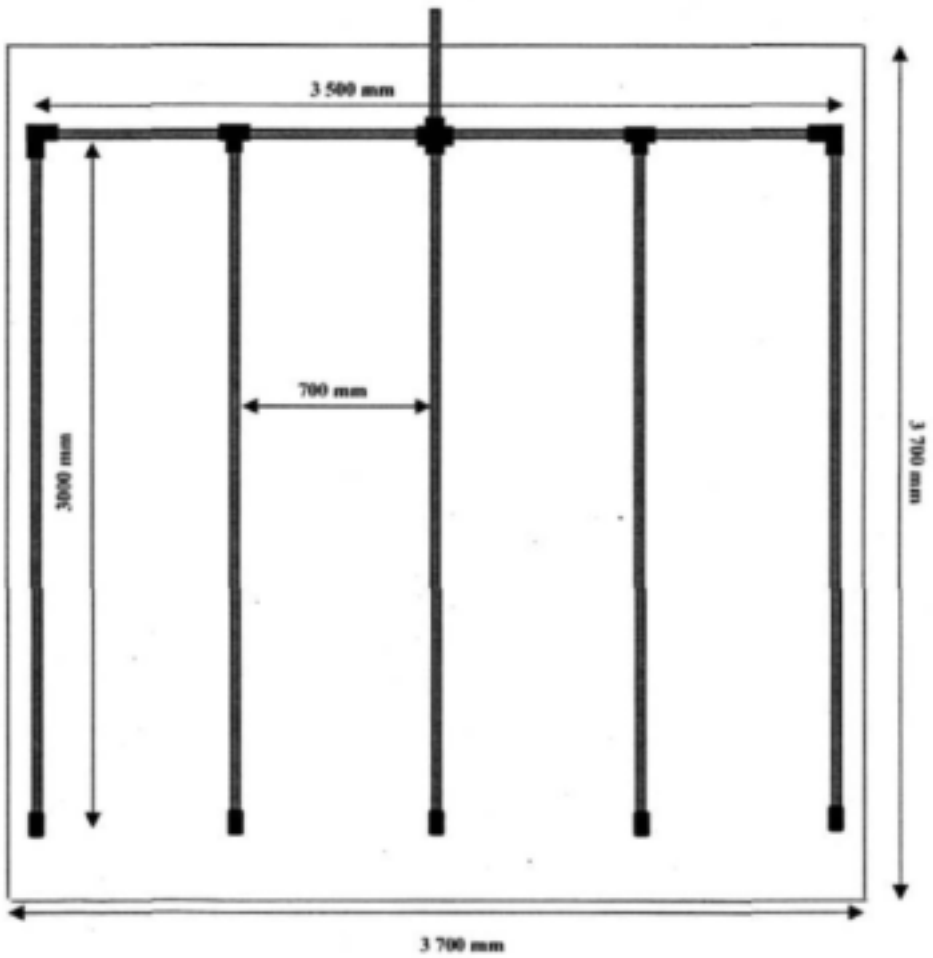

Figure 2.8 : Schematic diagram of the inlet manifold for SSRU 2

Figure 2.9 illustrates SSRU 2 re-commissioned as a DPBR.

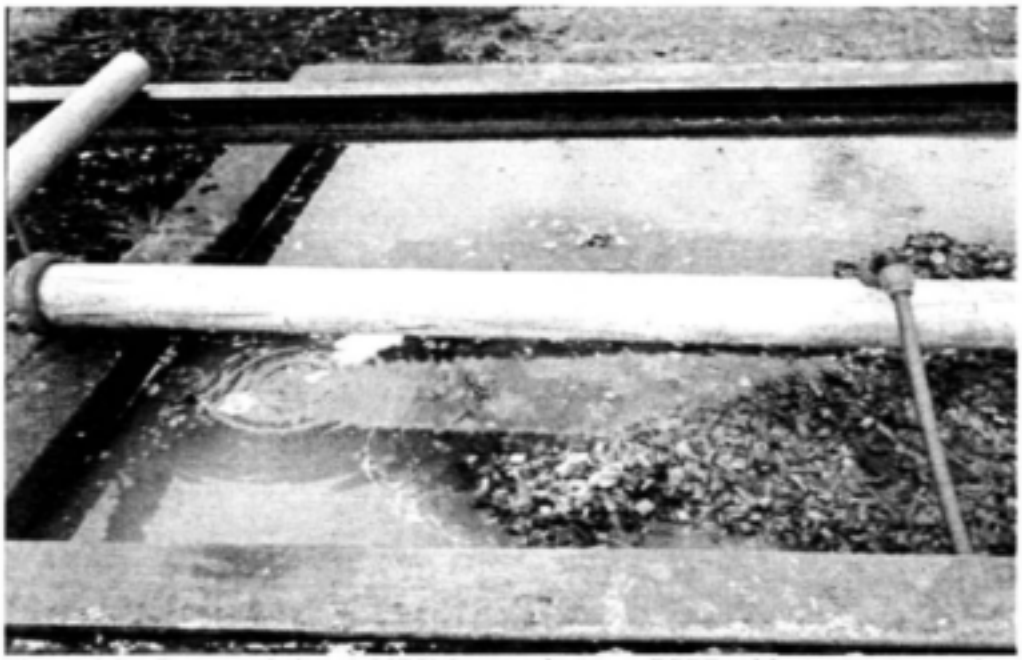

Figure 2.9 : Re-commissioned SSRU 2 operating as a DPBR with the top layer of wood chips clearly visible

2.2.2.2 Carbon sources

Table 2.7 summarises the carbon substrates and volume used to pack the DPBR.

Table 2.7 : Carbon Substrates in the DPBR

New design DPBR SSRU 3 reactor
Free board ($5.4m^3$)
Sewage sludge ($1m^3$)
Wood chips ($1m^3$)
Hay ($1m^3$)
Chicken litter ($1m^3$)
Sawdust ($2m^3$)
Manure ($1m^3$)
Hay ($1m^3$)
Chicken litter ($1m^3$)
Sewage sludge ($1m^3$)
Wood chips ($1m^3$)
Sawdust ($2m^3$)
Hay ($1m^3$)
Wood chips ($2m^3$)
Manure ($1m^3$)
Hay ($1m^3$)
Stone ($0.38m^3$)
Manifold

2.2.2.3 Molasses dosing unit

One of the cruxes of operating a successful passive reducing plant is the availability of biodegradable carbon at the influent section of the reactor (PHD, 2002).

In order to implement this design change, a 560 ℓ stainless steel container has been modified to operate using a concept known as a mariotte siphon (Figure 2.10). A mariotte siphon enables the

generation of a constant flow rate needed for the passive addition of a readily available carbon (molasses) to the system. This system was be implemented at VCC in April 2003 for SSRU 2 and the DPBR and the molasses feeding tank was refilled every 4-5 days. In order to revive the activity of SSRU 4, molasses was manually dosed to the reactor from November 2003. The concentration of molasses supplementation was 0.1 %.

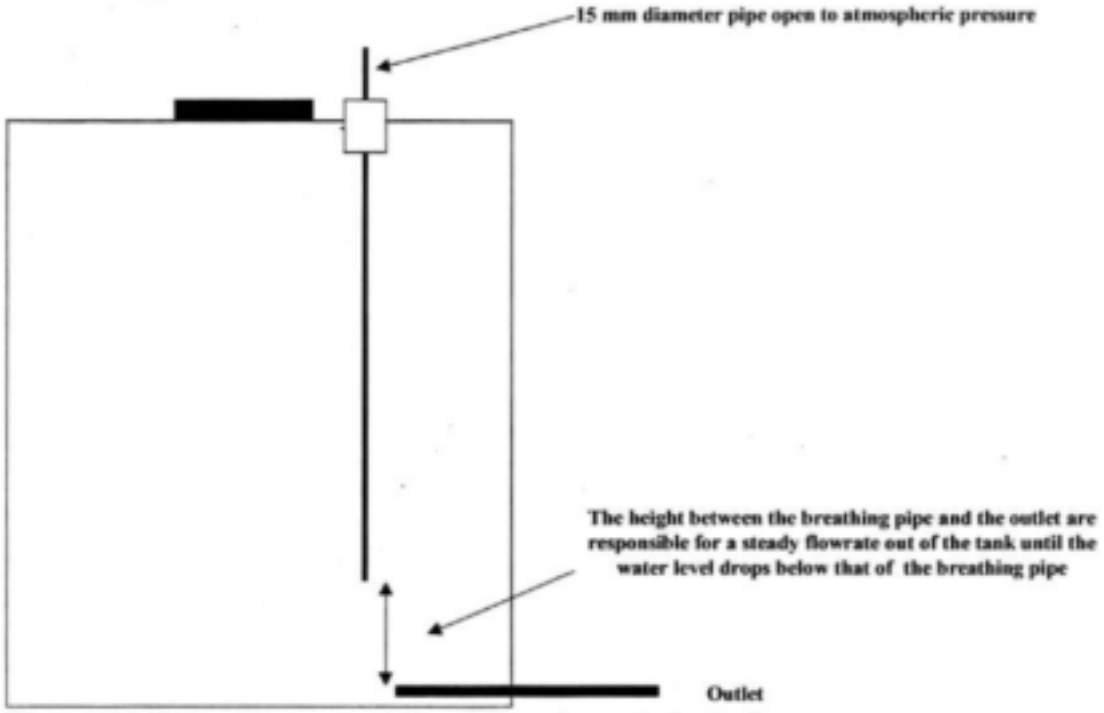

Figure 2.10 : Schematic representation of the molasses-dosing tank

2.2.2.4 Comparison between DPBR and the SRUs

In order to determine if the DPBR is outperforming the standard SRUs, the data obtained from the DPBR was compared to the SRUs for the same period of operation from start-up.

2.2.3 Wetland modifications

After an operational period of almost seven years (December 1996 – August 2003), the wetland installed as a post-treatment system at the VCC Passive Treatment Plant clogged to the extent that water bypassed the system by overflowing. Metal plates were placed at the influent to the wetland in an attempt to force the water through the system. This was however not successful.

The objectives of this aspect of the study were therefore to:

- Determine the cause of clogging by chemical and visual characterization of the wetland
- Decommission the wetland
- Re-commission wetland with available resources.

2.2.3.1 Determining the cause of wetland malfunction

The aerobic wetland was constructed as a shallow reed bed with a zigzag flow configuration as shown in Figure 2.11.

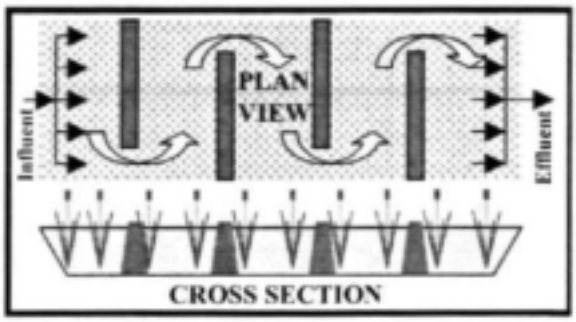

Figure 2.11 : Schematic representation of the aerobic wetland at the VCC Pilot Plant

The discharge from HSRU1, LSRU1 and LSRU2 was routed into the aerobic wetland to remove the organic and nutrient (N and P) loads. Outflow from the wetland was routed to the oxidation cascade. This wetland was not designed for a specific duty and was primarily added as a demonstration unit to illustrate the concept of an integrated anaerobic / aerobic passive treatment plant.

Liquid and solid samples were taken at the inlet, middle (a composite sample of 3 sampling points) and outlet of the wetland as depicted in Figure 2.12. Liquid samples were taken before disruption of the system using plastic bottles while solid samples were taken within the roots of the reeds using a spade. Samples were couriered to Johannesburg on ice and submitted for analysis.

The liquid samples were submitted to the PHD Analytical Facility and analysed for the following parameters:

- pH
- Redox potential
- Electrical conductivity
- Chemical oxygen demand
- Alkalinity
- Sulphate (mg/ℓ)
- Aluminium (mg/ℓ)
- Calcium (mg/ℓ)
- Copper (mg/ℓ)
- Iron (mg/ℓ)
- Lead (mg/ℓ)
- Magnesium (mg/ℓ)
- Manganese (mg/ℓ)
- Potassium (mg/ℓ)
- Sodium (mg/ℓ)
- Zinc (mg/ℓ)

Solid samples were submitted for the following analysis:

- Mineral compositions determined using XRD (Council for Geoscience, Pretoria)
- Microscopic study
- Major and trace elements using XRF (Department of Geology, University of the Witwatersrand)

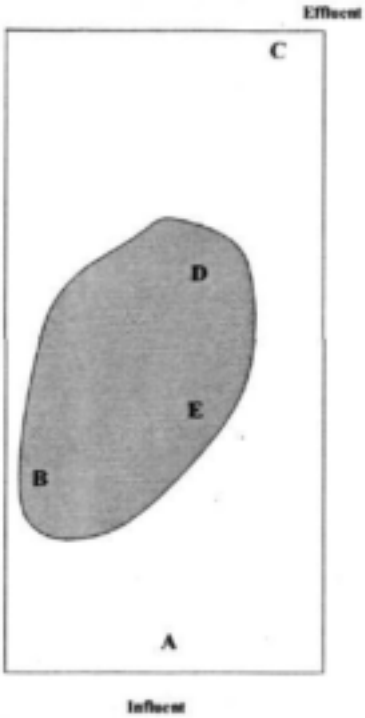

Figure 2.12 : Schematic representation of the sampling points in the wetland (A – E represents the sampling points)

2.2.3.2 Decommissioning of the wetland

Members of the VCC community assisted to manually decommission the wetland. Reeds were removed using spades to enable the flow of water through the wetland. A backactor was also used to assist with the decommissioning.

2.2.3.3 Recommissioning of the wetland

After excess sludge and reeds were removed from the wetland, treated water discharged from the SRUs was sent through the wetland for further polishing (Appendix G).

2.3 OPERATION AND MAINTENANCE OF VCC PILOT PLANT

The definition of passive treatment allows for regular, but infrequent maintenance of passive treatment plants. The degree of maintenance required and the frequency at which certain procedures need to be implemented need however to be established. The following procedure was followed to develop a maintenance schedule:

2.3.1 Assess available maintenance history of the VCC Pilot Plant

All of the problems experienced at the VCC Pilot Plant as well as maintenance performed at the plant were documented in detail. Problems experienced at the VCC Pilot Plant were assessed, categorised and summarised according to frequency of occurrence.

2.3.2 Develop maintenance schedule

The assessment of the maintenance history (Section 2.3.1) was used as a basis to develop a proposed maintenance schedule. This maintenance schedule was for a period of one year at the VCC Pilot Plant.

CHAPTER 3

RESULTS AND DISCUSSION OF THE WEST AND SOUTH DISCHARGES

West and South discharges from the former VCC mine are mixed in equal volumes, using splitter boxes before sending it through the SRUs for treatment. Site and water quality data for the period November 1996 – March 2004 will be discussed in this chapter.

3.1 EVALUATION OF THE WATER QUALITY OF THE WEST AND SOUTH DISCHARGES

3.1.1 pH

The pH of the West discharge was lower than that found for the South discharge (Table 3.1). The pH of the West discharge increased from Phase 1, averaging 2.24 (November 1996 – December 1998) to Phase 2, averaging 3.25 (August 1999 – March 2004) (Table 3.1). The average pH of the South discharge remained similar during Phase 1 (November 1996 – December 1998), averaging 4.59 and Phase 2 (August 1999 – March 2004), averaging 4.83 (Table 3.1). Daily pH of the West and South discharges are depicted in Figure 3.1. The stability of the pH of the West and South discharges decreased during Phase 2 (August 1999 – March 2004) with pH ranging between 0.92 and 7.46 for the West discharge and pH ranging between 2.05 and 8.05 for the South discharge (Table 3.1).

Table 3.1 : Statistics of West discharge and South discharge pH during Phase 1 (November 1996 – December 1998) and Phase 2 (August 1999 – March 2004)

	pH (Units)			
	West discharge		South discharge	
	Phase 1	Phase 2	Phase 1	Phase 2
Average	2.24	3.25	4.59	4.83
Minimum	1.09	0.92	2.60	2.05
Maximum	5.75	7.46	7.98	8.05
Standard deviation	0.50	0.87	0.52	0.71
N	1283	2128	1284	1881

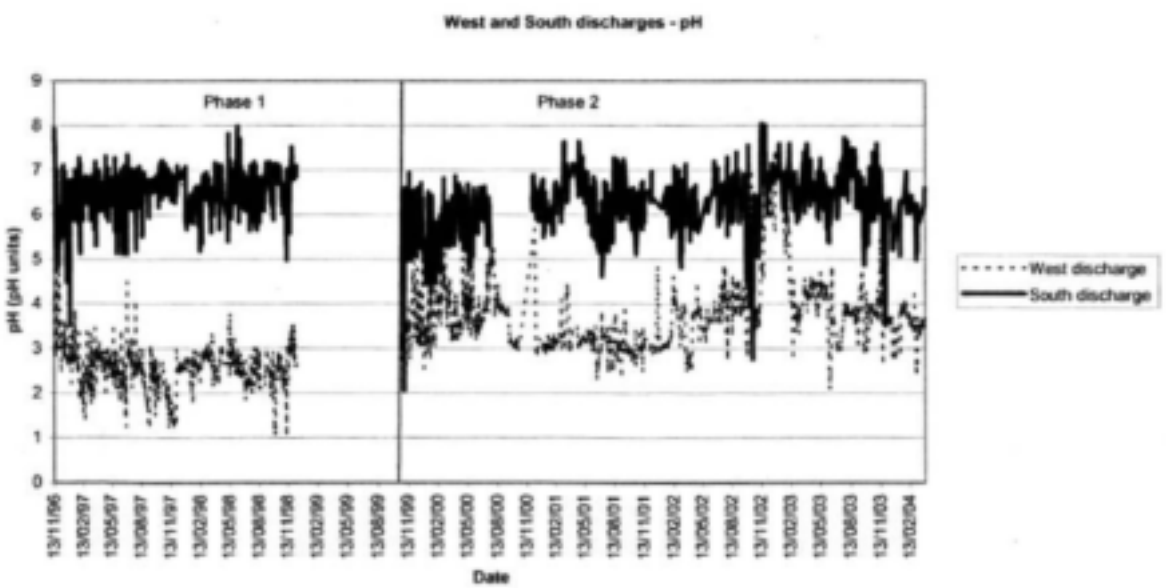

Figure 3.1 : Daily pH profile for the West and South discharges over the period November 1996 to March 2004

3.1.2 Sulphate Concentration of the West and South discharges

Monthly sulphate concentrations fluctuated over the experimental period (Table 3.2). The sulphate concentrations of the West discharge (ranging between 733 mg/ℓ and 2674 mg/ℓ) were continuously higher than the sulphate concentrations found in the South discharge (ranging between 484 mg/ℓ and 2289 mg/ℓ) (Table 3.2). The sulphate concentrations determined on a monthly basis for the West discharge and the South discharge are depicted in Figure 3.2.

Table 3.2 : Statistics of West discharge and South discharge sulphate concentration (mg/ℓ) during Phase 1 (November 1996 – December 1998) and Phase 2 (August 1999 – March 2004)

	Sulphate concentration (mg/ℓ)			
	West discharge		South discharge	
	Phase 1	Phase 2	Phase 1	Phase 2
Average	1843	1735	1254	1104
Minimum	901	733	914	484
Maximum	2448	2647	1808	2289
Standard deviation	300	324	174	320
N	45	56	44	50

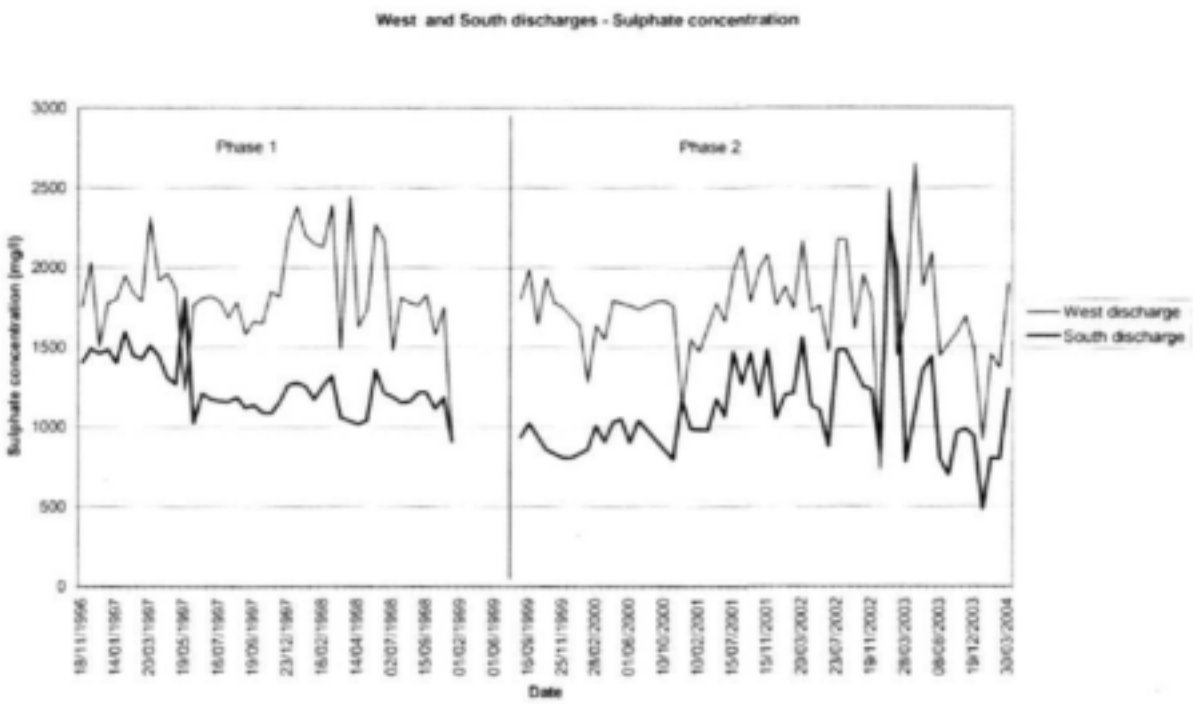

Figure 3.2 : Monthly sulphate concentration profile for West and South discharges over the period November 1996 to March 2004

3.1.3 Metal Concentrations of the West and South discharges

The statistical data of metals concentrations (iron, aluminium and manganese concentrations) for the West and South discharges is presented in Table 3.3. Metal concentrations fluctuated over time (Figure 3.3 – 4.5). The concentrations of aluminium, iron and manganese for the West discharge were higher than that found for the South discharge (Table 3.3).

Aluminium concentrations decreased in the West discharge from Phase 1 (November 1996 – December 1998), averaging 45.8 mg/l to Phase 2 (August 1999 – March 2004), averaging 34.6 mg/ℓ (Table 3.3). The same trend occurred for the iron concentrations in the West discharge (20.3 mg/ℓ during Phase 1 versus 13.0 mg/ℓ during Phase 2) (Table 3.3). Average manganese concentrations remained similar during Phase 1 and Phase 2 for the West discharge (16.6 mg/ℓ versus 16.0 mg/ℓ) (Table 3.3).

Both average aluminium and average iron concentrations increased for the South discharge from Phase 1 (November 1996 – December 1998) to Phase 2 (August 1999 – March 2004). The average manganese concentrations remained similar for the South discharge during Phase 1 and Phase 2 (5.87 mg/ℓ versus 5.35 mg/ℓ) (Table 3.3).

The wide ranges in aluminium and iron concentrations observed during Phase 2 (August 1999 – March 2004) correlated with the wide ranges of pH observed during the same period (Table 3.1 and Table 3.3).

Table 3.3 : Statistics of West discharge and South discharge metal concentrations (mg/ℓ) during Phase 1 (November 1996 – December 1998) and Phase 2 (August 1999 – March 2004)

	Aluminium concentration (mg/ℓ)			
	West discharge		**South discharge**	
	Phase 1	**Phase 2**	**Phase 1**	**Phase 2**
Average	45.8	34.6	0.56	1.13
Minimum	0.87	0.00	0.01	0.00
Maximum	84.8	74.6	5.06	16.1
Standard deviation	24.7	20.0	1.08	2.70
N	33	56	33	49
	Iron concentration (mg/ℓ)			
	West discharge		**South discharge**	
	Phase 1	**Phase 2**	**Phase 1**	**Phase 2**
Average	20.3	13.0	0.65	4.84
Minimum	1.41	0.67	0.01	0.01
Maximum	35.7	42.0	3.90	17.9
Standard deviation	9.92	7.61	1.16	5.88
N	32	45	32	41
	Manganese concentration (mg/ℓ)			
	West discharge		**South discharge**	
	Phase 1	**Phase 2**	**Phase 1**	**Phase 2**
Average	16.6	16.0	5.87	5.35
Minimum	8.28	4.79	2.75	3.36
Maximum	26.2	22.6	9.37	16.2
Standard deviation	4.04	3.87	1.64	2.13
N	32	41	32	37

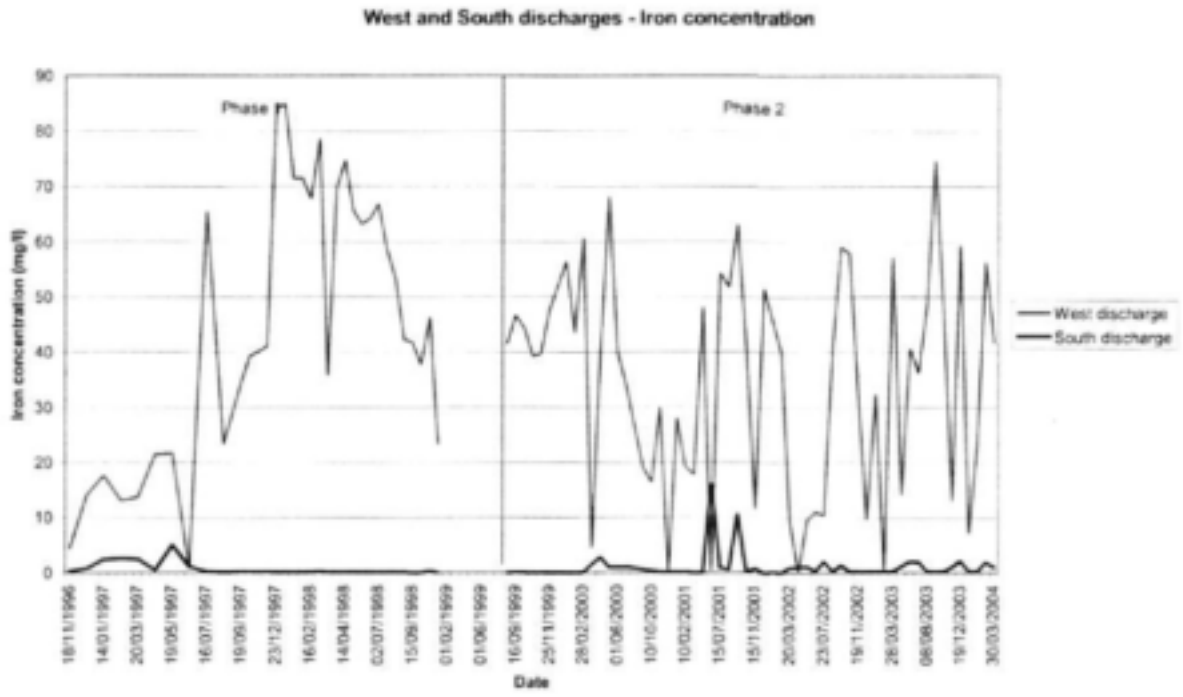

Figure 3.3 : Monthly aluminium concentration profile for West and South discharges over the period November 1996 to March 2004

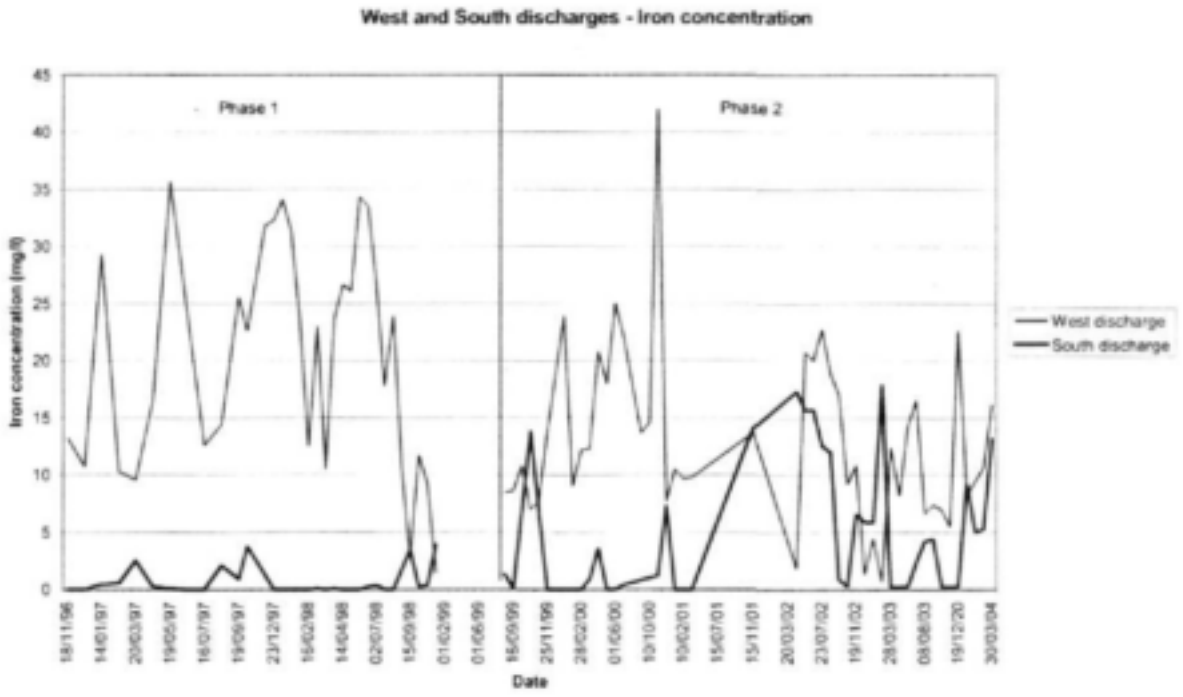

Figure 3.4 : Monthly iron concentration profile for West and South discharges over the period November 1996 to March 2004

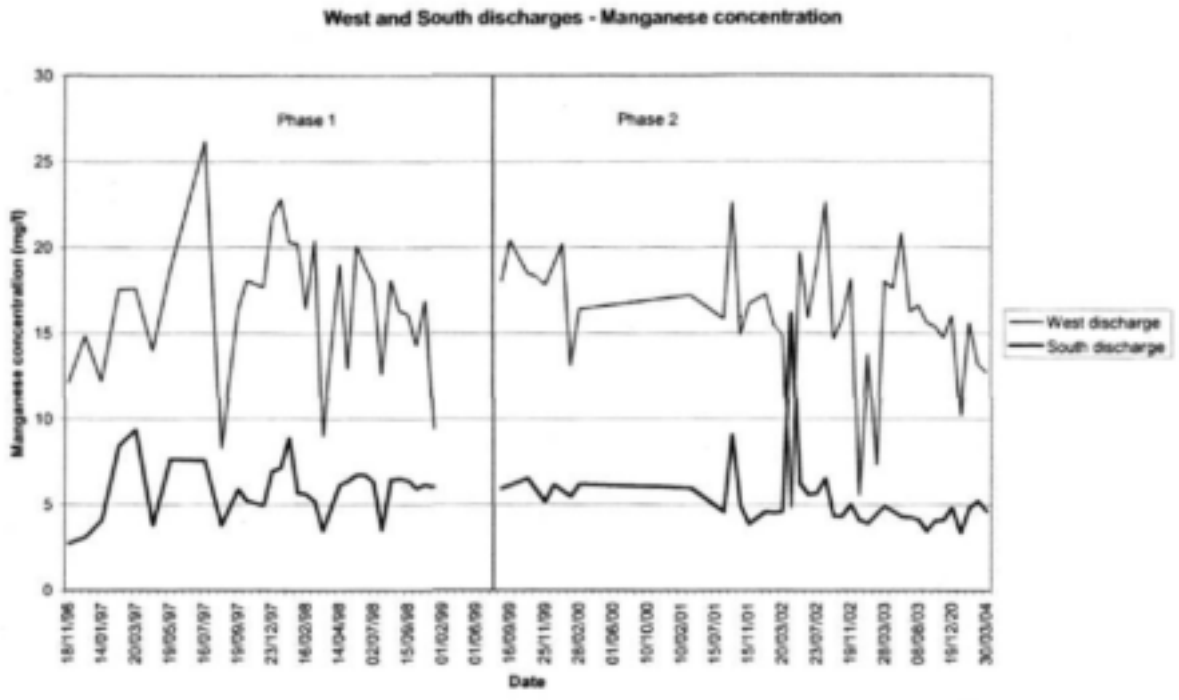

Figure 3.5 : Monthly manganese concentration profile for West and South discharges over the period November 1996 to March 2004

3.2 CONCLUSIONS WITH REGARD TO THE WEST AND SOUTH DISCHARGES

The following conclusions were made with regard to the West and South discharges:

- The pH of the West discharge is lower than the pH of the South discharge.
- The sulphate concentrations of the West discharge are higher than those found in the South discharge.
- The metal concentrations (aluminium, iron and manganese) of the West discharge are higher than those found in the South discharge.
- The West and South discharges were more stable during the first phase of operation (November 1996 – December 1998) than during Phase 2 (August 1999 – March 2004) in terms of pH, sulphate-, aluminium- and iron concentration.

CHAPTER 4

COMPARISON OF THE STANDARD REACTORS FOR THE PERIOD NOVEMBER 1996 TO MARCH 2004

The standard reactors (SSRU 1 to SSRU 4 and the LSRUs) have been in operation from November 1996 to March 2004. The comparison of these reactors will focus on the performance of the SRUs with respect to AMD neutralization (pH and alkalinity), sulphate reduction, sulphide production, and metal removal during Phases 1, 2 and molasses supplementation.

Table 4.1 lists the different Phases of operation and the modes of operation of the standard units.

Table 4.1 : Summary of the standard units at the VCC Pilot Plant showing phases and mode of operation

Date	Phase	Component	Description
Nov 1996 to Dec 1998	1	SSRU 1 SSRU 2 SSRU 3	Small units running in series with all other units
Nov 1996 to Dec 1998	1	SSRU 3 SSRU 4 HSRU 1	Units connected in series with effluent of SSRU 3 flowing through HSRU 1 before feeding SSRU 4
Nov 1996 to April 2002	1 & 2	LSRU 1 LSRU 2	Large units operated in single step and in parallel
Nov 1996 to Dec 1998	1	HSRU 1 HSRU 2	Units connected in series to SSRU 3 and SSRU 4
Jan 1999 to April 2002	2	SSRU 1 SSRU 4	Units connected in parallel to SSRU 2 and SSRU 3
Jan 1999 to April 2002	1 & 2	SSRU 2 SSRU 3	Units connected in series with outflow from SSRU 2 feeding SSRU 3
Jan 1999 to April 2002	2	HSRU 1 HSRU 2	Units decommissioned and not operational
Aug 2002	3	SSRU 3	Decommissioned and recommissioned as a degrading packed bed reactor (DPBR)
May 2003	2	SSRU 2	Molasses supplementation into the feed water line
Nov 2003	2	SSRU 4	Molasses supplementation into the feed water line

Appendixes A to F give detailed descriptions of the performance of the standard SRUs in terms of the different parameters evaluated.

4.1 COMPARISON OF STANDARD REACTORS IN TERMS OF AMD NEUTRALIZATION

4.1.1 pH

Overall, all units were responsible for increasing influent pH during both Phases of operation. During Phase 1, SSRU 1 increased the influent pH from 3.78 to 6.69, SSRU 2 decreased the influent pH from 6.66 to 6.46 and SSRU 3 decreased the influent pH from 6.46 to 5.69. The influent pH of SSRU 4 increased from 4.72 to 5.12 after passing through the HSRU 1.

The average effluent pH of LSRU 2 was higher than the average effluent pH of LSRU 1 (6.74 versus 6.54) during Phase 1. This could be ascribed to LSRU 2 reaching anaerobic conditions sooner than LSRU 1 due to the mode of operation where LSRU 2 operated in an upflow configuration while LSRU 1 operated in a downflow configuration. Anaerobic conditions promote sulphate reduction with the production of alkalinity leading to increased pH.

During Phase 2, there was an initial increase in pH after operation of the pilot plant was re-commenced. However, this was followed by fluctuations in effluent pH. The influent pH of SSRU 1 increased from 3.76 to 5.22 during Phase 2. Molasses supplementation led to an increase in influent pH 4.54 to 5.35 in the effluent of SSRU 2. SSRU 3 was responsible for an influent pH increase of 4.17 to 5.43 in the effluent during Phase 2. The influent pH of SSRU 4 increased from 3.89 to 4.62 during Phase 2, while molasses supplementation led to an increase in pH from 4.43 to 5.80. The large SRUs were responsible for similar pH increases represented by 3.88 for the influent to 5.50 for the effluent and 3.87 for the influent to 5.12 for the effluent, for LSRU 1 and LSRU 2 respectively.

These results indicate that the overall neutralisation ability of the units was higher during Phase 1 than Phase 2 coinciding with results obtained for most sulphate reducing units with regards to sulphate reduction, where the initial activity was higher due to the availability of readily degradable carbon. Once the readily available carbon is utilised sulphate reduction efficiencies decrease as only the more recalcitrant carbon remains. After Phase 2 no neutralisation of pH occurred, molasses supplementation has led to initiation of AMD pH neutralisation. This effect was expected as molasses supplementation would enhance biodegradation of the recalcitrant carbon leading to sulphate reduction and corresponding increase in alkalinity.

4.1.2 Alkalinity production

The addition of alkalinity to the SRUs results from the process of sulphate reduction where SRB reduces sulphate to sulphide, and bicarbonate ions are produced. It is expected that the addition of alkalinity should be proportional to the sulphate reduction activity of the SRUs and the utilisation of readily available carbon. As a result, there would be more alkalinity produced during Phase 1 when sulphate reduction is high and when molasses (as a readily available carbon) is supplemented to the units leading to enhanced biodegradation of recalcitrant carbon than during Phase 2 where there only recalcitrant carbon left in the units.

Alkalinity production to the standard units during Phases 1 and 2, and molasses supplementation is presented in Figures 4.1 and 4.2.

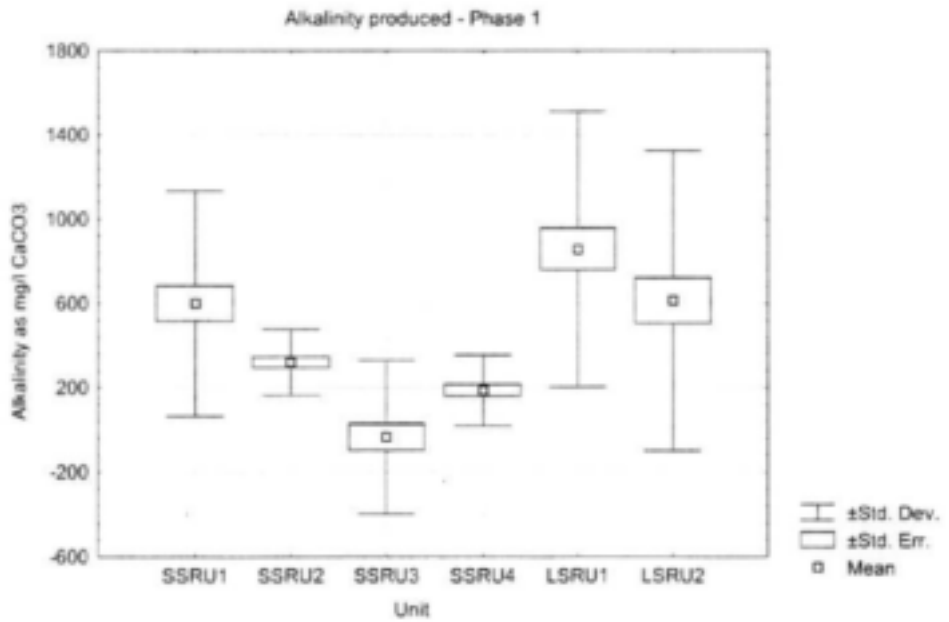

Figure 4.1 : Box and Whisker plot showing alkalinity addition during Phase 1 (November 1996 – December 1998)

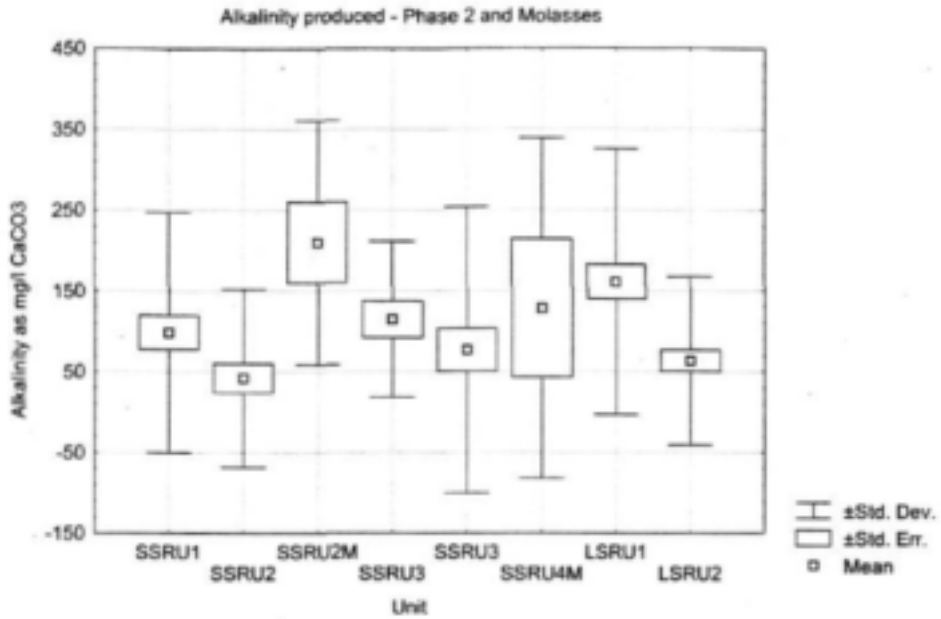

Figure 4.2 : Box and Whisker plot showing alkalinity addition during Phase 2 (August 1999 - March 2004) and molasses supplementation (M) for SSRU 2 (April 2003 – March 2004) and SSRU 4 (November 2003 - March 2004)

Overall, there was more alkalinity added to all units during Phase 1 than during Phase 2. This is shown by the maximum average alkalinity addition of 800 mg/ℓ and 150 mg/ℓ during Phases 1 and 2 respectively (Figures 4.1 and 4.2). The supplementation of molasses to SSRU 2 led to an increase in the average alkalinity added to the unit (Figure 4.2). This coincided with the pH results as discussed above. Molasses supplementation also led to an increase in alkalinity production in SSRU 4 (Figure 4.2).

During Phase 1, the SSRUs connected in series showed a stepwise decrease in alkalinity production between SSRU 1 and SSRU 3, while SSRU 4 had a higher alkalinity production compared to SSRU 3. This is due to the intermediate step of sulphide removal through HSRU connected to SSRU 4, thus decreasing sulphide toxicity to SRB and increasing sulphate reduction activity in that unit. The highest average alkalinity addition per phase was observed for LSRU 1 (858 mg/ℓ $CaCO_3$ during Phase 1 and 161 mg/ℓ during Phase 2).

4.2 COMPARISON OF STANDARD REACTORS IN TERMS OF SULPHATE REDUCTION AND SULPHIDE PRODUCTION

4.2.1 Sulphate reduction

Sulphate reduction activity of the SRUs was higher during Phase 1 than Phase 2. This could be attributed to the availability of readily degradable carbon during Phase 1 to drive sulphate reduction while only the more recalcitrant carbon remained during Phase 2. During Phase 1 the average sulphate reduction ranged between 0.25 mg/ℓ (SSRU 3) to 649 mg/ℓ (LSRU 1) while the average sulphate reduction ranged between 0.25 mg/ℓ (SSRU 4) and ~200 mg/ℓ (LSRU 1 and LSRU 2) for Phase 2 (Figure 4.4). The reduction of sulphate during Phase 1 in the SSRUs connected in series decreased stepwise between SSRU 1 and SSRU 3. The low sulphate reduction activity of SSRU 3 during Phase 1 was attributed to the high sulphide content in the influent, which is toxic to SRB.

The removal of sulphide between SSRU 3 and SSRU 4 through the HSRU during Phase 1 resulted in a decrease of sulphide toxicity and therefore an increased reduction in sulphate in SSRU 4 compared to SSRU 3 (Figure 4.3).

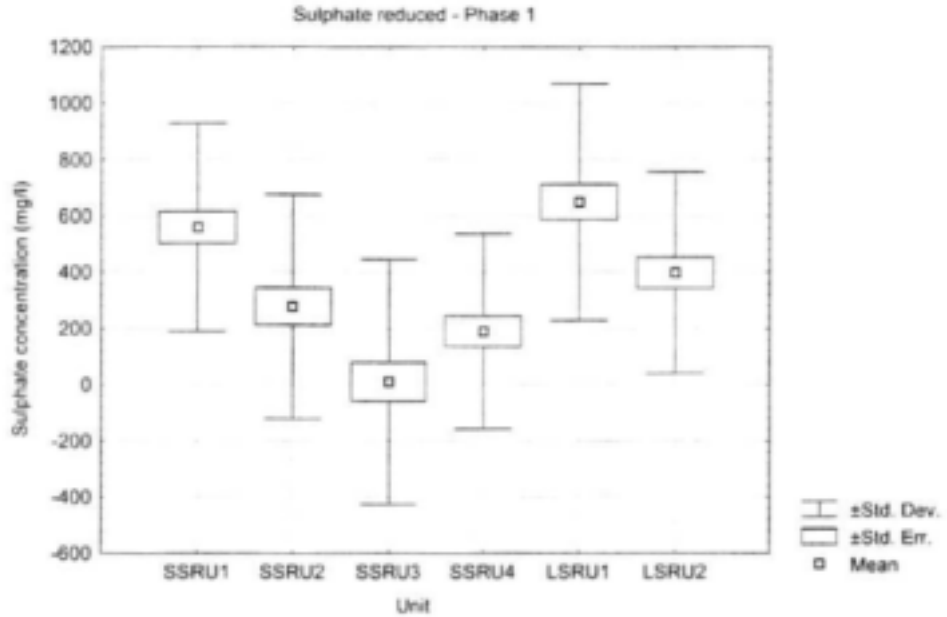

Figure 4.3 : Box and Whisker plot showing sulphate reduction during Phase 1 (November 1996 – December 1998)

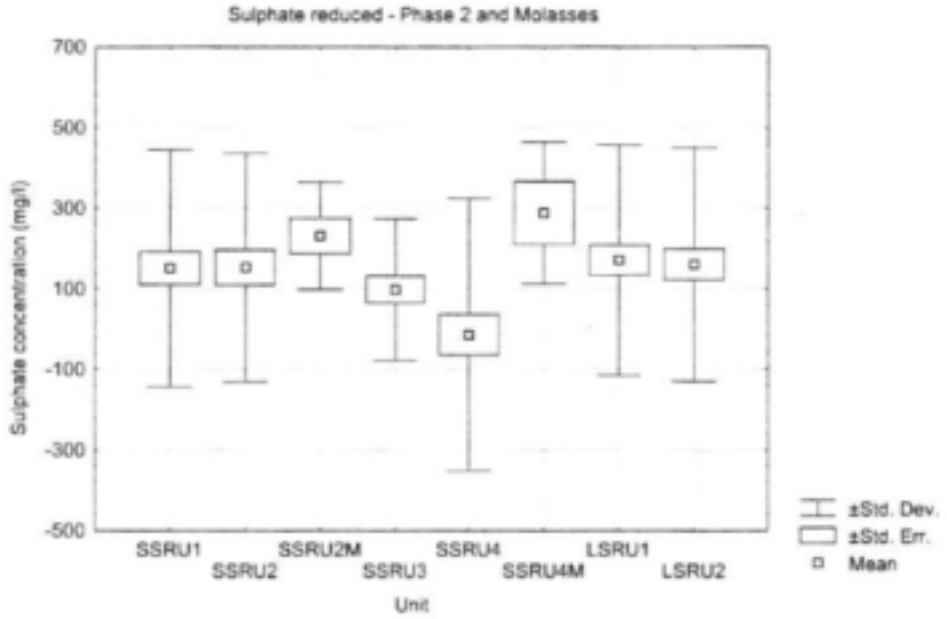

Figure 4.4 : Box and Whisker plot showing sulphate reduction during Phase 2 (August 1999 - March 2004) and molasses supplementation (M) for SSRU 2 (April 2003 – March 2004) and SSRU 4 (November 2003 - March 2004)

The supplementation of molasses in SSRU 2 and SSRU 4, led to an increase in average sulphate reduction (Figure 4.4). SSRU 2 had an average sulphate load removed of 30.7 g/m^3 carbon /d while SSRU 4 had an average sulphate load removed of 36.2 g/m^3 carbon /d.

4.2.2 Sulphide production

The average production of sulphide was higher during Phase 1 for standard operation (ranging between 4.58 mg/ℓ and 76 mg/ℓ) than Phase 2 standard operation (Ranging between 1.37 mg/ℓ and 18.8 mg/ℓ) (Figures 5.5 and 5.6), coinciding with the average sulphate reduction results (Figures 5.3 and 5.4). Although it would be expected that LSRU 1 should have the highest sulphide production to

correspond with the high sulphate reduction observed, the highest average sulphide concentration was produced during Phase 1 for SSRU 1 (Figure 4.3 and 5.5).

During Phase 2, the average sulphide produced for all units was below 20 mg/ℓ, while the supplementation of molasses led to an increase in the average sulphide production of SSRU 2 and SSRU 4 (Figure 4.6). The sulphide results coincided with sulphate reduction observed (Figures 5.3 and 5.4) and alkalinity production (Figures 5.1 and 5.2). The sulphate reduction activity of the units was higher during Phase 1 than Phase 2 due to the abundance of readily degradable carbon in the units during Phase 1 compared to Phase 2. Once the readily available carbon is depleted and only the recalcitrant carbon remained, sulphate reduction in the units decreased, coinciding with lower alkalinity production and lower sulphide production.

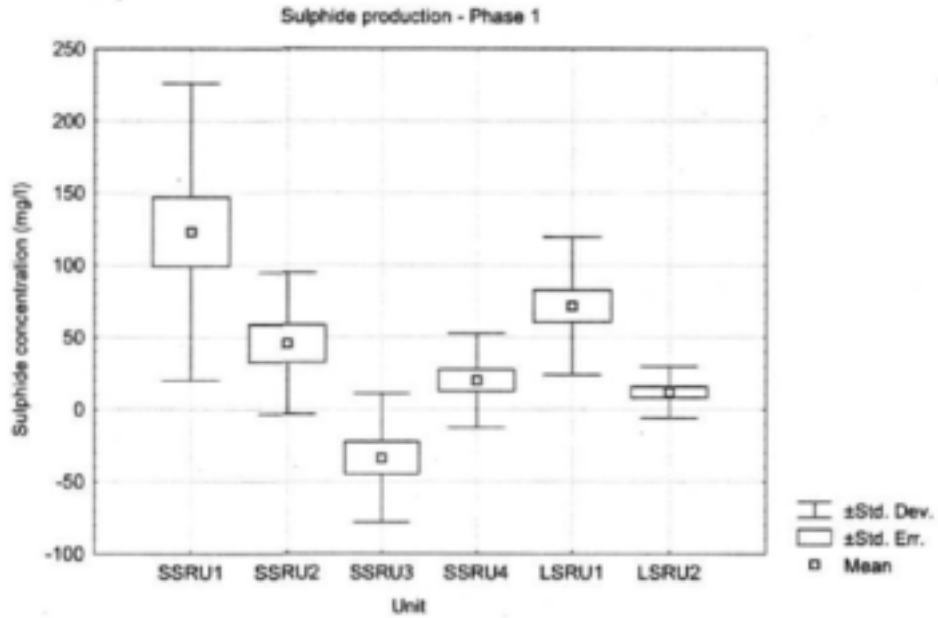

Figure 4.5 : Box and Whisker plot showing sulphide production during Phase 1 (November 1996 – December 1998)

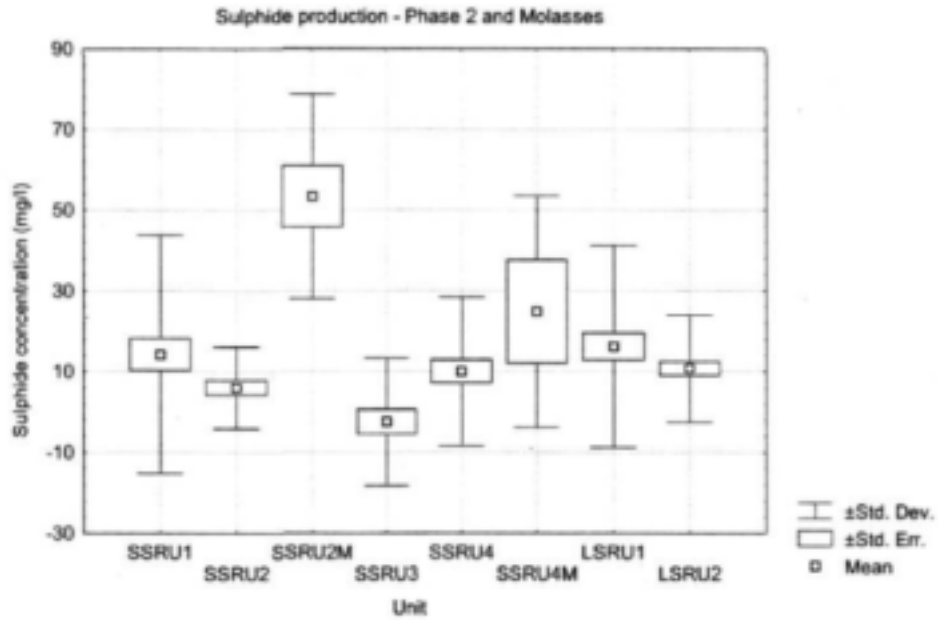

Figure 4.6 : Box and Whisker plot showing sulphide production during Phase 2 (August 1999 - March 2004) and molasses supplementation (M) for SSRU 2 (April 2003 – March 2004) and SSRU 4 (November 2003 - March 2004)

There was an increase in sulphide production in SSRU 2 and SSRU 4 after molasses supplementation (Figure 4.6). This was substantiated by the increase in sulphate reduction observed (Figure 4.4).

4.3 COMPARISON OF STANDARD REACTORS IN TERMS OF METAL REMOVAL

4.3.1 Manganese

Manganese removal was observed in all of the SRUs ranging between an average of 0.25 mg/ℓ and 8.7 mg/ℓ during both phases (Figures 5.7 and 5.8). The highest average manganese removal took place in LSRU 1 and LSRU 2 during Phase 1 (Figure 4.7) and in SSRU 2 during Phase 2 (Figure 4.8).

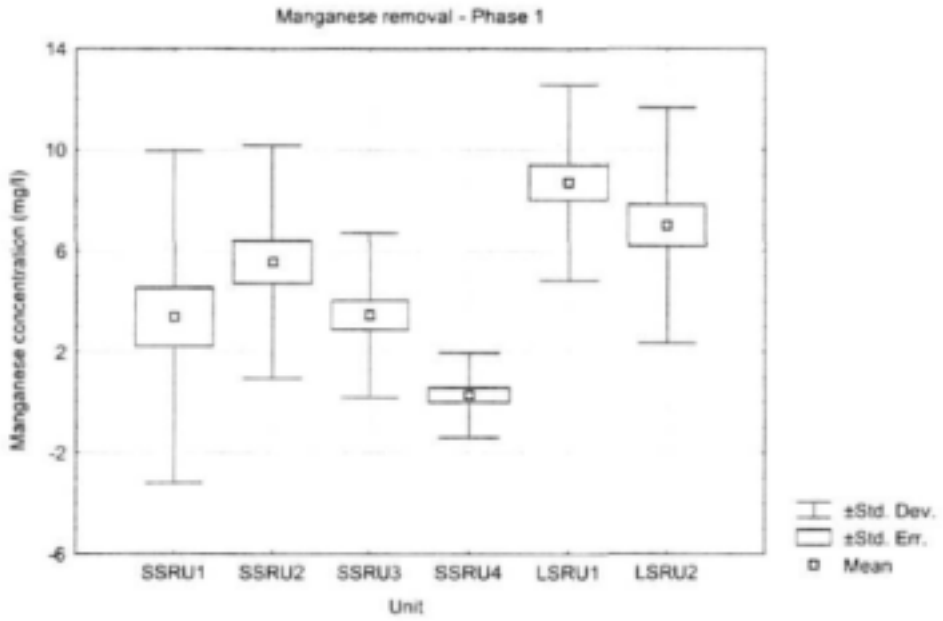

Figure 4.7 : Box and Whisker plot showing manganese removal during Phase 1 (November 1996 – December 1998)

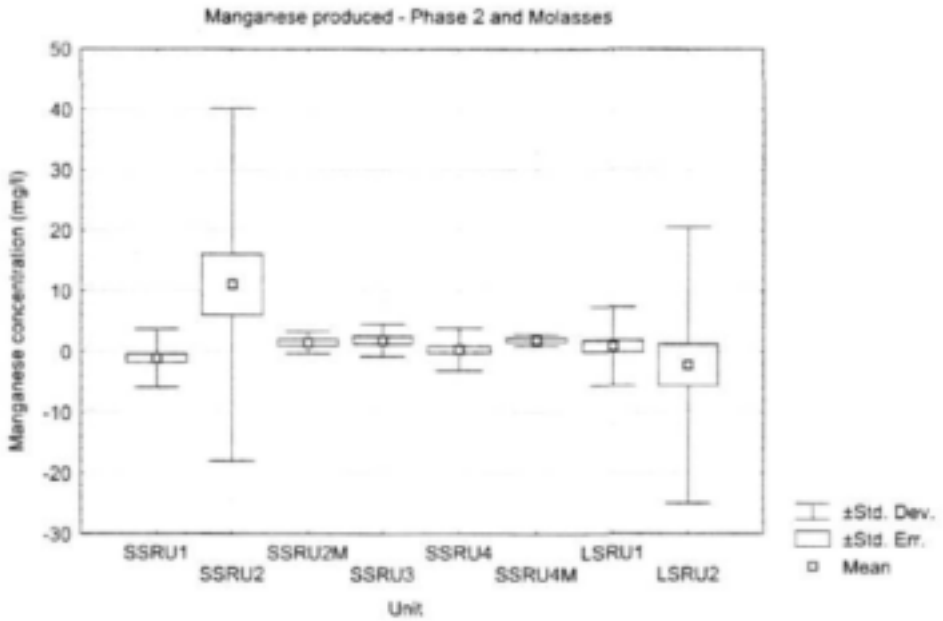

Figure 4.8 : Box and Whisker plot showing manganese removal during Phase 2 (August 1999 - March 2004) and molasses supplementation (M) for SSRU 2 (April 2003 – March 2004) and SSRU 4 (November 2003 - March 2004)

4.3.2 Aluminium

The removal of aluminium from the SRUs results from the formation of an aluminium sulphide precipitate, which settles out of solution. Therefore, it would be expected that high sulphide production would coincide with high aluminium removal.

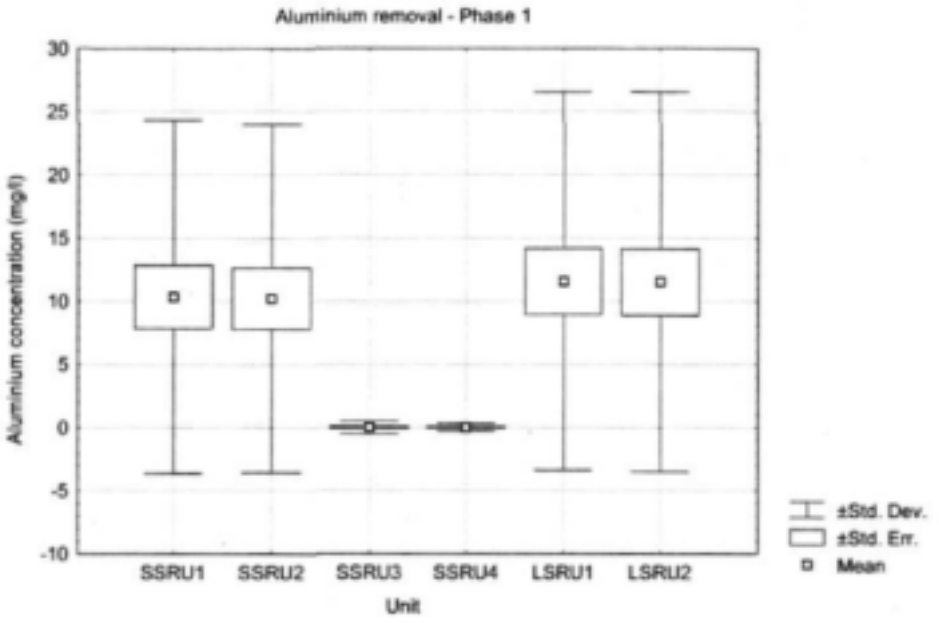

Figure 4.9 : Box and Whisker plot showing aluminium removal during Phase 1 (November 1996 – December 1998)

The average aluminium removal during Phase 1 ranged between 0.25 mg/ℓ and 12 mg/ℓ and between 0.25 mg/ℓ and 17 mg/ℓ during Phase 2. The highest aluminium removal during Phase 1 was demonstrated by SSRU 1 and SSRU 2 (Figure 4.8) and was ascribed to the high sulphide produced during Phase 1 (Figure 4.5). Similarly, the high average aluminium removal observed in LSRU 1 (Figure 4.8) correlated with the second highest average sulphide production after SSRU 1 (Figure 4.5). Although SSRU 3 received influent containing high sulphide concentrations the lowest removal of aluminium was observed (Figure 4.9). This coincided with low sulphate reduction (Figure 4.3) and sulphide production (Figures 5.5). SSRU 3 and SSRU 4 were responsible for the lowest removal of aluminium (Figure 4.9).

During Phase 2, sulphide production in the SRUs was generally low <20 mg/ℓ (Figure 4.6) and the removal of aluminium varied between the SRUs (Figure 4.9). Although higher removal of aluminium was expected during molasses supplementation due to an increase in sulphide production which would precipitate the metals out, it was not the case (Figure 4.10).

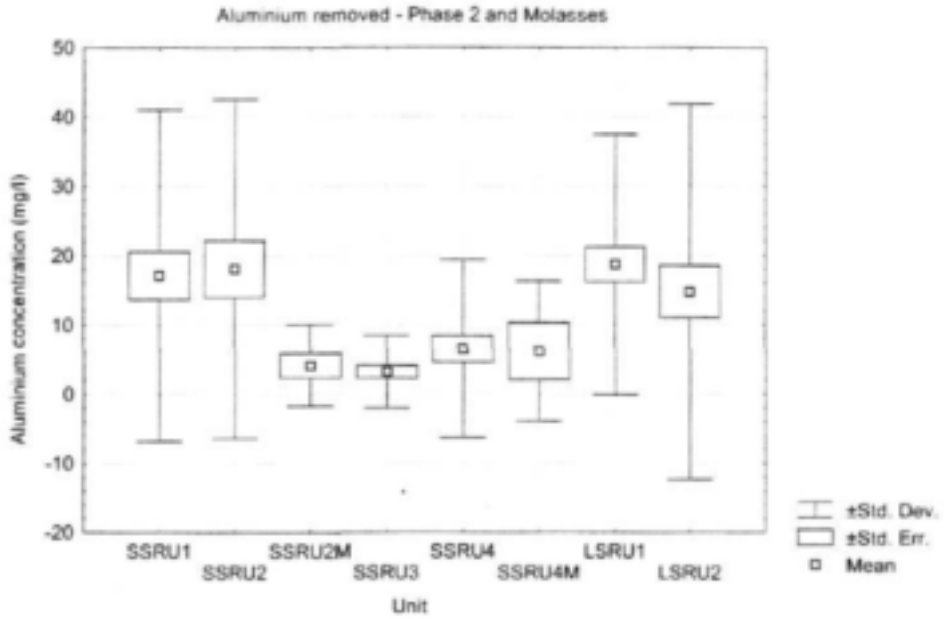

Figure 4.10 : Box and Whisker plot showing aluminium removal during Phase 2 (August 1999 - March 2004) and molasses supplementation (M) for SSRU 2 (April 2003 – March 2004) and SSRU 4 (November 2003 - March 2004)

4.3.3 Iron

Iron removal from the SRUs occurs in the same manner as aluminium (*e.g.* iron sulphide precipitate, Section 4.3.2). The removal of iron during Phase 1 ranged between 0.25 mg/ℓ and 2.00 mg/ℓ (Figure 4.11).

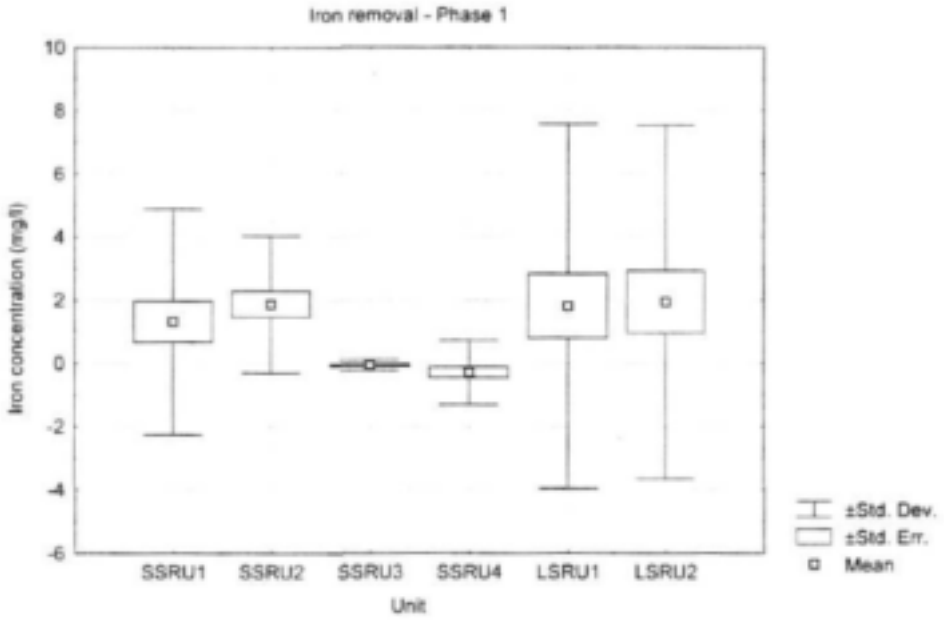

Figure 4.11 : Box and Whisker plot showing iron removal during Phase 1 (November 1996 – December 1998)

SSRU 1 (Phase 4) showed the highest iron removal, averaging 9.4 mg/ℓ (Figure 4.12). Increased sulphide production coincided with increased iron removal (SSRU 2 and SSRU 4) due to molasses supplementation (Figure 4.6 and 5.12).

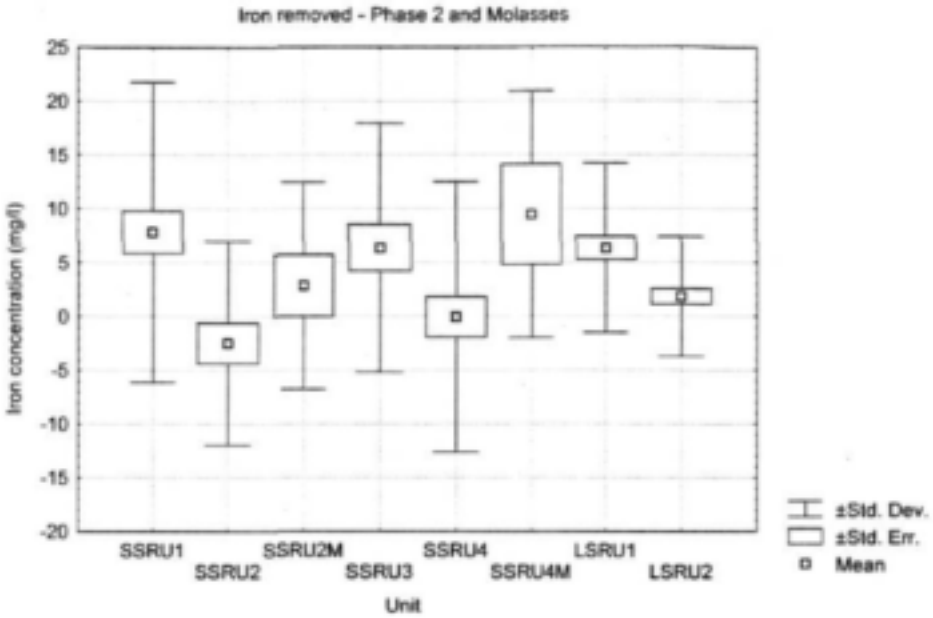

Figure 4.12 : Box and Whisker plot showing iron removal during Phase 2 (August 1999 – March 2004) and molasses supplementation (M) for SSRU 2 (April 2003 – March 2004) and SSRU 4 (November 2003 – March 2004)

4.4 COMPARISON OF STANDARD REACTORS IN TERMS OF REDOX POTENTIAL

The optimum Redox potential for effective sulphate reduction is –200 mV (PHD, 2002). Only LSRU 1 had a negative average Redox potential (-10 mV, Figure 4.13). The rest of the SRU had positive average Redox potentials in the range of 0 mV to 75 mV (Figure 4.13). The positive Redox potential of the SRUs has a direct impact on the low sulphate load reduced in the SRUs. Molasses supplementation to the feed line of SSRU 2 has resulted in a decrease of Redox potential from 30 mV to –110 mV (Figure 4.13). These results correlated with the increased sulphate reduction activity, increased pH neutralisation and sulphide production observed in SSRU 2 after molasses supplementation (Figure 4.2, 5.4 and 5.6). Although molasses was being supplemented to SSRU 4, the output redox potential was still positive after five months of operation and SSRU 4 needs to be monitored further.

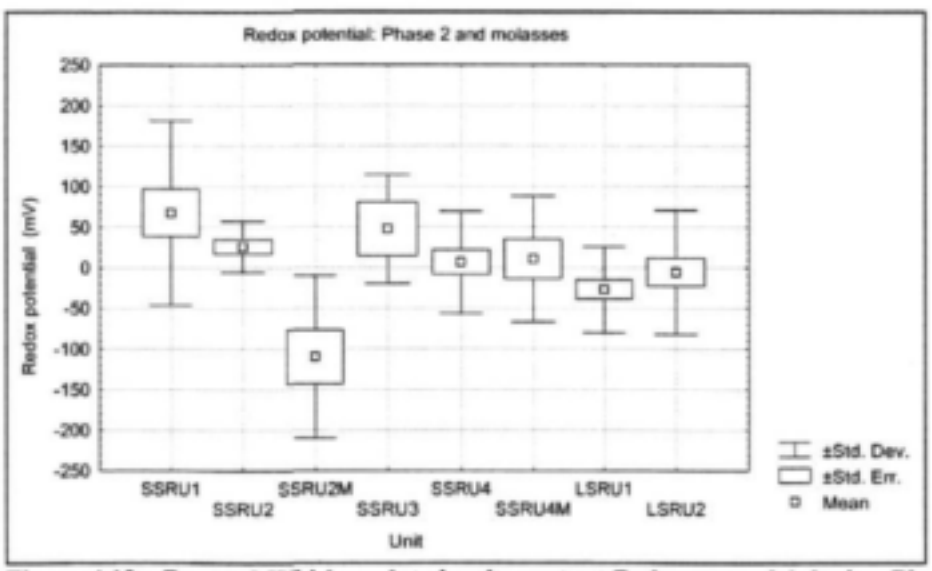

Figure 4.13 : Box and Whisker plot showing output Redox potential during Phase 2 (May 2002 -March 2004) and molasses supplementation (M) for SSRU 2 (April 2003 – March 2004) and SSRU 4 (November 2003 - March 2004)

4.5 CONCLUSIONS AND RECOMMENDATIONS WITH REGARD TO THE STANDARD REACTORS

4.5.1 Conclusions

The following conclusions were reached after assessing the data of the standard reactors:

- Overall, the sulphate reduction efficiency, alkalinity production and sulphide production of the units was higher during Phase 1 than Phase 2. This was ascribed to the availability of readily degradable carbon used to drive sulphate reduction. This high activity was marked by increased neutralisation ability (pH and alkalinity), sulphate reduction and sulphide production.
- The parallel connection of the large units was more efficient than the series connection of the small units during Phase 1. The series connection resulted in increased levels of sulphide in the influent of the subsequent reactor, which could lead to sulphide toxicity and a decrease in sulphate reduction activity.
- The upflow units (SSRU 3 and SSRU 4) connected in series had a lower sulphate reduction activity compared to the downflow units (SSRU 1 and SSRU 2).
- There were fluctuations in metal removal between the units and between the different phases.
- The addition of molasses led to increased sulphate reduction activity of SSRU 2 and SSRU 4, expressed as increased sulphate reduction, sulphide production, alkalinity addition and pH increase.

4.5.2 Recommendations

- It is recommended that the use of a 'kick-start' carbon be implemented with the units that have been in operation for 7 years in order to increase their sulphate reduction activity.
- Further monitoring of the reactors that have been supplemented with molasses is necessary to evaluate the long-term effect of kick-start carbon supplementation on performance.

CHAPTER 5

DECOMMISSIONING OF SSRU 3 AND RECOMMISIONING IT AS A DEGRADING PACKED BED REACTOR (DPBR)

Due to the lack of sulphate reduction in SSRU 3, it was selected as the SRU to be decommissioned (Appendix C). A new SRU was built and operated using the principles of the degrading packed bed reactor (DPBR). Chapter 5 will focus on the decommissioning of SSRU 3 and the recommissioning of a DPBR whilst Chapter 6 deals with the performance of the DPBR.

5.1 DECOMMISSIONING OF SSRU 3

SSRU 3 was decommissioned in accordance with the methods as described in Section 2.2 (Chapter 2). Prior to the decommissioning of SSRU 3, a sulphur biofilm was noticed in one of the corners of the SSRU 3 (Figure 5.1).

Figure 5.1 : Sulphur biofilm forming on the surface of SSRU 3

The different layers of carbon could not be clearly distinguished during decommissioning of SSRU 3. This could be ascribed to the compaction of the carbon over a 6 year period (1996-2002) as well as the biodegradation of the carbon. Where carbon layers could still be identified, solid samples were taken and submitted to Rhodes University for analysis. The following results were obtained from the liquid sample collected at the bottom of the SSRU 3.

Variable analysed	Variable concentration (mg/l)	Influent concentration (mg/l)
Elemental sulphur	48.6	-
VFA_{Total}	80.3	-
Sulphide	38.6	1.23
Sulphate	1563	1502
Aluminium	8.62	7.47
Iron	2.45	0.64
Manganese	12.7	9.63

The sulphide concentration at the bottom of the reactor was higher than the influent concentration due to the anaerobic conditions. The metal concentrations at the bottom of the reactor were higher than the influent and this could be attributed to the metal precipitated out the AMD during treatment in the unit.

Sections of the surface of the reactor were covered with algae (Duckweed Lemna sp.) (Figure 5.2).

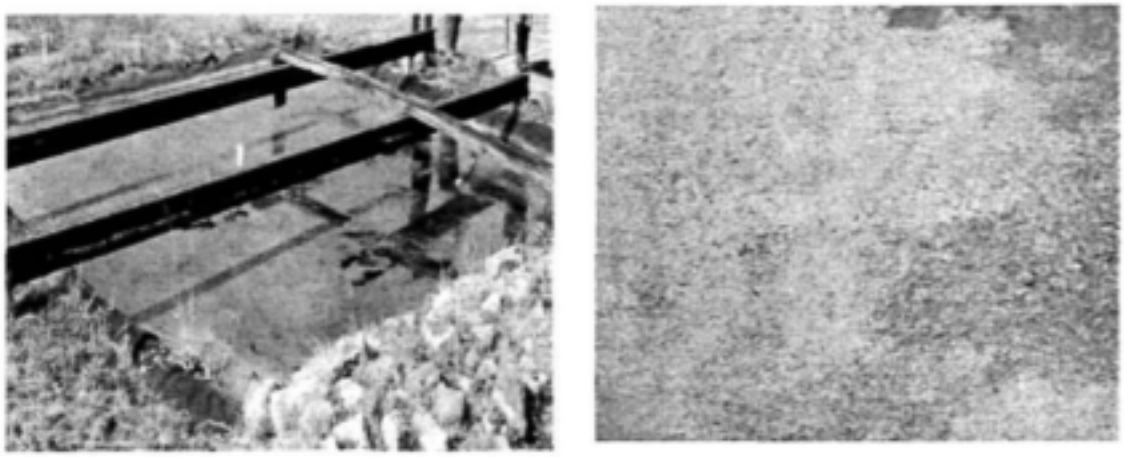

Figure 5.2 : Duckweed growing on the surface of the reactor

A layer of dead algae was observed underneath the duckweed. Numerous insects (adults and larvae) were observed alive on the surface of the water.

During the decommissioning process, the first visible carbon layer observed was sawdust (approximately 15-20 cm thick). The thickness of the sawdust layer varied and appeared to be deepest at the centre (Figure 5.3).

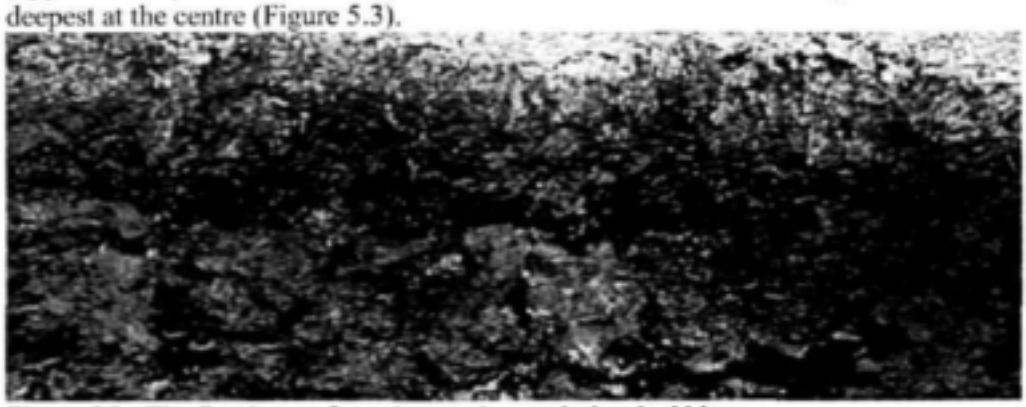

Figure 5.3 : The first layer of sawdust underneath the algal biomass

The first layer of stone (dolerite) beneath the sawdust was covered with a yellow-white biofilm/layer (Figure 5.4). This was unusual as it occurred in an anoxic zone below a sulphate-reducing zone (evidenced by odour and colour).

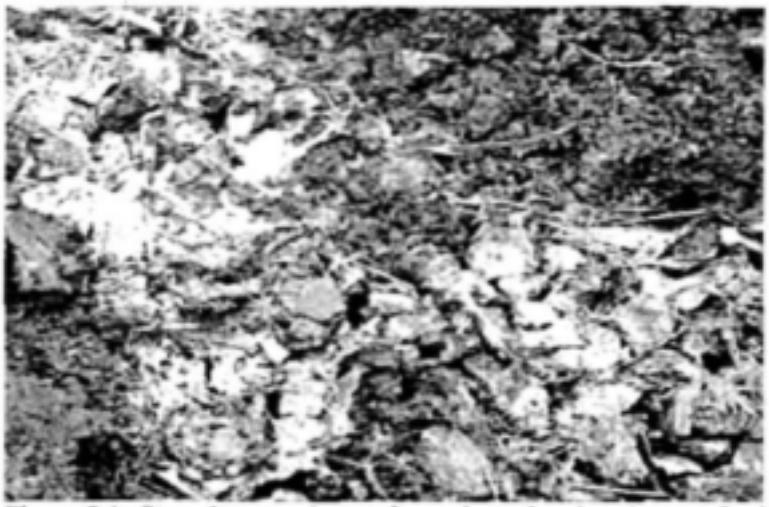

Figure 5.4 : Stone layer underneath sawdust, showing elemental sulphur covering the stones

The layer of stone (dolerite) was approximately 60 cm deep, and was followed by another layer of sawdust. The layer of sawdust was less than 10 cm deep and was followed by another large layer of dolerite. A layer of hay was found beneath the dolerite layer (Figure 5.5). The hay appeared structurally unchanged and retained its tensile strength.

Figure 5.5 : A layer of hay between the dolerite

Upon exposure of the final carbon layer, it was noticed that the water seeping out of the remaining unpacked reactor had white material in it that appeared to be sulphur (this was not tested).

A photograph was taken of the depth profile of SSRU 3 (Figure 5.6). It was apparent that the majority of the reactor was composed of dolerite stone and that very little carbonaceous material was still present or easily observed.

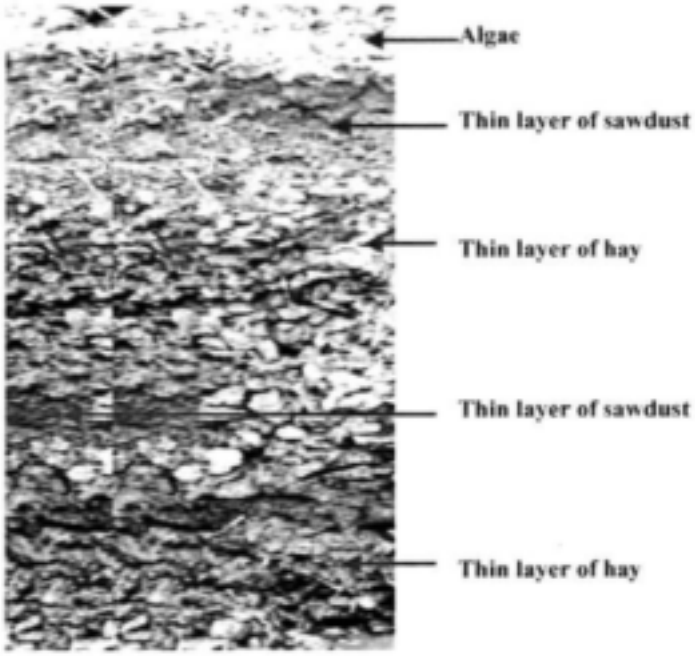

Figure 5.6 : A depth profile of SSRU 3 with the majority of the unit consisting of dolerite stones

This reactor was operated in an up flow configuration and fed with sulphide-rich water from SSRU 2. From the depth profile, it was apparent that sulphate reduction took place in the top layers of carbon, as the bottom layers of carbon of the unit did not seem to be biodegraded. A white layer of sulphur indicated that sulphide oxidation occurred just above the layer of active sulphate reduction. The water pumped out of SSRU 3 was black and smelt strongly of sulphide. This further indicates that some sulphate reduction occurred in SSRU 3.

5.2 RECOMMISSIONING SSRU 3 AS A DEGRADING PACKED BED REACTOR (DPBR)

A DPBR was constructed, packed and operated on the principles of the patented Integrated Managed Passive Treatment (IMPI) Technology (Figure 2.6). A detailed description on the results obtained from operating the DPBR is given in Chapter 7.

5.3 CONCLUSIONS

5.3.1 Decommissioning of SSRU 3

The following conclusions were reached after decommissioning of SSRU 3:

- The decommissioned reactor had thin layers of carbon that compacted over time and did not allow for easy visual characterisation or identification of the different layers of carbon present.
- The sawdust seemed to have been degraded more than the other waste carbon sources.
- Hay was virtually intact and biodegradation of the hay limited.
- The volume of bulking agent was high in comparison with the volume of carbon used to pack the bioreactor.

5.3.2 Re-commissioning of SSRU 3 as DPBR

- The SSRU 3 was re-commissioned successfully.
- The thickness of the carbon layers should be increased in order to prevent mixing of the carbon sources during compaction of the unit.

CHAPTER 6

RESULTS AND DISCUSSION ON THE EVALUATION OF PERFORMANCE OF THE DEGRADING PACKED BED REACTOR (DPBR)

The crux of the success of the Degrading Packed Bed Reactor (DPBR) lies in the continuous supplementation of readily available carbon to the system. Sufficient readily available carbon is dosed to the influent of the DPBR to make the top layer of the system anaerobic by initiating anaerobic metabolic processes and provide the right redox potential conditions for sulphate reduction to commence. As the water moves through the DPBR more sulphate reduction occurs, adding more alkalinity and sulphide to the system. High alkalinity enhances lignocellulose degradation through the swelling of the lignocellulose while high sulphide concentrations prevent the repolimerisation of the lignin. With the enhancement of lignocellulose degradation, the phenomena existing with passive treatment systems where the unavailability of carbon to drive sulphate reduction causes system malfunction, is overcome and successful sulphate reduction is maintained over extended periods.

6.1 EVALUATION OF DPBR IN TERMS OF DAILY WATER QUALITY DATA

6.1.1 Flow Rate

The average influent flow rate for the period October 2002 - March 2004 compared to the theoretical flow rate is summarised in Figures 2.3 and 2.4 (Chapter 2). The reason that actual flow rates were lower than the theoretical flow rates could be ascribed to periods where DPBR was operated using only one type of AMD. This scenario occured either when the West Discharge AMD pipeline was blocked or the pump pumping the South Discharge AMD to the storage tank was not operational. Periods where actual flow rates were higher than theoretical flow rates could be ascribed to heavy rains. Table 6.1 depicts the statistics of the flow data for the period October 2002 - March 2004 for the DPBR.

Table 6.1 : Statistics of the influent and effluent flow rates of the DPBR (October 2002 – March 2004)

DPBR		
	Influent flow (m^3/d)	Effluent flow (m^3/d)
N	676	671
Average	2.11	1.84
Minimum	0.39	0.42
Maximum	4.32	8.64
Standard deviation	0.63	0.83

Figure 6.1 illustrates the fluctuations in influent and effluent flow rates over time (October 2002 - March 2004). The flow rates were increased from November 2003 to March 2004 (Figure 6.1).

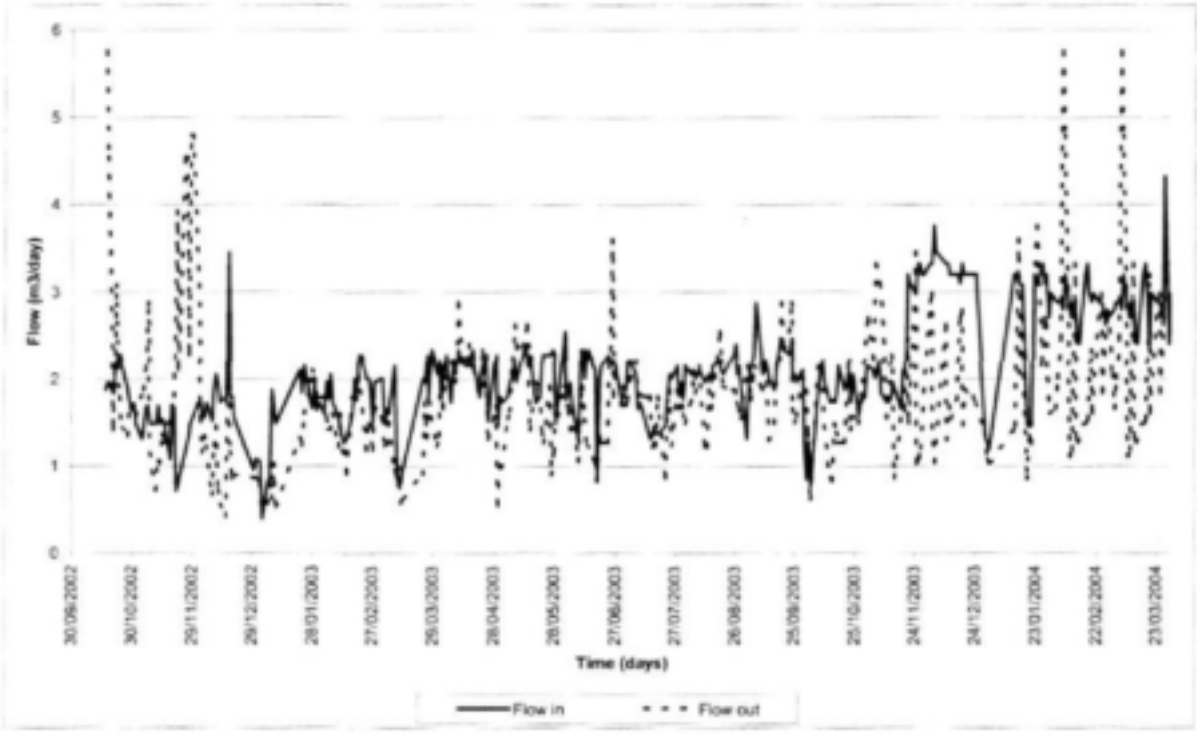

Figure 6.1 : Daily flow readings of the DPBR (October 2002 - March 2004)

6.1.2 pH

The DPBR was responsible for increasing the influent pH from an average of 4.72 to an average of 5.72 (Table7.2).

Table 6.2 : Statistics of the influent and effluent pH of the DPBR (October 2002 – March 2004)

DPBR		
	Influent pH	Effluent pH
N	651	642
Average	4.72	5.72
Minimum	3.00	3.68
Maximum	7.81	7.84
Standard deviation	0.94	0.62

The fluctuation in influent pH could be ascribed to problems experienced with influent water supply where only one of the discharge (West or South discharges) is used as feed (Figure 6.2). However, the prevalent trend shows that DPBR led to neutralization of influent water throughout the evaluation period (October 2002 - March 2004).

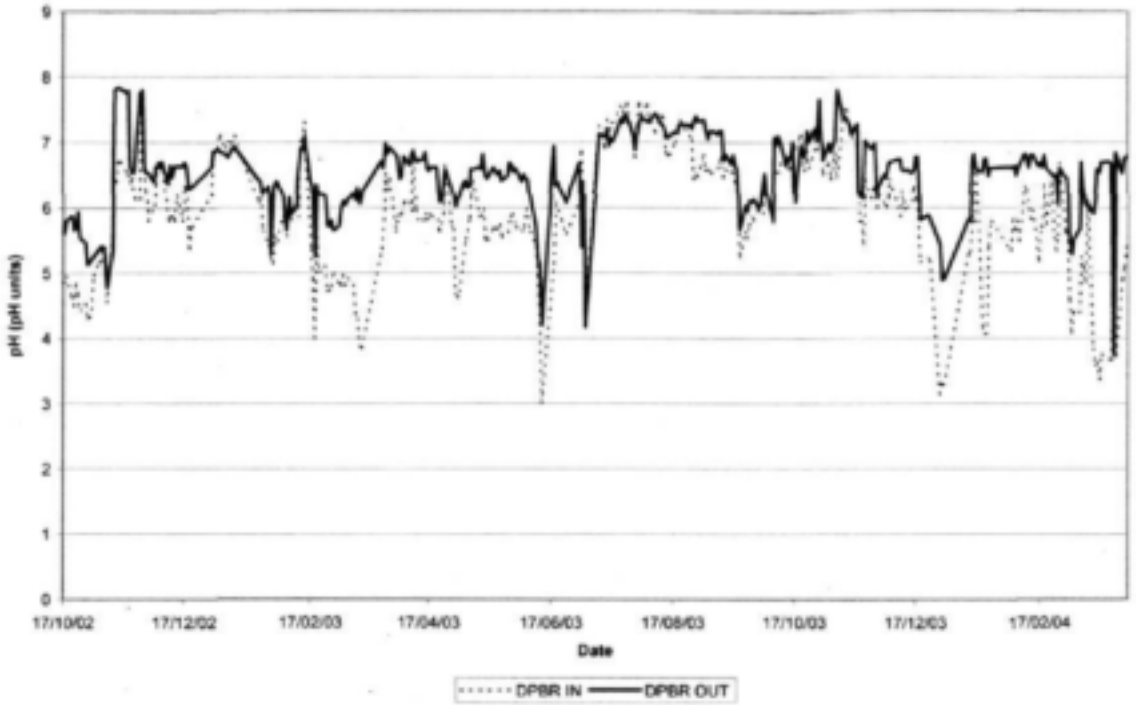

Figure 6.2 : Daily pH Values of the DPBR for the period October 2002 - March 2004

6.1.3 Electrical conductivity values

The electrical conductivity data is depicted in Figure 6.3. The average effluent electrical conductivity value was marginally higher than the average influent conductivity value (152 mS/m versus 143 mS/m) (Table 6.3).

Table 6.3 : Statistics of the influent and effluent EC of the DPBR (October 2002 – March 2004)

Electrical conductivity (mS/m)		
	Influent	Effluent
N	673	649
Average	143	152
Minimum	86	94
Maximum	213	353
Standard deviation	20.6	26.0

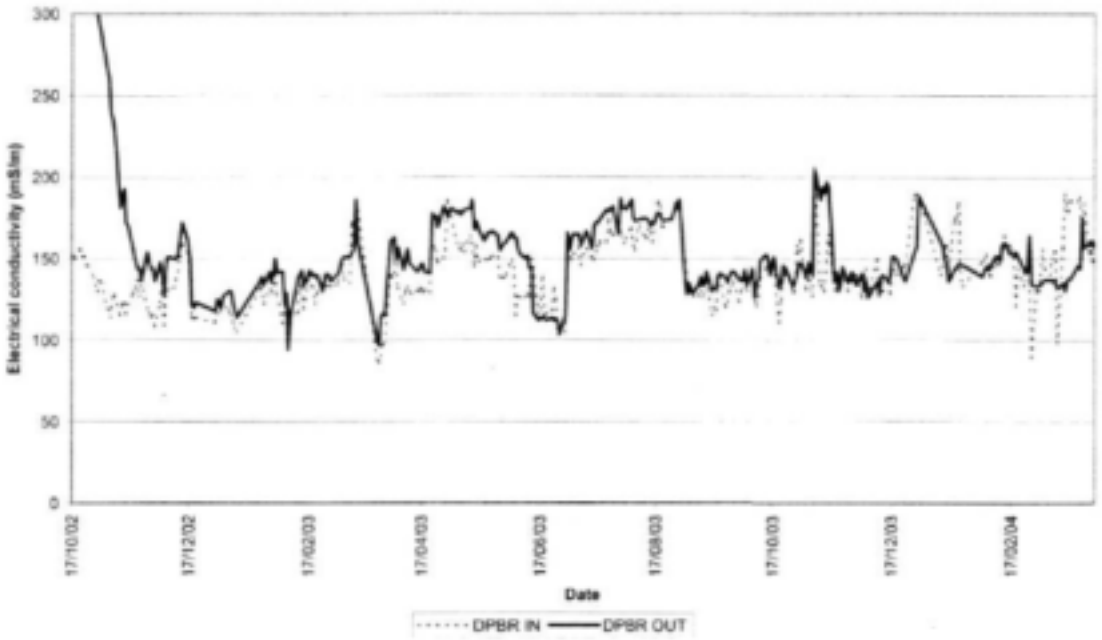

Figure 6.3 : Daily EC values of the DPBR (October 2002 - March 2004)

6.1.4 Temperature Values

The temperature profile of the feed water shows a very strong seasonal cyclical trend, varying from 11-21 °C in winter, to 18-28 °C in summer. During the evaluated period, the outflow temperature was very similar to the inflow temperature throughout the year (Figure 6.4).

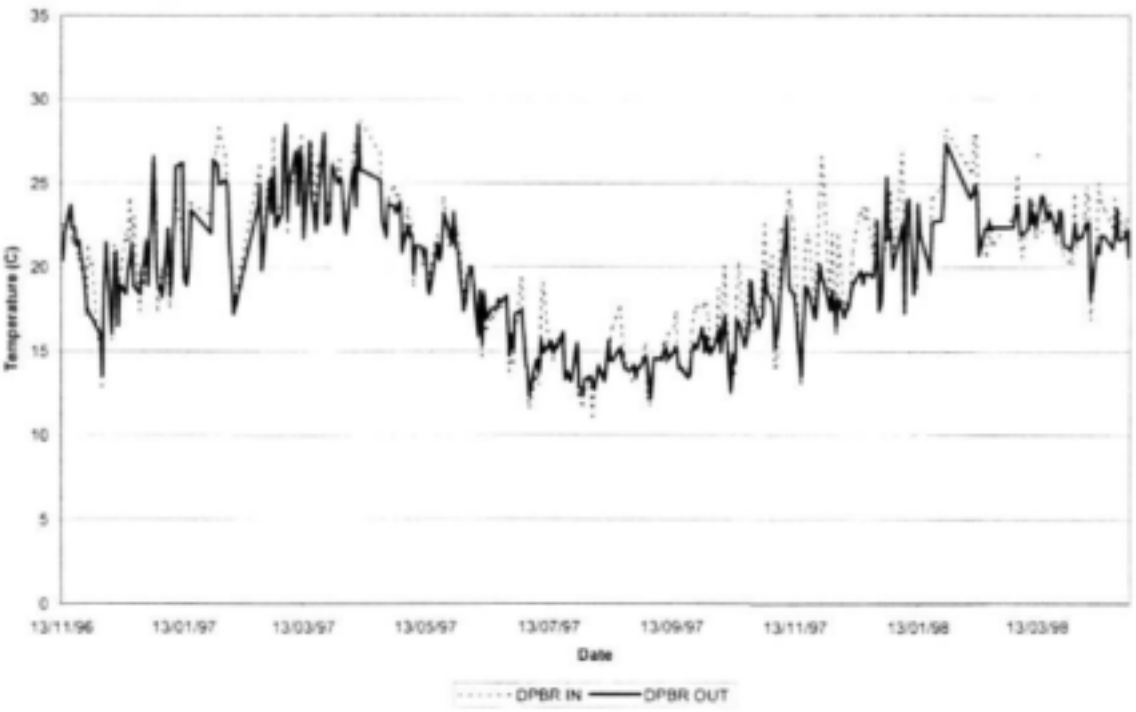

Figure 6.4 : Daily temperature values of the DPBR (October 2002 - March 2004)

6.2 EVALUATION OF PERFORMANCE IN TERMS OF MONTHLY WATER QUALITY PARAMETERS

6.2.1 Performance with regard to Metal Removal

Influent metal concentrations fluctuated during the period of operation (October 2002 – March 2004). The DPBR was effective in removing iron and aluminium from the influent water with a percentage removal of 87 % for iron and 82 % for aluminium (Table 6.4). Only 20 % of manganese was removed by the DPBR (Table 6.4).

Table 6.4 : Mean DPBR metal removal (October 2002 - March 2004)

PHASE	Iron			Aluminium			Manganese		
	Influent concentration (mg/l)	Effluent concentration (mg/l)	Percentage removed (%)	Influent concentration (mg/l)	Effluent concentration (mg/l)	Percentage removed (%)	Influent concentration (mg/l)	Effluent concentration (mg/l)	Percentage removed (%)
DPBR	2.69	0.34	87.2	5.17	0.92	82.1	9.10	7.33	19.5

Monthly influent and effluent metal concentrations for the DPBR are represented in Figures 6.5 to 6.7 for manganese, aluminium and iron.

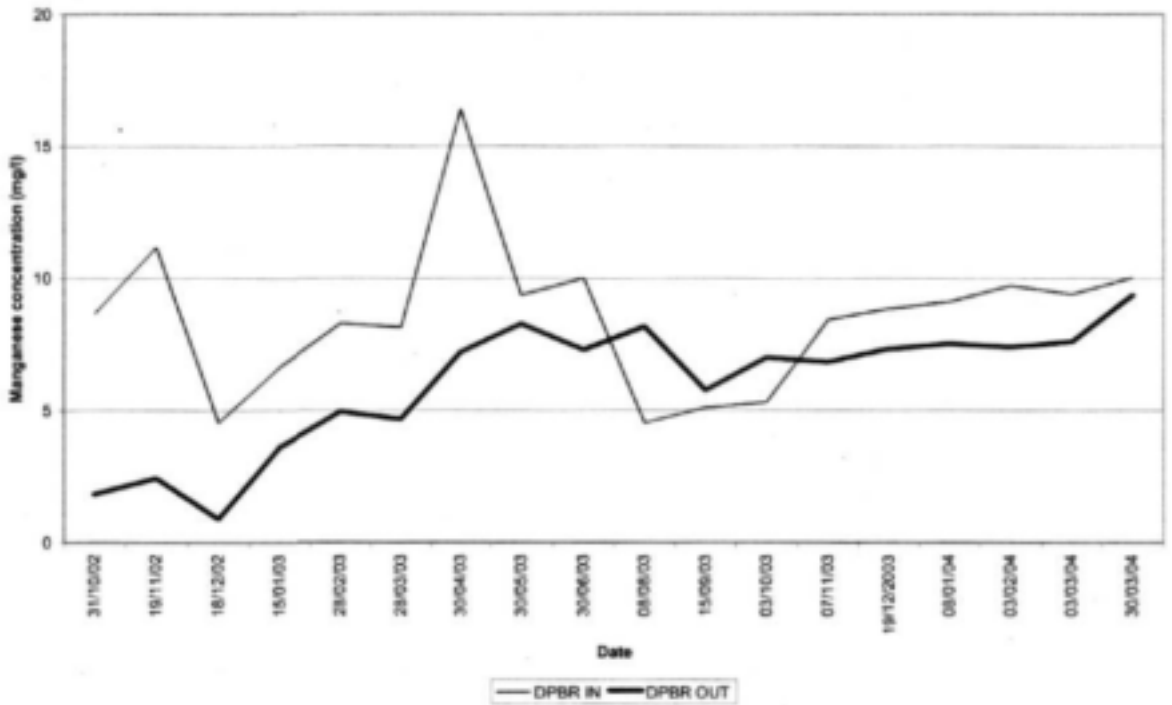

Figure 6.5 : Monthly manganese inlet and outlet concentrations for DPBR (October 2002 - March 2004) performance seem to decrease over time

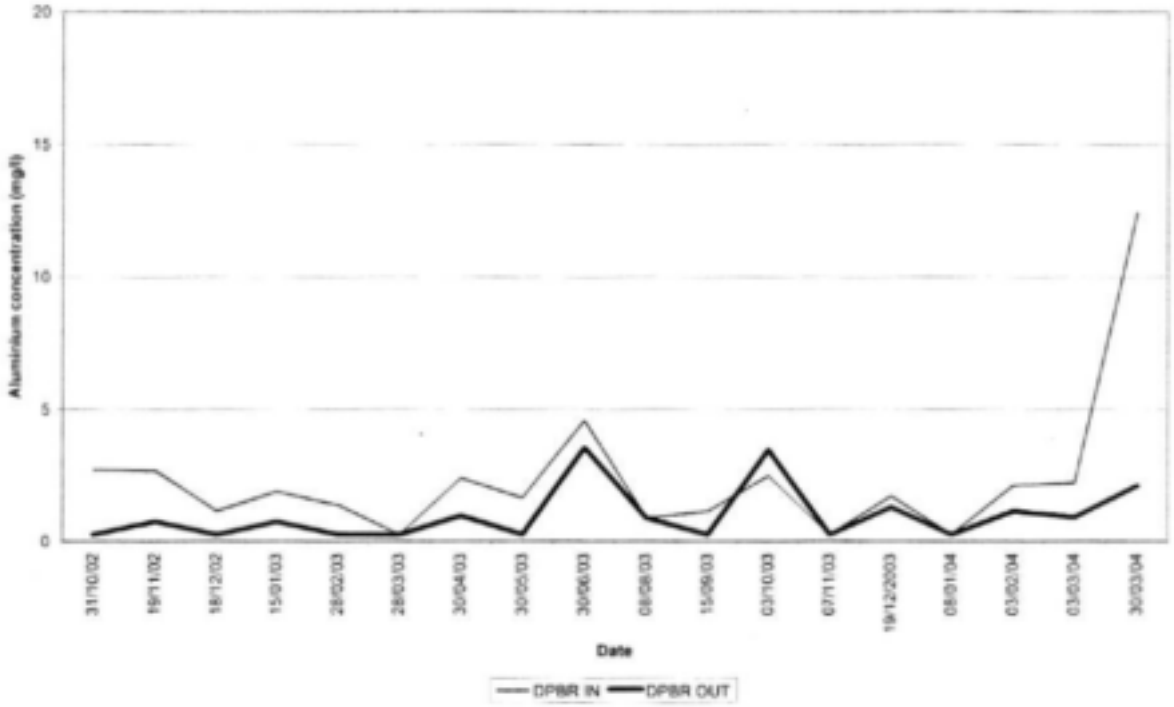

Figure 6.6 : Monthly aluminium inlet and outlet concentrations for DPBR (October 2002 - March 2004)

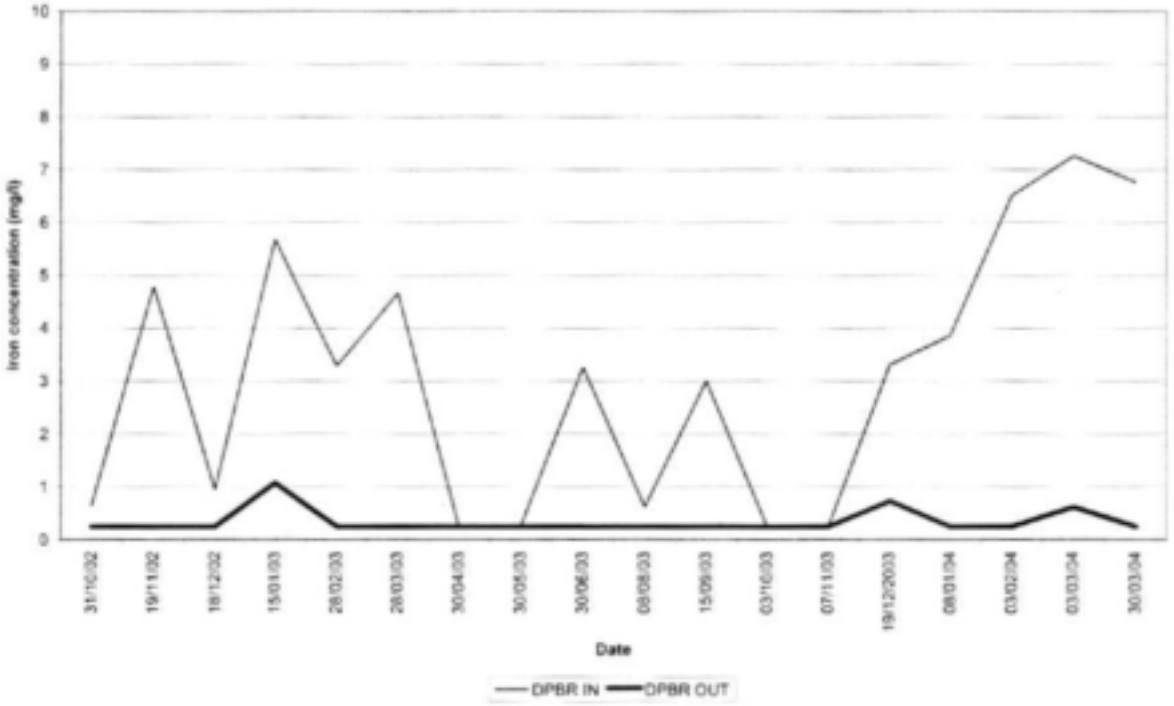

Figure 6.7 : Monthly iron inlet and outlet concentrations for DPBR (October 2002 - March 2004)

6.2.2 Performance with regard to Organics

The effluent COD concentrations of the DPBR followed typical trends observed with passive treatment systems where high COD values are initially found due to soluble carbon being washed from the system (Figure 6.8). As time progress and sulphate reduction occurs, readily available carbon is used and only the more recalcitrant carbon is left in the system. It is here where the enhancement of lignocellulose degradation keeps the system going and supports the continuation of sulphate reduction to occur. Effluent COD values remained higher than influent COD values (Table 6.5 and Figure 6.8). The fact that effluent COD values remained high after 18 months of operation, indicates that the DPBR principle of enhancing lignocellulose degradation to produce a effluent with high volatile fatty acids to drive sulphate reduction in the secondary sulphate removal unit is working. A longer evaluation period is however required to verify the continued production of effluent with high COD values from the DPBR.

Table 6.5 : Average organic loading performance of the DPBR (October 2002 - March 2004)

COD		
Influent mg/ℓ	**Effluent mg/ℓ**	**Add mg/ℓ**
53.2	582	529

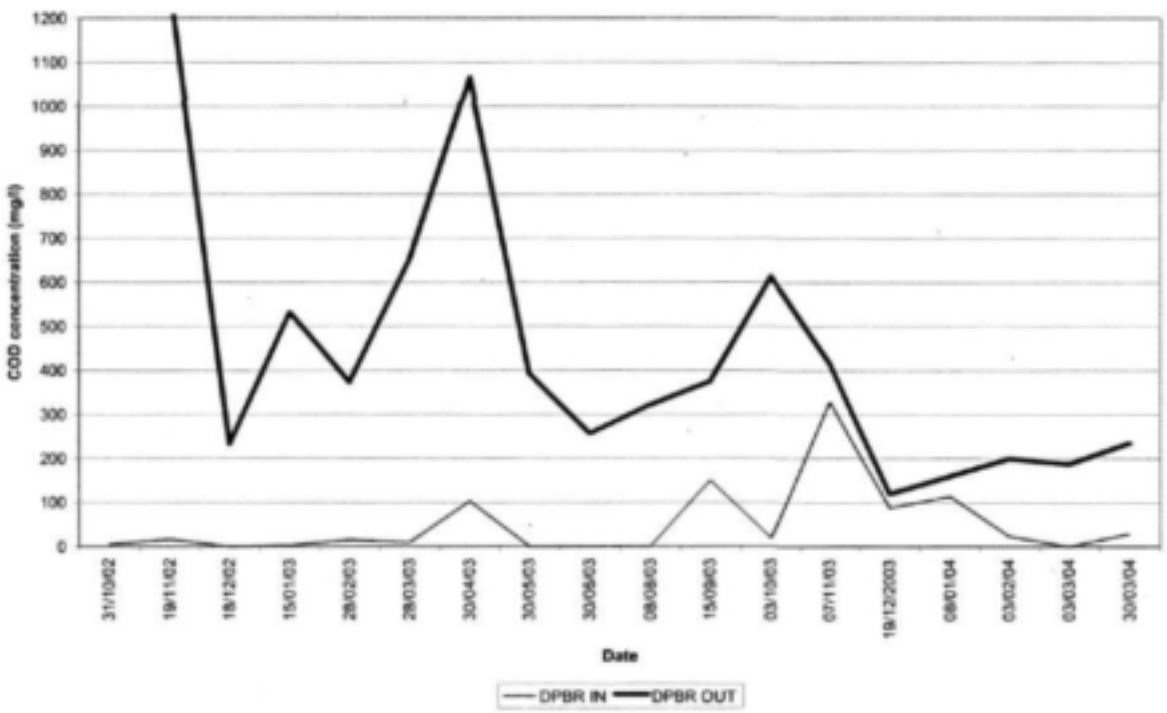

Figure 6.8 : Monthly COD inlet and outlet concentrations for DPBR (October 2002 - March 2004)

6.2.3 Performance with regard to Alkalinity

The DPBR was responsible for a high addition of alkalinity to the treated water (Table 6.6). This coincided with the high sulphate loads reduced as well as with the high production of sulphides (Table 6.7 and Table 6.10). The high alkalinity addition to the DPBR effluent may be attributed to the availability of carbon where readily available carbon sources are initially available to drive sulphate reduction.

Table 6.6 : Statistics of the influent and effluent alkalinity of the DPBR (October 2002 – March 2004)

DPBR		
	Influent alkalinity ($CaCO_3$)	Effluent alkalinity ($CaCO_3$)
N	18	17
Average	125	948
Minimum	<0.05	461
Maximum	940	2242
Standard deviation	224	446

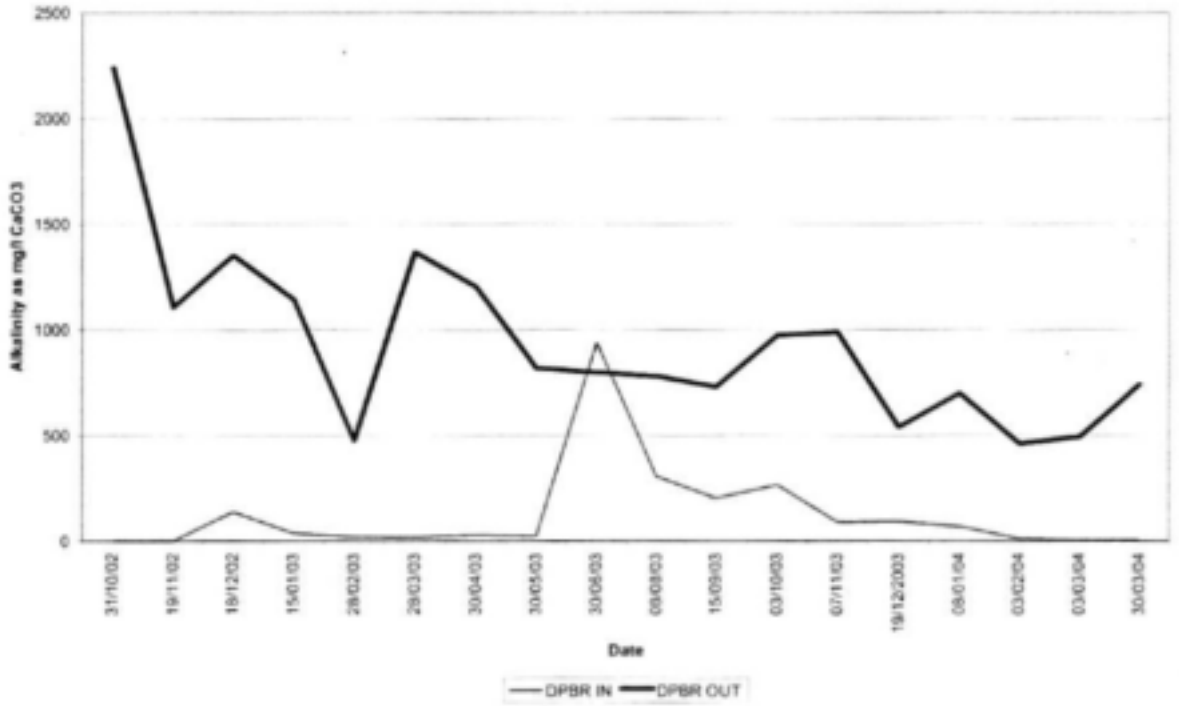

Figure 6.9 : Monthly inlet and outlet alkalinity concentration for DPBR (October 2002 - March 2004)

6.2.4 Performance of the DPBR with regard to Sulphate Reduction

The primary purpose of the sulphate reducing units is the reduction of sulphate and it is, therefore, necessary to evaluate the sulphate data in detail. The data for the DPBR (October 2002 - March 2004) has been summarised in Table 6.7 and Table 6.8. The influent and effluent sulphate load and sulphate concentrations are depicted in Figures 6.10 and 6.11 respectively. The DPBR was responsible for the highest load of sulphate reduced when compared to SSRU 1, averaging 60 g/m^3 carbon /d (Table 6.8). The highest sulphate loads reduced were observed when higher sulphate loads entered the DPBR (Figure 6.10).

It must however be noted that when the DPBR was commissioned, the proper procedure was not followed with regards to designing a passive treatment plant. Normally, kinetic column studies would be performed first using different carbon source mixtures and the actual AMD operated at different retention times and the right operating conditions selected for maximum sulphate reduction. Although the physical configuration of the DPBR was changed from a inverted truncated pyramid to a rectangular configuration, the same carbon sources as previously used in SSRU 3 were used for packing in an attempt to compare the results with the standard SRUs. Thus, a repetition of previously used carbon sources used at the VCC Pilot Plant was used and not the correctly selected combination of carbon, which would probably lead to higher sulphate reduction.

Table 6.7 : Statistics of the influent and effluent sulphate concentration of the DBPR (October 2002 – March 2004)

DPBR		
	Influent sulphate concentration (mg/ℓ)	Effluent sulphate concentration (mg/ℓ)
N	18	18
Average	1431	816
Minimum	841	264
Maximum	2613	1551
Standard deviation	452	353

Table 6.8 : Average sulphate reduced for the DPBR (October 2002 – March 2004)

Sulphate concentration reduced (mg/ℓ)	**Sulphate reduced (%)**	**Sulphate load reduced ($g/m^3/d$)**
615	23.5	59.6

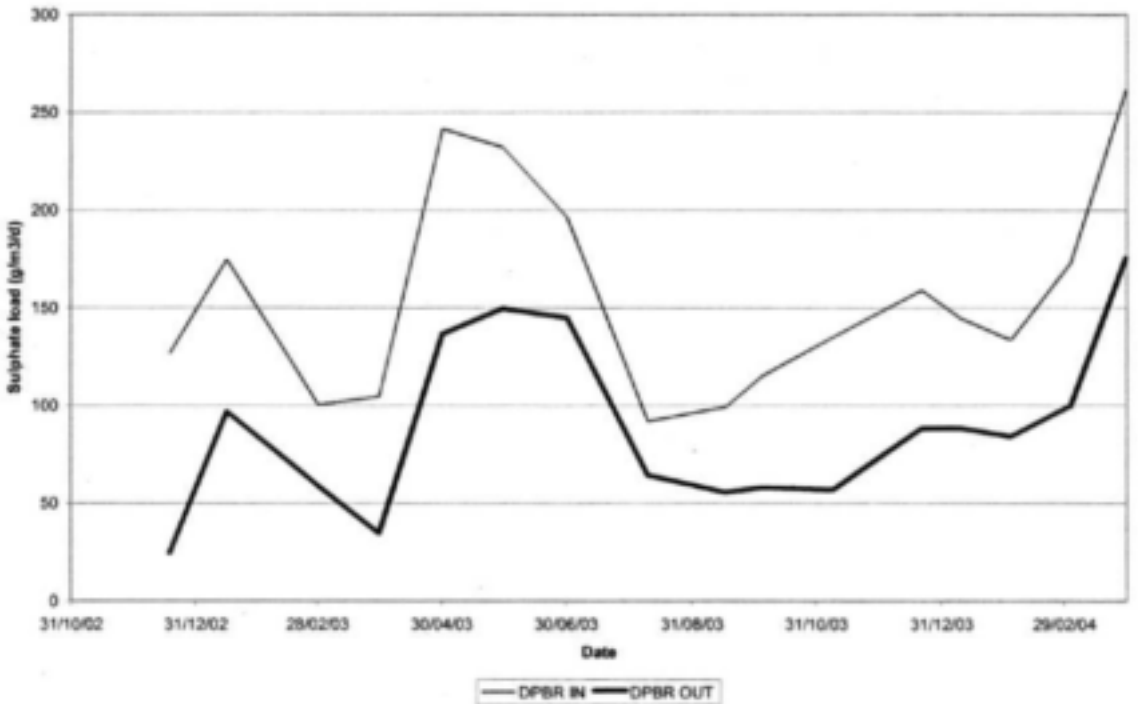

Figure 6.10 : Monthly inlet and outlet sulphate load for DPBR (October 2002 - March 2004)

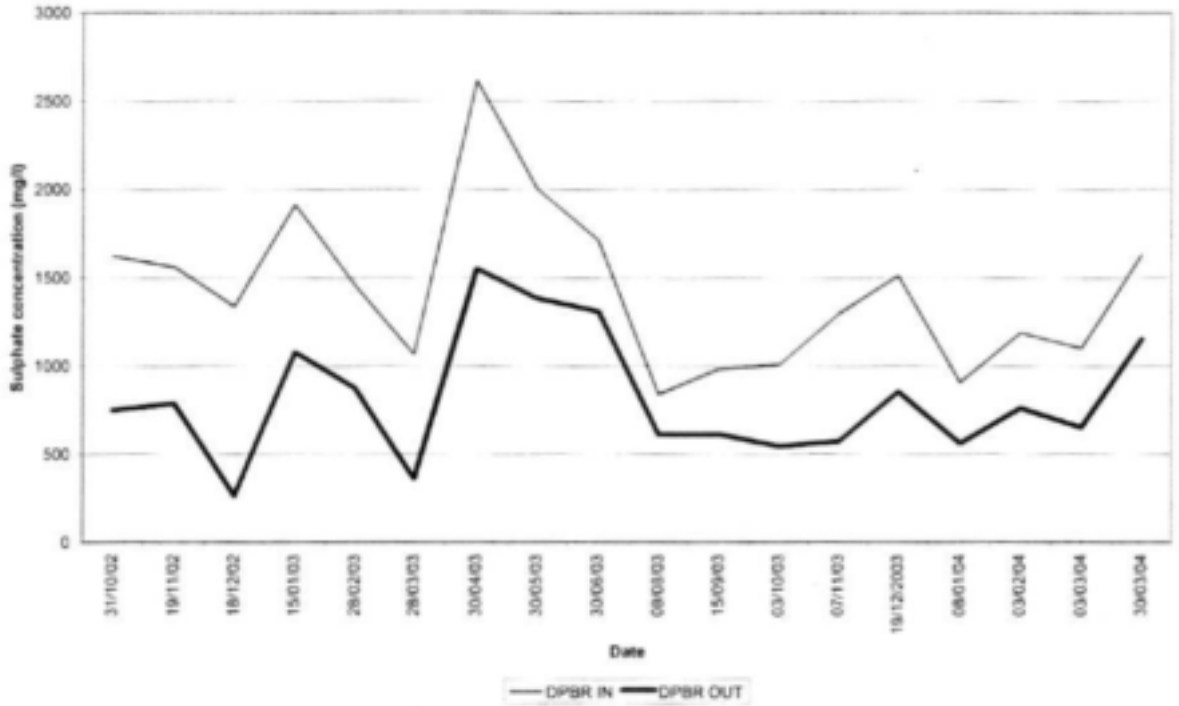

Figure 6.11 : Monthly inlet and outlet sulphate concentration for DPBR (October 2002 - March 2004)

6.2.5 Performance with regard to Sulphide Production

Table 6.9 gives a statistical representation of the influent and effluent sulphide concentrations. The monthly sulphide data is depicted in Figure 6.12. The DPBR was characterized by high sulphate reduction (Table 6.8). This was substantiated by the high production of sulphide observed, averaging 111mg/ℓ when compared to the average influent value of 2.1 mg/ℓ (Table 6.9).

Table 6.9 : Statistics of the influent and effluent sulphide concentration of the DPBR (October 2002 to March 2004)

DPBR		
	Influent sulphide concentration (mg/ℓ)	Effluent sulphide concentration (mg/ℓ)
N	18	18
Average	2.01	111
Minimum	<0.05	54
Maximum	10.8	156
Standard deviation	2.98	33.3

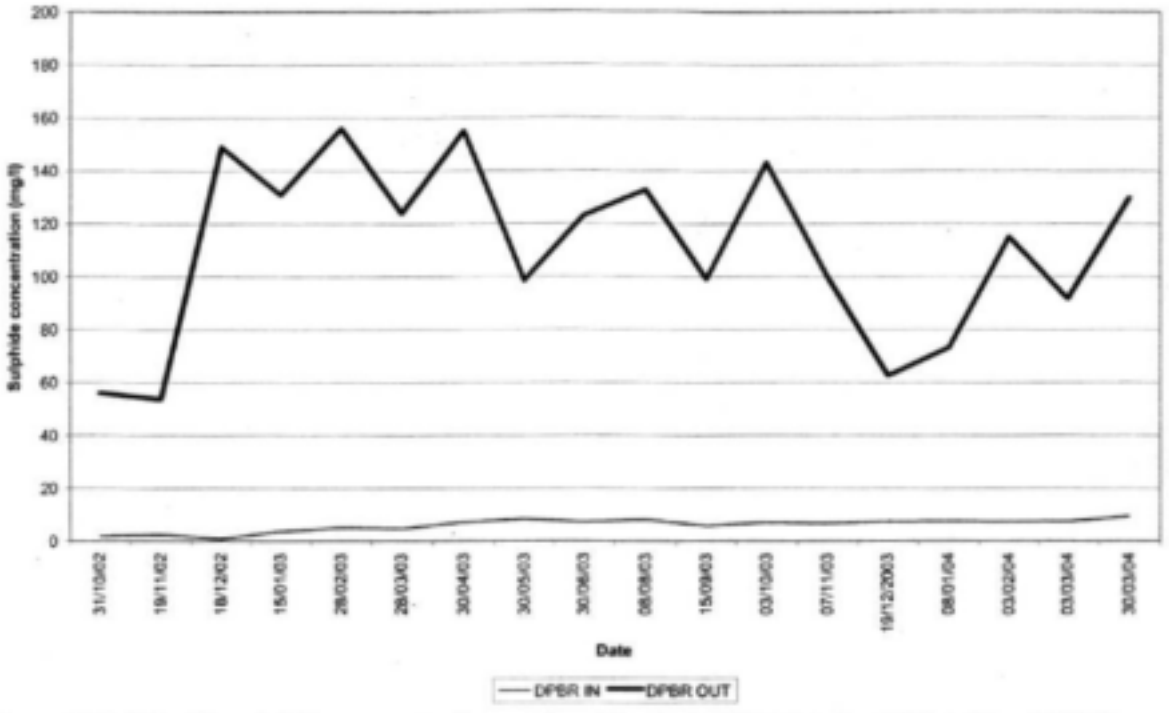

Figure 6.12 : Monthly sulphide concentration produced by the DPBR (October 2002 to March 2004)

6.3 CONCLUSIONS WITH REGARD TO PERFORMANCE OF DPBR

The following conclusions can be made with regard to the DPBR:

- The influent flow varied due to the effect of rainfall and blockages to the feed water lines.
- The DPBR was responsible for an increase in pH.
- The DPBR successfully removed iron and aluminium from the system.
- Although kinetic column studies were not performed and a site specific process designed, the DPBR exceeded the target sulphate load reduced of 60 g/m^3 carbon /d. Further monitoring of the DPBR is required in order to determine the long-term sustainability of sulphate reduction based on the DPBR principle.
- The DPBR is the first SRU in the multi-staged Integrated Managed Passive Treatment process and the effluent water will still be treated further in order to obtain acceptable discharge water quality standards.

CHAPTER 7

COMPARISON OF THE PERFORMANCE OF THE DEGRADING PACKED BED REACTOR (DPBR) WITH STANDARD REACTOR (SSRU 1)

In order to evaluate the validity of the Integrated Managed Passive Treatment (IMPI) system, the data obtained from the DPBR was compared to that of SSRU 1 for the first 17 months of operation. The DPBR has been in operation from October 2002 -March 2004 and this data is compared to that of SSRU 1 over the period November 1996 –April 1998. This data excludes the periods of glucose and acetic acid supplementation and no molasses supplementation occurred in SSRU 1. SSRU 1 was selected for comparison with the DPBR as it closely resembled the operation of the DPBR *e.g.* both have the same volume of carbon, no bulking agent and have received a direct mixture of West and South Discharge AMD since their commissioning.

The comparison of these reactors will focus on AMD reclamation including pH neutralisation, alkalinity production, sulphate load reduction, sulphate concentrations reduced, sulphide production and the removal of metals (manganese, aluminium and iron).

Chapter 6 and Appendix A give detailed descriptions of the performance of the DPBR and SSRU 1 respectively.

7.1 COMPARISON OF PERFORMANCE IN TERMS OF pH NEUTRALISATION

The DPBR received feed with an average influent pH of 4.72 while the influent pH to SSRU 1 was 3.86. Both reactors were able to increase the effluent pH averaging 5.72 for the DPBR and 6.70 for SSRU 1 (Table 7.1).

Table 7.1 : Statistics of the influent and effluent pH of DPBR and SSRU 1 (November 1996 - April 1998)

DPBR		
	Influent pH	**Effluent pH**
Average	4.72	5.72
Minimum	3.00	3.68
Maximum	7.91	7.84
Standard deviation	0.94	0.62
N	651	642
SSRU 1		
	Influent pH	**Effluent pH**
Average	3.86	6.70
Minimum	2.24	5.35
Maximum	7.51	7.96
Standard deviation	0.95	0.27
N	1055	1047

The graphs depicting daily influent and effluent pH for the DPBR and SSRU 1 are shown in Figures 7.1 and 7.2 respectively. It is clear that the influent pH values of SSRU 1 fluctuated remarkably when compared to the DPBR influent (Figures 7.1 and 7.2).

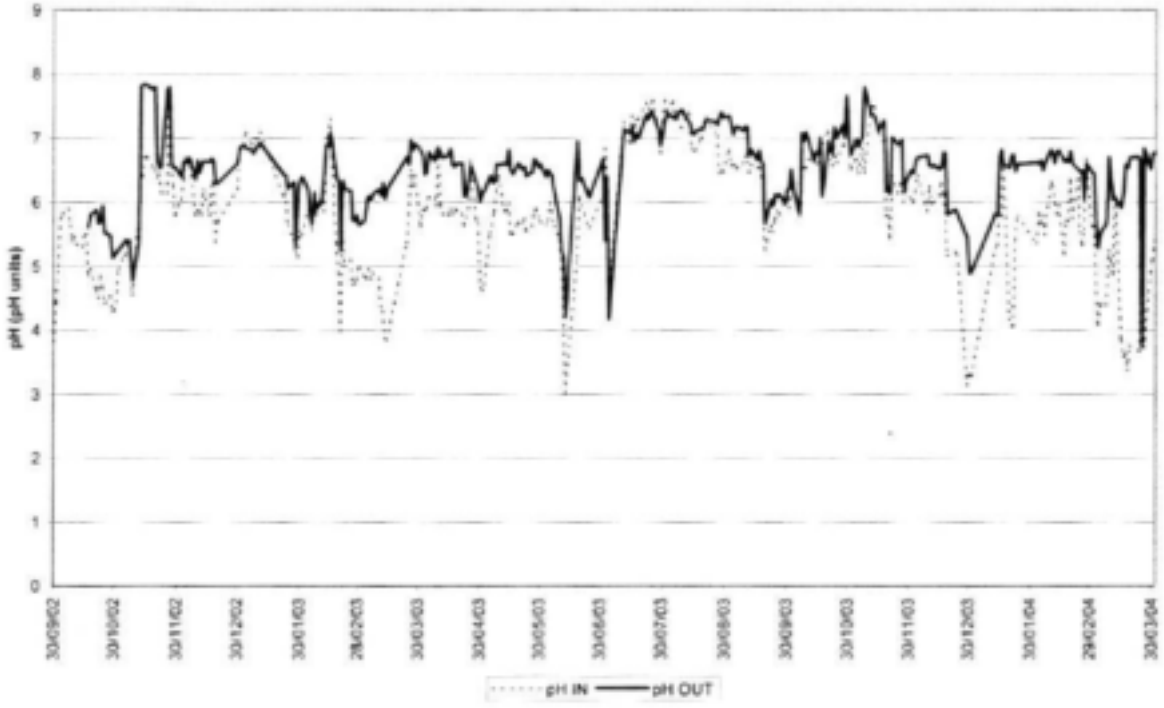

Figure 7.1 : Daily influent and effluent pH data of the DPBR for the period October 2002 –March 2004

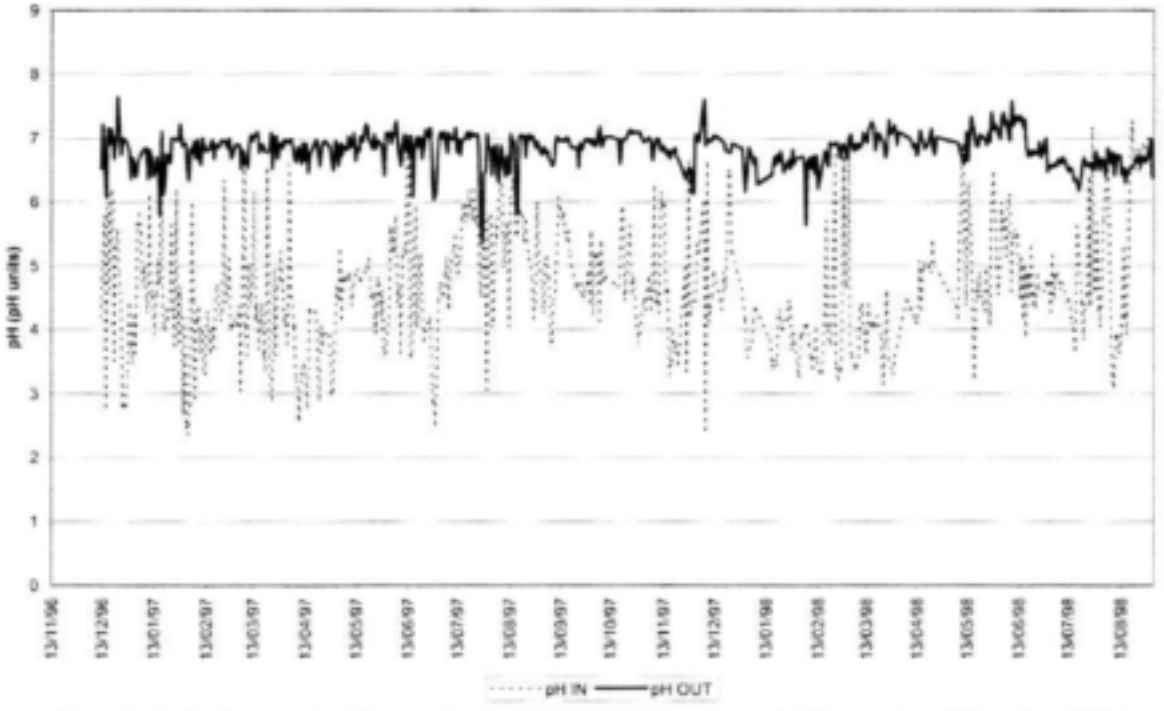

Figure 7.2 : Daily influent and effluent pH data of SSRU 1 for the period November 1996 –April 1998

7.2 COMPARISON IN TERMS OF ALKALINITY GENERATION

During the process of sulphate reduction, bicarbonate ions are produced subsequently increasing the pH. An average of 948 mg/ℓ of alkalinity was generated by the DPBR while 539 mg/ℓ was generated by SSRU 1 over the same evaluation period from commissioning (Table 7.2).

Table 7.2 : Statistics of the influent and effluent alkalinity of DPBR (October 2002 - March 2004) and SSRU 1 (November 1996 - April 1998)

DPBR		
	Influent alkalinity ($CaCO_3$)	**Effluent alkalinity ($CaCO_3$)**
Average	125	948
Minimum	0.25	461
Maximum	940	2242
Standard deviation	224	446
N	18	17
SSRU 1		
	Influent alkalinity ($CaCO_3$)	**Effluent alkalinity ($CaCO_3$)**
Average	41.1	539
Minimum	0.25	108
Maximum	240	2978
Standard deviation	74.9	513
N	36	36

When complex carbon such as lignocellulose is used to drive sulphate reduction, high sulphate reduction is observed during the first phases of operation when biodegradable carbon is available. As only the more recalcitrant carbon is left, sulphate reduction decreases. Alkalinity generation fluctuated over the experimental period of both units (Figure 7.3). However, the DPBR generated more alkalinity than SSRU 1 over the same period (Figure 7.3). These results coincide with sulphate reduction (Figure 7.5) and sulphide generation (Figure 7.6) over the same period.

The graph showing monthly alkalinity addition for the DPBR and SSRU 1 is depicted in Figure 7.3.

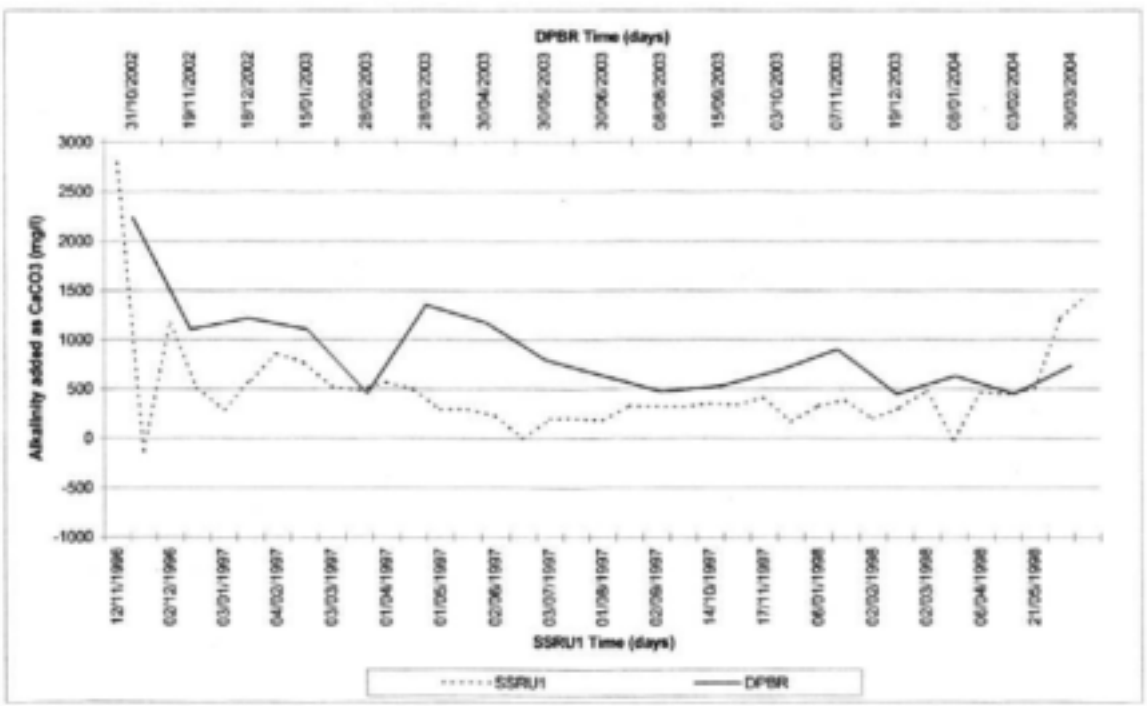

Figure 7.3 : Monthly alkalinity addition to the DPBR (October 2002 – March 2004) and SSRU 1 (November 1996 – April 1998)

7.3 COMPARISON OF PERFORMANCE IN TERMS OF SULPHATE REDUCTION AND SULPHIDE PRODUCTION

The statistical data for SSRU 1 and the DPBR showing sulphate reduction is presented in Tables 7.3 and 7.4. The DPBR has shown a higher average sulphate concentration and load reduced for the same period of operation than SSRU 1 (59.6 g/m^3 carbon/d versus 46g/m^3 carbon/d).

Table 7.3 : Statistics of the influent and effluent sulphate concentration of DPBR (October 2002 - March 2004) and SSRU 1 (November 1996 - April 1998)

DPBR		
	Influent sulphate concentration (mg/l)	**Effluent sulphate concentration (mg/l)**
Average	1431	816
Minimum	841	264
Maximum	2613	1551
Standard deviation	452	353
N	18	18
SSRU 1		
	Influent sulphate concentration (mg/l)	**Effluent sulphate concentration (mg/l)**
Average	1503	1073
Minimum	1300	298
Maximum	1886	1554
Standard deviation	150	227
N	36	36

Table 7.4 : Average sulphate reduced for the DPBR (October 2002 -March 2004) and SSRU 1 (November 1996 -April 1998)

Phase	**Sulphate concentration removed (mg/l)**	**Sulphate removed (%)**	**Sulphate load removed (g/m^3/d)**
DPBR	615	42.9	59.6
SSRU 1	430	28.6	46.2

The graphs depicting sulphate concentration and load removed are shown in Figures 7.4 and 7.5 respectively.

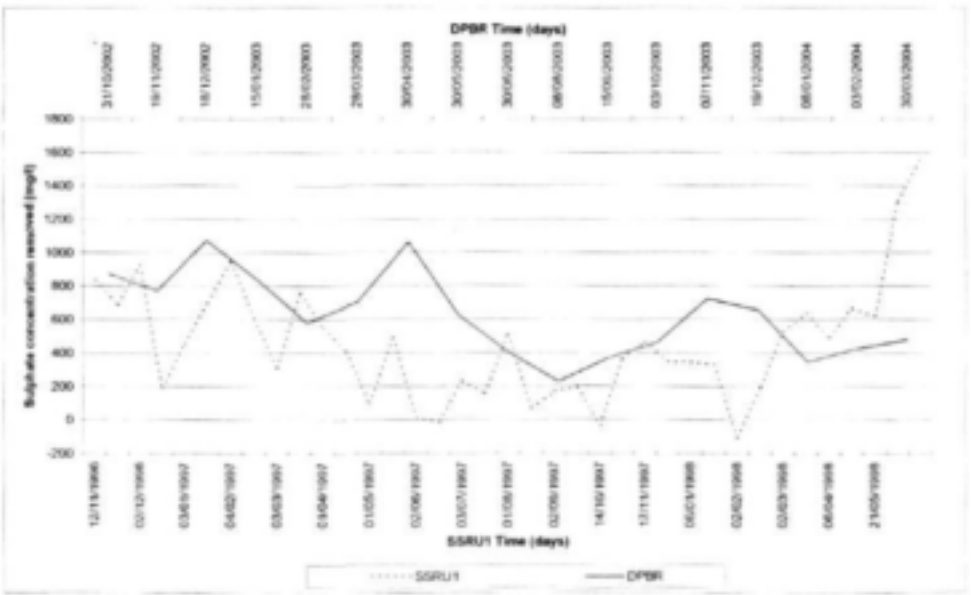

Figure 7.4 : Monthly sulphate concentration removed from the DPBR (October 2002 – March 2004) and SSRU 1 (November 1996 – April 1998)

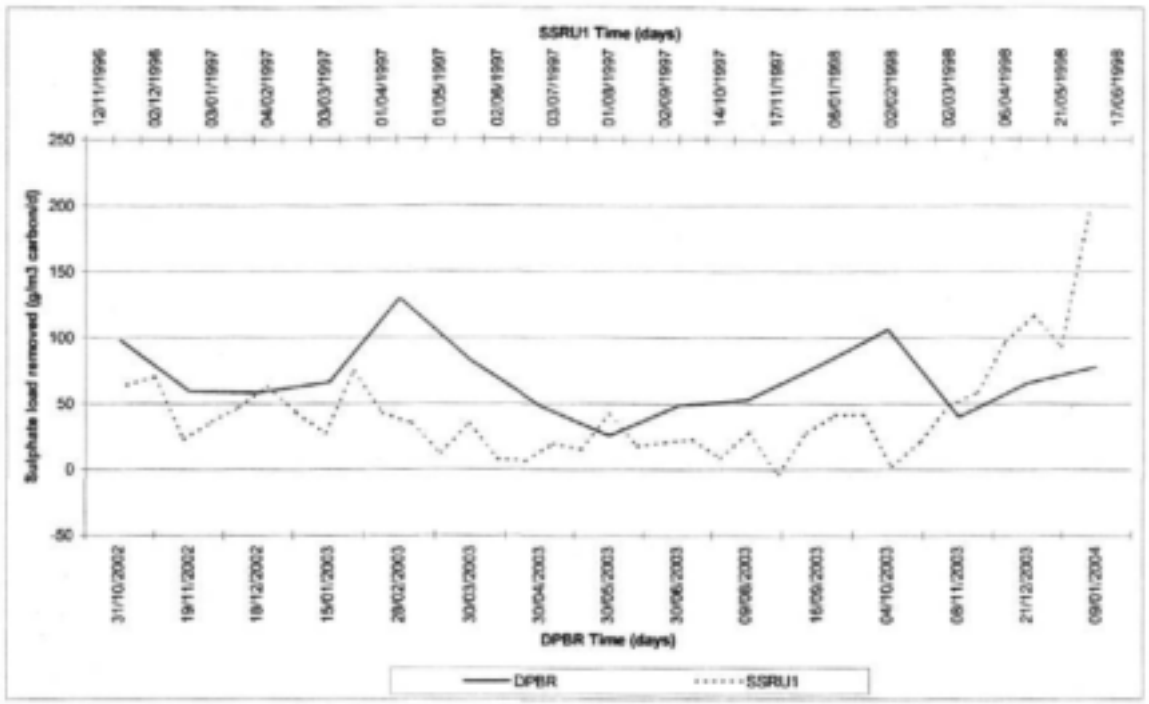

Figure 7.5 : Monthly sulphate load removed from the DPBR (October 2002 – March 2004) and SSRU 1 (November 1996 – April 1998)

DPBR produced higher concentrations of sulphide compared to SSRU 1 for the same period of operation (Figure 7.6). This coincided with the higher alkalinity generation, sulphate load and concentration reduced observed in the DPBR compared to SSRU 1.

The sulphide statistical data for the DPBR and SSRU 1 is shown in Table 7.5.

Table 7.5 : Statistics of the influent and effluent sulphide concentration of DPBR (October 2002 - March 2004) and SSRU 1 (November 1996 - April 1998)

DPBR		
	Influent sulphide concentration (mg/l)	**Effluent sulphide concentration (mg/l)**
Average	2.01	111
Minimum	<0.05	54
Maximum	10.8	156
Standard deviation	2.98	33.3
N	18	18
SSRU 1		
	Influent sulphide concentration (mg/l)	**Effluent sulphide concentration (mg/l)**
Average	5.38	67.2
Minimum	0.88	0.80
Maximum	12.0	245
Standard deviation	3.89	72.9
N	36	36

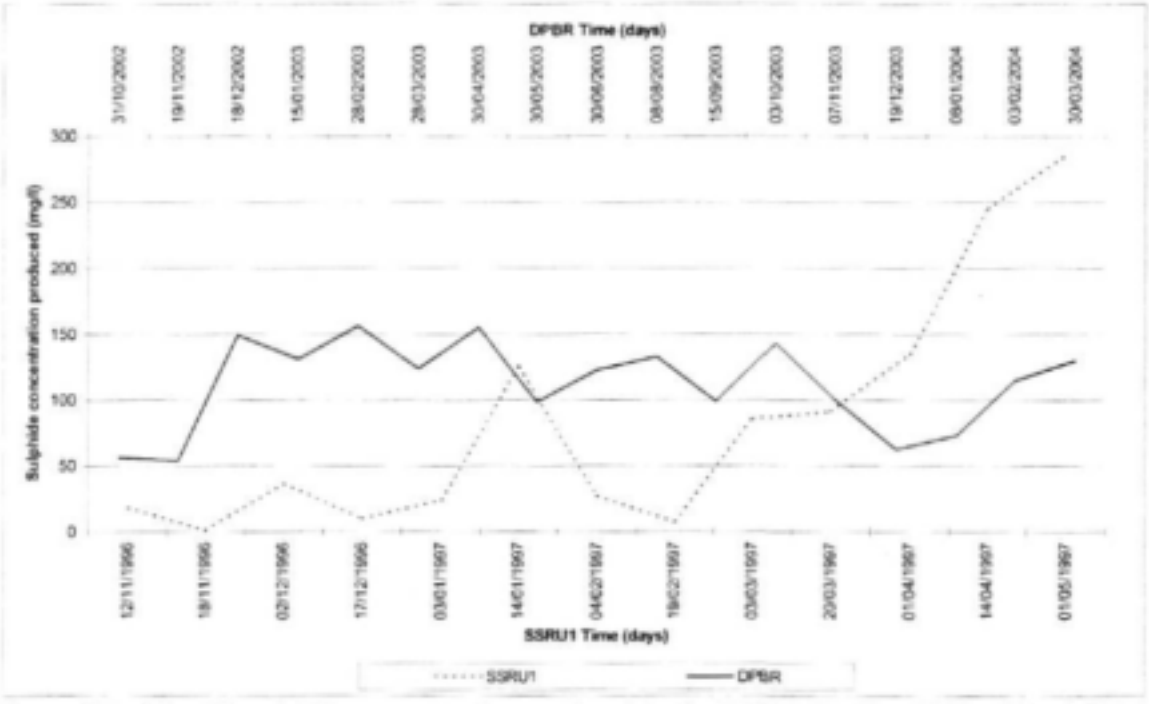

Figure 7.6 : Monthly sulphide concentration produced in the DPBR (October 2002 – March 2004) and SSRU 1 (November 1996 – April 1998)

7.4 COMPARISON IN TERMS OF METAL REMOVAL

The average percentage removal of metals in the DPBR and SSRU 1 is summarised in Table 7.6. Higher percentage removal for aluminium and manganese were found in SSRU 1 compared to the DPBR (Table 7.6). However, iron removal was higher in the DPBR compared to SSRU 1 (87 % versus 53 %) (Table 7.6).

Table 7.6 : Performance with regard to metal removal showing mean for DPBR (October 2002- March 2004) and SSRU 1 (November 1996 – April 1998)

	Iron			Aluminium			Manganese		
	Influent concentration (mg/l)	**Effluent concentration (mg/l)**	**Percentage removed (%)**	**Influent concentration (mg/l)**	**Effluent concentration (mg/l)**	**Percentage removed (%)**	**Influent concentration (mg/l)**	**Effluent concentration (mg/l)**	**Percentage removed (%)**
DPBR	2.69	0.34	**87.2**	5.17	0.92	**82.1**	9.10	7.33	**19.5**
SSRU 1	1.61	0.76	**52.8**	9.37	0.55	**94.1**	9.58	4.23	**55.8**

Average metal concentration removals are represented in Figures 7.7 to 7.9 for manganese, aluminium and iron.

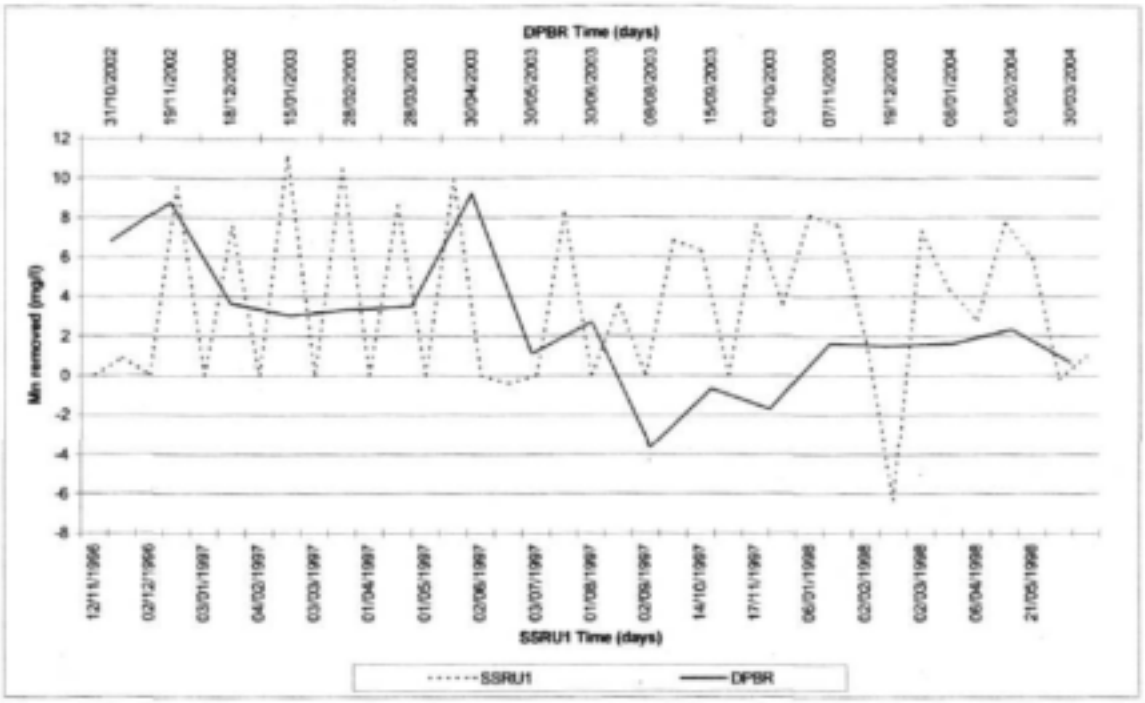

Figure 7.7 : Monthly concentration of manganese removed from the DPBR (October 2002- March 2004) and SSRU 1 (November 1996 – April 1998)

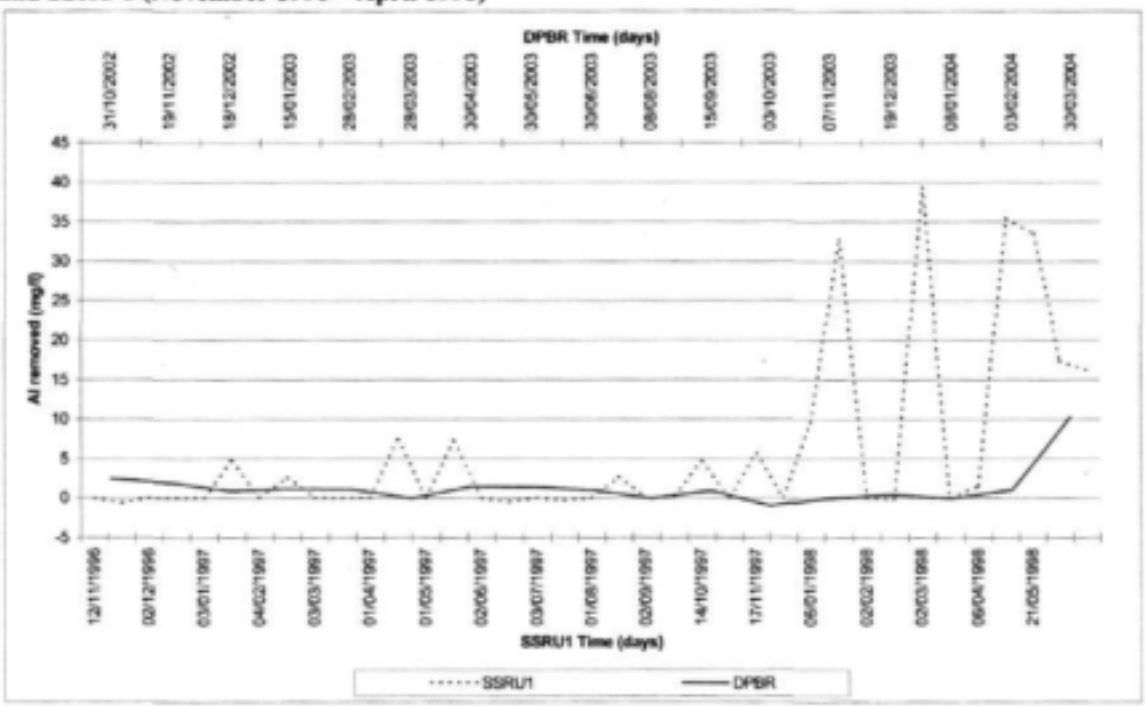

Figure 7.8 : Monthly concentration of aluminium removed from the DPBR (October 2002- March 2004) and SSRU 1 (November 1996 – April 1998)

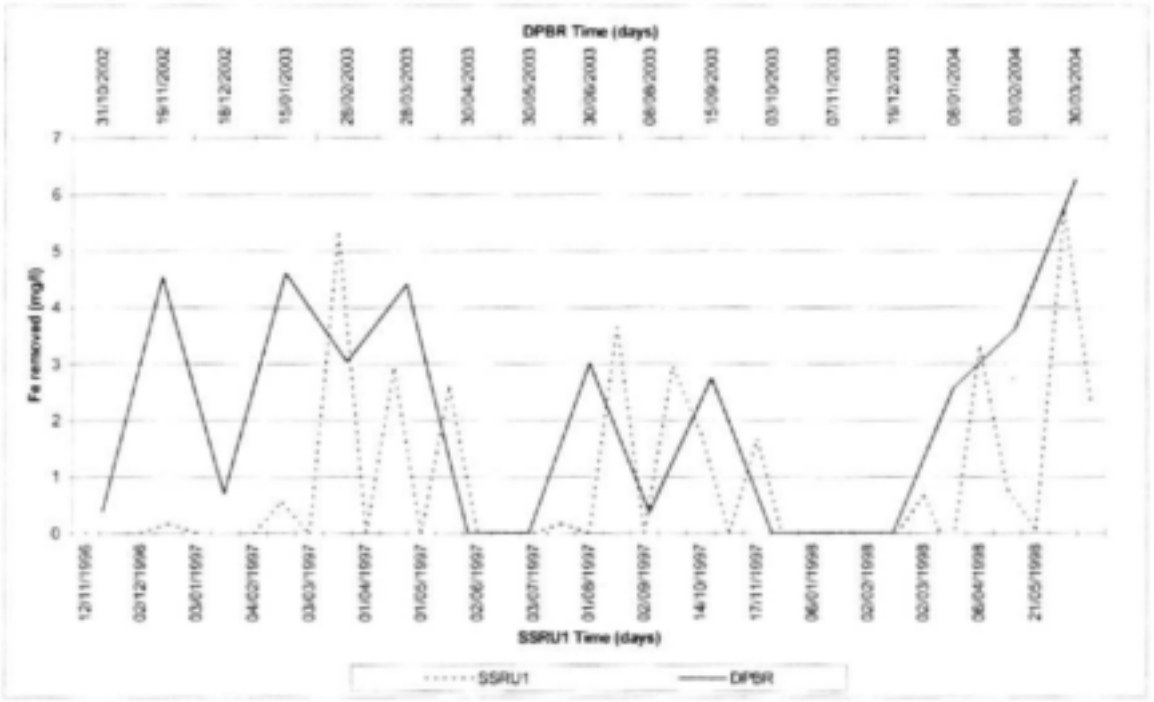

Figure 7.9 : Monthly concentration of iron removed from the DPBR (October 2002- March 2004) and SSRU 1 (November 1996 – April 1998)

7.5 CONCLUSIONS REACHED ON THE PERFORMANCE OF THE DPBR

The following conclusions can be made with regard to DPBR performance versus SSRU 1:

- Both DPBR and SSRU 1 increased the pH of the influent water over the same period of operation after being commissioned.
- The sulphate reduction activity of the DPBR was higher than that of SSRU 1 as reflected by a higher alkalinity generation, sulphate concentration, load removal and sulphide production.
- There was a higher efficiency of aluminium and manganese removal by SSRU 1 compared to the DPBR, while iron removal was higher in the DPBR than SSRU 1.
- The implementation of the IMPI process, as patented after the Innovation Fund project, resulted in the desired result of enhanced sulphate reduction at the VCC pilot plant.
- When comparing the older VCC sulphate reduction units with the DPBR results it is clear that the new DPBR technology has moved the sulphate reduction process to a higher level.
- To test the long-term performance of the DPBR, further assessment (~7 years) is needed.

7.6 RECOMMENDATIONS

It is recommended that the long-term performance of the DPBR is monitored further.

CHAPTER 8

PREVENTATIVE MAINTENANCE OF THE VCC PILOT PLANT AND GUIDELINES FOR DESIGN PARAMETERS

It is our belief that one of the primary reasons why passive treatment technology has previously so often failed to perform over the long-term is the lack of a maintenance programme. Therefore passive treatment is defined as a water treatment system that utilises naturally occurring energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and ***requires regular but infrequent maintenance to operate successfully over its design life***. The knowledge obtained from operating a pilot passive treatment plant at VCC for 8 years and the problems experienced forms a good basis for the development of a maintenance program.

8.1 access available maintenance history of the VCC pilot plant

After accessing the maintenance history available at the VCC pilot plant (November 2001 to March 2004), the information was summarised according to areas where maintenance was required, the problems experienced and the frequency of these at which these problems (Table 8.1).

Table 8.1 : A historical summary of maintenance areas, problems experienced and frequency at which problems were experienced (November 1996 to March 2004)

Area	Problem	Frequency
Splitter boxes	South Discharge sludge accumulation leads to flow rate change	5 – 7 days
	Leaves and sand	After heavy rains
	Corrosion	3 months
West Discharge pipe	Air locks	10 –14 days
	Blockage by leaves and debris	After heavy rains
South Discharge pipe	No water supply	When there is no electricity (Infrequent)
South and West Discharge weirs	Clogged by sand and debris	After heavy rains
Pump	Reset	After power failure (Infrequent)
Inlet and outlet pipes	Airlocks	14 – 20 days
Grass and Weed	Overgrown	4 – 6 weekly
Reeds	Overgrown	Seasonal
Animals	Trespass and feed from the reactors	Regular
Molasses tanks	Air locks	After filling up

8.1.1 Splitter boxes

The operator on site is responsible for the cleaning of the small splitter boxes on a weekly basis. Heavy rains introduce leaves and sediment into the splitter boxes resulting in cleaning performed randomly as required. The large splitter box situated at the pump house requires more frequent maintenance as it is located close to a flowing stream and therefore more susceptible to clogging by debris (3 - 4 days). The iron hydroxide present in the South Discharge AMD forms a red sludge responsible for the clogging of the flow regulating v-notches on the splitter boxes. This is cleaned on a weekly basis. The adjustable metal plates at the back of the splitter boxes have been treated with bitumen in an attempt to prevent corrosion. However, the first signs of corrosion were observed only two months after operation commenced (January 2002).

8.1.2 South Discharge pipeline

As the South Discharge is situated below the pilot plant, an electrical pump is used to pump South Discharge AMD to the storage tank. Problems are seldom experienced and the main cause occurs after power failures when airlocks are introduced into the pipeline. The airlocks then need to be manually flushed from the system. The definition of passive treatment does not allow for the usage of pumps to supply AMD to the plant. One of the criteria of operating a passive treatment plant is that there must be topographical gradient to maintain the gradient fed of AMD to the plant and hence in future designs no electricity will be used.

8.1.3 West Discharge pipeline

The length (~ 1 km) of the West Discharge pipeline contributes to more blockages than experienced at the South Discharge pipeline. Blockage is usually caused by the formation of air locks as well as by sand and leaves introduced into the pipe after heavy rains. If an airlock exists, the operator disconnects the pipeline and lets the water run freely. When the pipeline is blocked by debris, it is flushed clean using a diesel pump brought to the site. The West Discharge pipeline has been vandalised on a number of occasions and pieces of it stolen. It was therefore decided to cover the West Discharge pipeline with a layer of bricks and cement where it was exposed at the West Discharge weir. The rest of the pipeline is buried underground and less problems are experienced with this section of the pipeline.

8.1.4 South and West Discharge Weirs

Generally, the South Discharge weir runs smoothly. The West Discharge weir on the other hand, is clogged frequently with sand, especially after heavy rains. The operator checks the West Discharge weir after flow problems or rain events are experienced.

8.1.5 Pump

Overall, no problems are experienced with the pump itself except that it has to be reset after power failures and was stolen once. The fact that the electrical cables have been stolen 3 times during the last 14 months resulting in a shortage of South Discharge AMD to operate the pilot plant. If this occurs, the pilot plant is operated on West Discharge AMD alone and this water is the more acidic AMD. This emphasises the importance of a passive treatment plant operating without electricity.

8.1.6 Inlet and Outlet pipes

Except for SSRU 3 and LSRU 2, few blockages are experienced with the inlets to the SRUs. The fact that SSRU 3 operated in series with SSRU 2 until August 2002 could have contributed to the blockages experienced.

It seems as if more problems are experienced with the outlet pipes of the units, which often blocked due to airlocks. In order to obtain flow again, the operator orally blows air into the pipes and let the water run for a few minutes before reconnecting. Heavy rains lead to increased flow rates into the units and the outlet pipes cannot handle the increased volumes of water. This leads to units overflowing. As the wetland receives water from all upstream units, it also tends to overflow after heavy rains.

8.1.7 Grass and Weeds

Grass and weeds are cut at least once a month when the pathways are overgrown at the plant. The weeds tend to grow back quite fast. The situation improved after spraying the pathways with weed killer.

8.1.8 Reeds

Reeds only grow in the SRUs operating in down-flow configurations as the sulphide produced in up-flow SRUs hampers the growth of reeds. The operator removes reeds within reach but the reeds soon grow back.

8.1.9 Animals

Problems experienced with cattle roaming around the pilot plant and drinking water from the SRUs and evaporation pans ceased after installation of an electrical fence.

8.1.10 Molasses dosing tanks

After re-filling of the molasses dosing tanks, air locks in the breather pipe and debris blocking the outlet pipe prevented supplementation. The operator blows into the breather pipe of the molasses-dosing tank to remove air locks and uses a cloth to filter out any debris in the AMD.

8.1.11 Wetland

The wetland clogged resulting in overflow and not all of the water being treated in the oxidation cascade. Hydraulically, this expected compaction would reduce the efficiency of metal and COD removal in the wetland.

8.2 Developing and evaluating a preliminary maintenance schedule

Based on the historical maintenance data at the pilot plant a fortnightly maintenance schedule was developed in an attempt to develop maintenance programmes for future full-scale passive treatment systems. The preliminary maintenance schedule is summarised in Table 8.2.

Although there were some exceptions, *e.g.* after heavy rains and vandalism, the pilot plant operator only performed maintenance on a two-weekly basis over a year. This maintenance schedule was tested for a year at VCC.

Table 8.2 : The maintenance schedule for VCC pilot plant

	Task	Frequency
Splitter boxes	Cleaning and setting of flow rates (if required)	14 days or after heavy rains
South and West Discharge pipelines	Check for any blockages or vandalism	14 days or no water flow
South and West Discharge weir	Clean out sand and debris	14 days or after heavy rains
Pump	Check flow rate settings	14 days
Inlet and outlet pipes	Check for any blockages	When there is no flow
Molasses tanks*	Blow into breather pipe Filter debris in the AMD	When filling up ~ 4 to 5 days

8.3 COMPILING AN ACTIVITY LIST FOR MAINTENANCE

An operator will be performing maintenance on a fortnightly basis or after heavy rains are experienced in the area. The operator will need a bakkie and a diesel pump.

The following activities need to be incorporated into the maintenance programme that will be in use for at least two weeks for a full-scale passive treatment plant consisting of SRUs, sulphide oxidation bioreactors, a post-treatment facility and a pre-treatment facility:

8.3.1 AMD feed lines

The following maintenance needs to be performed on the AMD feed lines:

- Back-flushing of AMD feed lines
- Cleaning of weirs to remove sand and debris

8.3.2 Splitter boxes

The following maintenance needs to be performed on the splitter boxes:

- Cleaning of splitter boxes
- Checking of flow rates
- Setting of flow rates if the flow rates are not within 10 % of required flow.

8.3.3 Molasses dosing tank

The following maintenance needs to be performed on the molasses tanks:

- Replenishment of the molasses dosing tanks with required concentration of a thoroughly mixed molasses solution
- Setting flow rate of molasses dosing

8.3.4 Sulphate removal units

The following maintenance needs to be performed on the sulphate removal units:

- Flushing of influent distribution units using a diesel pump
- Checking for any blockages in the influent or effluent pipelines to the units and removing blockages through flushing the pipelines using a diesel pump.
- Checking that no water is overflowing at the sides of the units and if so, change the hydraulic head accordingly
- Replacement of carbon as the carbon bed is degraded with fresh carbon
- Removal of reeds from the sulphate removal units

8.3.5 Sulphide oxidation bioreactor

During the process of sulphate reduction, hydrogen sulphide is produced. To prevent the reoxidation of sulphide back to sulphate, sulphide is oxidized microbiologically to elemental sulphur. The produced sulphur needs however to be removed. The exact method of sulphur harvesting would be finalised when the most feasible sulphide oxidation bioreactor is finalised (still under R&D by Rhodes University and being funded by the WRC).

The following maintenance needs to be performed on the sulphide oxidation bioreactor:

- Harvesting of sulphur or pumping of sulphur into storage dams
- Cover the harvested sulphur to prevent debris from entering the dams.
- Drain out the water from the sulphur
- Drying of the sulphur

8.3.6 Wetland

The following maintenance needs to be performed on the wetland:

- Removal of excess reeds from the wetland
- Cleaning of wetland after a period of approximately 5 years. This will entail the removal of sludges from the wetland as well as removing excess reeds
- Check the inflow and outflow ports
- Maintain maximum flow path

8.3.7 Oxidation cascade

The following maintenance needs to be performed on the oxidation cascade:

- Ensuring that the torturous pathway in the oxidation cascade is effectively distributing the water and that the water is not short-circuiting
- Check inflow and outflow weir for clogging

8.3.8 Pre-treatment or anoxic limestone drains (ALDs)

Although the VCC Pilot Plant did not have a pre-treatment process for increasing the influent pH to the systems, pre-treatment may be required at other sites. Pre-treatment may be performed using an anoxic limestone drain (ALD). The following maintenance needs to be performed on the pre-treatment facility:

- Back-flushing of ALDs every two to four months
- Replacing of limestone when required
- Check if the pH meets the target required of the DPBR

8.3.9 Sampling and analysis

Sampling needs to be performed by the operator on a monthly basis and samples send to an accredited laboratory to evaluate the performance of the passive treatment system. The variables for which the samples need to be analysed include pH, electrical conductivity, sulphate concentration, sulphide concentration, COD concentrations, manganese, iron and aluminium concentrations. The pH and flow rate of the influent and effluent water at different stages of the process should also be checked on-site and reported.

Standard methods should be used for sampling, especially when taking anaerobic samples for sulphide determinations.

8.3.10 General

General maintenance will include the following:

- Checking for vandalism
- Keeping the site neat (*e.g.* removing reeds from the SRUs, cutting grass, spraying weed with weed killer).

8.4 GUIDELINES FOR DESIGN PARAMETERS

From the vast hands-on experience obtained with passive treatment plants over the last 8 years of operation at VCC and laboratory scale studies, various factors have been identified as critical in the process and need to be taken into consideration when designing a full-scale plant.

8.4.1 Implementation procedure for IMPI Technology

Pulles Howard & de Lange Incorporated (PHD) have developed a suite of novel integrated passive mine water treatment technologies referred to as:

IMPISURE:	Removal of sulphates, metals and acidity
IMPIMATE:	Removal of metals and acidity
IMPIPLUME:	Removal of sulphates, metals and acidity in groundwater plumes

While the nine-year research programme, including the 8 years at VCC has resulted in the development of a detailed descriptive process model that serves as the basis for plant and process design, the implementation of the technology needs to take account of various site-specific factors. The treatment process is a biological one and therefore needs to be customized to take account of unique site conditions, specifically the following:

1. Each mine water has a unique chemistry that affects the biological process design and the commissioning and operating procedures.
2. The technology requires a large inventory of carbon substrate on initial construction and each site will have a unique blend of carbon substrate that is sourced as close as possible to the plant.
3. Each site has unique physical features that affect the civil construction and the available hydraulic driving head.

In order to address these uncertainties as clearly indicated by the VCC study, PHD have developed a standardized 4-phase implementation procedure that ensures that the above factors are fully defined and incorporated into the existing descriptive process model in order to produce an optimized site-specific plant design. This procedure is shown schematically in Figure 8.1.

PHASE 1: DEVELOP SITE-SPECIFIC PROCESS DESIGN PARAMETERS

Step 1: Obtain all historical water quality records and any information that may exist on predicted future water qualities for the anticipated design life of the plant. Evaluate these data in order to obtain a current and possibly future characterisation of the water to be treated. Establish and confirm the desired treatment objectives, *i.e.* which contaminants need to be removed and to what levels? Define the design treatment duty of the passive treatment plant and establish whether the IMPISURE or IMPIMATE is required.

Step 2: Based on the existing descriptive process model, undertake a first-order conceptual process design in order to establish a first estimate of the volume of carbon required as an initial inventory. Undertake a survey to establish potential carbon sources within a 25km radius of the proposed plant location and obtain representative samples of this carbon material. Undertake batch anaerobic evaluations of the carbon samples and compare to PHD's carbon source performance database in order to obtain a ranking of carbon source suitability. Select a carbon mix or suite of mixes, to be utilized in the kinetic column studies as being representative of the desirable carbon mix for a full-scale passive treatment plant.

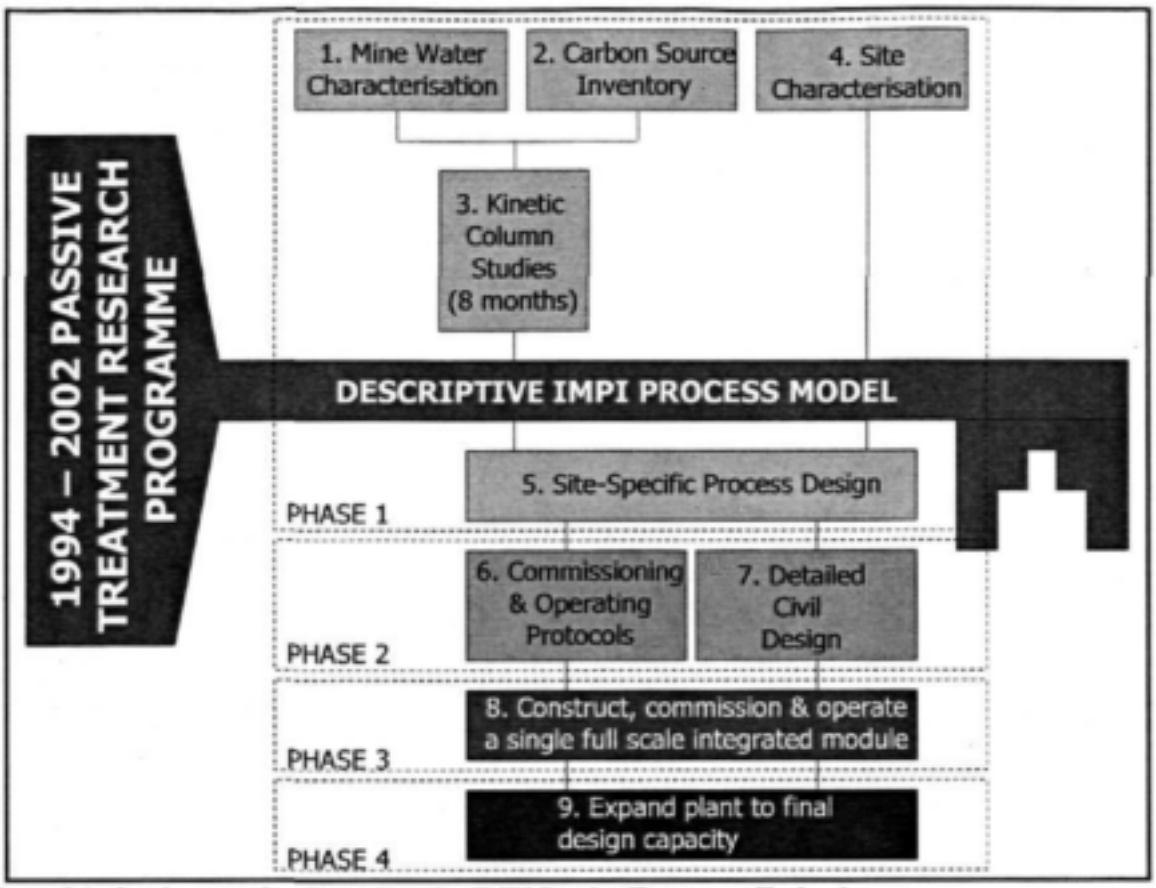

Figure 8.1 : Implementation Procedure for IMPI Passive Treatment Technology

Step 3: Undertake kinetic passive treatment column evaluations in PHD's passive treatment laboratory using the carbon mix selected in Step 2 and using the actual mine water to be treated. PHD have developed and constructed a mobile passive treatment laboratory facility that comprises 24 continuously fed passive treatment reactors and a dedicated analytical laboratory. Full-time technical staff are employed to operate these facilities.

In order to customize the descriptive IMPI process model to optimally treat the actual mine water under investigation, a set of 8 columns will be operated for a period of 36 weeks. The experimental programme that will be applied to these reactors is aimed at establishing performance criteria specific to the mine water and carbon mix at the site. It is not appropriate to undertake such experimental work on full-scale modules that each contains 1000 m^3 or more of carbon substrate and the column reactors are used for this purpose. A 36-week test period is required to overcome the initial 60-90 day commissioning period and to generate sufficient data to enable extrapolation over a 20-year design life. A typical data set for sulphate removed, alkalinity added and sulphide produced is shown in Figure 8.2.

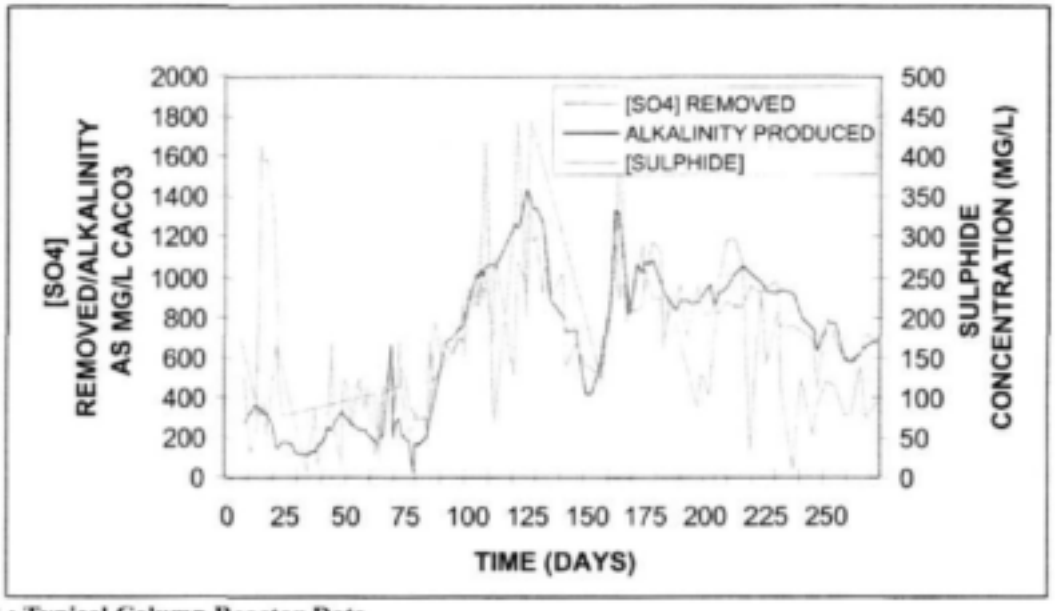

Figure 8.2 : Typical Column Reactor Data

The experimental programme will also develop the specific commissioning and operating procedures that may be required to ensure satisfactory treatment of difficult-to-treat mine waters. As part of the experimental programme, analyses of influent and effluent will be undertaken for sulphate, sulphide, COD, alkalinity, pH, redox potential, iron, aluminium and manganese.

Step 4: Undertake site evaluations in order to establish potential physical locations for the proposed passive treatment plant components. These site evaluations will include establishment of the following data:

- Obtain record of flow rates of water to be treated, including information on peak flow conditions.
- Establish available static hydraulic head on the water to be treated and establish practical limits to increasing this head.
- Obtain a site survey plan accurate to 0.5m contour levels for the selected potential site.
- Establish relevant floodlines and plot them onto the site survey plan.
- Excavate test pits down to 4-5m in order to establish ground conditions. Subject soil samples to suitable laboratory tests to determine structural and hydraulic properties.
- Prepare a scoping EIA report regarding the suitability of the proposed site for construction of a passive treatment plant.

Step 5: Utilise the data generated in Steps 1-4 in order to develop a site-specific process design that can be used as the basis for a detailed civil engineering design for the full-scale plant. This site-specific process design is fundamentally based on the descriptive IMPI process model that then incorporates inputs from Steps 1-4 described above to ensure that it is optimized in terms of the actual mine water to be treated and the actual carbon substrates to be used.

PHASE 2: DETAILED CIVIL DESIGN, COMMISSIONING & OPERATING PROTOCOLS

Step 6: Based on the column studies undertaken as part of Step 4, the site-specific commissioning and operating protocols will be defined and appropriate commissioning and operating manuals will be prepared. These protocols / manuals will also document the management, monitoring and auditing requirements for the particular plant.

Step 7: Based on the process design prepared in Step 5, and taking account of the developed commissioning and operating protocols, a detailed civil engineering design will be prepared. The design will be based on the construction of a single full-scale integrated module, although all water distribution and collection systems will be designed with the objective of future addition of modules (Phase 4) to handle the full flow of water to be treated. Drawings and tender enquiry documents will be developed to enable tenders to be sought for the actual plant construction and for subsequent plant commissioning and operation.

This step will also include the completion of a proper EIA with the necessary water use licences to enable the plant to be constructed and operated.

PHASE 3: CONSTRUCT SINGLE FULL-SCALE INTEGRATED MODULE

Step 8: Once the construction tender has been awarded, construction work will be undertaken to construct the plant in accordance with the civil design. Construction work will need to be closely supervised to ensure that work meets the specifications and that static commissioning objectives are met. Once construction has been completed, full wet commissioning will commence – this commissioning may take as long as 90 days. The commissioning phase will also be used to ensure that the operating contractor is fully trained to adequately operate the plant. Once the plant is deemed fully commissioned, it will revert to the standard operational sequence and the appointed operating contractor will assume his/her operational duties. It is envisaged that Phase 3 should have a duration of 12-18 months before moving to Phase 4.

PHASE 4: EXPAND PLANT TO FINAL DESIGN CAPACITY

Step 9: Once the operation of the single full-scale module has proceeded satisfactorily for a period of 12-18 months, a decision can be made to expand the plant (*i.e.* construct additional parallel full-scale modules) to treat the full mine water flow. The performance of the single operating full-scale module will be reviewed and, if necessary, the process design prepared in Step 5 will be reviewed and modified. Steps 6, 7 and 8 will then be redone for the additional full-scale modules.

8.4.2 Design criteria

Section 8.4.1 describes the implementation process of the IMPI Technology. From this it is clear that site-specific parameters such as water quality, topography of the site and the availability of carbon in the area play a major role in the development of site-specific design. The kinetic column studies are therefore essential as design criteria for the IMPI Technology.

8.4.2.1 Site characterisation

Site characterisation plays a major role in the implementation of the IMPI technology. If the site does not confer to the set requirements, passive water treatment of contaminated mine water will not be possible.

A site and layout for a passive treatment system should be selected on the basis of:

- Location with respect to mine workings and the specific location of current and future mine water decant and seepage points (PHD *et al.*, 2000).
- The availability of land, since substantial areas may be allocated for other land uses.
- A minimum area of 5 hectares are required to treat 1 Mℓ of acid mine drainage (AMD) per day.

- Buffer zone between the passive treatment system and the receiving water body is recommended to capture poor quality effluent and to protect the facility against flood damage (PHD *et al.*, 2000).
- Accessibility for future operations and maintenance (PHD *et al.*, 2000).
- Geotechnical constraints such as the presence of sensitive aquifers, availability of construction materials (PHD *et al.*, 2000).
- Favourable topographical gradient of at least 10 m to allow gravity flow through the passive treatment system (Figure 2).
- Stormwater management to allow the diversion of upslope runoff around the plant site (PHD *et al.*, 2000).

Figure 8.3 gives a schematic representation of the topographical gradient required for an IMPI system.

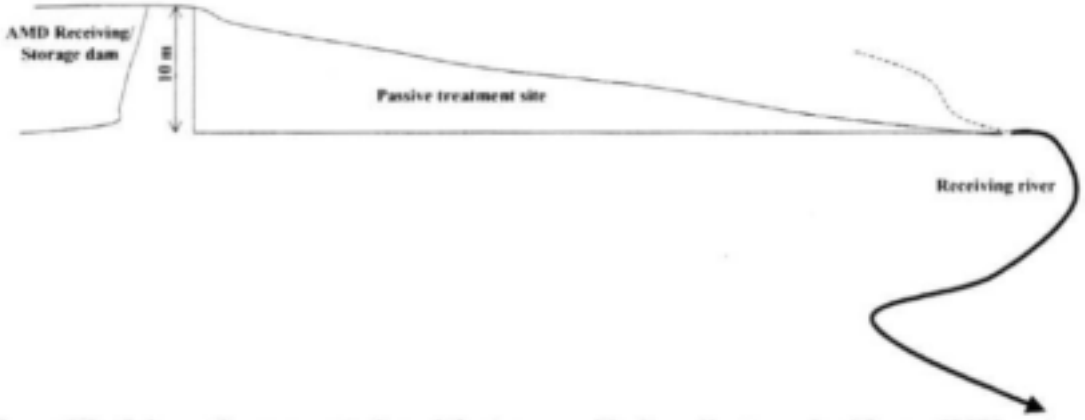

Figure 8.3 : Schematic representation of the topographical gradient required for an IMPI system

8.4.2.2 Modular design

The sulphate reducing passive treatment units have to be integrated with other unit treatment systems such as balancing, flow division, pre-neutralisation, polishing, recycling *etc*.

It is desirable to go for a modular design to allow for:
- Flexibility in terms of flow distribution
- Ability to take certain units out of commission for maintenance and retrofitting purposes.
- Some units in future have to be replenished with limestone or carbon substrate, etc. It is then essential to still achieve a reliable treatment while one of the modular units is decommissioned for such replenishment and replacement purposes (PHD *et al.*, 2000).

Figure 8.4 illustrates the modular design approached for the IMPI technology. A passive treatment plant responsible for the remediation of 1 Mℓ of contaminated AMD will consist of 5 modules. Each module will consist of a DPBR, PSOR, SSRR and SSOR (Figure 8.4).

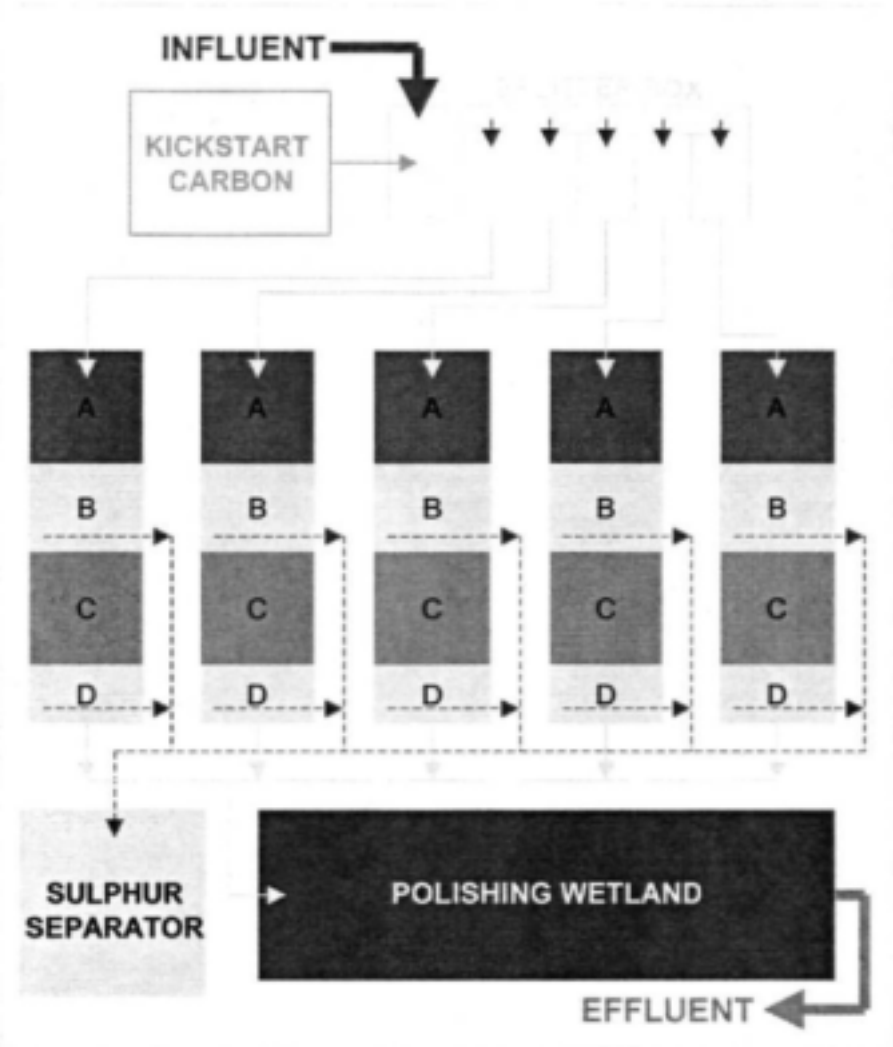

Figure 8.4 : Modular design of the IMPI Technology

8.4.2.3 Configuration of individual sulphate removal units

The configuration of individual sulphate removal units should be designed so as to:

- Allow distribution of the influent flow to come into contact with the entire body of carbon substrate.
- Allow and promote intimate contact between the flow and carbon substrate.
- Prevent and minimise short-circuiting of the flow, which will prevent effective utilisation of the available carbon source.
- Promote plug flow which is beneficial in terms of the process kinetics.
- Prevent build up of large head losses, which invariably lead to short-circuiting and/or reduction in the unit treatment capacity (PHD *et al.*, 2000).

8.4.2.4 Geometric configuration

A sulphate reducing unit having a rectangular shape was found to have the best hydraulic behaviour (Fourie, 2002). It has however the problem of requiring the construction of vertical sides. This either requires the installation of structural support such as concrete walls or the excavation of vertical soil faces, which must then be supported structurally (Fourie, 2002). According to Fourie (2002), the cost implications preclude the use of the use of this option. The best option which provided the best balance between optimum utilisation of the reactor volume and relative ease of construction was found to be a combination between a rectangular and truncated inverted triangle (Figure 8.5).

Figure 8.5 : Schematic representation of the best cost-saving full-scale reactor geometric design

Based on the fact that the rectangular shape reactor geometric design had the best hydraulic properties and hydraulic short-circuiting is a major problem with passive treatment systems, it was decided to opt for the rectangular geometric design over the design illustrated in Figure 8.5.

8.4.2.5 Construction materials

Due to the large size of passive treatment systems, it will require the preferential use of locally available construction materials to be affordable. Construction materials could include:

- Soil to construct embankments, pits, impoundments, *etc.*
- Crushed stone to construct open channel drains, wave attenuation, energy dissipaters, etc.
- Local vegetation may be established on some of the wetland systems (PHD *et al.*, 2000).

8.4.2.6 Selection of carbon sources

For every 1 Mℓ of AMD treated per day, 6000 m^3 carbon is required at start-up to fill the sulphate removal units. The selection of an appropriate blend of carbon source mixtures thereof will depend on:

- Local availability (preferably within a 25 km radius from the plant to limit transportation costs) and supply.
- Kinetic column studies.
- Cost.
- Biodegradable carbon release characteristics

Things to take into consideration when using wood as a carbon source:

- Conventional industrial woodchippers only process trees/logs with a maximum diameter of 300 mm. This restricts the trees used as carbon sources to those having a diameter smaller than 300 mm.
- Conventional industrial woodchippers only process trees/logs with a maximum length of 3 m. This implies that trees need to be cut in lengths of 3 m before chipping can commence.
- The processing time required to chip the wood will depend on the wood chipper available.
- Wood chip processing time required must be taken into account when constructing the passive treatment plant.
- The physical characteristics of the woodchips e.g. woodchip size will have an effect on the hydraulics of the system as well as on the available surface area for biodegradation. The smaller the woodchip size the more effective the biodegradation thereof will be.
- Younger trees are preferred over old trees.

Things to consider when using grass as a carbon source:

- Although the carbon characterisation studies (Coetser, 2003) did not show significant differences between the three types of grasses tested (Wild grass, Eragrostis grass and Blue Buffalo grass), the chemical composition and thus the nutritional values of different grass types varies and will have an influence on the kinetic performance of the system.
- Fresh grass would be the preferred option and bailing time needs to be planned as to have the shortest possible period between bailing and the actual packing of the units.

Things to take into account when using manure as a carbon source:

- Manure tends to form impermeable layers causing hydraulic short-circuiting and therefor the thickness of the manure layer should not be too thick.

Things to consider when using chicken litter as carbon source:

- Chicken litter tends to form impermeable layers causing hydraulic short-circuiting and therefor the thickness of the manure layer should not be too thick.

Inoculation of sulphate reducing unit:

- A mixture of anaerobic and anoxic digestor sludges is the preferred option.
- Inoculation of the system should be uniform.
- The sulphate reducing unit should be inoculated frequently though out the different layers of the unit.

8.4.2.7 Carbon substrate permeability

The hydraulic design of a passive treatment system is very sensitive to the permeability of the carbon substrate. Previous studies on passive treatment systems indicated that the characteristic permeability of a substrate could vary over a wide range due to the heterogeneous nature of most natural carbon sources. It was found that the measured permeability at different points in the SRU and at different times can vary by as much as an order of magnitude. Laboratory scale tests done on fresh substrate do not necessarily give a reliable indication of the permeability. As a practical measure, it is recommended to base the design on a substrate permeability that is one order of magnitude lower than the average laboratory measured permeability done on fresh carbon substrate. This constraint will preclude the construction of very deep sulphate removal systems with long flow paths, due to the associated high hydraulic head necessary to drive these systems (PHD *et al.*, 2000).

Fourie (2002) simulated three different substrate materials *i.e.* Eragrostis grass, bagasse and pine woodchips in a reactor containing layers of various substrates. The preferred sequence of these layers was bagasse closest to the inlet, followed by grass and then woodchips. It was noted that in order to achieve the possible hydraulic and treatment efficiencies in the full-scale reactors, the placing and compaction of the substrate needs to be undertaken carefully and requires some degree of quality control. If a layer of substrate were simple dumped in place, with no construction quality control, it is highly likely that preferential flowpaths would occur and the efficiency of the reactor would be compromised. On the other hand, if the substrate layers were over-compacted, the hydraulic conductivity of the material could decrease by at least one order of magnitude, severely affecting the reactor's residence time.

8.4.2.8 Flow

Proper flow control is important from the perspective of:

- Reliable conveyance systems with a minimum risk of clogging and backup.
- Flexibility in terms of flow distribution to different passive treatment units.
- Ability to monitor flow at different points in the plant (PHD *et al.*, 2000).

Mine waters have an inherent tendency towards corrosion, scale formation, precipitation and deposition of debris. It is generally found that closed, piped or conduit systems are prone to clogging with time and are maintenance intensive. It is therefore preferable to utilise open channel free flow systems that are not prone to clogging and are easily accessible to remove any debris and dirt. This will however only be possible where anaerobic conditions are required to prevent the reoxidation of sulphide back to sulphate.

Certain parts of the flow distribution system may have to be under pressure due to the pressure requirements to pass flow through some treatment units. This will then require a certain minimum amount of pipework to be installed. Any pipework should be designed to allow:

- Access for cleaning systems. Access points to closed pipework should not be more than 50 m apart.
- Points at which the precipitates and dirt dislodged from the pipes during cleaning operation can be collected and removed from the pipework. This material should never be allowed to enter any of the treatment units due to the negative impact on the flow distribution system caused by clogging (PHD *et al.*, 2000).

Flow distribution between different passive treatment units is essential. Allowance must always be made to enable flexible flow distribution since individual units may change over time (PHD *et al.*, 2000). Simple systems such as splitter boxes with v-notches should be used.

Flow monitoring is also essential for the following reasons:

- Evaluation of the flow and pollution load distribution between individual treatment units.
- Assessment of any flow losses by evaporation/seepage from individual units (PHD *et al.*, 2000).

It is recommended to install flow control and flow distribution boxes and these structures can be easily fitted to accommodate some form of flow measurement (PHD *et al.*, 2000).

Splitter boxes operated at the Vryheid Coronation Colliery (VCC) passive treatment plant corroded within months of installation even when using galvanised steel covered with bitumen.

8.4.2.9 Raw mine water quality

The raw mine water quality will depend on the mining operations of the mine and rainfall/evaporation. The raw mine water quality will improve during the wet seasons and deteriorate with increased mining operations. The passive treatment plant needs to be designed to treat contaminated water with the poorest water quality predicted for the mine.

The "ideal" raw mine water quality should have:

- a pH > 4.5 (No pre-treatment required)
- Sulphate concentrations < 5000 mg/ℓ

8.4.2.10 Temperature

Although the DPBRs have an insulating effect, the performance of the passive treatment plant is seasonal. The passive treatment plant needs to be designed taking the lowest sulphate loads removed during winter conditions into account.

8.4.2.11 Inhibitory compounds

The mechanism of inhibition is not fully understood or agreed upon, nor are the toxic levels. Many compounds which are essential in small amounts become toxic at higher concentrations. Threshold toxicity level is influenced by antagonism, synergism and acclimation. For example, heavy metals and sulphides can be individually toxic, but combined, insoluble metal sulphides are precipitated and the toxicity is removed.

Reported toxic levels of compounds differ widely and are dependant on the chemical form. The following ranges are generalised but may be used as a rough guide:

- sulphides 100 - 200 mg/ℓ
- soluble heavy metals 1 mg/ℓ
- sodium 2300 – 8000 mg/ℓ
- potassium 500 – 10 000 mg/ℓ
- calcium 2000 – 6000 mg/ℓ
- magnesium 1200 – 3500 mg/ℓ
- ammonium 1700 – 4000 mg/ℓ
- chloride 5000 mg/ℓ
- free ammonia 170 mg/ℓ (PHD, 1998)

Studies performed by PHD indicated that the threshold value for sulphide inhibition is around 300 mg/ℓ.

Sulphate reducing bacteria is strict anaerobes and contamination with oxygen in the DPBR should be avoided at all times.

8.4.2.12 Pre-treatment

If the pH of the acid mine drainage is lower than pH of 4.5 a pre-treatment step needs to be incorporated into the passive treatment system. It would be wise to leave adequate land space for the incorporation of a pre-treatment step even if the water does not have an acidic pH presently. This will enable the incorporation of a pre-treatment process if the water chemistry changes over the long term and requires pre-treatment.

8.4.2.13 Molasses supplementation

Molasses supplementation will be performed at a percentage of 0.05 % (0.05 g in 100 ml).

8.4.2.14 Maintenance

Maintenance needs to be incorporated into the design criteria on a 2 weekly basis of passive treatment plants (Chapter 8).

8.5 CONCLUSION

The knowledge obtained from operating a passive treatment pilot plant at VCC, allowed for the identification of problem areas with operating such a system and the development of a maintenance programme. The maintenance schedule has been implemented for a period of 1 year, adjusted and refined.

Although a full-scale IMPI system has not been build and operated to date, the experience obtained from laboratory-scale and pilot plant studies has enabled us to identify various factors which need to be incorporated into the design of full-scale passive treatment plants.

CHAPTER 9

DISCUSSION

Although sulphate-enriched wastewaters are generated in a number of industrial processes, including tanning, paper manufacture and metals processing, the main contributors to large-scale pollution from this source in South Africa are the gold and coal mining industries (Rose, 2002). Mining operations, give rise to the oxidation of sulphur species through both biological and physico-chemical processes, leading to the generation of acid mine drainage (AMD). While the time-scale over which care and treatment will be required is uncertain, best estimates indicate an ongoing commitment lasting from many decades to several centuries (Rose, 2002). The long-term burden of this problem, and sustaining ongoing treatment over the time-frames involved, will almost certainly fall on the community, despite progressive mine closure legislation and comprehensive regulation governing the polluter-pays principle.

The need for a long-term and sustainable response to address AMD pollution has focussed interest in biological treatment approaches. These have concentrated on active and passive treatment systems, both of which rely on microbial activity related to the biological sulphur cycle, including bacterial sulphate reduction and the associated precipitation of metals as sulphide salts (Rose, 2002). Various sulphate removal technologies are available including trench reactors; anaerobic filters; mixed, anaerobic packed bed; fluidised bed; gas-lift; sequencing batch and baffled reactors (Hulshoff Pol *et al.*, 2001). Notwithstanding the reactor type and the particular treatment approached used, widespread application of active biological AMD treatment has not yet been seen on any large scale. This could be attributed to the high costs involved with bioreactor construction, the cost of carbon and electron donor sources for biological sulphate reduction as well as the degree of maintenance and supervision required.

While the active treatment of mine dewatering wastewaters is practised in most operating mines, the need to demonstrate long-term sustainable treatment following the termination of these operations, has become a prime requirement for achieving formal mine closure certification (Rose, 2002). This has placed increasing focus on the use of passive treatment systems. Passive treatment refers to a water treatment system utilising naturally available energy sources such as microbial metabolic energy, photosynthesis, chemical energy, the use of natural topographical gradients to regulate flow and requires regular but infrequent maintenance. This definition implicates that a passive treatment system may be constructed where no electricity is available. No security risks are involved as:

- flow is regulated using passive treatment methods *e.g.* splitter boxes and not through electrical pumps
- no copper valves and fittings are used
- pipelines using unplastised poly vinylidine chloride (uPVC) pipes are buried underground
- sulphate reducing bioreactors are buried underground.

A pilot passive treatment plant was constructed, operated and monitored at Vryheid Coronation Colliery (VCC) since 1996. Performance of the pilot plant was measured against a target sulphate removal rate of 60 g sulphate/m^3 of carbon/day required to render the process economically viable (PHD Internal Report, 1999). To our knowledge, this passive treatment pilot plant is the longest operated and monitored passive treatment plant in existence. The performance of the different sulphate reducing units (SRUs) varied over time and in the long-term none of the SRUs achieved the target sulphate load removed. During the start-up period, when there was an abundance of readily degradable carbon, driving sulphate reduction, there was a higher rate of sulphate reduction. This coincided with AMD neutralisation and sulphide production. Sulphate reduction decreased as the readily degradable carbon was depleted and only the recalcitrant carbon was left. Metal removal in the SRUs was also higher at start-up decreasing over time. This could be attributed to higher sulphide production during active sulphate reduction and the formation of metal sulphides.

Various detailed studies where performed at the VCC Pilot Plant in an attempt to determine causes for system malfunction or failure including a chemical, physical and microbiological study (Coetser, 2003). One of the short-comings of the SRUs was the hydraulic design of the SRUs as inverted truncated pyramids which led to the short-circuiting of water through the system and only the centre core of the reactor was hydraulically active.

Due to the location of the South Discharge's location the VCC Pilot Plant could not be operated in the true sense of "passive" as this discharge had to be pumped to a header tank before it could be gravity fed to the SRUs. Power failures and electrical cables being stolen resulted in the VCC Pilot Plant only being fed with West Discharge having a lower pH and higher metal concentrations.

The process of sulphate reduction results in the addition of nutrients and COD to the influent water and this requires a post-treatment stage in order to meet water discharge quality standards. The wetland effectively removed nutrients, metals and COD from the system while the oxidation cascade was effective in removing residual manganese from the system.

The most important parameter preventing sulphate reduction found was the prevailing oxic conditions in the bulk of the units. In the presence of significant microbial activity, oxygen present in the system would have been consumed during the biodegradation of organic matter. System malfunction was therefore ascribed to the lack of carbon biodegradation and thus the unavailability of readily biodegradable carbon to drive sulphate reduction.

New methods for sustaining successful long-term operation of passive treatment systems therefore had to be developed. A descriptive model of events occurring in the mobilisation of lignocellulose as a carbon and electron source in experimental wood chip packed columns and the development of the patented Degrading Packed Bed Reactor (DPBR) under the auspices of the Department of Art, Culture, Science and Technology (DACST) led to a breakthrough in passive treatment. During this process, readily available carbon is applied at the influent (carbon recharge zone) of the SRU. Microbial metabolic processes are initiated removing oxygen from the system establishing anaerobic conditions and negative redox potentials essential for sulphate reduction. As sulphate reduction commences, sulphide and alkalinity concentrations increase. As the AMD moves through the SRU more sulphate reduction occurs leading to higher sulphide and alkalinity production. Studies performed at Rhodes University indicated that high alkalinity concentrations lead to the swelling of lignocellulose making it more accessible for microbial degradation. Lignocellulose is a very complex polymer which repolimerises quickly after microbial cleavage has occurred. Sulphide prevents the repolimerisation of lignocellulose as it binds with the cleaved sites making the lignocellulose more acceptable for further microbial degradation. Once the lignin structure has been opened, hemicellulose and cellulose, the more readily degradable constituents of lignocellulose can be microbially degraded leading to the production of volatile fatty acids to drive sulphate reduction.

These enhancement strategies developed during the DACST funded project were successfully implemented at the VCC Pilot Plant *i.e.* SSRU 3 was decommissioned and recommissioned as a DPBR (operational for a period of 18 months) and SSRU 2 and SSRU 4 were supplemented with molasses. The major differences between the standard SRUs operated and the DPBR are summarised in Table 9.1

Table 9.1 : Design and operational differences between the standard SRUs and the DPBR

Variable	Standard SRUs	DPBR
Configuration	Inverted truncated pyramid	Rectangle
Hydraulic activity	Only centre core active	Entire unit active
Reactor size (m^3)	23.3	25.9
Supplementation	No supplementation	Supplemented with molasses
Waterproofing	Units sealed with a manure layer followed by lining with plastic sheeting	Unit built with a double brick wall and plastered with cement containing waterproofing material and painted with two layers of Bitumen

Table 9.2 summarises the average sulphate concentration removed and the average sulphate load removed of the different units over the different operational phases. The DPBR achieved the target sulphate load removed of 60 g/m^3 carbon /d when compared to the standard SRUs (Chapter 6). Although the DPBR was supplemented with molasses, supplementation only contributed an average COD concentration of 50 mg/ℓ in the influent to the DPBR while the average concentration of sulphate reduced was 615 mg/ℓ (Chapter 6). Molasses could therefor not be the only carbon source responsible for driving sulphate reduction and molasses was probably responsible for the enhancement of ligno-cellulose degradation, which sustained the reduction of sulphate.

Glucose and acetic acid supplementation to SSRU 1 led to the highest sulphate loads removed observed (Table 9.2). Due to the costs involved with supplementing these organics, it would not be economically feasible to supplement the SRUs with glucose or acetic acid on a continuous basis.

Table 9.2 : Comparison of sulphate load removed and sulphate concentration removed of the DPBR and the SRUs for the different phases of operation

Unit	Phase	Period	Sulphate concentration reduced (mg/ℓ)	Sulphate reduced (%)	Sulphate load reduced (g/m^3 carbon/d)
DPBR	Not applicable	October 2002 – March 2004	615	23.5	59.6
SSRU 1	1 – Standard operation	November 1996 – March 1998	386	25.6	31.3
	1 – Glucose supplementation	April 1998 – August 1998	939	62.0	176
	1 – Acetic acid supplementation	September 1998 – October 1998	917	78.8	172
	2	August 1999 – March 2004	155	10.8	14.4
SSRU 2	1	November 1996 – December 1998	247	9.10	25.0
	2	August 1999 – April 2003	150	10.1	14.2
	Molasses supplementation	May 2003 – March 2004	158	5.9	30.7
SSRU 3	1	November 1996 – December 1998	1	0.05	8.72
	2	August 1999 – March 2004	117	9.12	19.5
SSRU 4	1	November 1996 – December 1998	218	10.8	14.9
	2	August 1999 – October 2003	40	3.12	4.1
	Molasses supplementation	November 2003 – March 2003	249	14.6	36.2
LSRU 1	1	November 1996 – December 1998	649	33.5	17.6
	2	August 1999 – March 2004	171	11.5	9.17
LSRU 2	1	November 1996 – December 1998	417	21.5	11.9
	2	August 1999 – March 2004	160	10.6	9.80

It must be noted that the sulphate loads obtained with the DPBR were lower than the sulphate loads removed during the DACST project, averaging 400 g/m^3 carbon /d. This could be attributed to the fact that kinetic column studies were not performed to optimise passive treatment systems for site specific scenarios as well as scale-up. Each mining site has AMD with different chemical characteristics and carbon sources that are specific to the surrounding areas. The research performed on the carbon characterisation and sulphate reduction capacity are used as guidelines to select

mixtures of carbon sources to sustain sulphate reduction over the short, medium and long term to ensure effective sulphate reduction over an extended period. It also assists with the selection the readily available carbon necessary to establish the right redox potentials in the SRU to initiate sulphate reduction. Although each carbon source is unique in its chemical make-up, the chemical characteristics linked to carbon sources and sulphate reduction enables us to predict the performance of a carbon source in terms of its sulphate reduction capacity and thus the selection of suitable carbon source mixtures.

The carbon sources for the DPBR at VCC were therefore not packed with carbon sources based on kinetic column studies but with carbon sources used in the standard SRUS for comparison reasons. The DPBR outperformed SSRU 1, which had similar packing and operational conditions for the same period of operation.

Although the DPBR achieved the target sulphate load removed of 60 g/m^3 carbon /d, the effluent sulphate concentrations were still high averaging 816 mg/ℓ after 24 % reduction (Chapter 6). It must be kept in mind that the optimum conditions for sulphate reduction did not exist for the DPBR and that sulphate reduction would be higher if the right operating conditions were selected through kinetic column studies. Also the Integrated Managed Passive (IMPI) treatment system consist of more than one sulphate reducing unit and that more SRUs will be incorporated into the system to achieve the discharge water quality objectives.

The supplementation of molasses to SSRU 2 and SSRU 4 led to increased sulphate loads removed and SSRU 2 had an average increase of 16.5 g/m^3 carbon /d while SSRU 4 had an average increase of 32.1 g/m^3 carbon /d.

One of the units in the IMPI treatment system, which are still undergoing refinements is the sulphide oxidation bioreactor (SOBR), oxidising hydrogen sulphide to elemental sulphur. PHD is optimistic about the full-scale implementation of the SOBR after refinements have been finalised by Rhodes University. Other existing processes for the removal of sulphides from the system exist including zero-valent iron reactors operated as a passive reactor and electrochemical reactors using iron as a sacrifcial electrode in an active reactor.

Passive treatment systems are not a "walk away" solution. For passive treatment to be sustainable maintenance must be performed. For maintenance to be sustainable, it must be run as a profitable business. For a profitable business to be sustainable, it must generate regular cashflow, therefore, successful passive treatment must have regular maintenance. PHD has developed a preliminary maintenance schedule which need to be implemented on a fortnightly basis. This allows for an operator to visit the plant with a diesel pump to unblocked clogged pipes, top-up molasses dosing tanks *etc.* as specified in Chapter 8.

PHD has developed a preliminary maintenance guideline which have been implemented and monitored at the VCC Passive Treatment Plant. It was found that maintenance could be performed fortnightly and will include the replenishment of the readily available carbon, setting of flow rates of splitter boxes, sampling of the passive treatment plant, checking for blocked pipes and general maintenance at the plant (Chapter 8 gives a detailed description on the maintenance procedures).

Kinetic column studies form the basis of developing the design criteria of a passive treatment plant. Optimal operating conditions for sulphate reduction is determined using site specific carbon sources and the actual mine water. Various other design criteria need to be taken into consideration including hydraulics, topographical gradient *etc.* PHD has developed preliminary design criteria for the construction of full-scale passive treatment plants.

Based on conceptual designs that have been prepared, the estimated capital cost of an IMPISURE plant designed to remove 1000 mg/ℓ sulphates; 95% of iron and aluminium and 85% of manganese from a flow of 1000 m^3/day is R3 million. The corresponding operating cost is estimated to be

R0.60/m^3. Based on these estimations, passive treatment using the IMPI Technology makes the process economically feasible when compared with other active processes.

The international standard for "successful" sulphate load removal is in the order of 30 g/m^3 carbon /d (*Pers. comm.* Pulles, 2004). These are for units, which have been operational for periods of only two years. This is half of the target PHD has set to passive treatment systems to be economically feasible and similar to the results, which were obtained for the standard operated at the VCC Pilot Plant for the same period of operation.

CHAPTER 10

GENERAL CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

10.1.1 Long–term performance of the pilot plant

The SRUs at the VCC pilot plant have shown that the degradation of complex carbon sources takes place in stages over time. In the start-up period, when there is an abundance of readily degradable carbon driving sulphate reduction, there is a higher rate of sulphate reduction. This is characterised by AMD neutralization (pH increase and alkalinity generation), sulphate removal and sulphide production. Over time when the readily degradable carbon is depleted, and only the recalcitrant carbon is left, the rate of sulphate reduction decreases. None of the SRUs achieved the target sulphate load reduced of 60 g/m^3 carbon /d. Redox potentials were not condusive of sulphate reduction and hydraulic short-circuiting contributed to the low sulphate reduction observed.

Although the SRUs were insulated to a certain degree, sulphate reduction activity decreased during winter periods.

Metal removal in the SRUs is higher during the start-up period and decreases over time. This could be attributed to higher sulphide production during active sulphate reduction and the formation of metal sulphides.

The process of sulphate reduction results in the addition of nutrients and COD to the influent water and this requires a post-treatment stage in order to meet water discharge quality standards. The aerobic wetland effectively removed nutrients, metals and COD from the system. Re-oxidation of sulphide to sulphate occurred in the oxidation cascade. The design and operational criteria of the biological removal of sulphide from the system is in the process of being finalised under a different WRC project. The oxidation cascade was effective in removing residual manganese from the system. An increase in effluent COD of the oxidation cascade was observed and could be attributed to the presence of dead algal debris. This phenomenon poses a discharge problem.

10.1.2 Performance Enhancement Strategies

During the operation of a DPBR, readily available carbon or kick-start carbon is fed to the system. This conditions the water by initiating anaerobic metabolic processes removing oxygen from the system and establishing the right redox potentials. Sulphate reduction starts adding sulphides and alkalinity to the system. The presence of high concentrations of sulphides and alkalinity prevents the re-polymerisation of complex carbon such as lignocellulose thereby enhancing the degradation thereof.

The commissioned DPBR has been operating for a period of 18 months. Thus far, it has shown a constant and high sulphate reduction activity compared to SSRU1 over the same period of operation after being commissioned, further monitoring is required to test the hypothesis of the DPBR principle. The average sulphate load removed from the DPBR was 60 g/m^3 carbon/d (30 % increase when compared to SSRU 1). The DPBR was however not packed in accordance of the implementation of the IMPI Process where kinetic column studies would be used to optimise the process according to site-specific parameters.

Molasses supplementation to SSRU 2 and SSRU 4 has led to an increase in sulphate reduction and sulphide production after a period of only five months. pH neutralisation and alkalinity generation however remained low. The target sulphate load reduced for SSRU 2 increased from 14.2 g/m^3 carbon/d during Phase 2 to 30.7 g/m^3 carbon/d after 9 months of molasses supplementation. This

represents a 116 % improvement in sulphate load removal. The sulphate load removed in SSRU 4 increased from 4.10 g/m^3 carbon/d during Phase 2 to 36.2g/m^3 carbon/d after 5 months of molasses supplementation. This represents an improvement of 783 % in sulphate load reduced.

The enhancement strategies were therefore implemented with success.

10.1.3 Operation and Maintenance Guidelines

The following factors needs to be incorporated into the operational and maintenance guidelines (estimated for 2 weekly visits):

- Checking for vandalism.
- Keeping the site neat (*e.g.* removing reeds from the SRUs, cutting grass, spraying weed with weed killer).
- Flushing of influent distribution units using a diesel pump.
- Checking for any blockages in the influent or effluent pipelines.
- Checking of flow rates and setting of flow rates if the flow rates are not within 10 % of set-point.
- Replenishment of the molasses dosing tanks with required concentration of a thoroughly mixed molasses solution and setting of flow rates.
- Harvesting of sulphur or pumping of sulphur into storage dams.
- Rehabilitation of the wetland after a period of approximately 7 years. This will entail the removal of sludge from the wetland as well as removing excess reeds.
- Ensuring that the torturous pathway in the oxidation cascade is effectively distributing the water and that water is not short-circuiting.

10.1.4 Guidelines for Design parameters

10.1.4.1 Implementation procedure for IMPI Technology

The IMPI Technology is a biological treatment process and needs to be customised to take account of unique site conditions, specifically the following:

- Unique chemistry of each mine water
- Carbon substrate sources as close as possible to the plant
- Unique physical features of the site.

Kinetic column studies are performed and a site-specific process design developed. Operating conditions are customised for optimal sulphate reduction incorporating the actual mine water and carbon sources available in the area of the passive treatment plant. The correct mixtures and ratios of carbon are selected and the optimal retention time determined.

Based on the kinetic column studies and the process design, detailed civil designs and commissioning and operating protocols are generated. Construction of a single full-scale integrated module will then be undertaken. Once construction has been completed, full scale commissioning will commence and after commissioning, it will revert to the standard operational sequence.

Once the operation of the single full-scale module has proceeded satisfactorily for a period of 12-18 months, the plant will be expanded to the final design capacity.

10.1.4.2 Design criteria

The following criteria needs to be incorporated when designing a full-scale passive treatment plant:

- The definition of passive treatment does not allow for the use of any valves, electricity driven pumps or any other devices requiring electricity to function.

- Site characterisation:
    - Location with respect to mine workings and specific location of current and future mine water decant and seepage points
    - Availability of land
    - A buffer zone between the passive treatment system and the receiving water body is recommended to capture poor quality effluent and to protect against flood damage
    - Favourable topographical gradient
    - Stormwater management to allow the diversion of upslope runoff around plant site.
- Modular design allows for flexibility in terms of flow distribution, the ability to take certain units out of commission for maintenance and retrofitting purposes.
- Configuration of individual SRUs should be designed so as to:
    - Allow distribution of the influent flow to come into contact with entire body of carbon substrate
    - Allow and promote intimate contact between flow and carbon substrate
    - Prevent and minimise short-circuiting of flow
    - Promote plug flow
    - Prevent build up of large head losses.
- Geometric configuration: The best option which provides the best balance between optimum utilisation of the reactor volume and relative ease of construction was found to be a combination between a rectangular and truncated inverted pyramid.
- SRUs will be built as down-flow reactors as:
    - Upflow reactors pose a problem when clogged as the distribution unit is at the base of the unit and its maintenance could require the excavation of the reactors
    - readily available carbon needs to replenish regularly and if a solid carbon sources *e.g.* bagasse is used it will be replaced at the top of the reactor
- Design criteria should enable back flushing of the units.
- The kick-start carbon needs to be dosed passively into the reactor.

10.2 RECOMMENDATIONS

The following recommendations can be made with regards to passive treatment of acidic water:

- The DPBR principles should be used when designing a full-scale passive treatment system.
- A post-treatment system is required for the removal of nutrients and excess COD from the effluent.
- A sulphide oxidation reactor is required for the removal of sulphide from the effluent.
- A maintenance schedule should be implemented (Two weekly).

The implementation of the IMPI process, as patented after the Innovation Fund project, resulted in the desired result of enhanced sulphate reduction at the VCC pilot plant. When comparing the older VCC sulphate reduction units with the DPBR results it is clear that the new DPBR technology has moved the sulphate reduction process to a higher level. The use of the rapid breakdown kick start carbon source (molasses) has also indicated that it is effective in increasing sulphate reduction for the older sulphur reduction units that were no longer achieving the required performance. The results of the DPBR and the kick start carbon supplementation at VCC has shown encouraging results that need to be monitored for at least another year.

CHAPTER 11

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Other related WRC reports available:

Determination of the suitability of alternative carbon sources for sulphate reduction in the passive treatment of mine water

S Dill; TE Cloete; L Coetzer; L Zdyb

The current project aims:

- To identify the range of carbon sources available in the country taking economical factors like available quantities and transport costs into consideration.
- To determine test procedures regarding total carbon content, available carbon for bacterial reduction and sustainability of carbon release over time for the identified carbon sources.
- To develop a test procedure to obtain sulphate reduction kinetics for the different carbon sources under passive treatment conditions.
- To test the developed procedure on a model carbon source mixture which should provide carbon over a short, medium and long term period.

The main objective of the project (to develop a quick test method to assess the suitability of potential carbon sources for passive treatment systems) has largely been met. The work undertaken during the project gave valuable insights into the suitability of certain defined and undefined carbon sources for the use of sulphate reduction in small-scale anaerobic reactors. The methodology developed was found to be reproducible and low in cost, and can easily be implemented in other laboratories to screen potentially suitable carbon sources for sulphate reduction. The issue of carbon release from complex carbon sources over time, was found to be more complex than anticipated and only superficially addressed as part of the developed conceptual model.

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