

## CHAPTER 5

(Submitted for publication in Water SA)

### A conceptual model for the passive treatment of acid mine drainage

A model may be defined simply as a purposeful representation or description (often written in mathematical terms) of a system (Cloete and Mafema, 1997). In terms of this definition, models are used in a variety of disciplines and Engineering is no exception. Models are used to represent a system or process in a way that is easier to understand and to study. They are used to predict the behaviour of a system or process under different conditions. Models are also used to test hypotheses and to evaluate the effectiveness of different strategies. In the context of acid mine drainage (AMD) treatment, models are used to predict the performance of different treatment technologies and to evaluate the effectiveness of different strategies. This paper presents a conceptual model for the passive treatment of AMD. The model is based on the principles of mass and energy balance and is used to predict the performance of different treatment technologies. The model is presented in the form of a flow diagram and a series of descriptive statements.

The physical model is a spatial-scale representation of the system. For example, the laboratory and pilot-scale experiments used by scientists and engineers to investigate AMD treatment and behaviour are physical models (Cloete and Mafema, 1997).

The conceptual model provides a qualitative description of the system at a higher level than detailed observations. These models can be presented as schematic diagrams (e.g. flow diagrams) or as a series of descriptive statements (Cloete and Mafema, 1997).

## CHAPTER 5

### A conceptual model for the passive treatment of acid mine drainage

#### 5.1 Introduction

A model may be defined simply as a purposeful representation or description (often simplified) of a system of interest (Cloete and Muyima, 1997). In terms of this definition, models are widely used in Science and Engineering. For example, microbiologists and sociologists study model organisms (e.g. *E. coli*) and model communities; engineers apply models in the design of a diverse variety of systems (e.g. wastewater treatment plants). Many different types of models exist; these can be broadly categorized into (1) physical, (2) conceptual, (3) mathematical (Simeonov *et al.*, 1996), (4) steady state and (5) dynamic models (Cloete and Muyima, 1997).

The physical model is a spatial scaled representation of the system. For example, the laboratory- and pilot-scale experiments used by scientists and engineers to investigate system response and behaviour are physical models (Cloete and Muyima, 1997).

The conceptual model provides a qualitative description of the system and usually is developed from detailed observations; these models can be presented as schematic diagrams (e.g. flow diagram) or as a series of narrative statements (Cloete and Muyima, 1997).

The mathematical model provides a quantitative description of the system (Cloete and Muyima, 1997). With mathematical models the rates of the processes acting in the system and their stoichiometric interaction with the compounds are formulated mathematically. The mathematical formulations need to be incorporated in a solution procedure that takes account of the physical constraints and characteristics imposed by the system in which the processes take place, e.g. temperature, mixing conditions, etc (Cloete and Muyima, 1997). For the design and operation of biological wastewater treatment systems, it is the mathematical models that have proved most useful (Simeonov *et al.*, 1996). By providing quantitative descriptions, they allow predictions of the system response and performance to be made (Cloete and Muyima, 1997). From the predictions design and operational criteria can be identified for optimization of system performance. Also, mathematical models can serve as very powerful research tools. By evaluating model predictions, it is possible to test hypotheses on the behaviour of the wastewater treatment system (e.g. biological processes, their response to system constraints, etc) in a consistent and integrated fashion (Cloete and Muyima, 1997). This may direct attention to issues not obvious from the physical system, and lead to a deeper understanding of the fundamental behavioural patterns controlling the system response. In essence, mathematical models can provide a defined framework which can direct thinking (design, operation or research). Although this usually is very advantageous, it does have some disadvantages – the framework can restrict innovative and new developments (Cloete and Muyima, 1997).

The more complex the system, the more reliable the model. To

use the model, the information, model parameters are identified and the known

The steady state models have constant flows and loads and tend to be relatively simple (Cloete and Muyima, 1997). This simplicity makes these models useful for design; in these models complete descriptions of system parameters are not required, but rather the models are oriented to determining the more important system design parameters.

The dynamic models have varying flows and loads and accordingly include time as a parameter; the dynamic models are more complex than the steady state ones (Cloete and Muyima, 1997). The dynamic models are useful in predicting time dependent system response of an existing or proposed system; their complexity, however, requires that the system parameters have to be completely defined (Cloete and Muyima, 1997). For this reason the use of dynamic models for design is restricted. Often the steady state design and dynamic kinetic models evolve interactively: The dynamic kinetic models can provide guidance for the development of the steady state design models; they help identify the design parameters that have a major influence on the system response and help eliminate those processes that are not of major importance at steady state (Cloete and Muyima, 1997).

For the dynamic models with their greater complexity, only those parameters that appear to be of importance are considered for inclusion in the model (Cloete and Muyima, 1997). Usually information from lower levels of organization is microbiological and/or biochemical, and the more complete this information is the more reliable the model. To make use of this information, “model” organisms are identified and the known

microbiological and biochemical characteristics of the organism used (Cloete and Muyima, 1997).

These tasks cannot be completely sequentially, but rather the model tends to evolve with the tasks being undertaken interactively (Cloete and Muyima, 1997). For example, to identify processes and compounds, one needs to have some initial conceptualization of the system behaviour, i.e. a rudimentary conceptual model. As more information becomes available from model application and testing, aspects of the rudimentary model are improved as new compounds and processes are identified for inclusion, or processes already included are modified.

The final use for the model needs to be identified; if it is for design, steady state models usually are adequate, if for simulation a dynamic model is required (Cloete and Muyima, 1997). Also, the objectives of the model should be matched to the functions that are required of the biological treatment system.

From the above, it is apparent that to develop conceptual model for the passive treatment of acid mine drainage a number of tasks need to be completed including:

- Identifying the objectives for the model.
- Describing the conditions within which the model is to operate.
- Identification of the essential compounds utilized and formed.
- Identification of the processes acting on these compounds.

- Conceptualization of a mechanistic model that qualitatively describes the kinetic and stoichiometric behaviour of the processes and compounds.
- Mathematically formulation the process rates and stoichiometry.
- Setting up a solution procedure that incorporates the process rates, stoichiometry and transport terms.
- Calibration of the model and test its response against that observed experimentally (Cloete and Muyima, 1997).

Not all of the above tasks fall within the scope of this model. The objectives of this conceptual model, were to:

- Account for major events of interest occurring within the passive acid mine drainage treatment system;
- Assist in identifying the parameters that significantly influence the system response and thereby give guidance for the establishment of design criteria (this will include identification of essential compounds utilized and formed and identification of the processes acting on these compounds) and
- Assist in identifying possible causes for system malfunction or failure, and in devising remedial measures.

## 5.2 Major events of interest occurring within the system

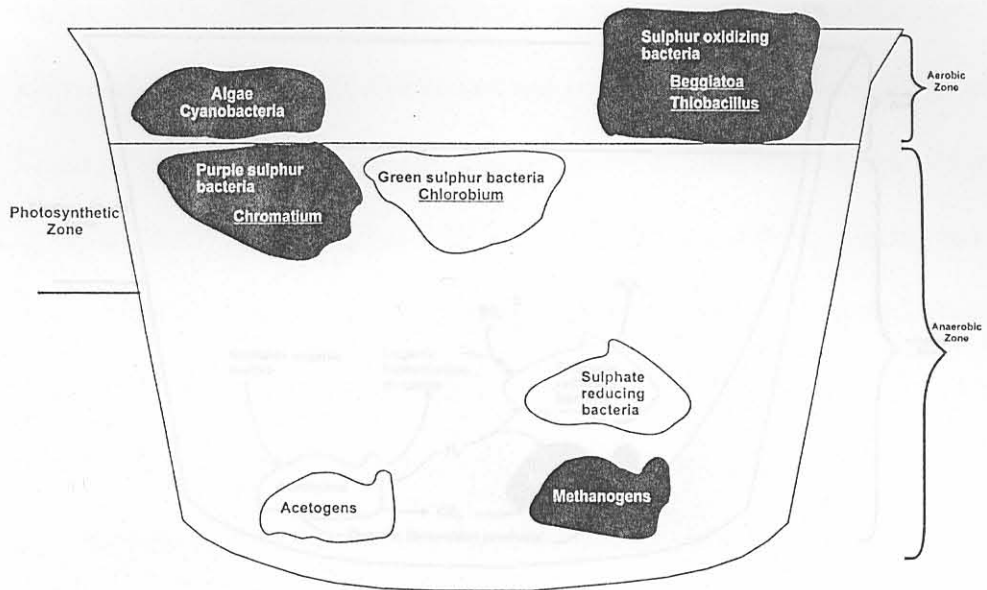


Figure 1. Organisms playing a role in the passive treatment system of acid mine drainage

The microbial consortia active in anaerobic treatment execute a complex process involving many classes of bacteria and several intermediate steps. A passive treatment system can be divided into two major zones, the aerobic zone and the anaerobic zone, with a photosynthetic zone at the top where light can penetrate. The most important organisms which play a role in the aerobic zone are algae, cyanobacteria and sulphur oxidizing bacteria e.g. *Beggiatoa* and *Thiobacillus*, while Purple sulphur bacteria e.g. *Chromatium*, Green sulphur bacteria e.g. *Chlorobium*, acetogens, sulphate reducing bacteria and methanogens are important in the anaerobic zone. Purple sulphur bacteria and methanogens are important in the anaerobic zone. Purple sulphur bacteria and Green sulphur bacteria are also photosynthetic bacteria. The role of these organisms will now be discussed in detail.

## 5.2.1 Methanogenic bacteria, acetogens and sulphate reducing bacteria

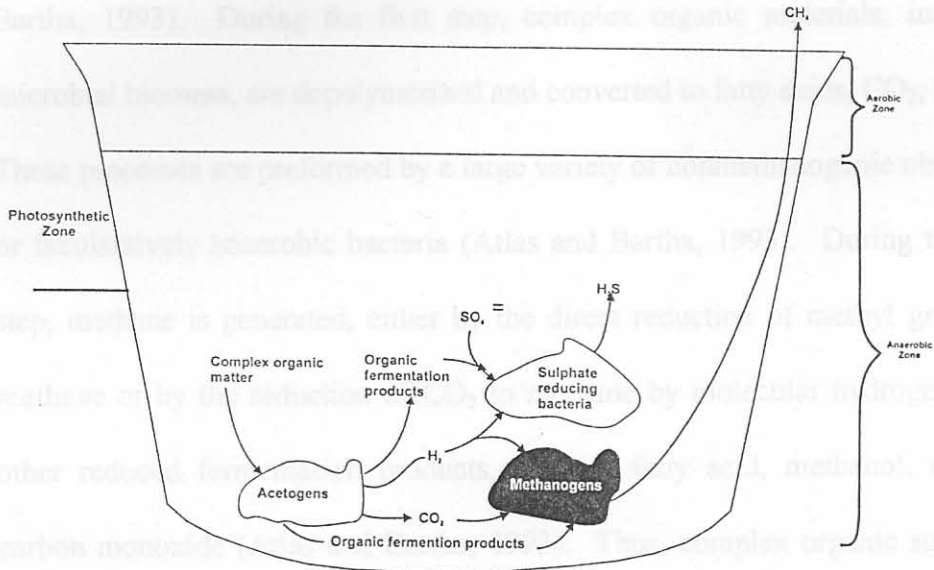


Figure 2. The role of methanogenic bacteria, acetogens and sulphate reducing bacteria in the passive treatment system of AMD.

### 5.2.1.1 Methanogens

Methanogens are methane-producing prokaryotes, a group of archaeobacteria capable of reducing carbon dioxide or low-molecular-weight fatty acids to produce methane (Atlas and Bartha, 1993). Methanogens are obligate anaerobic bacteria (Prescott *et al.*, 1990) which thrive in anaerobic environments rich in organic matter and are often of ecological importance (Prescott *et al.*, 1990). The rumen and intestinal tract of animals, freshwater and marine sediments, swamps and marshes, and anaerobic sludge digesters are only a few of these environments.



The anaerobic digestion of wastes can be considered as a two-step process, even though it really is a coupled sequence of microbiological interactions (Atlas and Bartha, 1993). During the first step, complex organic materials, including microbial biomass, are depolymerized and converted to fatty acids,  $\text{CO}_2$ , and  $\text{H}_2$ . These processes are preformed by a large variety of nonmethanogenic obligately or facultatively anaerobic bacteria (Atlas and Bartha, 1993). During the next step, methane is generated, either by the direct reduction of methyl groups to methane or by the reduction of  $\text{CO}_2$  to methane by molecular hydrogen or by other reduced fermentation products, such as fatty acid, methanol, or even carbon monoxide (Atlas and Bartha, 1993). Thus, complex organic substrates must be hydrolyzed to simpler organics after which they are fermented to volatile acids by the acidogens (Speece, 1996). Obligate hydrogen producing acetogens convert volatile acids longer than two carbons to acetate and  $\text{H}_2$  gas. The acetate and  $\text{H}_2$  are finally converted to methane by methanogens (Speece, 1996).

Hydrogen is an important precursor of methanogenesis (Cohen, 1993). Most of the so far isolated methanogens are able to utilize  $\text{H}_2$ . In methanogenic sediments and rice fields,  $\text{H}_2$  usually accounts for about 30% of methane production (Cohen, 1993).

Methanogenesis is rate-controlled (Speece, 1996).

Sulphide is an obligate nutrient requirement for anaerobic biotechnology and must be provided to insure process stability (Speece, 1996). There is an obligate requirement for sulphide by methanogens but it seems to be easily satisfied as long as there are a few mg/L of sulphide in solution (Speece, 1996). The optimal growth and the specific rate of methane production requires between 0.001 and 1.0 mg/L sulphur as S (Speece, 1996).

As an example, in one study sulphide was inadvertently omitted from the nutrient solution fed to a reactor for 2 months, and the effluent COD increased from 100 to 1900 mg/l for an influent COD of 5000 mg/L (Speece, 1996). Within a day of returning sulphide to the nutrient solution methane production nearly tripled and within a period of 2 weeks the filtered COD decreased to about 100mg/L.

In another study undertaken to research the stimulatory role of sulphate in methanogenesis, a laboratory reactor which had been metabolizing 30kg/m<sup>3</sup>-d of acetate abruptly ceased gas production within one day because the sulphide supply was inadvertently exhausted (Speece, 1996). Supplementation of 20mg/L of sulphide caused resumption of full gas production within 24 hours.

Sulphide production shunts energy in the electron donor to H<sub>2</sub>S, and therefore stoichiometrically reduces CH<sub>4</sub> production (Speece, 1996).

The severe limitation of just one trace metal can drastically alter metabolism of some MPB (Speece, 1996). Therefore it is possible that such a principle may also apply to SRB, which probably have developed specialized techniques for obtaining their trace metal requirements in the presence of sulphide (Speece, 1996).

The inhibition of acetate-utilization by methanogens is controlled by  $H_2S$  (Speece, 1996). Not all methanogens exhibit the same toxicity response to  $H_2S$ , so it is to be expected that the literature reports would vary on the response of different classes of methanogens to a given concentration of  $H_2S$  depending on which class of MPB was predominant in that particular system (Speece, 1996). At an alkaline pH the inhibitory effect of  $H_2S$  was higher than at neutral or acidic pH (Speece, 1996).

#### 5.2.1.2 Sulphate reducing bacteria

SRB are a group of organisms which share an ability to couple the reduction of sulphate and other sulphur compounds to the oxidation of a variety of electron donors (De Bruyn, 1992). Due to the fact that SRB are very strict anaerobes, it is insufficient to only exclude oxygen from culture medium when growing pure cultures (De Bruyn, 1992). In the absence of sulphate, some are known to be capable of fermentative growth, but none can grow with oxygen as electron acceptor, and oxygen always inhibits their growth (Postgate, 1979). SRB are responsible for dissimilatory sulphate reduction, where sulphate acts as an

oxidizing agent for the dissimilation of organic matter (De Bruyn, 1992). Virtually all of the reduced sulphur is released into the external environment as the sulphide ion, usually substantially hydrolysed to free  $H_2S$ . Sulphate reduction in polluted water usually ceases because the sulphate is exhausted rather than because all the organic material has been used.

bacteria, change the reactor pH

The presence of SRB in anaerobic digestion systems was therefore not surprising since they are active during the mineralization of organic carbon (Joubert, 1987). If the SRB were, thus, to be used during the production of elemental sulphur, many of the intermediary process phases leading to the formation of sulphide, could be solved (Joubert, 1987). One of the major problem areas in this process is still the inability of the SRB to actively ferment many "primary substrates" such as carbohydrates (Joubert, 1987). At present it would consequently be essential to combine the metabolic activities of an acidogen with the SRB. In practice, however, it will probably be more rational to select the activities of several SRB, rather than to operate with a bacterial consortium, to attain this objectives (Joubert, 1987).

explaining the complexity of the terminal part of an process

Several strains of oxygen-tolerant SRB are known (Cohen, 1993). Those resistant to high oxygen levels require hydrogen for growth (Cohen, 1993). Other strains are seemingly facultative SRB, namely they may switch from heterotrophic aerobic growth to anaerobic sulphate reduction mode (Cohen, 1993). Another

nitrate competition (Joubert, 1987) however, the dominance of the sulph

group of isolated SRB are oxygen sensitive when grown in axenic culture and can cope with oxygen only when grown in co-culture with thiobacilli (Cohen, 1993).

According to McCartney and Oleszkiewicz (1991), SRB generate sulphides that may result in product inhibition of SRB and/or toxicity to methane producing bacteria, change the reactor pH via generation of alkalinity, reduce the rate of methanogenesis and decrease the quantity of methane produced by competing for the available carbon and/or hydrogen.

The main bacterial groups which utilize carbon dioxide and sulphate as electron acceptors in the anaerobic process are the methanogens and the sulphate-reducers which also closely interact in anoxic environments (Joubert, 1987). Since these bacterial groups occupy rather similar ecosystems and are both strict anaerobes, they seem to have a somewhat competitive association (Joubert, 1987). The availability of sulphate in anaerobic environments will, to a large extent, determine the dominant terminal process (Joubert, 1987). The microbial interactions between these two groups are therefore of particular interest in explicating the complexity of the terminal degradation process and were therefore studied in anaerobic digesters and in freshwater and marine sediments (Joubert, 1987).

In exceptional cases methanogenesis, in itself, have also been observed in high-sulphate ecosystems (Joubert, 1987). However, the dominance of the sulphate-

reducers over methanogens in high-sulphate environments does not necessarily imply that sulphate-reduction will always be the dominant terminal process in anaerobic mineralizations (Joubert, 1987). Methanogenesis has been shown to dominate in deeper layers of marine sediment where sulphate is depleted or where the sediment is highly enriched with organic matter (Joubert, 1987). Recent studies have also shown that the SRB were poor competitors in comparison to methane-producing bacteria in high-rate anaerobic reactors (Joubert, 1987). The methanogens were observed to gain dominance in the anaerobic reactor even when the reactor was initially colonized mainly by sulphate-reducers (Joubert, 1987). These significant observations were to some extent ascribed to the better colonization and adherence characteristics of the methanogens to the fixed carrier matrix in the reactor (Joubert, 1987). Proposed mechanisms for the apparent inhibition of methanogenesis in high-sulphate environments are mostly unsatisfactory, but a number of fundamental aspects possibly responsible for this inhibition have been presented as likely explanations (Joubert, 1987).

Thus, under anaerobic conditions, acetogenic bacteria are responsible for the degradation of complex organic matter to organic fermentation products,  $H_2$  and  $CO_2$ . Methanogens utilize the  $CO_2$  and organic fermentation products to produce methane while SRB utilizes  $H_2$  in the presence of sulphate to produce  $H_2S$ . Therefore, SRB and methanogens compete for available  $H_2$  and carbon sources.

The alkali and alkaline earth sulphides dissociate in solution to yield free  $H_2S$  as well as  $HS^-$  and  $OH^-$  ions. Since  $H_2S$  is volatile the pH of the environment thus tends to become alkaline. Over a long period this alkalinity is neutralized by atmospheric  $CO_2$ , so that the carbonate and bicarbonate accumulate. During periods of active sulphate reduction, however, the environment tends to become alkaline unless compensating metabolic reactions leading to acid formation are taking place simultaneously, or unless the sulphide is trapped as insoluble derivatives of heavy metals.

$H_2$  is a characteristic product of anaerobic fermentations, and the presence of hydrogenase in the majority of SRB enables them to utilize  $H_2$  for sulphate reduction. Scavenging of  $H_2$  has been suggested as one interpretation of the incompatibility of sulphate-reducing and methane-producing bacteria (Prescott *et al.*, 1990).

### 5.2.1.3 Acetogens

In the case of anaerobic treatment, the slowest step is characterized by an accumulation of substrate buildup found just prior to the rate controlling step (Speece, 1996). If this form of substrate is a non-acid organic (e.g. alcohol) there may be no adverse impact on the overall consortia (Speece, 1996). The slowest growing members of the consortia often are the propionic- or acetic acid-utilizers. An accumulation of these organic acids can overwhelm the reserve bicarbonate alkalinity (Speece, 1996). Such malfunction may cause a decrease in pH which

can have a drastically adverse impact upon the entire microbial consortia (Speece, 1996). Unfortunately the greatest inhibition of a low pH may also be directed at the propionic- and acetic-utilizers themselves, compounding the problem (Speece, 1996).

It should be evident from this series reaction analogy that the anaerobic process works well as long as each subsequent class of organisms processes the organic intermediaries at least as fast as they are produced (Speece, 1996). Since microbial processes function at a rate proportional to their substrate concentration, an accumulation of substrate may result before they are able to process it as fast as it is passed on to them (Speece, 1996).

Figure 3 The role of algae and Cyanobacteria in the conceptual model of the passive treatment system of aerobically treated effluent

Algae can be described as unicellular organisms that use light energy and carbon dioxide to produce oxygen and other products for growing and oxygen-producing phytoplankton (Preston et al., 1978). Algae can be either autotrophic or heterotrophic, but most are photoautotrophic, and require only light and CO<sub>2</sub> as their principal source of carbon and energy sources (Preston et al., 1978).



## 5.2.2 Algae and Cyanobacteria

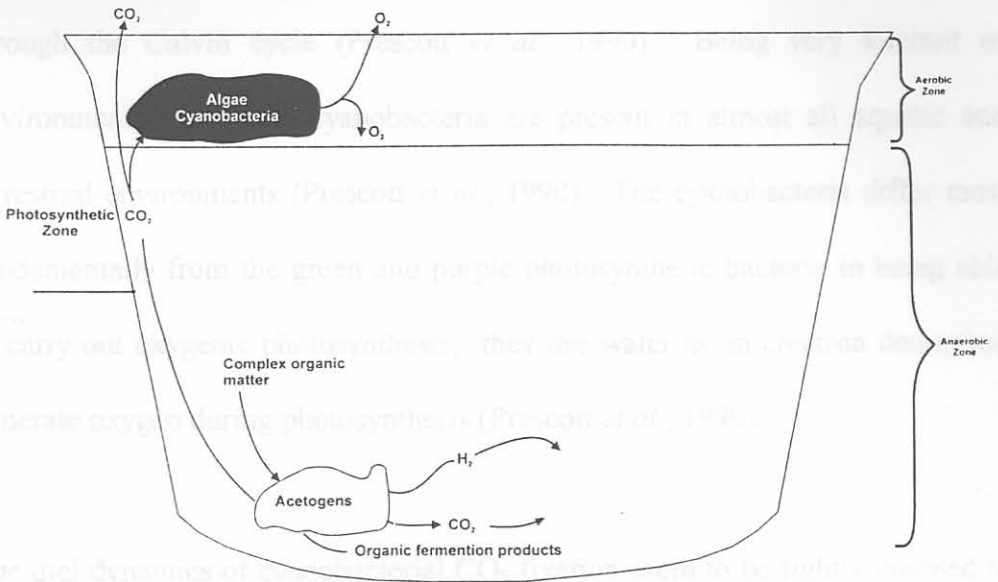
carbon and energy sources (Prescott *et al.*, 1990).

The cyanobacteria are the largest and most diverse group of photosynthetic bacteria (Prescott *et al.*, 1990). Cyanobacteria assimilate carbon dioxide through photosynthesis (Prescott *et al.*, 1990). Being very hardy and environmentally diverse, cyanobacteria are present in almost all aquatic and terrestrial environments (Prescott *et al.*, 1990). The cyanobacteria differ from the green and purple photosynthetic bacteria in being able to carry out oxygenic photosynthesis; they use water as an electron donor and generate oxygen during photosynthesis (Prescott *et al.*, 1990).

The redox dynamics of cyanobacteria are thought to be tightly coupled to  $\text{CO}_2$  production by SRB and methane production by methanogens (Cohen, 1993).

Figure 3. The role of algae and Cyanobacteria in the conceptual model of the passive treatment system of acid mine drainage.

Sulphate reducers and methanogens are believed to be strictly anaerobic bacteria and require negative redox potentials for growth (Cohen, 1993). Thus illumination during daytime  $\text{O}_2$  production is so high that  $\text{O}_2$  concentrations in microzones overlap with those of sulphate reduction and methane production (Cohen, 1993). In other words, anaerobic processes such as sulphate reduction and methanogenesis may be affected dynamically by photosynthetic  $\text{O}_2$  production (Cohen, 1993). Preliminary observations indicate that sulphate



*al.*, 1990). Chemoheterotrophic algae require external organic compounds as carbon and energy sources (Prescott *et al.*, 1990).

The cyanobacteria are the largest and most diverse group of photosynthetic bacteria (Prescott *et al.*, 1990). Cyanobacteria assimilates carbon dioxide through the Calvin cycle (Prescott *et al.*, 1990). Being very tolerant of environmental extremes, cyanobacteria are present in almost all aquatic and terrestrial environments (Prescott *et al.*, 1990). The cyanobacteria differ most fundamentally from the green and purple photosynthetic bacteria in being able to carry out oxygenic photosynthesis; they use water as an electron donor and generate oxygen during photosynthesis (Prescott *et al.*, 1990).

The diel dynamics of cyanobacterial CO<sub>2</sub> fixation seem to be tightly coupled to CO<sub>2</sub> production by SRB and methane production by methanogens (Cohen, 1993).

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reduction and methanogenesis are at least partially operative and sometimes even highly enhanced in the presence of oxygen (Cohen, 1993).

During anaerobic conditions, both algae and cyanobacteria may use the  $\text{CO}_2$  produced by acetogens during anaerobic degradation of complex organic matter.

### 5.2.3 The role of purple sulphur bacteria, green sulphur bacteria and sulphur oxidizing bacteria

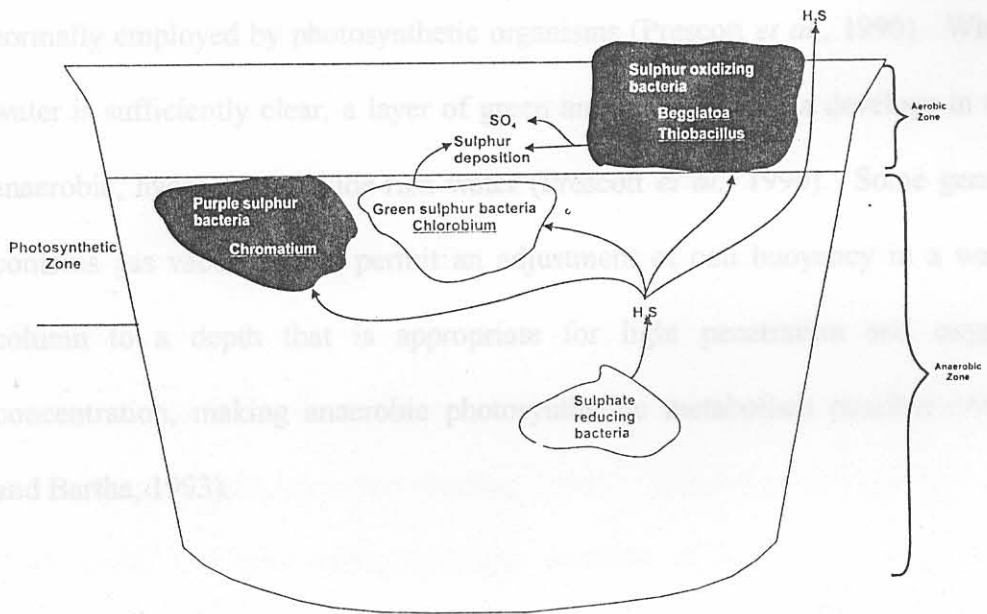


Figure 4. The role of purple- and green sulphur bacteria, and sulphur oxidizing bacteria in the conceptual model of the passive treatment system.

### 5.2.3.1 Purple sulphur bacteria

The purple sulphur bacteria are strict anaerobes and usually photolithoautotrophs (Prescott *et al.*, 1990). These bacteria oxidize hydrogen sulfide to sulphur and deposit it internally as sulphur granules (Prescott *et al.*, 1990). Typical purple sulphur bacteria are *Thiospirillum*, *Thiocapsa*, and *Cromatium* which are found in anaerobic, sulphide-rich zones of lakes (Prescott *et al.*, 1990). These bacteria produce carotenoid pigments and may appear orange-brown, red-brown, purple-red, or purple-violet (Atlas and Bartha, 1993). Due to the fact that purple and green photosynthetic bacteria grow best in deeper anaerobic zones, they cannot effectively use parts of the visible spectrum normally employed by photosynthetic organisms (Prescott *et al.*, 1990). When water is sufficiently clear, a layer of green and purple bacteria develops in the anaerobic, hydrogen sulphide-rich water (Prescott *et al.*, 1990). Some genera contains gas vacuoles that permit an adjustment of cell buoyancy in a water column to a depth that is appropriate for light penetration and oxygen concentration, making anaerobic photosynthetic metabolism possible (Atlas and Bartha, 1993).

### 5.2.3.2 Green sulphur bacteria

Green sulphur bacteria are a small group of obligately anaerobic photolithoautotrophs that use hydrogen sulphide, elemental sulphur, and hydrogen as electron sources (Prescott *et al.*, 1990). Sulphur is produced by sulphide oxidation and is deposited outside the cell (Prescott *et al.*, 1990). Green sulphur

bacteria produce green or green-brown carotenoid pigments (Atlas and Bartha, 1993). These bacteria flourish in the anaerobic, sulphide-rich zones of lakes.

### 5.2.3.3 Sulphur oxidizing bacteria

Reduced sulphur compounds are capable of supporting chemolithotrophic microbial metabolism in the presence of oxygen (Atlas and Bartha, 1993).

*Beggiatoa*, *Thioploca* and *Thiotrix*, are filamentous, microaerophilic bacteria capable of oxidizing  $H_2S$  to water and water (Atlas and Bartha, 1993). In the absence of  $H_2S$ , these sulphur globules are slowly oxidized further to sulphate.

Some species of *Thiobacillus* are also able to oxidize  $H_2S$  and other reduced sulphur compounds and, because they have a low acid tolerance, deposit elemental sulphur rather than generate sulphuric by further oxidation (Atlas and Bartha, 1993). These *Thiobacillus* and the filamentous sulphur bacteria are facultatively chemolithotrophic while other members of the genus *Thiobacillus* species produce sulphate from the oxidation of elemental sulphur and other inorganic sulphur compounds (Atlas and Bartha, 1993). *Beggiatoa* is very versatile metabolically and can oxidize hydrogen sulphide to form large intracellular sulphur grains and can subsequently oxidize the sulphur to sulphate (Prescott *et al.*, 1990).

Sulphates are common minerals in soils and water, so sulphate reduction, once established, can continue for long periods provided organic matter is available

(Postgate, 1979). The sulphide found is a chemical reducing agent, tending to preserve the anoxic environment necessary for activity of SRB (Postgate, 1979). Ecologically, zones of sulphate reduction are the foci of ecosystems called 'sulfureta', in which other sulphur bacteria grow in association with the SRB, in which coloured, photosynthetic sulphide-oxidizing bacteria grow in a zone whose depth is determined by the depth to which light penetrates (Postgate, 1979). Above that zone, dissolved sulphide and dissolved air co-exist and aerobic sulphide-oxidizing bacteria (e.g. *Beggiatoa* in fresh waters) may be found as well as thiobacilli (Postgate, 1979). These organisms oxidize reduced sulphur back to sulphate and by thus recycling sulphur they tend to perpetuate the sulfuretum: by their autotrophic and photosynthetic CO<sub>2</sub> fixation they also regenerate organic matter and help to perpetuate the system (Postgate, 1979). Since the SRB generate sulphide and the oxidizers fix CO<sub>2</sub>, the sulfuretum can act as an anaerobic primary producing system (Postgate, 1979). But it is limited by the amount available of either sulphide (for CO<sub>2</sub> fixation) or pre-formed organic matter (for H<sub>2</sub>S formation) (Postgate, 1979). These sulfureta readily become populated by appropriate bacteria and, because of the reducing action of H<sub>2</sub>S, have a considerable degree of ecological stability (Postgate, 1979).

Thus, green sulphur bacteria (e.g. *chlorobium*) and purple sulphur bacteria (e.g. *chromatium*) can utilize the H<sub>2</sub>S produced by SRB, anaerobically, while sulphur oxidizers (e.g. *thiobacillus*) can utilize the H<sub>2</sub>S aerobically. Sulphur oxidizing

SRB bacteria produces sulphate and sulphur deposits from  $H_2S$ , while green sulphur bacteria only produces sulphur deposits.

### 5.3 Conceptual model for the passive treatment system of AMD

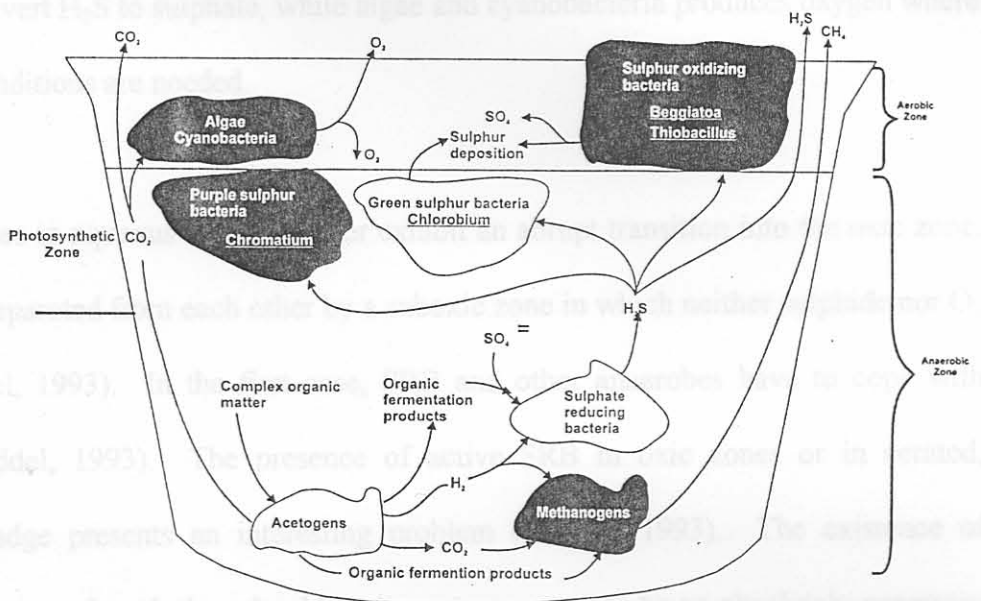


Figure 5. Conceptual model for the passive treatment system of AMD.

### 5.4 Microbiological conversions which could cause system malfunction

Due to the fact that SRB and methanogens live under strict anaerobic conditions with similar pH and temperature ranges, they are in competition with each other. In normal ecosystems such as freshwater and marine sediments and also in anaerobic digesters,

SRB are normally dominant and methanogenesis was found to be inhibited by the presence of sulphate (Isa *et al.*, 1986). However, there are several factors influencing the competition between SRB and methanogens. These include sulphate concentration in feed, maximum specific utilising rate, free energy of the reaction, nutrient availability, temperature, substrate type etc. (Speece, 1996). Methanogenesis must be inhibited during the passive treatment of AMD. Other microbial processes which need to be eliminated are that of the sulphur oxidizers, the algae and the cyanobacteria. Sulphur oxidizers convert  $H_2S$  to sulphate, while algae and cyanobacteria produces oxygen where anaerobic conditions are needed.

Reduced zones in aqueous habitats either exhibit an abrupt transition into the oxic zone, or both are separated from each other by a suboxic zone in which neither sulphide nor  $O_2$  exist (Widdel, 1993). In the first case, SRB and other anaerobes have to cope with oxygen (Widdel, 1993). The presence of active SRB in oxic zones or in aerated, activated sludge presents an interesting problem (Widdel, 1993). The existence of microniches, even though they should be important, seems to be no absolutely necessary for active sulphate reduction; in oxic layers with active sulphate reducers, microniches could not be detected by the use of microsensors (Widdel, 1993).



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