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BIOTECHNOLOGY FOR SUSTAINABLE HYDROMETALLURGY

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Abstract

High rate bacterial catalyzed processes can serve to improve hydrometallurgical operations. These solutions are not only economical but also environmental sustainable. With references around the globe, the value of this new approach is recognized by industry worldwide. For instance, metals can safely and economically be separated from process and waste streams using biotechnologically produced sulfide, recovering a valuable metal sulfide product instead of a waste gypsum stream for disposal.

Both the natural biological sulfur and nitrogen cycles offer bioconversions that are applied on industrial scale. The shared advantage of these processes is that waste compounds are converted in either a reusable raw material or in a harmless product. This way, natural product cycles can be closed. Applications based upon bioconversions are for example:

Sulfur based: Bioleaching, reduction of oxidized sulfur compounds to elemental sulfur, metal recovery with biogenic produced H_2S, SO_2 removal from gas streams, etc.

Nitrogen based: Ammonia removal using the anammox-process, biological removal of NOx from gas streams, nitrate removal from water streams, etc.

Metals: Bacterial processes for the reduction of metals such as uranium, selenium And manganese have proven to offer great potential for clean-up of groundwater streams.

This paper contains a description of the above applications. Further, a short introduction on engineered high rate bioreactor systems and a description of industrial biotechnological applications will be provided.

Introduction

The potential of integrating biotechnological processes in mining and metallurgical operations has gained a lot of recognition over the past years. Traditionally, biotechnology has mainly been used in mining for bioleaching purposes. Bioleaching is familiar to miners and metallurgists and there is a general acceptance of the potential of this approach. There are however several other biotechnologies that can be applied to advantage in this area and which are not as well known as bioleaching. This paper will focus upon these new, high rate bioprocess routes. Both the natural biological sulfur and nitrogen cycles offer bioconversions that are successfully applied on industrial scale. The shared advantage of these high efficiency processes is that waste compounds are converted at ambient pressure and temperature in either a reusable raw material or in a harmless product. This way, natural product cycles can be closed, enabling environmental sustainable production/operation.

Besides an introduction about the possibilities offered by high rate biotechnology and the natural sulfur and nitrogen cycles, various case studies will be addressed in this paper.

High Rate Biotechnology

When describing environmental biotechnology, it is important to make a distinction between high and low rate bioreactors. With high rate biotechnology we mean that engineered reactors are used, in which the bioconversion capacity is maximised. Examples of high rate solutions are the UASB/IC technology for conversion of mixed organic compounds from wastewater into reusable methane (instead of lagoons) or sulphate reduction bioreactors (instead of wetlands). In these systems only naturally occurring bacteria are used.

The advantages of high rate biotechnology as compared to low rate are:

- smaller reactor volumes; low space requirement
- better process control
- higher conversion efficiencies; better defined products

Compared to chemical processes, high rate biotechnology is cleaner, safer and more cost-effective because biological processes work at ambient temperature and pressure and consume low amounts of chemicals, while the conversion rate of these bioconversions is very high. In many cases raw materials can be recovered from waste or process streams.

The statement that high rate biological processes are more robust than many comparable chemical technologies finds more and more supporters with the increasing number of plants installed. These supporters understand that biotechnology should in fact be regarded and approached as biologically catalysed chemical technology. In general, bacteria can handle considerably more severe process fluctuations than many chemical catalysts.

Globally, some 2,000 high rate bioreactors treat a huge variety of waste streams. Most of these plants treat high strength industrial waste water. Organic compounds from waste water are converted to biogas, which is generally utilized as alternative for natural gas. Applications of high rate wastewater treatment are widely spread over the industrial world; Paper manufacturing, breweries, distilleries, and chemical industries have since long embraced the advantages involved.

Since the early eighties however, more and more attention has been given on the development of high-rate reactors for the conversion of inorganic compounds. Especially bioconversions of sulfur compounds were subject to intense research. In the early nineties the first industrial applications resulting from these studies were successfully commissioned. In the meantime, some 50 high rate bioreactors specially designed for the conversion of sulfur compounds (mainly for H_2S, sulfate and heavy metal removal) have been built. These plants can be found in mining & metallurgy, petrochemical industry, natural gas winning, chemical industry and various other industries.

Also on the field of conversion of nitrogen compounds big steps have been made. Attractive alternatives for the traditional nitrification/denitrification processes have been developed and successfully applied.

In the below table examples of available high rate bioconversions are provided:

Table I: Examples of available bioconversions

Compound	**Reaction with**	**End product**
H_2S	Air	Elemental Sulfur
SO_2	Ethanol/Hydrogen and air	Elemental Sulfur or H_2S
SO_4^{2-}	Ethanol/Hydrogen and air	Elemental Sulfur or H_2S
Sulfur	Ethanol/hydrogen	H_2S
$MeSO_4$	Ethanol/Hydrogen	MeS
NO_3^{2-}	(M)ethanol	N_2
$NH4^+$	Air	N_2
NO	Ethanol	N_2
UO_4^{2-} / UO_2^{2+}	Ethanol/Hydrogen	UO_2
SeO_4^{2-}	Ethanol/Hydrogen	Se°
MoO_4^{2-}	Ethanol/Hydrogen and H_2S	Mo_2S_3 / MoS_2
CrO_4^{2-} / $Cr_2O_7^{2-}$	Ethanol/Hydrogen	Cr_2O_3 / $Cr(OH)_3$

Bioconversion Of Sulfur Compounds

Sulfate And Heavy Metal Removal

The group of anaerobic micro-organisms characterized as sulfate reducing bacteria are able to reduce oxidized sulfur components to hydrogen sulfide or H_2S [2, 4, 5, 6, 8]. In order to reduce oxidized sulfur components to hydrogen sulfide the bacteria use a substrate, which is oxidized simultaneously. For this purpose organic compounds like ethanol can be used. For large scale applications hydrogen gas is used, which is produced on site by reforming natural gas, LPG or naphta [4, 5, 8]. This so-called electrondonor or reductant mainly determines the operational costs. The equations for sulfate reduction with ethanol and hydrogen gas are as follows:

$$3\ SO_4^{2-} + 2\ C_2H_5OH \rightarrow 3\ HS^- + 3\ H_2O + 3\ HCO_3^- + CO_2 \quad (1)$$

$$SO_4^{2-} + 4\ H_2 + H^+ \rightarrow HS^- + 4\ H_2O \quad (2)$$

This bio-produced or biogenic H_2S can be readily used to precipitate metals from solution [1, 3, 7, 9]. The use of H_2S for this purpose generally leads to better metal removal efficiencies and a product which is more compact, stable and re-usable than the respective metal hydroxides or carbonates.

When, besides metals, sulfate has to be removed to low levels, the anaerobic biological treatment is followed by a second biological treatment step in which the excess of hydrogen sulfide is oxidized to elemental sulfur (3):

$$HS^- + ½ O_2 \ ? \ S^o + OH^- \qquad (3)$$

Combined with equation (2), this leads to the overall formula:

$$H_2SO_4 + 4 H_2 + ½ O_2 \ ? \ S^o + 5 H_2O \qquad (4)$$

It is important to note that by applying this process acidity can be destroyed without the use of alkaline chemicals. This is of particular interest for treatment of waste sulfuric acid or acidic streams containing sulfate and heavy metals, such as Acid Mine Drainage (AMD).

Using this method sulfate can be removed to below 200 ppm, which is far below the 1500 ppm reached in traditional lime treatment. Instead of (polluted) gypsum, elemental sulfur is produced (only 20 % of the sludge volume vs. gypsum) with the possibility of recycling the sulfur to a sulfuric acid plant.

Biogenic H_2S Production And Metal Recovery

If removal of sulfate from a liquid stream is not required, the cheapest way to biologically produce hydrogen sulfide is the reduction of elemental sulfur [6, 7, 9]. Only 2 electrons are required for the reduction of sulfur to H_2S, whereas for sulfate reduction to H_2S 8 electrons are needed:

$$6 S° + C_2H_5OH + 3 H_2O \rightarrow 6 H_2S + 2 CO_2 \qquad (5)$$

Paques developed the Thiopaq® BSG (Biogenic Sulfide Generator) process for this purpose. The produced hydrogen sulfide is stripped from the bioreactor by recycling gas from the bioreactor to a gas/liquid contactor in which the H_2S is transferred to the stream to be treated. Metals in the liquid stream will react with the sulfide and can be harvested as metal sulfides.

In this set-up there is no direct contact between the bacteria and the liquid stream treated, so issues with regard to possible toxic compounds in the liquid stream or temperature concerns are of no concern.

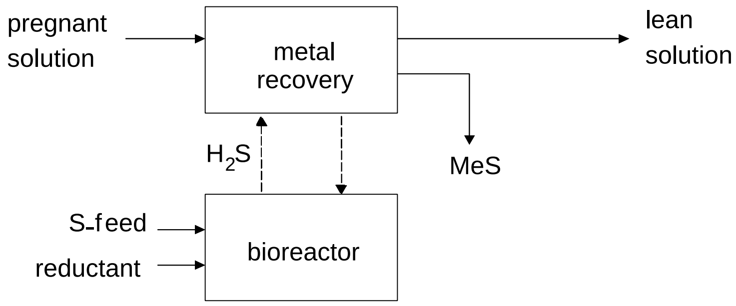

Figure 1: Block Process Diagram Metal Recovery using Biogenic H_2S

Using sulfate reducing bacteria, cost-effective and safe H_2S can be produced on demand and on-site as an attractive alternative to the traditional sources of sulfide [5, 6, 7].

SO_2-Removal

The same technological principles as described for sulfate removal can be used to convert SO_2 into H_2S and/or elemental sulfur. In essence this process uses a buffered sodium carbonate solution as scrubber liquid that absorbs the SO_2 as bisulfite. The carbonate buffer is regenerated in an anaerobic bioreactor where the sulfite/sulfate is reduced to sulfide using e.g. hydrogen or ethanol as reductant. The sulfide can be stripped as hydrogen sulfide (6b) or it can be oxidized with air to elemental sulfur (6a). Both options remove the acidity from the system that was introduced through SO_2 dissolution:

$$SO_2 + 3H_2 + \frac{1}{2} O_2 \rightarrow S^0 + 3 H_2O \quad (6a)$$

$$SO_2 + 3H_2 \rightarrow H_2S + 2 H_2O \quad (6b)$$

For facilities with varying H_2S requirements, it is well possible to operate an installation which is able to produce both H_2S and sulfur. In times when H_2S is needed for metal precipitation, this can be harvested from the plant and in times when the H_2S requirement decreases, sulfur can be produced instead. In times of excessive H_2S requirements, sulfur could be bio-converted into H_2S again. This offers maximum flexibility.

H_2S Removal

For H_2S Removal from gasses and airstreams, biological sulfide oxidation can be integrated in an alkaline scrubber system [10]. The resulting installation consists of a scrubber tower and a bioreactor. This technology is marketed by Shell as the “Shell-Paques process” for natural gas desulfurisation and by Paques as “Thiopaq® Scrubber” for all other applications. The main reactions taking place are:

Absorption and hydrolysis of H_2S (chemical reaction):

$$H_2S_{(g)} + OH^- \rightarrow HS^- + H_2O \quad (7)$$

Biological sulfur formation (biological reaction):

$$HS^- + \frac{1}{2} O_2 \ ? \ S^o + OH^- \quad (3)$$

Since the process liquid is continuously recycled from the bioreactor to the scrubber, the chemical costs of this system are very low. Furthermore, the inherent high sulfide removal efficiency (effluent concentrations of 1 ppm H_2S can be guaranteed), the process-robustness and reuse possibility of the formed sulfur are recognized main advantages.

Bioconversions Of Nitrogen Compounds

Bacteria have been used for the removal of nitrogen compounds for decades. Much is known about the conventional nitrification/denitrification processes, which are used to remove both ammonium and nitrate. New developments however, have extended the range of industrial applicability of processes derived from the biological nitrogen cycle [11].

NH_4 Removal

The partial nitrification and anaerobic ammonium oxidation (Anammox) processes are a completely new concept in the biological removal of ammonia from industrial wastewater and gas. No less than 70% of the oxidation energy for nitrification and 100% of the electrondonor for denitrification can be saved. Nitrogen removal based on this concept consists of two treatment steps: partial nitrification followed by anaerobic ammonium oxidation.

The first step is the partial nitrification of ammonia. In this step 50% of the ammonia is biologically converted to nitrite:

$$2\ NH_3 + 1.5\ O_2 \rightarrow NH_4^+ + NO_2^- + H_2O \qquad (8)$$

The second step is the anaerobic oxidation of ammonia (the Anammox process). In this step, ammonia and nitrite are biologically converted to nitrogen gas:

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2\ H_2O \qquad (9)$$

The partial nitrification and Anammox processes are a very cost-efficient method (90% reduction of operational costs compared to conventional technology) for ammonia removal from medium to high strength waste streams containing little or no organic carbon, such as for example effluents from anaerobic wastewater treatment. Also *sour water* from the oil and gas industry and NH_3-containing gasses can be treated effectively using these processes.

NO_3 Removal

For stand-alone nitrate removal, denitrification in high rate bioreactors is still the state of the art:

$$6\ NO_3 + 5\ CH_3OH + CO_2 \rightarrow 3\ N_2 + 6\ HCO_3^- + 7\ H_2O \qquad (10)$$

For applications in mining and metallurgy however, there are three distinctive disadvantages of this approach: cyanide is often present and may inhibit bacterial activity and the alkalinity produced in equation (10) may cause carbonate scaling and unwanted pH-increase. Paques has developed an alternative biological approach to overcome these problems:

$$6\ NO_3 + 5\ S^o + 2\ H_2O \rightarrow\ 3\ N_2 + SO_4^{2-} + 4\ H^+ \qquad (11)$$

Should cyanide be present in the stream to be treated this will immediately react with the sulfur present to form thiocyanide, which is far less toxic to bacteria than cyanide. This enables the process to deal with cyanide peaks. Further, the pH decrease resulting from equation (11) is often desired in the streams treated, not just for scaling prevention, but also in order to comply with discharge demands. For alkalinity reasons this process is for instance applied for nitrate removal from drinking water.

<u>NOx Removal</u>

In order to meet the new challenges of removing NO_x from flue gasses, a new and unique process for NO_x removal was developed by Biostar, called "*BioDeNO$_x$*" [12]. In this process NOx is removed and biologically converted to nitrogen gas. The absorbent is an $FeII[EDTA]^{2-}$ solution that is continuously biologically regenerated and then recycled back to the scrubber.

The overall reaction that takes place at ambient conditions and at atmospheric pressure in the *BioDeNO$_x$* process is:

$$2NO + C_2H_5OH \longrightarrow N_2 \uparrow + 2CO_2 + 2H_2O \qquad (12)$$

Nitric oxide (NO) is converted to harmless nitrogen gas. The system consists of two main parts: the absorption step and the biological conversion.

The NO_x is present in flue gases as NO and NO_2. NO_2 dissolves readily in water and is easily removed. NO is normally 95% of the total NO_x and is difficult to dissolve in water. In the *BioDeNO$_x$* process, an iron chelate is used that reacts with NO to form a nitrosyl complex, which enables the NO to dissolve in the aqueous phase.

$$NO + Fe^{II}[EDTA]^{2-} \longrightarrow Fe^{II}[EDTA]NO^{2-} \qquad (13)$$

In the *BioDeNO$_x$* process, the regeneration of the active $Fe^{II}[EDTA]^{2-}$ from the nitrosyl complex is solved by an inexpensive, simple biological regeneration. The reduction of the nitrosyl complex is similar to the processes that occur in denitrifying waste water systems. The reaction used in the *BioDeNO$_x$* process is shown below where ethanol is used as the reducing agent.

$$6Fe^{II}[EDTA].NO^{2-} + C_2H_5OH \longrightarrow 6Fe^{II}[EDTA]^{2-} + 3N_2 + 2CO_2 + 3H_2O$$
(14)

The regenerated $Fe^{II}[EDTA]^{2-}$ is then available to be recycled to absorb NOx in the scrubber.

Overall costs savings of 50%, high removal efficiencies (>80%) and the possibility of easily integrating this process in existing FCC flue gas desulfurisation units are the main advantages of this new process compared to its alternatives.

Bioconversions Of Metals And Metal Oxides

Some metals do not precipitate easily as metal sulfides at certain valences. For these metals anaerobic bacteria from the sulfur cycle can be used for reduction to a lower valence in order to trigger precipitation. This could be as the metal sulfide but also as metal oxides, carbonates or even as the elemental metal. Examples are selenium, molybdenum and uranium [14]. This approach offers a great potential for, amongst others, the clean-up of groundwater streams.

Industrial Applications

As a company, Paques has realised over 500 industrial high rate bioreactors in a variety of industries. Anglo American, Pasminco and Umicore [15] are examples of clients in the mining and metallurgical industry. In this section five key examples are briefly described.

H_2S Removal From Natural Gas, Brooks, AB, Canada

Together with Shell, Paques has developed the Shell-Paques® process for H_2S removal from (high pressure) natural gas. Shell markets this process worldwide.

The first biotechnological purification plant for the desulphurisation of natural gas based on the Shell-Paques process® was taken into operation in the second half of September 2002 [10]. The bacteria are exposed to the gas at high pressure and the plant produces about 0.9 tons of sulphur per day. The gas is extracted from well sites that are on or adjacent to the properties of over forty Canadian landowners located around the Bantry North facility. The plant is built under licence by the company New Paradigm Gas Processing Ltd. This is a subsidiary of the Canadian technology company CCR Technologies Ltd. The plant was built for Encana Resources, a major Canadian gas producer, and is located northeast of Brooks, Alberta.

The Shell-Paques® biological technology was selected because it was the best available technology for this application. The alternative was acid gas re injection which was too expensive and therefore not feasible. The required H_2S out concentration in the product gas was < 4 ppmv which was immediately met at start up.

The Bantry Shell-Paques unit is designed to remove and recover hydrogen sulfide from four natural gas fields. The natural gas stream of 322,000 nm^3/day is scrubbed to remove 2000 ppm H_2S with the spent scrubbing liquid being regenerated in the bioreactor and recycled to the scrubber, as described in previous paragraphs of this paper.

Metal Recovery From Acid Mine Drainage At Caribou Mine, NB, Canada

Caribou is a zinc mine owned by Breakwater Resources Ltd. located near Bathurst, New Brunswick, which is currently not operating due to low metal prices. The mine, however, continues to operate a lime treatment plant to treat underground mine drainage, which has an average flow of 700 m^3/day. The mine also has a sizeable deposit of old tailings, stored separately by the previous operator, containing significant quantities of pyrite, zinc and copper. Over the years these tailings have become a source of acidity and soluble metals due to oxidation and a solution is required to retreat and/or reclaim the tailings.

BioteQ, a licensor of the above described Thiopaq® Biogenic Sulfide Generator, reached an agreement with Breakwater in June 2001 to construct a treatment plant to remove metals from the mine drainage upstream of the existing lime plant [6, 13]. The plant, based on the flowsheet of figure 1, was started up in November 2001 and by January 2002 had reached a steady state operating capacity required to meet water treatment needs at that time of the year.

The plant operated throughout 2002 recovering a saleable zinc concentrate, including the removal of copper, cadmium and lead from the wastewater prior to it entering the existing lime treatment plant for iron and aluminum removal. The treated water was discharged to local receiving waters within the guidelines of existing permits

During the fall of 2002, the plant feed averaged 660 mg/L Zn, 19 mg/L Cu and 337 Fe^{3+}, with some peak concentrations well above the average for the period. These concentrations can be compared with the design values of 450 mg/L Zn, 30 mg/L Cu and 15 mg/L Fe^{3+}. The plant, however, coped with the unpredictable and highly variable metal content in the acid water with metal recovery exceeding design expectations for copper, with consistent copper recovery to <0.01 parts per million in the discharge.

During its operation in 2002, the plant recovered nearly 35 tonnes of zinc concentrate containing copper, cadmium and lead. The concentrate was delivered and accepted for sale to the nearby Brunswick Mine under contract with Noranda. Operation of the BioSulphide-Thiopaq plant upstream of the lime plant has resulted in significantly reduced water treatment costs at Caribou due to lime savings, reduced sludge production as well as concentrate sales. Further, of long-term environmental significance, lime sludges contained none or only trace amounts of heavy metals.

Currently, the installation of a second plant at Caribou is under evaluation. The plant would incorporate a leach stage in which metals will be solubilized from the tailings in a controlled manner utilizing existing acid drainage for recovery in an expanded BioSulphide-Thiopaq plant. The treated tailings could then be deposited in the existing main tailings impoundment.

The Stage 2 plant will have a nominal design capacity of 2100 m^3/day and will allow the processing of 210 tonnes/day of contaminated tailings. In addition to ongoing treatment of the mine drainage, the plant will selectively recover copper and zinc into separate concentrates, together with cadmium, lead and other heavy metals. Based on current engineering estimates, approximately 1 million pounds of copper (450 tonnes) and 4.2 million pounds of zinc (1,900 tonnes) would be recovered annually.

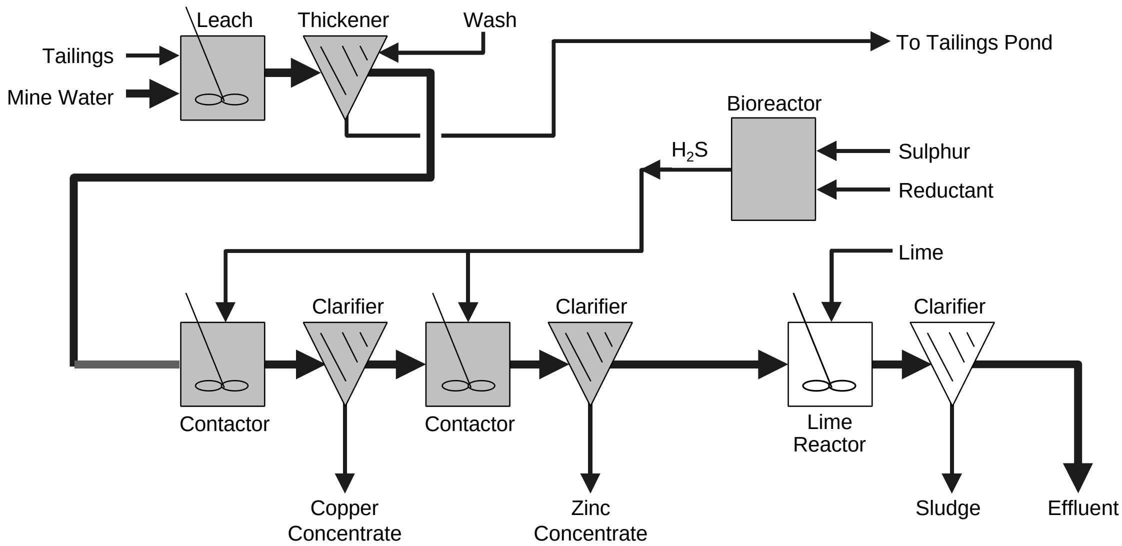

Figure 2: Stage 2 Block Process Diagram Metal Recovery at Caribou

Demonstration Of NOx Removal From FCC Flue Gas At hold Refinery,USA

During a four month period, particulate, SO_x and NO_x were successfully removed from a FCC (Fluid catalytic cracking) flue gas stream at the Hold[12]. Particulate and SO_x were removed with a 99% efficiency by the well known Dynawave scrubbing technology offered by Monsanto Envirochem. The NO_x removal percentage of > 90% was achieved by the above described Biodenox technology, which essentially post-treated the desulfurised gas stream.

NO_x removal was successfully demonstrated in this demonstration project, with NO_x removal percentages continuously being > 90% with outlet NO_x concentrations well below 10 ppmv. The NO_x was scrubbed from the flue gas using a normal spray scrubber while the conversion to nitrogen gas and the regeneration of the chelate occurred in the sump of the scrubber and in a specially designed high rate bioreactor.

Scrubber Leed And Magnesium Bleed Treatment At Pasminco Budel Zinc, Netherlands

Budel Zink B.V., a Pasminco Ltd. owned company, has operated a zinc refinery at Budel-Dorplein in the Netherlands since 1973. Over 200,000 tons of zinc are produced annually. The conventional roast-leach-electrowin process produces various wastewater streams containing sulfate and zinc. Until mid 2000 these streams were treated conventionally by neutralisation with lime resulting in the production of gypsum.

Increasing legislative restrictions prohibited further production of residues at the Budel Zink site as from July 2000. For this reason alternative wastewater treatment processes were studied over several years in order to come to a process in which production of gypsum is avoided and in which an effluent can be produced which is compliant to the applicable legislation. Paques' THIOPAQ® technology was selected. This high rate technology converts zinc and sulfate into a zinc sulfide product, which is recycled to the refinery [8].

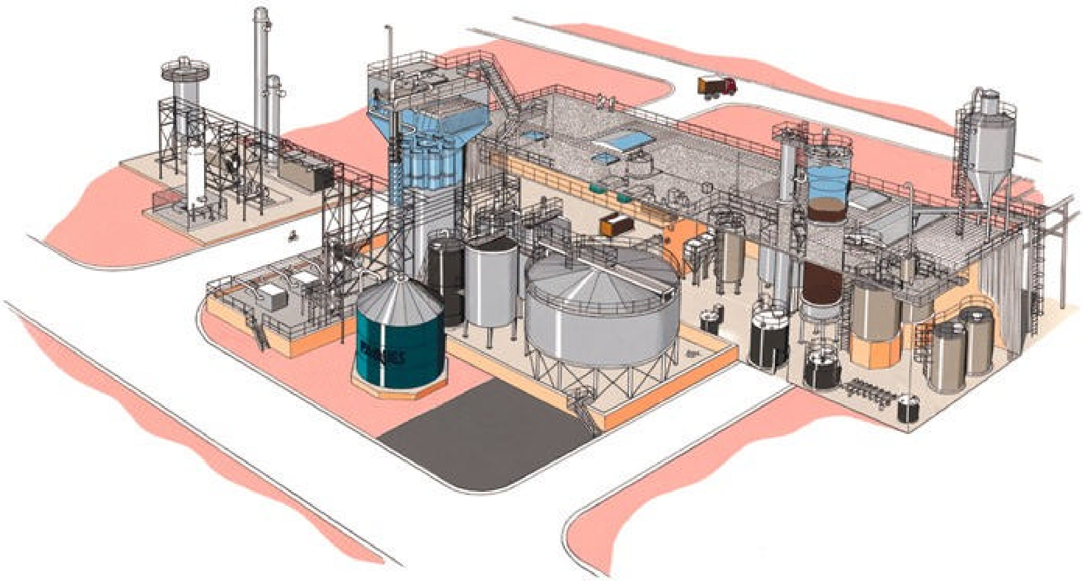

Figure 3: Overview Drawing of the Full Scale Plant

<u>$ZnSO_4$ Reduction:</u> At Budel Zink two streams are treated with this bioconversion process:

- Wash Tower Acid (scrubber discharge from the roaster acid plant). Typically this is about 25 m^3/h containing 10 g/l H_2SO_4, 0.5 g/l HF, 1 g/l HCl and 0.5 g/l Zn.
- Magnesium bleed. This bleed is necessary to prevent accumulation of magnesium in the electrolyte. Typically 0.5 m^3/h of Purified Solution and/or Spent Electrolyte has to be bled from the circuit in order to control the magnesium concentration. The magnesium bleed contains 15 g/l Mg and up to 300 g/l of sulfate.

The THIOPAQ® plant was realised at Budel Zink in 1999 and forms the heart of the process configuration for high strength sulfate water treatment. The block scheme of the process is presented below:

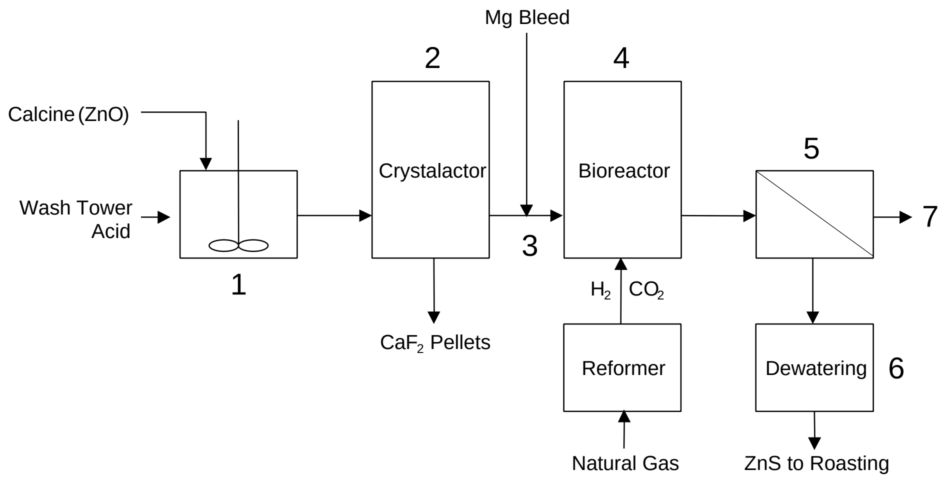

Figure 4: Schematic Flow Diagram for the Biological Process Route

1. Neutralisation of Wash Tower Acid with calcine (ZnO).
2. Fluoride removal by precipitation as CaF_2 in a Crystalactor®.
3. Mixing with magnesium bleed (Zn electrolyte).

4. Biological conversion of $ZnSO_4$ to ZnS, using hydrogen as an electron donor. Hydrogen is produced on-site using a reformer unit, which converts natural gas and steam into H_2 and CO_2.
5. Precipitation and separation of the produced ZnS.
6. De-watering of the produced ZnS.
7. Treatment of the bioreactor effluent in the existing Paques' groundwater treatment installation where the excess sulfide is converted into elemental sulfur.

Environmental Impact: Treatment of the wash tower acid with the conventional neutralisation process led to the production of large volumes of gypsum (18 tons/day) and effluent characteristics which were not compliant to legislation. With the successful implementation of the THIOPAQ® technology using a high rate sulfate reduction bioreactor no gypsum is produced and an improvement of the water quality has been realised. In addition re-usable calcium fluoride and valuable zinc sulfide are produced. Zinc sulfide (10 t/d) is recycled to the roaster feed.

In the below tables the main data of the Budel plant are summarised:

Design capacity	H_2S production Influent	3200 kg/day 40 m^3/h

Production	ZnS CaF_2	10 t/day 0 – 0.9 t/day

Water quality	Compound (ppm)	**In**	**out**
	SO_4	15000	< 300
	Zn	10000	< 0.2
	F^-	500	< 50

Conclusions

High rate biotechnology offers many possibilities to solve recovery and environmental issues in a broad range of industries. Numerous applications have shown the technology to be safe and robust. For the mining and metallurgical industry current and potential applications include:

- Low cost and safe H_2S production for use as a reagent in metallurgical processes
- Selective metal recovery from metallurgical and waste streams
- Metal reduction for environmental control
- Sulfate reduction and removal to meet environmental regulations
- Sulfate reduction to allow recycle of industrial water
- SO_2 removal by conversion to H_2S and/or elemental sulfur

Further, competitive new processes for the removal of nitrogen compounds from gas and water streams are available.

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