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Nordic co-operation

Nordic co-operation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, the Faroe Islands, Greenland, and Åland.

Nordic co-operation has firm traditions in politics, the economy, and culture. It plays an important role in European and international collaboration, and aims at creating a strong Nordic community in a strong Europe.

Nordic co-operation seeks to safeguard Nordic and regional interests and principles in the global community. Shared Nordic values help the region solidify its position as one of the world's most innovative and competitive.

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Preface

This work was conducted as a part of the “Water conscious mining” (WASCIIOUS) project, funded by NordMin – a Nordic Network of Expertise for a Sustainable Mining and Mineral Industry. The project was initiated in April 2014 and was finished in November 2016.

The use of metals in modern society has been constantly increasing in recent years. Finland, Sweden and Norway have developed national mineral strategies, which especially emphasize the importance of continued exploration and exploitation of minerals by sustainable mining activities. It is important to secure sustainable metal production in the Nordic countries with a higher level of environmental awareness and safer production than in countries outside Europe and to minimize the dependence on imports from politically unstable areas without having influence on impacts on the environment.

Mining and quarrying have unavoidable impacts especially on the water quality in areas surrounding the mines. Especially the sensitive Arctic environment in the Nordic countries presents the need to minimize the discharges into the environment by using good management practices and by developing cost-effective water treatment techniques. Some examples of societal implications of mining that stress the importance of the use of clean technologies are:

- Employment: The minerals sector not only covers the mining industry, which produces metallic ores and industrial minerals, but other extractive industries that refine rock material and natural stones. The minerals sector also includes companies that produce the machinery, equipment, technology and services required for extraction and mining. According to Eurostat, in 2013 mining and quarrying alone directly employed about 70,000 persons in the Nordic countries.
- Recreational use of the area when the environment changes (influence on tourism): a clean environment is of great marketing value for tourism, the production of safe food and a safe living environment.
- Location of the mine: in the Nordic countries the mines are situated in arctic areas with fragile nature. The use of clean technologies reduces conflicts with the population living in the areas.

The main objective of the project has been to develop a technology concept for water conscious mining, where innovative water and tailings treatment technologies provide good-quality water for recycling and discharge and enable safe disposal and/or utilization of tailings.

The project was co-ordinated by VTT from Finland. The project group consisted of the following research partners:

- VTT Technical Research Centre of Finland Ltd (co-ordinator).
- Lappeenranta University of Technology (LUT), Finland.
- Luleå University of Technology (LTU), Sweden.
- SINTEF Stiftelsen, Norway.
- Norwegian University of Science and Technology (NTNU), Norway.
- ÍSOR Iceland Geosurvey, Iceland.
- VEOLIA Water Technologies, Denmark.
- Outotec Oyj, Finland.
- ÅF-Consult Ltd, Finland.
- Boliden Kevitsa Mining formerly FQM Kevitsa Mining.
- Dragon Mining Oy, Finland.
- LKAB Luossavaara-Kiirunavaara AB, Sweden.
- FinnMin – Finnish Association of Extractive Resources Industry.
- SveMin – Swedish Association of Mines, Mineral and Metal Producers.

The work was done in a large consortium of 14 partners. All partners were not involved in all tasks presented in this report. Common conclusions of the consortium are presented in Chapter 6. Each chapter and sub-chapter 2–5 also include conclusions that represent the opinion of the respective author.

The main authors of the report were:

- VTT: Margareta Wahlström, Tommi Kaartinen, Jarno Mäkinen and Henna Punkkinen.
- LUT: Antti Häkkinen, Maria Mamelkina and Ritva Tuunila.
- LTU: Pertti Lamberg and Maria Sinche Gonzales.
- Sintef: Marius Sandru and Heidi Johnsen.
- NTNU: Jens-Petter Andreassen.
- ÍSOR: Vigdís Harðardóttir and Hjalti Franzson.
- Veolia: Christina Sund.
- Outotec: Kaj Jansson.

Terms and definitions

Acid mine drainage (AMD)	Water that has been acidified by sulphuric acid as the result of interaction with sulphide minerals that have undergone chemical oxidation due to mining activity.
Ettringite	Calcium aluminium sulphate mineral.
Hazardous waste	Hazardous waste is a waste, which due to its (intrinsic) chemical or other properties poses a risk to the environment and/or human health. Waste considered as hazardous in the European List of Waste are marked with an asterisk in the List of Waste.
Inert waste	Waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant, and in particular not endanger the quality of surface water and/or groundwater. (1999/31/EC)
Landfill	A waste disposal site for the deposit of the waste onto or into land (i.e. underground).
Mine	Area under the control of an operator where mining occurs (see mining) including common related infrastructures and waste management activities.
Mining	Any activity involved in the prospecting, extraction, treatment and storage of solid mineral resources originating from deposits in the earth's crust, other than construction materials.
Non-hazardous waste	Waste not regarded as hazardous waste.
Tailings	The waste solids or slurries that remain after treatment of minerals by separation processes (e.g. crushing, grinding, size sorting, flotation and other physico-chemical techniques) to remove the valuable minerals from less valuable rock.
Waste rock	Part of the mineralization, with or without low grades of value minerals, which cannot be processed profitably.

Abbreviations

AMD	Acid Mine Drainage.
BIA	Brakerstyrt Innovasjonarena (Research Programme founded by The Research Council of Norway).
CAPEX	Capital Expenditure.
EC	Electrocoagulation
EFC	Eutectic Freeze Crystallization.
GARD	Global Acid Rock Drainage Guidance.
MBBR	Moving bed biofilm reactor.
MEND	Mine Environmental Neutral Drainage Programme, http://mend-nedem.org/default/
MiMi	Mitigation of the Environmental Impact from Mining Waste (Swedish Research Programme funded by the Swedish Foundation for Strategic Environmental Research (Mistra).
NF	Nanofiltration.
NOEC	No Observed Effect Concentration.
OPEX	Operating Expenditure.
RO	Reverse Osmosis.
SEM	Scanning Electron Microscope.
SS	Suspended Solids.
TSS	Total Suspended Solids.
UF	Ultrafiltration.
WII	Water Impact Index.

Summary

Mining industry as consumer of large amounts of water is also under today's pressure to strive towards more sustainable use of resources. The starting point for this transition is to increase the internal recycling of water and thus reduce the amount of fresh water needed, and also to separate the clean waters entering the mine area from the waste waters of the mine operations. This calls for new technologies to separate the water streams with different qualities and to treat the new types of waters.

The project aimed at

1. surveying current practices, their economic and environmental impacts and resources available for alternative practices
2. identifying the requirements for recycling and disposal
3. identifying and evaluating the key technologies for water management and treatment
4. reviewing technologies for tailings de-watering and treatment
5. developing and evaluating aspects of a low water consumption mine concept
6. the sustainable continuation of Nordic collaboration and research.

The work was based on laboratory testing, previously published results and information shared between project partners and their extensive links to the mining industry. The work was divided into tasks led by different project partners.

The study on current practice in water treatment in Nordic mines revealed that there are significant differences in the compositions of the mine water to be treated as well as differences in the requirements for treatment either for discharge to the environment or for the water recycling/reuse. Based on the results from the inquiry, it was decided to focus on the removal of sulphate, specific metals (Cu, Ni, Zn), and also to a limited extent on the removal of nitrogen compounds. The starting point was a state-of-the-art review on commercially available technologies or proven technologies tested at least with pilot studies.

The following technologies were studied in the project: electrocoagulation, biosorption, chemical precipitation, membrane processes, eutectic freeze crystallization, adsorption and finally also biological processes for nitrogen removal. The technological readiness levels of the studied technologies varied from research-based to proven technologies. The laboratory tests were partly performed with synthetic water and partly with real mining water samples obtained from industry partners. However, it must be emphasized that test-runs with real mine water in conditions as close as possible to real conditions are crucial for a reliable

evaluation/assessment of the applicability of the technology. Some tests were also conducted in pilot scale with the already proven technologies.

In addition to the results from the proven technologies, the performed experiments with research-level technologies – often as combinations of several technologies – also showed good removal of key components. For sulphate removal, it can be concluded from the performed experimental tests with the tested mine waters that ettringite precipitation yielded in low residual concentrations in treated water. The achieved sulphate removal efficiencies were also promising with electrocoagulation and ultrafiltration membranes. Eutectic freeze crystallization seems to be suited especially for waters with high salt concentrations, but it is still in the development stage. Biosorption was not found to be a suitable method for sulphate removal.

Good results were achieved for metals removal with a precipitation/coagulation/sedimentation process and co-precipitation processes. Ettringite precipitation, electrocoagulation and eutectic freeze crystallization (after 2–3 washing times of the ice) also reduced metal contents. With the membranes tested, about 50% of the metals were removed from the treated waters. Biosorption was not applicable for metal removal in this context.

In the performed pilot study with the biological fixed film process, MBBR removed nitrogen from the treated water to low concentrations.

It was concluded in the experimental work that, to achieve low concentrations, a combination of methods is needed and should be further studied.

Computational simulations of water treatment and recycling practices were performed for two mines, and these provided useful information on the impact of treated and recycled water on the complete water balance, the removal of species, and the operational costs. The use of simulation tools in the selection and combination of technologies is therefore recommended.

In conclusion, it can be said that there are proven technologies available for the removal of key substances from waters that are generated by today's mining processes. The choice of suitable technology depends on the water quality required and especially on the level of pollutants to be removed as well as on the treatment costs. The possible use of the treated water as process water or alternatively discharge to the receiving water body determines the goal of water treatment. Furthermore, the arctic conditions influence the selection of the treatment concept and also the big variation in flows from winter to spring time with the melting snow. Mine water composition or treatment requirements might change, thus posing further needs for new cost-efficient technological concepts for the treatment of waters to achieve low residual concentrations. The project has given insights into new, low water-footprint mine design concepts and procedures for sustainability evaluation and created a solid basis for developing the required technologies.

The project also included a desk study without any experimental work on alternative technologies for the removal of water from tailings. Management of tailings was addressed by comparing the impacts (costs, environment, risks, etc.) of some currently available alternatives. A simplified calculation study performed showed some

potential for cost savings and revealed possibilities to minimize the risks related to tailings management.

Finally, the project resulted in the establishment of a future Nordic research platform, an R&D network related to environmental issues in mining for the Nordic region to promote the exchange of ideas and collaboration in future project calls, and to propose ideas for future projects.

1. Introduction

- Responsible partner: VTT.
- Contributors: All.

1.1 Water conscious mine – concept

Large volumes of water are used in mining especially in connection with the extraction and processing of ores. The key features in water conscious mine concepts presented in the Finnish guidance “Best Environmental Practice in Metal Mining Operations” [1] are following:

- High recycling degree of mine water during the whole lifetime of the mine.
- Collection and treatment of mine water in a way that it does not pose a risk for human health in the mining area and the neighbouring environment.
- Discharge of water to the environment in a way that will not cause significant contamination of the downstream waterways.
- Sludges from water treatment and tailings are disposed of in a way that potential environmental impacts can be minimized.

Wastewater characteristics are mainly defined by ore mineralogy but also by the selected enrichment process. Every mine site is unique in terms of ore type, plant location, water quality, and climate conditions, etc. Therefore, the technical solutions in ore processing as well as solutions in water treatment and treatment of tailings vary highly from one mine to another. Furthermore, the climatic conditions in the Nordic region call for solutions suitable for huge flows – often millions of cubic metres a year – and very cold water. The difference of mining in arctic or near arctic areas compared to temperate regions has been very little addressed.

The mining and enrichment of sulphide minerals as well as other ores containing low concentrations sulphides result in mine waters with elevated concentrations of sulphate and heavy metals. Traditionally, neutralization with lime has been the dominant way to limit pollution from water discharged into the environment from the mine. However, the challenges with lime treatment are the large sludge volumes generated and the long-term chemical stability of the sludges. Furthermore, lime treatment is not a selective process for metal removal and cannot be used alone to reduce the sulphate level in water below 2,000 mg/l.

All mine waters have different characteristics – some are easy to recycle and reuse, while others demand advanced treatment. Water recycling sets needs for treatment

systems that prevent the accumulation of certain compounds, which otherwise could potentially have a negative effect on the process and result in a reduced yield or quality. By keeping the water streams with different qualities separated and applying customized water treatment methods, higher recycling rates could be reached.

Figure 1: Typical main water flows of a metal mine [3]

As all process water normally ends up in the tailings pond, it is primarily from here but also from waste rock deposits, that leakage of potentially harmful substances into the environment can occur. When ores containing sulphides are mined, the tailings and waste rock contain residual sulphides, which by the influence of oxygen from air can produce acid mine drainage (AMD) solubilizing harmful substances such as heavy metals from the mineral residues. Massive tailings ponds also present a risk of spill into the environment both through seepage (bottom and walls) as well as by structural failure of the dam. Several severe incidents with tailings pond failures have occurred in the last couple of years, for example in Spain, Brazil, Canada, Hungary and Finland, which have raised awareness of the risks. When striving for water conscious mining, all the challenges including water treatment for recycling, tailings dewatering, waste rock storage and process water treatment must be addressed.

There is currently a great potential for further development of mining in Northern Europe, especially in the Nordic countries, which is also drawing international interest because of an attractive political and regulatory environment. It is therefore important for this region to stimulate innovative initiatives to secure a sustainable mining sector, which also involves responsibilities for changing the traditional course of thinking towards a more environmentally conscious one when it comes to water and waste. This will not only provide the Nordic mining industry the conditions for long-term excellence and improved competitiveness, but also encourage universities, institutes and private companies engaged to become international spearheads in this sector. Canada was the

first region to address these issues probably because of a large and very active mining sector and at the same time a very fragile environment [2, 3].

Innovative thinking and implementation of new technologies offer possibilities to update and improve practices in the mining industry. The treatment of tailings and water recycling are mostly dealt with and discussed as separate issues, although their integration and system approach are essential for the development of sustainable and efficient mineral processes.

1.2 Objectives

The focus of this project was to develop technology concepts for innovative water and tailings management using technologies customized for the climatic conditions of the mining industry in the Nordic region. The target was to provide good-quality water suitable for recycling or discharge and to enable the safe disposal and utilization of tailings.

Figure 2: Artic conditions at a Nordic mine

Photo by Samrit Luoma, GTK

The specific aims were

- to establish a future Nordic research platform, an R&D network related to environmental issues in mining for the Nordic region to promote the exchange of ideas and collaboration in future project calls, and to propose ideas for future projects

- to identify and pre-evaluate the suitable technological alternatives for water and tailings treatment. The evaluation was made against the requirements set for recycled waters and safe utilization or disposal of tailings in the Nordic countries, keeping in mind the integration of solutions for water and tailings treatment
- to investigate and evaluate innovative technological solutions and to develop new know-how for mine water and tailings treatment. The main focus in new technology development was among other electrochemical treatment methods combined with existing methods (membranes, solid/liquid separation, eutectic freezing crystallization, biosorption, physical/chemical and biological methods)
- to develop simulation tools that can assist the mines in selecting the most efficient overall water management strategy for the complete mining activity
- to propose a technology concept and a plan for further development of the concept (including R&D proposals) for water conscious mining including recycling of process waters, safe (potentially dry) disposal of tailings and ideas for treatment solutions for discharged waters.

1.3 Nordic partners and Nordic excellence network

The project consortium represents forerunners within academic, research and industry bodies that will create a professional network and further brand the Nordic region as a top mining destination. In general, the project created an excellent basis for more extensive and active collaboration within the Nordic countries by generating information transfer and by establishing new co-operation relationships. Table 1 lists the roles of the partners involved in the Wascious project.

Table 1: Co-operation and area of expertise of project partners

Partner	Area of expertise field in the Wascious project	Co-operation in Wascious-project between partners
Research partners		
VTT Ltd, Finland	Sulphate and metal precipitation, biosorption, tools for solid waste characterization, literature reviews	Characterization of sludges from electrocoagulation process, overall project management and communication, coordination of surveys of current practice in Nordic mines
Lappeenranta University of Technology (LUT), Finland	Electrocoagulation and dewatering of slurries	Linking of process to other technologies, experimental data as input to simulation of water balance
Sintef, Norway	Development of tailored membranes for the removal of unwanted substances (sulphate...)	Part of laboratory work performed at LUT
NTNU, Norway	Eutectic freeze crystallization	Linking of process to electrocoagulation technology and membrane technology
Luleå University of Technology, Sweden,	Water recycling modelling using the HSC water balance model	Case studies: LKAB- Svappavaara and Kevitsa, characterization of solid residues from electrocoagulation experiments

Partner	Area of expertise field in the Wascious project	Co-operation in Wascious-project between partners
ISOR, Iceland	Data need for selection of potential technologies, aspects of concern in planning new gold extraction in Iceland	Active technology transfer and exchange of information on different technologies
Solution providers		
Outotec Oyj	Scenarios for tailings management	Exchange of information on technological solutions
Veolia	Pilot studies focusing on metal precipitation, nitrogen removal	Case studies: LKAB- Svappavaara and Kevitsa Exchange of information on technological solutions
ÅF Consulting	Planning of solutions in practice	Customer aspects in development of solutions
Participating mines and end-users		
Dragon Mining Oy, Finland	Collection and supply of water samples for laboratory tests, data on mine water	Information on treatment needs
Boliden Kevitsa Mining formerly FQM Kevitsa Mining	Water balance calculations and assistance for pilot studies	Information on treatment needs
LKAB Luossavaara-Kiirunavaara AB, Sweden	Water balance calculations and supply of waters for laboratory tests	Information on treatment needs
FinnMin – Finnish Mining Association	Contacts to Finnish mines	Data on mine operations, conditions, regulatory aspects
SveMin – Swedish Association of Mines, Mineral and Metal Producers	Contact to Swedish mines	Data on mine operations, conditions, regulatory aspects

This project has strengthened the Nordic research and knowledge in mine water management. There are limited resources in each Nordic country owing to their relatively limited sizes. Therefore, cross-border collaboration and exchange of information are crucial for technological development. Because the Nordic countries share a similar cultural behaviour, co-operation is easy and straightforward. Project co-operation also gives an opportunity to improve networking amongst the stakeholders, i.e. the mining industry, research organizations and technology providers.

The results from this project support the national strategic work on the management of mine water and mining waste. Furthermore, the results stimulate the development of environmental technology, for example regarding advanced clean technologies at a Nordic level. The goal is to ensure sustainable raw material extraction with low environmental impact seen from a lifecycle perspective.

Research regarding the management of mine water and tailings has been carried out in several national research projects, and to a limited extent in EU projects with the involvement of Nordic stakeholders (research organizations, mine companies, technologyproviding companies). One of the objectives has been to enable the exchange of information between partners on research carried out in specific projects.

Table 2: Links to national research programmes in the Nordic countries

Country	Specification	Link (further information)
Nordic	NordMin 2012–2016 A Nordic Network of Expertise for a sustainable mining and mineral industry funded by the Nordic Council of Ministers. Several projects supported.	http://www.ltu.se/research/subjects/Malmgeologi/Nordmin
Finland	Tekes Green Mining research programme (2011–2016): The central content of the programme consists of two thematic areas: 1) Intelligent and minimum-impact mines 2) New mineral resources In total over 30 research projects have been financed.	https://www.tekes.fi/ohjelmaj-palvelut/ohjelmaj-verkostot/green-mining/
Norway	NYKOS – New Knowledge on Sea Deposits (2014–2019) founded in the BIA programme, The research Council of Norway	https://www.forskingsradet.no/prosjektbanken/#!/project/236658/en
Sweden	MiMi project: Höglund & Herberts 2004 [4] Vinnova: Swedish Mining and Metal Producing Industry Research and Innovation Programme (2013–2016)	http://www.vinnova.se/sv/Resultat/Projekt/?query=gruvforskning&sn=SiteSeekerIndex

The vision is to establish a Nordic research platform related to environmental issues in mining for the Nordic region, enabling the exchange of ideas, further development related to the mining industry's needs as well as collaboration in future project calls, and facilitating ideas for future projects.

Figure 3: Partners involved in the Wascious project. Mines involved: Orivesi Mine Finland (Dragon Mining Oy), Kevitsa Mine Finland (Boliden) and LKAB (Sweden)

1.4 Dissemination of project results

The dissemination of the project in over 15 conferences or seminars and publication of results or plans for publication in 7 (of which 5 pending) scientific and popular journals were important targets in the project. A list of published articles is compiled under the respective technology development in Chapters 3 and 5. A project flyer was created in the project (available at NordMin webpage):

- http://www.ltu.se/cms_fs/1.120328!/file/WASCIOUS_brochure.pdf

The project has also supported the doctoral thesis of Maria Mamelkina on water treatment by electrocoagulation at LUT, Finland.

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2. Current solutions for mine water management

- Responsible partner: VTT.
- Contributors: All.

2.1 Objective of the survey

The aim of this work was to collect data about the current practices on water management at Nordic metal mines, and based on this information identify the key focus areas for technology development in the experimental studies and also to assess potential areas for improvement in mine water treatment.

All research partners and some industrial partners were involved in the work.

2.2 Operating metal mines in Nordic countries

2.2.1 *Finland*

Figure 4 shows the map of Finland with active mines and exploration projects in 2016 (http://new.gtk.fi/export/sites/en/information/services/maps/GTK_kaivokset_ja_tutki_muskohteet.pdf). Next sub-sections include short descriptions of active metal mines in Finland in 2016. Information related to the mines is in general somewhat older.

Figure 4: Mines and exploration projects in Finland in 2016
Active Metal Ore Mines and Current Projects

August 2016

Precious Metals

1. Iso-Kuotko gold - Agnico-Eagle Ltd
2. Hanhimäki gold - Dragon Mining Ltd & Agnico-Eagle Ltd JV
3. Kittilä gold - Agnico-Eagle Ltd
4. Kettukuninko gold - Taranis Resources Inc.
5. Naakenavaara gold - Taranis Resources Inc.
6. Kutuvuoma gold - Aurion Resources Oy
7. Rompas gold, uranium - Mawson Resources Ltd
8. Suhanko-Konttijärvi PGE - Gold Fields Arctic Platinum Oy
9. Kussamo gold - Dragon Mining Ltd
10. Kopsa gold - Belvedere Mining Oy
11. Piilola gold - Mineral Exploration Network (Finland) Ltd
12. Taivaljärvi silver - Sotkamo Silver AB
13. Pampalo gold - Endomines Oy
14. Hattu Belt gold - Endomines Oy
15. Rämepuro gold - Endomines Oy
16. Oskonmäki gold - BR Gold Mining Oy
17. Orivesi gold - Dragon Mining Oy
18. Jokisivu gold - Dragon Mining Oy
19. Kaapelinkuuma gold - Dragon Mining Oy

Base Metals

1. Riikonkoski copper, gold - Taranis Resources Inc.
2. Kevitsa nickel, copper, PGE - Boliden AB
3. Sakatti nickel, copper, PGE - AA Sakatti Mining Oy
4. Sodankylä nickel, copper, PGE - Magnus Minerals Oy
5. Lantinen Koillismaa (LK) nickel, PGE - Finmore Mining Oy
6. Kuhmo nickel - Boliden Kyliähti
7. Talvivaara nickel, zinc, copper - Terrafame Mining Oy
8. Pyhäsalmi zinc, copper, pyrite - First Quantum Minerals Ltd
9. Kyliähti copper, gold, zinc, nickel, cobalt - Boliden Kyliähti
10. Outokumpu copper - FinnAust Mining Plc
11. Hammasslahti copper - FinnAust Mining Plc
12. Valkeseenranta, nickel, copper - Boliden Kyliähti

Diamond

1. Kuhmo - Karelian Diamond Resources Plc

Other Commodities

1. Kolari iron, gold, copper - Hannukainen Mining Oy
2. Kemi chromium - Outokumpu Chrome Oy
3. Mustavaara vanadium - Mustavaaran Kaivos Oy
4. Otanmäki vanadium, iron, titanium - Vuorokas Oy

Source: GTK, Finland, 2016.

Jokisivu

- Location: Lat. 61° 7' 2"N, Long. 22° 37' 28"E.
- Operator: Dragon Mining Oy.
- Metals mined: Au.
- Mining method: Open pit.

Dragon Mining Oy mines gold in Orivesi and Jokisivu. Ores from both mines are transported to a mill in Sastamala.

Jokisivu mine is located 8 km southwest of Huittinen municipality. The deposit was discovered in 1964, but mining was not started before 2009. Jokisivu is an underground mine. The proved and probable ore reserve at the Jokisivu Gold Mine totals 261,000 t @ 3.5 g/t gold (28,900 ounces) as of 1 September 2015 (www.dragonmining.com/jokisivu). It is mainly free gold, but lesser proportions are locked inside arsenopyrite [1].

Kemi

- Location: Lat. 65° 46' 43"N, Long. 24° 41' 47"E.
- Operator: Outokumpu Chrome Oyj.
- Metals mined: Cr.
- Mining method: Underground.

Outokumpu Oyj's Kemi Cr-mine is the only chromium mine in the EU. It is located 7.5 km from Kemi town in northern Finland. The deposit was discovered in 1959, and enrichment of ore started in 1969. Operation was started as open pit mining, and underground mining started in 2003. Since 2006 all the production has come from underground operation. 1.3 Mt of ore is mined on a yearly basis, the Cr₂O₃ concentration of which is 26.5%. Proven reserves in 2010 were 37 Mt [1].

Kevitsa

- Location: Lat. 67° 41' 27"N, Long. 26° 57' 49"E.
- Operator: Boliden Kevitsa Mining formerly FQM Kevitsa Mining.
- Metals mined: Ni, Cu, Au, Pt, Pd.
- Mining method: Open pit.

Boliden Mineral ABs Kevitsa nickel-copper-platinum group elements (PGE) mine is located approximately 140 kilometres north-northeast of Rovaniemi. The deposit was discovered in 1985, and mining was commenced in 2012. Mining is carried out in an open pit. 6.7 Mt of ore were mined in 2015 (www.boliden.com).

Kittilä

- Location: Lat. 67° 54' 50"N, Long. 025° 24' 00"E.
- Operator: Agnico Eagle Mines.
- Metals mined: Au.
- Mining method: Underground.

Agnico Eagle's Kittilä gold mine is located around 35 km northeast of Kittilä municipality in Northern Finland. The deposit represents one of the biggest gold deposits in Europe. Commercial production of gold was commenced in 2008 as open pit mining. Today all the mining is done underground. In 2014 the amount of ore mined

was 1.2 Mt. Proven reserves in 2011 were 21.4 Mt (7). The ore at the Kittilä mine is refractory, making gold extraction relatively difficult because the gold is generally locked inside the two main sulphide minerals – arsenopyrite and arsenic-rich pyrite. Only about 4% is fine-grained “free gold” (not locked in sulphide grains) and is easier to extract (www.agnicoeagle.fi).

Kylylahti

- Location: Lat. 62° 51' 32"N, Long. 29° 19' 47"E.
- Operator: Boliden Mineral AB.
- Metals mined: Cu, Zn, Au.
- Mining method: Underground.

Boliden's Kylylahti mine is located in Polvijärvi, eastern Finland. The operations were commenced in early 2012. The operation comprises the Kylylahti underground mine located in the municipality of Polvijärvi, and the Luikonlahti processing plant located in Kaavi, some 43 km trucking distance from the mine. The yearly amount of ore mined is around 550,000 t. Current products are copper, gold and zinc (www.boliden.com).

Orivesi

- Location: Lat. 61° 39' 10"N, Long. 24° 09' 40"E.
- Operator: Dragon Mining Oy.
- Metals mined: Au.
- Mining method: Underground.

Dragon Mining Oy mines gold in Orivesi and Jokisivu. Ores from both mines are transported to a mill in Sastamala.

Orivesi mine is located in Orivesi some 40 kilometres northeast of Tampere in southern Finland. The deposit was discovered in 1982, and mining operations started in 1994. Mining is done underground, and the yearly amount of ore mined is around 200,000 t [1].

Pampalo

- Location: Lat. 62° 59' 10"N, Long. 31° 15' 45"E.
- Operator: Endomines Oy.
- Metals mined: Au.
- Mining method: Open pit & underground.

Endomines Oy's Pampalo mine is located 45 kilometres northeast of the municipality of Ilomantsi in eastern Finland. The gold deposit was discovered in 1990, and mining operations were started in 2010. The mine is operated both as an open pit and an underground mine. The yearly total amount of mined ore is around 370,000 t. Gold in the Pampalo deposit exists mainly as fine-grained (~0.03 mm in diameter) and is

mostly found in separate grains together with silicate minerals and pyrite. (https://fi.wikipedia.org/wiki/Pampalon_kultakaivos).

Pyhäsalmi

- Location: Lat. 63° 39' 32"N, Long. 026° 02' 33"E.
- Operator: First Quantum Minerals.
- Metals mined: Cu, Zn.
- Mining method: Underground.

First Quantum minerals Ltd.'s Pyhäsalmi Zn-Cu-S-mine is located in Pyhäjärvi in central Finland. The deposit was discovered in 1958 and operations were started already in 1962 as open pit mining. The open pit mining was stopped in 1975, after which all mining has been done underground. The ore contains around 3% chalcopyrite (CuFeS_2) 4% sphalerite (ZnS) and 66% pyrite (FeS_2). Around 1.4 Mt of ore is mined yearly. [1]

Talvivaara

- Location: Lat. 63° 58' 30"N, Long. 28° 00' 30"E.
- Operator: Terrafame.
- Metals mined: Ni, Zn, Co, Cu.
- Mining method: Open pit.

Terrafame's Talvivaara mine is a multimetal-mine located some 10 km southwest of Sotkamo town in central Finland. The deposits were discovered in the 1970s. Mining was started in 2008 from an open pit, which is still the method for mining. The Talvivaara deposit is a low-grade but large sulfidic Ni-Zn-Cu-Co deposit hosted by highly sulfidic-graphitic muds and turbiditic wackes (www.gtk.fi). Bioheap leaching is applied to produce metals. The mine is primarily focused on nickel and zinc. During the past couple of years, the mine has faced serious issues related mostly to the water management, and the amounts of ore mined have varied significantly. In full production around 18 Mt of ore would be transported to the heaps yearly (www.terrafame.fi).

2.2.2 Sweden

A map of Sweden with active mines in 2012 is shown in Figure 5 (Sveriges mineralstrategi 2013, <http://www.regeringen.se/rapporter/2013/02/n2013.02/>). Next sub-chapters contain short descriptions of Swedish metal mines in operation in 2013.

Figure 5: Mines in Sweden in 2012. Blue symbols: Iron; Red symbols: Base metals; Yellow symbols: Gold; Green symbols: industrial minerals

Source: SGU, Sweden, 2017.

Aitik

- Location: Lat. 67° 4' 18"N, Long. 20° 58' 10"E.
- Operator: Boliden Mineral AB.
- Metals mined: Cu, Au.
- Mining method: Open pit.

The Aitik copper deposit is located in the County of Norrbotten, northern Sweden. The deposit was discovered in the late 1930s, and production commenced in 1968 when large-scale, bulk-mining technology made exploitation feasible. The deposit is a low-grade porphyry style, chalcopyrite-pyrite mineralization hosted by Paleo- to Mesoproterozoic metamorphosed Svecofennian sediments and intrusives. Proven and probable ore reserves on 31 December 2011 were 710 Mt, with 0.25% Cu, 1.6 g/t Ag, and 0.15 g/t Au. During 2013, 30.07 Mt of ore and 38.24 Mt of waste rock were mined. [2]

Björkdal

- Location: Lat. 64° 56' 10"N, Long. 20° 35' 25"E.
- Operator: Björkdalsgruvan AB.
- Metals mined: Au.
- Mining method: Open pit and underground.

The Björkdal gold deposit is located in the Skellefte mining district in northern Sweden. The deposit was discovered in 1983, and open pit mining operations began in 1988. The gold occurs in sheeted quartz veins hosted by a granodioritic – tonalitic intrusion. Minor amounts of sulphides are present in the quartz veins. In 2014, proven and probable reserves were 6.544 Mt of ore with 2.05 g/t Au. During 2013, 1.26 Mt of ore and 3.04 Mt of waste rock were mined. [3]

Garpenberg

- Location: Lat. 60° 18' 45"N, Long. 16° 11' 30"E.
- Operator: Boliden Mineral AB.
- Metals mined: Zn, Pb, Cu, Ag, Au.
- Mining method: Underground with paste-fill.

The Garpenberg deposit is located in the Bergslagen mining province in south-central Sweden. The deposit is a polymetallic, limestone-and volcanic-hosted sulphide deposit. In 2008, proven reserves were 17 Mt at 5.6% Zn, 2.3% Pb, 104 g/t Ag, and 0.3 g/t Au. During 2013, 1.593 Mt of ore and 0.256 Mt of waste rock were mined. The ore was refined into 2,872 t of Cu concentrate, 36,071 t of Pb concentrate, and 126,752 t of Zn concentrate. [4]

Kankberg

- Location: Lat. 64° 55' 20"N, Long. 20° 16' 05"E.
- Operator: Boliden Mineral AB.
- Metals mined: Au, Ag, Te.
- Mining method: Underground with backfill.

The Kankberg mine is located in the Boliden Area in the Skellefte mining district, northern Sweden. The ore is polymetallic volcanic-hosted massive sulphide (VMS) deposit occurring in felsic metavolcanic rocks. The mine was in operation during the 1990s as a zinc and copper mine, and reopened in 2012 as a gold and tellurium mine. The ore reserve is about 2.78 Mt, with 4.1 g/t Au and 186 g/t Te. During 2013, 0.298 Mt of ore was mined. The ore is processed at the Boliden ore concentrator. Waste rock is backfilled into the mine. [5]

Kristineberg

- Location: Lat. 65° 3' 55"N, Long. 18° 33' 50"E.
- Operator: Boliden Mineral AB.
- Metals mined: Zn, Cu, Pb, Au, Ag.
- Mining method: Underground with backfill.

The Kristineberg mine is located in the western part of the Skellefte mining district in northern Sweden. The ore is a polymetallic volcanic-hosted massive sulphide (VMS) deposit occurring in felsic to intermediate and minor mafic metavolcanic rocks. Since the mine opened in 1940, 22.4 Mt of ore have been produced, with 1.0% Cu, 3.64% Zn, 0.24% Pb, 1.24 g/t Au, and 36 g/t Ag. During 2013, 0.681 Mt of ore were mined. The ore is processed at the Boliden ore concentrator. Waste rock and tailings from the Boliden concentrator are backfilled into the mine. [6]

Kiirunavaara

- Location: Lat. 67° 50' 23"N, Long. 20° 10' 40"E.
- Operator: Luossavaara-Kiirunavaara AB.
- Metals mined: Fe.
- Mining method: Underground, sub-level caving.

The Kiruna iron ore mine is located in the County of Norrbotten, northern Sweden, and is the world's largest underground iron ore mine. The deposit is an apatite – iron ore consisting of magnetite, hosted by felsic metavolcanic rocks. The iron content exceeds 60%. During 2014, 28.2 Mt of ore, 8.5 Mt of waste rock and 2.5 Mt of tailings were produced at the Kiruna mine. The ore was refined into 13.2 Mt of iron ore pellets. [7]

Malmberget

- Location: Lat. 67° 11' 50"N, Long. 20° 42' 25"E.
- Operator: Luossavaara-Kiirunavaara AB.
- Metals mined: Fe.
- Mining method: Underground, sub-level caving.

The Malmberget mine is located in the County of Norrbotten, northern Sweden, and is the second largest iron ore mine in Sweden. The deposit is an apatite-iron ore hosted by felsic to intermediate metavolcanic rocks, with magnetite as the dominant ore mineral. Hematite is present in significant amounts in certain parts of the deposit. The iron content exceeds 60%. During 2014, 15.7 Mt of ore, 4.1 Mt of waste rock and 2.2 Mt of tailings were produced at the Malmberget mine. The ore was refined into 8.5 Mt of iron ore products, of which 6.7 Mt were iron ore pellets. [7]

Svappavaara

- Location: Lat. 67° 38' 18"N, Long. 21° 00' 45"E.
- Operator: Luossavaara-Kiirunavaara AB.
- Metals mined: Fe.
- Mining method: Open pit.

The Svappavaara area is located in the County of Norrbotten, northern Sweden. Several apatite-iron ore deposits hosted by intermediate metavolcanic rocks are located in the area. The deposits are dominated by magnetite, with varying amounts of hematite. Ore from these deposits as well as from the Kiirunavaara mine is processed at an iron ore processing plant located at Svappavaara. In 2015, the Gruvberget deposit is in operation, and production is about to commence at the Leveäniemi deposit. During 2014, 2.0 Mt of ore and 10.3 Mt of waste rock were produced at the Gruvberget mine, and 3.3 Mt of iron ore pellets were produced at the Svappavaara plant. [7]

Lovisagruvan

- Location: Lat. 59° 43' 20"N, Long. 15° 10' 07"E.
- Operator: Lovisagruvan AB.
- Metals mined: Zn, Pb.
- Mining method: Underground with backfill.

The Lovisa mine is located in the Bergslagen mining province in south-central Sweden. The deposit was discovered in 1985 and is small but rich in zinc and lead ore, originally estimated to have contained 0.4 Mt of ore with 22% Zn, 14% Pb, and minor amounts of Ag. During 2013, 39,815 t of ore and 28,816 t of waste rock were mined. The ore is processed at the Garpenberg mine concentrator, and waste rock is used as backfill in the mine, without being transported to the surface. [8]

Mauriliden

- Location: Lat. 65° 3' 55"N, Long. 19° 30' 45"E.
- Operator: Boliden Mineral AB.
- Metals mined: Zn, Cu, Pb, Ag, Au.
- Mining method: Open pit.

The Maurliden mine is located in the Skellefte mining district in northern Sweden, and consists of two open pit mines, the Maurliden and Eastern Maurliden mines. The ore is a polymetallic volcanic-hosted massive sulphide (VMS) deposit occurring in felsic metavolcanic rocks. During 2013, a total of 0.276 Mt of ore was mined in the Maurliden and Eastern Maurliden mines. The ore is processed at the Boliden ore concentrator. Waste rock is deposited close to the open pits. [9]

Renström

- Location: Lat. 64° 55' 25"N, Long. 20° 5' 35"E.
- Operator: Boliden Mineral AB.
- Metals mined: Zn, Cu, Pb, Au, Ag.
- Mining method: Underground.

The Renström mine opened in 1952 and is the deepest mine in Sweden (1340 m). The ore is located in the eastern part of the Skellefte mining district in northern Sweden. It is a polymetallic volcanic-hosted massive sulphide (VMS) deposit occurring in felsic metavolcanic and metasedimentary rocks.

From 1953 to 2007 approximately 10 Mt of ore has been produced, with 6.3% Zn, 1.4% Pb, 0.7% Cu, 2.9 g/t Au, and 148 g/t Ag. In 2007, reserves and resources were estimated to about 4 Mt. During 2013, 0.239 Mt of ore was mined. The ore is processed at the Boliden ore concentrator, and waste rock from the mine and tailings from the Boliden concentrator are backfilled into the mine. [10]

Zinkgruvan

- Location: Lat. 58° 48' 48"N, Long. 15° 6' 27"E.
- Operator: Zinkgruvan Mining AB.
- Metals mined: Zn, Pb, Cu, Ag.
- Mining method: Underground.

The Zinkgruvan mine is located in the Bergslagen mining province in south-central Sweden. The ore is a stratiform, massive Zn–Pb–Cu–Ag sulphide deposit, hosted by metatuffites with beds of marble, dolomite, and quartzite. In 2014, ore reserves were estimated to be 11.6 Mt of Zn-rich ore, and 3.4 Mt of Cu-rich ore. During 2013, 1.14 Mt of ore was mined (0.924 Mt of Zn/Pb ore at 8.5% Zn, 4.2% Pb, and 138 g/t Ag, and 0.222 Mt of Cu ore at 1.7% Cu). The production in 2013 generated 0.975 Mt of tailings, of which 0.283 Mt was backfilled into the mine as paste-fill, and 0.692 Mt was deposited in the Enemossen tailings impoundment. [11]

2.2.3 Norway

Figure 6 shows the active mines and important resources in 2015 (received from NGU, 2017).

Figure 6: Mines in Norway 2015. Blue symbols: Mines in operation; Red symbols: Potential mines in future

Source: NGU, Norway, 2017.

In 2015 there were three active metal mines in Norway (see further: <https://www.regjeringen.no/en/dokumenter/strategy-for-the-mineral-industry/id717109/>). Below are short descriptions of these operations. Similar data to Finnish and Swedish metal mines was not available.

Sydvaranger (Bjørnevatn) represents one of the largest iron reserves in Norway, having estimated reserves of 565 Mt of ore grading 31% iron. In 2013 the mine was operated by Sydvaranger AS (<http://sydvarangergruve.no/>, https://en.wikipedia.org/wiki/Bj%C3%B8rnevatn_mine).

Kvanneveann iron mine in Mo i Rana is operated by Rana Gruber AS. Until 1999, iron ore was only mined by open pit methods. Today Rana Gruber operates the Kvanneveann underground mine as well as satellite deposits which are mined by open-pit methods. The extractable ore in the Kvanneveann Mine is estimated at 44.8 Mt based on sub-level caving between level 219 m to 123 m above sea level. The average iron content is estimated at 33.5%, including a magnetite content estimated at 3.5%. The ore in the underground mine is transported by trucks and crushed at the new underground crushing station. Conveyor belts transport the ore to the central underground storage silo. Ore from the open pit operations is taken the main crusher and blended with the underground ore in the silo. The crushed ore from the silo is loaded into railway wagons. The loading takes place underground due to the special climate conditions of the area. The ore is then transported by rail to the dressing plant at Gullsmedvik. (<http://www.ranagruber.no/index.php?id=2>).

Tellnes is the largest titanium deposit in Europe and probably the largest titanium deposit in production in the world today. The ore reserves are 380 Mt averaging 18% TiO₂ of which approx. 15% TiO₂ is as ilmenite (30% ilmenite) and 3% of the TiO₂ is within other minerals. Production from the Tellnes open pit is 2 Mt of ore and 1.6 Mt of waste rock, resulting in a production of approx. 580,000 t ilmenite concentrate (<http://www.mindat.org/loc-18742.html>). In 2013 the mine was operated by Titania A/S (<https://www.regjeringen.no/en/dokumenter/strategy-for-the-mineral-industry/id717109/>).

Store Norske is operating on coal mine at Spetsbergen. Two more have recently been closed down.

2.2.4 References

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11. Zinkgruvan Mining AB 2013. Miljörapport för Zinkgruvan Mining AB år 2013.

2.3 Summary of waste water qualities and quantities at metal mines

2.3.1 Data collection

A template was circulated among participating project partners to collect uniform data on current waste water quantities and qualities. The template is shown in Table 3.

Table 3: Template for data collection regarding waste water quantities and qualities at Nordic metal mines

Mine site	Remarks			
Fresh water intake, Mm ³ /a				
Water recycling rate (if available)				
Concentrations of contaminants in effluents and corresponding limit values	Effluent 1	Effluent 2	Effluent N	Limit values
Water discharge, Mm ³ /a				
Water discharge m ³ /h, average/peak				
pH				
Suspended solids, mg/l				
Contaminant 1, mg/l				
Contaminant 2, mg/l				
Contaminant 3, mg/l				

2.3.2 Finland

A summary of all the data collected from Finnish metal ore mines is shown in Table 4.

Table 4: Summary of waste water quantity and quality data together with corresponding limit values from Finnish metal mines. All limit values and current discharge values for concentrations are monthly average values. All data is from public environmental reports. Abbreviations: SS – suspended solids, WAD-cyanide – weak acid dissociable cyanide

Mine (year)	Details	Waste water discharge, Mm ³ /a	Regulated substances and limit values	Current discharge (water stream no.)
Kittilä (2014)	Au sulphide ore, underground mine	1: Mine water 2.1 2: Process water from tailings pond 0.74	pH: <10 SS: 20 mg/l As: 1.0 mg/l Sb: 0.5 mg/l Ni: 0.5 mg/l WAD-cyanide: 0.4 mg/l	7.5 (1). 8.2 (2) 1.1 mg/l (1). 2.2 mg/l (2) 0.03 mg/l (1). 0.13 mg/l (2) 0.30 mg/l (1). 0.05 mg/l (2) 0.04 mg/l (1). 0.04 mg/l (2) 0.008 mg/l (2)
Pyhäsalmi (2014)	Zn, Cu sulphide ore, underground mine	Water from clarification pond 4.7	pH: 5.5–9.5 SS: 10 mg/l Cu: 0.2 mg/l Zn: 1.0 mg/l	7.1 3.7 mg/l 0.02 mg/l 0.17 mg/l
Kevitsa (2015)	Ni, Cu sulphide ore, open pit mine	Water from clarification pond 2.3	pH: 6–9.5 SS: 10 mg/l Cu: 0.1 mg/l Ni: 0.3 mg/l SO ₄ : 2,000 mg/l	6.8–9.2 1.1–3.8 mg/l 0.001–0.002 mg/l 0.01–0.38 mg/l 266–694 mg/l

Mine (year)	Details	Waste water discharge, Mm ³ /a	Regulated substances and limit values	Current discharge (water stream no.)
Pampalo	Au ore, underground mine	Water from tailings pond 0.15 (estimate)	pH: 6–9.5 SS: 20 mg/l As: 0.2 mg/l Ni: 0.5 mg/l	No representative data available
Talvivaara (2014)	Ni, Zn, Co, Cu	Several water streams, total 4.8	pH: <10 SS: 20 mg/l SO ₄ : 6,000 mg/l Cu: 0.3 mg/l Mn: 6 mg/l Ni: 0.3 mg/l Zn: 0.5 mg/l Hg: 0.0005 mg/l Fe: 4 mg/l U: 0.01 mg/l Cd: 0.01 mg/l	No uniform data available
Orivesi (2014)	Au ore	Mine water 0.06	pH: 6.0–8.5 SS: 10 mg/l Al: 3 mg/l Zn: 3 mg/l	6.4–8.8 3.5 mg/l 1.8 mg/l 1.0 mg/l
Jokisivu (2014)	Au ore	Mine water 0.09	pH: 6.5–9.0 SS: 20 mg/l	7.6–8.1 7.4
Kylylahti	Cu, Co, Ni, Zn ore		SS: 10 mg/l	No data found
Luikon-lahti processing plant (2013)	Cu, Co, Ni, Zn ore from Kylylahti mine	Process water from clarification pond 2.6	pH: 6.0–8.0 Fe: 3 mg/l (target value) Ni: 0.3 mg/l (target value) Cu: 0.3 mg/l (target value) Co: 0.3 mg/l (target value) As: 0.1 mg/l (target value) SS: 15 mg/l (target value)	6.7–7.2 0.33* (* calculated from yearly load kg/a and yearly discharge m ³ /a) 0.11 * 0.004 * 0.005 * 0.02 * 0.002 *

2.3.3 Sweden

A summary of all the data collected from Swedish metal mines is shown in Table 5.

Table 5: Summary of waste water quantity and quality data together with corresponding limit values from Swedish metal mines. Swedish data was collected mainly from public environmental reports (miljörapport) and represent year 2013 (see references in 2.2.4). Data from Boliden mines was added by Boliden. Abbreviations: SS – suspended solids, WAD-cyanide – weak acid dissociable cyanide

Mine	Details	Waste water discharge, Mm ³ /a	Regulated substances and limit values	Current discharge
Aitik (2015)	Cu, Au sulphide ore, Open pit mine	Process water from clarification pond 8.4	pH 6.2–7.5 monthly average, 6–8 max SO ₄ ²⁻ : 750 mg/L monthly average, 1 350 mg/L max Cd: 0.24 µg/l monthly average, 0.5 µg/l max Co: 12 µg/l monthly average, 24 µg/l max Cu: 12 µg/l monthly average, 24 µg/l max Ni: 12 µg/l monthly average, 24 µg/l max Zn: 24 µg/l monthly average, 48 µg/l max	6.6–7.25 742 mg/l 0.086 µg/l 10.47 µg/l 4.08 µg/l 5.1 µg/l 10.6

Mine	Details	Waste water discharge, Mm ³ /a	Regulated substances and limit values	Current discharge
Björkdal (2013)	Au ore, open pit & underground mine	1: Mine water 0.58 2: tailings pond 0.30	SS: 15 mg/l NO ₃ -N: 20 mg/l NO ₂ -N: 0.2 mg/l	14.6 mg/l (1) 21.7 mg/l (1) 0.49 mg/l (1)
Garbenberg (2015)	Zn, Pb, Cu, Ag, Au sulphide ore, underground mine	Discharge from tailings pond 3.5	SS: 10 mg/l As: 40 µg/l Cd: 1 µg/l Cr: 5 µg/l Cu: µg/l Pb: 40 µg/l Zn: 300 µg/l N tot: 10 mg/l	2.7 mg/l 2.6 µg/l 0.14 µg/l 0.5 µg/l 2.0 µg/l 0.3 µg/l 61.5 µg/l 5.9 mg/l
Kankberg (2015)	Au, Ag, Te sulphide ore, underground mine	Water from clarification pond 0.69	N tot: 60 mg/l Tot ext. aliphatic 0.5 mg/l As: 15 µg/l Cu: 30 µg/l Pb: 3 µg/l Cd: 1.5 µg/l Zn: 200 µg/l	39 mg/l 0.1 mg/l 1.6 µg/l 4.3 µg/l < 0.5 µg/l 0.3 µg/l 102 µg/l
Kristineberg (2015)	Zn, Cu, Pb, Au, Ag sulphide ore, underground mine	tailings pond 2.97	SS: 10 mg/l N tot: 10 mg/l pH > 7 Cd 2 µg/l Cu 15 µg/l Pb 5 µg/l Zn 300 µg/l Ni 5 µg/l As 5 µg/l	2.2 mg/l 3.1 mg/l 8.1 0.7 µg/l 3.6 µg/l < 0.2 µg/l 76 µg/l 0.7 µg/l < 1 µg/l
Kiirunavaara (2013)	Fe ore, underground mine	Process water from clarification pond 4-9	SS: 10 mg/l	4.2
Malmberget (2013)	Fe ore, underground mine	Process water from clarification pond 4-9	SS: 10 mg/l	<10 mg/l (<4.0-18)
Lovisagruvan (2013)	Zn, Pb sulphide ore, underground mine	Mine water from clarification pond 0.06	SS: 15 mg/l Pb: 200 µg/l Zn: 400 µg/l N tot.: 10 mg/l	10.8 mg/l 167 µg/l 411 µg/l 3.7 µg/l
Mauriliden (2015)	Zn, Cu, Pb, Ag, Au sulphide ore, open pit mine	Water from clarification pond 0.32	SS: 15 mg/l As: 40 µg/l Cd: 5 µg/l Cu: 20 µg/l Pb: 3 µg/l Zn: 400 µg/l Tot ext aliphatic 0.5 mg/l N tot.: 10 mg/l	6.7 mg/l 34.3 µg/l 3.2 µg/l 14.5 µg/l 0.32 µg/l 328 µg/l < 0.1 mg/l 4.2 mg/l
Renström (2015)	Zn, Cu, Pb sulphide ore, underground mine	Outflow from treatment plant 1.25	SS: 20 mg/l N tot: 20 mg/l As: 20 µg/l Cd: 4 µg/l Cu 30 µg/l Zn 1,000 µg/l	7.0 mg/l 12.5 mg/l 2 µg/l 1.2 µg/l 2.2 µg/l 520 µg/l
Zinkgruvan (2013)	Zn, Pb, Cu, Ag sulphide ore, underground mine	Water from clarification pond 0.24	SS: 5 mg/l Cd: 0.50 µg/l Cu: 20 µg/l Pb: 75 µg/l Zn: 500 µg/l	2.5 mg/l 0.22 µg/l 1.7 µg/l 34 µg/l 180 µg/l

2.3.4 Norway

Water quality data was not widely and publicly available from Norwegian metal mines for the purposes of this report.

Waste water quantity data from the Sydvaranger mine (Bjørnevatn) was not available. The environmental permit of the mine (2008.190.T, 2008) does not set limit values for compounds in the effluents from the mine site. The mine has a permit to discharge 4 Mt per year of fine suspended solids (tailings) and 65 t of chemicals (polyacrylamide (50 t, polyDADMAC (15 t) per year in Bøkfjorden and Langfjorden.

According to the emission report of the Kvanneveann mine in 2015 (<http://www.norskeutslipp.no/en/Miscellaneous/Company/?CompanyID=5124>), the mine released some 20.5 M m³ of waste water together with 2.8 Mt of suspended solids (tailings), both of which are disposed of in the Ranfjorden fjord.

The environmental permit of Tellnes mine sets limits for daily release of suspended solids together with nickel (1.5 kg/day) to be discharged in various water bodies (Jøssingfjorden, Logsvassdraget and in the river Sandvekkelava, Environmental Permit no. 408/2000-052). The emission report of the Kvanneveann mine in 2015 includes annual emissions for many contaminants in the water, but no volume of discharged wastewater (<http://www.norskeutslipp.no/en/Miscellaneous/Company/?CompanyID=5123>).

2.4 Summary of current waste water treatment practices at metal mines

2.4.1 Finland

Table 6: Current water treatment operations at Finnish metal mines

Mine	Details	Water treatment operations	Volume of treated water (Mm ³ /a)	Performance characteristics
Kittilä (2014)	Au sulphide ore, underground mine	Cyanide destruction from cyanide leaching process water. Water from flotation tailings pond and mine water enter overflow wetlands, after which they are discharged to a river	0.86 ¹	Removal efficiencies: SO ₄ 10%, As 98%, Sb 84%, N tot. 60%
Pyhäsalmi (2015)	Zn, Cu sulphide ore, underground mine	Liming of water, settling at tailings and clarification ponds. Aeration of effluent at winter time	6.9	Not available
Kevitsa (2015)	Ni, Cu sulphide ore, open pit mine	Liming of water in flocculation tank, clarification pond, optionally neutralization after clarification (sulfuric acid)	1.8	Not available
Pampalo	Au ore	Clarification at tailings pond	0.5 (estimate from permit application)	Not available
Talvivaara	Ni, Zn, Co, Cu	Neutralization + clarification	No uniform data available	Not available
Orivesi (2014)	Au ore	Mine water neutralization with NaOH + settling ponds	approx. 0.1	Not available
Jokisivu (2014)	Au ore	Settling ponds	0.09	Not available
Kylylahti	Cu, Zn, Au	No data available		

2.4.2 Sweden

Table 7: Current water treatment operations at Swedish metal mines

Mine	Details	Water treatment operations	Approximative Volume of treated water (Mm ³ /a)	Performance characteristics
Aitik (Sweden)	Cu, Au sulphide ore, Open pit mine	Liming of water waste rock and tailings seepage water prior to sedimentation in the tailings pond, with further reduction of suspended solids in clarification pond.	45	¹⁾
Garbenberg (Sweden)	Zn, Pb, Cu, Ag, Au sulphide ore, underground mine	Dewatered tailings are back filled (paste-fill). Treatment plant for oxygen consuming compounds, thiosalts and metals using Fenton-process (Addition of hydrogen peroxide, iron sulphate and lime). Treats water from tailings pond. Biological Treatment plant for nitrogen removal in mine water using the MBBR®-technology	6	Reductions: As 81% Cd 83% Cu 84% Pb 92% Zn 89% Thiosalts: 98.5% Nitrogen 87%
Björkdal (Sweden)	Au ore, open pit & underground mine	Clarification ponds (after the tailings pond)	1	Not known ¹
Kankberg (Sweden)	Au, Ag, Te sulphide ore, underground mine	Groundwater from the mine and surface water are collected and pumped to a treatment plant and then on to the tailings and ponds at the Boliden concentration plant. In the treatment plant the pH is raised to 9.5 with slaked lime in a mixing well. The metals precipitate as sludge in two parallel sedimentation ponds. The metal sludge is excavated and backfilled in to the mine. The water is released into a clarification pond and from the clarification pond released in to a ditch. The water from the ditch eventually feeds in to the tailings pond in Boliden, where the water is treated again.	0.7	Removal efficiencies: As and Pb > 90% Cd, Cu and Zn > 95%
Kristineberg (Sweden)	Zn, Cu, Pb, Au, Ag sulphide ore, underground mine	Water pumped from the mine is treated in a water treatment plant before it runs through three of the remediated tailings impoundments. The last Impoundment 4 is limed before the water is discharged into a receiving stream.	3	Removal efficiencies: As > 85% Pb, Cu and Zn > 99% Ni and Cd > 97%
Kiirunavaara (Sweden)	Fe ore, underground mine	Clarification pond (after the tailings pond). In addition, a pH-adjusting plant is installed at the outlet from the clarification pond. Sulfuric acid is added to the water when necessary in order to lower the pH-value and thereby reduce the ammonia content in outgoing water.	4–8 (The whole amount of water is not treated in the pH-adjusting facility. The pH is adjusted only if needed.	SS 24 mg/l -> 5.4 mg/l (clarification pond)
Malmberget (Sweden)	Fe ore, underground mine	Clarification ponds (after the tailings pond)	4–8	Not known ¹
Svappavaara (Sweden)	Fe ore, open pit mine	Clarification pond (after tailings pond)	1	Not known ¹
Lovisagruvan (Sweden)	Zn, Pb sulphide ore, underground mine	Clarification pond	0.06	Not known ¹

Mine	Details	Water treatment operations	Approximative Volume of treated water (Mm ³ /a)	Performance characteristics
Mauriliden (Sweden)	Zn, Cu, Pb, Ag, Au sulphide ore, open pit mine	Groundwater from the pits and surface water are collected and pumped to a treatment plant. The groundwater from the mine is pumped into a mixing tank where flocculant is added. After the tank the water is fed in to a settling pond where mineral particles are precipitated. From a clarification pond, the mine water is pumped in to the treatment plant. In the treatment plant the pH is raised to 10 with slaked lime. The metals are precipitated in lamella thickeners and centrifugal thickeners, Flocculants are added before the thickeners. After the treatment plant the water flows to settling and clarification ponds.	0.32	Removal efficiencies: Cd and Pb > 99.5% As, Cu and Zn > 99.9%
Renström (Sweden)	Zn, Cu, Pb sulphide ore, underground mine	Groundwater and surface water are collected and pumped to a treatment plant. The pH is raised with slaked lime to 9.5 in a mixing well. The metals precipitate in a lamella thickener. Flocculant is added to the water before the thickener. Water from the thickeners is fed to sand filters.	1.25	Removal efficiencies: Cd > 87% As > 92% Cu > 90% Zn > 84%
Zinkgruvan (Sweden)	Zn, Pb, Cu, Ag sulphide ore, underground mine	Clarification ponds (after the tailings pond)	?	Not known 1

Note: 1) Inlet water characteristics missing.

2.4.3 Norway

No water treatment examples or performance data were available from Norwegian metal mines. According to the available permits and reports (see Sections 2.2 and 2.3), the mine effluents are discharged into the receiving water bodies without treatment.

2.5 Possible future mining activities

2.5.1 Sulphide contamination from possible mines in Iceland

Exploration for precious metals in Iceland, in particular gold, has been ongoing for the last 25 years. Anomalies have been located which may develop in future into mining enterprises. These anomalies so far discovered are low sulphidation-low base metal type. Contamination because of mining activities has not been high on the agenda to date. It is, however, to be expected that environmental issues will be raised if a mine is opened.

The two anomalies presently most promising are located within sensitive hydrological areas, one which delivers river water to a lake and then a river that passes through the capital, Reykjavik. The other crosses fertile farmland and popular salmon rivers. Having the knowledge and experience of how to purify contamination will

therefore be of great importance. We look forward to learning from the extensive Scandinavian experience, and to incorporate the new thinking necessary when a mine is opened in Iceland.

2.5.2 *H₂S emission and contamination from hydrothermal power stations in Iceland*

Geothermal utilization is very extensive in Iceland where about 90% of all houses use geothermal energy for hot tap water and for central heating. This water is near free of HS⁻ (dissolved H₂S gas) and drinkable. About 1/3 of electrical power production comes from geothermal sources. These are from high-temperature geothermal systems, which in a way may be considered as the surface manifestations of the deeper geothermal resources that produce the ore enrichments.

The geothermal fluids are relatively H₂S and CO₂ enriched, which, as power production has increased, is now considered as a pollutant in the surrounding environment, both with regard to contamination with the underlying fresh groundwater systems and not least as air pollution. This has resulted in a large effort by the power companies to establish methods to get rid of this pollution. The aqueous S-enriched fluids are increasingly being re-injected back into the geothermal reservoir. The H₂S gas removal has been more problematic, but extensive tests are now underway to establish methods to pump this back into the underground reservoirs where H₂S will eventually recrystallize as sulphides.

2.5.3 *Example of water quality and quantity in an Icelandic power plant*

Most of the high-temperature systems in Iceland have freshwater composition with very low dissolved metal concentrations. A few partly saline high-temperature systems are presently being harnessed on the Reykjanes Peninsula, with the Reykjanes high-temperature system being most saline with fluids equivalent to that of seawater. Metal concentrations are thus very low and far below lower water quality limits within the low-salinity systems but increase towards higher salinity ones. The Reykjanes saline system is the most metal rich system and is compared here with the water quality values used in Iceland.

The following tables contain data from a geothermal site in Iceland. The data was fitted to the same templates with the metal mines to see possible similarities with the water streams from the mining industry.

Table 8: Water quality data from a geothermal site in Iceland

Location	Reykjanes Power station Turbine 1+2 2012	Remarks
Downhole fluid intake, Mt, 2012	15.640	The fluid is two phase; ~water (85%) + steam (15%)
Water reinjected	1.417	
Concentrations of contaminants in effluents and corresponding limit values µg/L	Discharge brine (M20272) which has been mixed with condensed water (~10%) and seawater (~80%)	Limit values This water flows to the sea which is in < 1km distance
°C	47	At sampling
As	13.9	III* Sample locations at the shore
Cd	0	<I*
Cr	0.149	<I*
Cu	1.47	II*
Ni	0.777	II*
Pb	0	<I*
Zn	0	<I*

Limit values shown in 2.6 exist in Iceland for metals in surface water. The limit values are based on protection of the biosphere.

Table 9: Icelandic limit values for metals in surface waters

	I	II	III	IV	V
Metal	µg/l	µg/l	µg/l	µg/l	µg/l
Cu	0.5	0.5-3	3-9	9-45	>45
Zn	5	5-20	20-60	60-300	>300
Cd	0.01	0.01-0.1	0.1-0.3	0.3-1.5	>1.5
Pb	0.2	0.2-1	1-3	3-15	>15
Cr	0.3	0.3-5	5-15	15-75	>75
Ni	0.7	0.7-17	15-45	45-225	>225
As	0.4	0.4-5	5-15	15-75	>75

Note: I: very little or no danger of impact.
 II: little danger of impact.
 III: proposed impact on delicate/sensitive biosphere.
 IV: Presumed impact.
 V: Always unsatisfactory water conditions for the biosphere/dilute area.

Table 10: Water quality data in and out to/from discharge brine diluted with condensed water at an Icelandic power station

Location	Reykjanes Power station, 2012		Remarks
Water treatment technology	Dilution		
Short description of technology	Discharge brine (~10%) is diluted with condensed water (~10%) and cold seawater (80%)		
Volume of treated water, Mt, 2012	15.640		
Other essential data (retention time etc.)			
Performance	Water IN (RN11+RN12) average 2012	Water OUT (average Turbine 1+2 (M20263+20264):2)	Wells RN11 and RN12 are the most powerful wells in each system
°C	199		At sampling
As µg/L	88	92.7	Turbine1+2 are 15 wells, average composition is taken from well RN11 and RN12
Cd µg/L	0.017	0.082	Turbine1+2 are 15 wells
Cr µg/L	0.15	0.000149	Turbine1+2 are 15 wells
Cu µg/L	0.681	1.185	Turbine1+2 are 15 wells
Ni µg/L	6.66	19.85	Turbine1+2 are 15 wells
Pb µg/L	0	0	Turbine1+2 are 15 wells
Zn µg/L	36	5.37	Turbine1+2 are 15 wells

2.6 Summary

Millions of cubic meters of waste water are discharged into the receiving water bodies from several metal mines in Sweden and Finland. In addition to the discharge limit values given as concentrations (mg or µg per litre), some mines also have limits for maximum amounts (kg/year) of regulated compounds that can be discharged yearly. Furthermore, almost all discharge limits refer to monthly average concentrations in effluents and not for peak concentrations.

2.6.1 Current limit values for mine effluents

In Sections 2.3 to 2.5 the mine-specific limit values for contaminants in mine effluents are summarized together with qualities and quantities of current effluents from Nordic metal mine sites. Based on the data gathering regarding current limit values, it appears that the concentration of suspended solids (SS) is regulated at almost every site in Sweden and Finland. Common limit values for suspended solids in mine effluents are in the range of 10 to 20 mg/l in both Finland and Sweden. The majority of Swedish metal

mines have limit values for nitrogen, most often as total nitrogen. Some Swedish mines also seem to face challenges in complying with the limit values for nitrogen. Finnish metal mines did not have limit values for nitrogen compounds at the time of data gathering. Regarding limit values for metals, Swedish metal mines most often have very strict limit values in comparison to Finnish mines. The Swedish limits for metals in mine effluents are typically in the range of micrograms or tens of micrograms per litre, whereas typical Finnish limit values are in the range of milligrams per litre or parts of it. Sulphate, a common challenge in waste waters at sulphide mines, is yet only regulated in a couple of cases in Finland and Sweden.

2.6.2 *Current practices in water treatment*

Clarification ponds for the removal of suspended solids are still today the most common water treatment method at Nordic metal mines. In the clarification pond the suspended solids settle to the bottom, and the overflow is discharged to the receiving water body, or alternatively is recycled back into the processing plant. At several mines, the clarification pond is also preceded by lime addition in order to raise the pH in water and precipitate dissolved metals. At sulphate concentrations above 2,000 mg/l also some gypsum will precipitate, which lowers the sulphate concentration slightly.

The recent strict limit values for nitrogen compounds in discharge from Swedish mines have resulted in implementation of nitrogen removal technologies at some Swedish mine sites.

2.6.3 *Selected target parameters for the experimental work*

Based on the data gathered from active metal mines, the project group made a decision on the target compounds on which the technology development for water treatment would concentrate.

Sulphate is becoming an increasing concern for discharge of water from especially mining of sulphide containing ores into inland water bodies. In contact with organic material in sediments, sulphate is reduced to sulphide and below pH 7.5 sulphide is partly present in the form of hydrogen sulphide. Hydrogen sulphide is toxic to aquatic animals because it interferes with the re-oxidation of cytochrome A₃ in respiration. The 96-hour lethal concentration 50 (LC₅₀) values for hydrogen sulphide for freshwater fish species range from 20 to 50 µg/L, and much lower concentrations stress fish and make them more susceptible to disease.

Limit values have been given for *nitrogen compounds* in water discharged from Swedish mine sites. Ammonia (measured as ammonium and converted to ammonia through pH equilibrium equations) and nitrate/nitrite are regulated at some sites in Sweden in addition to total nitrogen. A compilation of knowledge about the effects of ammonia was made by Canada's central environmental authority (CCME) [1]. The following average acutely toxic level (NH₃) for salmonids was found: 0.48 mg/l for rainbow trout (expressed as LC₅₀ for NH₃). Corresponding NOEC for rainbow trout was 0.025 mg / l. Based on these and similar tasks, CCME has developed guidelines, which

indicate the levels of various substances that should not be exceeded for a long time in fresh water to avoid the risk of damage to aquatic organisms [2]. For ammonia (NH_3) 19 $\mu\text{g/l}$ is recommended as a guideline to avoid chronic effects after prolonged exposition. In the Finnish Council of State decision 1172/1999 on protection on inland waters in order to protect living conditions of fish, there are mandatory and indicative nitrogen limit values for so called salmon and roach waters. The mandatory limit values for unionised ammonia NH_3 is 0.025 mg/l and for total ammonium NH_4 1.0 mg/l.

Low limits values for many metals in water discharged from several Swedish metal mines give justification to look also at metal removal from mine waters. Limit values for metals also exist in Finland, although they are often an order of magnitude higher than in Sweden. Some of the most common metals, *Copper, Nickel and Zinc* were chosen as key elements for the experimental work.

2.6.4 References

1. Environment Canada (2001). Ammonia in the aquatic environment. Priority substances list assessment report. ISBN 0-662-29192-1.
2. Canadian Council of Ministers of the Environment (2011). Canadian environmental quality guidelines for the protection of aquatic life.

2.7 State-of-the-art on water treatment

The purpose of this section is to briefly describe the current industrially available solutions for removing the key contaminants identified in the previous section. The following tables give a short introduction to the available technologies. More detailed information can be found from the references provided.

Table 11: State of the art technologies for sulphate removal

Technology (Reference no.)	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Chemical precipitation [1,2,5,7,8,11,15,19,21,25,27]	<p>In general, chemical precipitation usually consists of a reactor for addition of chemicals and mixing and a clarifier and/or a filter for the separation of solids and treated water. Co-precipitation also removes metals simultaneously.</p> <p>The addition of alkaline agent such as limestone (CaCO_3), CaO, or Ca(OH)_2, NaOH or Na_2CO_3 not only can be used to raise the pH and to achieve precipitation of metals, but also for some removal of sulphate as gypsum takes place when calcium chemicals are used. Lime is usually added to the reactor as water slurry. In addition, lime and cement kiln dusts, fluidized bed combustion ash, fly-ash, Ca(OH)_2, or seawater neutralized red mud (from bauxite processing) might potentially be used. The choice of alkaline reagent depends on site-specific criteria.</p> <p>Lime (Ca(OH)_2) addition to raise pH in sulphate bearing mine water to 10.5-12 results in gypsum ($\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$) precipitation at sulphate concentrations above approx. 2 000 mg/l thus lowering sulphate concentration in water. Solubility of gypsum is around 1,500-2,000 mg/l which represents the treatment efficiency of lime addition for sulphate removal.</p> <p>Resulting sludge in conventional "Low density treatment" (LDS) has solids content 2...7%. So-called High Density Treatment (HDS) can reach solids content > 30% by recycling sludge back to the neutralization tanks for crystal growth and applying more efficient flocculation. Thus, the volume of waste sludge and the chemical usage are reduced. HDS is described as "the current state-of-the-art lime neutralization process".</p> <p>Ettringite precipitation (addition of lime and aluminium reagent) can be used to remove sulphate to lower residual concentrations, even <100 mg/l. Ettringite processes have been developed for sulphate bearing mine waters with sulphate concentrations > 2 000 mg/l.</p> <p>Precipitation with Ba salts is another chemical precipitation option capable for very low residual sulphate concentrations</p> <p>Co-precipitation is likely the most applicable option at very high sulphate levels (>10,000 mg/l)</p>	<ul style="list-style-type: none"> + Proven technologies + Wide range of different reagents available + Commercial processes available (e.g. SAVMIN, Outotec's process, Veolia's LoSO₄, HDS (High Density Sludge), CSIR ABC) + The least costly method in general + Ettringite and barium salt processes produce water with low sulphate concentrations + Stable and easily controllable process + Adaptable to changes in water flow and quality + Can be operated on large water volume. 	<ul style="list-style-type: none"> - Big amount of sludge with low solids content and poor dewaterability requiring appropriate disposal is generated (especially in LDS) - Need for sludge treatment and disposal increases costs - Reagent costs high in some processes - The long-term stability of sludge and possible release of metals is a specific concern 	<p>Lime precipitation often results in residual SO_4-concentrations of 1,500–2,000 mg/l. Sufficient when relatively modest effluent quality standards need to be met.</p> <p>In general, HDS can result in SO_4-concentrations of <2,400 mg/l.</p> <p>Ettringite precipitation has shown to remove sulphate to levels <100 mg/l from mine waters. Also, precipitation with Ba salts is efficient.</p> <p>SAVMIN process has proven efficient for treatment of high sulphate waters, although it is expensive.</p>	Many commercial processes available (e.g. SAVMIN, Outotec's process, Veolia's LoSO ₄ , CSIR ABC)

Technology (Reference no.)	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Ion exchange [4,9,11,15, 19,21,23,26, 28,29,30]	<p>Ion exchange is a process where ions are reversibly exchanged between a substrate and its surroundings. The process utilizes a polymer resin packed column for the removal of target species. The resin contains active functional groups that capture target ions and release an equivalent ion to the solution. Usually the resin can exchange cations or anions, but some (amphoteric) are capable of exchanging both, depending on the pH. The loaded ions are removed from the resin by regeneration. The volume of regenerant solution is considerably smaller than the influent flow, thus resulting in effective concentration of target ions into regenerant.</p> <p>Ion exchange is mainly applicable for waters in the pH range of 4 to 8 containing low concentrations of suspended solids, Fe and Al. Suitable ion exchange columns can also be used to remove sulphate from mine wastewater. EARTH process recovers uranium, sulphate and metals. Conventional ion exchange processes are not applicable for high CaSO₄ waters due to scaling. Modified processes, such as GYPCIX (Gypsum Ion Exchange) are developed to overcome these problems. The GYPCIX process utilizes continuous fluidized bed ion exchange process to remove calcium and sulphate from water saturated with gypsum. The resin can be recovered by sulphuric acid and lime.</p>	<ul style="list-style-type: none"> + Removal can be targeted to specific contaminants + Suitable for dilute solutions + Low temperature dependence + Not sensitive for toxic substances + Relatively simple treatment systems + Modular configuration possible + GYPCIX: inexpensive chemicals, high water recovery. 	<ul style="list-style-type: none"> - Need for extensive pretreatment (e.g. pH adjustment, oxidation, solids removal) - Need for the treatment and/or disposal of regenerant as well as spent resin - High treatment costs - Limitations in cold conditions - Organic compounds, oxidants or high temperatures can degrade the resin - GYPCIX process produces large volume of gypsum sludge 	<p>The GYPCIX process is capable of > 95% sulphate removal. GYPCIX can be used to treat solutions with sulphate up to 2,000 mg/l. Results in sulphate concentration of 200 mg/l.</p>	<p>Ion exchange is not state-of-the-art in full-scale for mine water treatment but possesses future potential. Many processes seem to be technically efficient and can be used to reach water quality targets, but only a few processes are commercially viable (e.g. EARTH process) or widely used. GYPCIX is tested on a small scale, is not commercially viable.</p>
Membrane treatment [3,4,9,10,13, 21,26,27,28, 19,31,32,40]	<p>Different types of membranes can be utilized in sulphate removal. The separation is based on sieving effects as well as electrorepulsive forces due to membrane surface charge. Membrane distillation is a thermally driven process.</p> <p>Conventional nano (NF) or reverse osmosis (RO) process requires pretreatment (e.g. HDS high-density sludge process) of mine water in order to reduce metals concentration to an acceptable level considering membranes. In RO process, a semi-permeable membrane excluding all but pure water is used to separate strong and dilute solutions. By applying an external hydraulic pressure to the saline brine, water is forced to pass through the membrane against osmotic pressure.</p> <p>Electrodialysis (ED) uses electric potential in a separation of dissolved salts and water. ED is based on migration of dissolved solids (i.e. charged ions) through a membrane. Water molecules cannot pass the membrane and pure water stays on the other side. In electrodialysis reversal (EDR) the polarity of electrodes is periodically changed which reduces, e.g., membrane fouling. In addition, EDR is not sensitive to pH or temperature of the water. Sulphuric acid from mine water with high sulphate concentration can be recovered also by electrodialysis. However, this process has not been demonstrated on a large scale.</p>	<ul style="list-style-type: none"> + Wide range of pollutants can be removed, both organic and inorganic + Can remove monovalent ions unlike other treatment methods + Possibility for recovery of valuable resources + Produces high quality discharge water for further use + Low chemical consumption + Small footprint area + Modular configuration possible + Ease of operation + Considered as established technology to potentially be used for mine effluent treatment. 	<ul style="list-style-type: none"> - Need for extensive pretreatment to reduce concentrations of, solids, hardness, sulphate, silica etc. to acceptable level to protect the membranes - High operating (electricity, chemicals) and maintenance cost - High disposal costs for brine and pretreatment sludges - Risk of membrane fouling, probably due to suspension of SiO₂ particles 	<p>Conventional RO process is usually applicable for water with low calcium (< 100 mg/l) and sulphate (< 700 mg/l) concentrations. Processes like SPARRO can be applied to waters with high gypsum formation potential. It has been shown to reduce sulphate concentration from 6,639 mg/l to 152 mg/l. NF has been shown to reduce sulphate content from 1 850 mg/l to 65 mg/l. SPARRO is as of present only suited process for scaling water treatment.</p>	<p>The utilization of membrane distillation in water recovery as well as acid and metal concentration has been recently demonstrated for mining wastewater. However, as solids are often present in mine water, the implementation of membranes in the mine waste treatment has been slow. Also high costs may hinder the use of this technology. RO is a proven technology. Full scale plants exist SPARRO and NF have been tested on a pilot scale. Electrodialysis has not been demonstrated on a large scale.</p>

Technology (Reference no.)	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
SRB (sulphate reducing bacteria) systems [2,12,33,35, 36,37]	<p>Bioremediation relies on the ability of some microorganisms to generate alkalinity and immobilize metals. The most important alkalinity generating reactions are the reduction of ferric iron and sulphate as they are usually abundant in AMD.</p> <p>SRB systems are applicable for sulphate removal, as the SRBs are able to produce sulphatic H₂S in anaerobic conditions. SRB systems can be realized as passive systems or active sulphidogenic bioreactors. Active reactors are constructed and operated to optimize the production of H₂S. SRB systems can also be divided into solid reactant and liquid reactant bioreactors. In solid reactant systems an organic solid substrate is used (e.g. manure, compost, sawdust etc.) whereas in liquid reactant systems alcohol is used as substrate. The systems are operated anaerobically. The pH should be at least 5.5.</p>	<ul style="list-style-type: none"> + Compact systems + Considered technologically viable method for mine effluent treatment + Commercial processes exist. 	<ul style="list-style-type: none"> - High capital and operating costs - Formation of microbial population is time-consuming - Sensitive to pH and temperature changes, freezing of solid reactant bioreactors is possible during the winter - Reduction of substrate activity over time 	<p>The efficiency of sulphate removal depends on substrate quality and quantity. E.g. removal efficiencies from 58% to 100% have been achieved using different substrates. The SO₄ removal rate of various bioreactors has been 1 690–6,860 g/m³ d. The sulphate concentration of the influent in these experiments has varied from 1,200–8,150 mg/l. Some processes can reach < 300 mg/l ppm SO₄ levels for effluent.</p>	Commercial processes exist.

Table 12: State of the art technologies for removal of nitrogen compounds

Technology (Reference no.)	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Biological N removal [5,34,38,41,42,43]	<p>Microbial processes converting nitrogen compounds to nitrogen gas by nitrification-denitrification or anammox process (anaerobic ammonia oxidation). Different reactor systems as well as wetland systems can be utilized.</p> <p>Constructed wetlands can be an effective method for the removal of nitrogen from mine wastewaters where sufficient oxygen is available for optimal nitrification and adequate organic carbon is provided for denitrification reactions to proceed.</p> <p>Alternatively, constructed wetlands substituting autotrophic denitrification, in which elemental sulphur is utilized in place of organic carbon, can mitigate the need for external organic carbon addition associated with heterotrophic denitrification.</p> <p>Moving Bed Bio Reactor (MBBR), a fixed film biological nitrification and denitrification system, has been successfully implemented for controlled removal of nitrogen in mine water, also at low temperatures.</p> <p>Autotrophic denitrification with elemental sulphur (So): Reduction of NO₃⁻ or NO₂⁻ to N₂ with energy derived from inorganic oxidation-reduction reactions using reduced S compounds as electron donor and inorganic C compounds as C source.</p> <p>Anammox technology can be used in combination with systems which concentrate NH₄⁺ to improve biological nitrogen removal in dilute nitrogenous wastewater streams, such as mine effluents.</p>	<p>+ >99% efficiency can be achieved</p> <p>+ Moderate operational cost</p> <p>+ Proven technology</p> <p>+ Minimal impact on the environment; some applications such as constructed wetlands can enhance biological diversity and ecological sustainability</p> <p>+ Wetlands: Natural and safe, suitable for treatment of wastewater with low N concentration, suitable for large volumes</p> <p>+ Autotrophic denitrification: So is readily water-soluble and widely available, no external C source required</p> <p>+ MBBR process can be fully automated with real time process control ensuring performance also at varying load conditions and process temperature</p> <p>+ Anammox: low energy and no external carbon requirements when applied on a large scale.</p> <p>The minimization of surplus sludge production and compatibility with high volumetric loading rates, resulting in reduced operational and investment costs. Anammox bacteria have high affinity for NH₄⁺.</p>	<p>- May require biomass waste disposal</p> <p>- Normally requires addition of organic carbon source (methanol or ethanol)</p> <p>Sensitive to changes in flow rate and the presence of potentially toxic substances. pH and temperature-dependent becoming slow or inactive in cold climates</p> <p>- Post-treatment may be required</p> <p>- Wetlands: large areas needed for treatment. Low efficiency winter time.</p> <p>- Anammox requires minimum 15–20 degree water and is only applicable at high NH₄⁺ concentration.</p>	<p>Biological methods potentially offer an effective and inexpensive option for the removal of nitrogen from wastewaters. In mine applications some of these techniques may be limited by the temperature dependence especially in cold regions, and toxicity.</p> <p>E.g. the Anammox method is not suitable for subarctic conditions</p> <p>In sulphur-based autotrophic denitrification >90% NO₃⁻ removal has been achieved in the laboratory. Further research is required to fully assess the potential of this technology for N attenuation in mine and quarry wastewaters in cold climates.</p> <p>The performance of wetlands used for N attenuation is highly variable and largely dependent on the type of wetland or similar passive treatment system utilized, the characteristics of the influent water, the local climate, and the hydrologic regime.</p> <p>MBBR has proven efficient also at low temperatures. Full scale plants treating mine water in operation.</p> <p>Reported removal rate or efficiency: NO₃⁻/NO₂⁻: 60–99% NH₄⁺: 12–97%</p> <p>Efficiency depends on conditions in reactor/wetland, efficiency is good when optimal conditions for microbial processes are achieved.</p>	<p>Wetlands currently used, proven technology.</p> <p>MBBR full scale installations in operation in Canada and Sweden.</p> <p>Sulphur-based autotrophic denitrification is of potential interest for the treatment of N-enriched mine and quarry wastewaters, particularly for sites with waste S or limestone rock deposits; however, to date no full-scale applications of this technology have been documented.</p> <p>Anammox is a fairly new method, applied in full scale for some types of wastewater treatment. Further research is required to assess the feasibility and sustainability on full-scale low-temperature applications and at nitrogen concentrations normally found in mine water.</p>

Technology (Reference no.)	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Electrochemical methods [34, 38]	Electrochemical methods can be used to convert nitrogenous compounds to a desired form facilitating nitrogen removal as nitrogen gas or as pure ammonia. Thus, these methods offer a temperature-independent alternative for biological nitrogen removal techniques. High concentrations of ions such as Mg^{2+} , Ca^{2+} and SO_4^{2-} can be problematic as they can precipitate with changing pH or inhibit the movement and reactions of nitrogen ions. Methods such as electrochemically assisted stripping (electrochemical pH control and ammonia concentration at a surface electrode to capture ammonia), AmmEL (zeolite ion-exchange – brine treated with electro-oxidation), and electro-oxidation (non-specific oxidation/reduction for removal of organics and nitrogen as N_2) are evaluated as good or potential methods. Whereas bio-electrochemical systems (BES) (electrodes used as electron donors/acceptors for microbes) and electrocoagulation (coagulation of ions with cations from a dissolving electrode) are evaluated as poor technologies.	<ul style="list-style-type: none"> + No sludge, no waste disposal required + Easy to run periodically + No chemical addition required + Not dependent on temperature, pH, organic carbon, toxins + High removal efficiency + Moderate operational cost + Electrochemically assisted stripping: Lower energy demand than electro-oxidation, ammonia recovered for reuse. 	<ul style="list-style-type: none"> - pH effects may influence effectiveness - Post-treatment may be required - Some methods require a high chlorine concentration for indirect ammonia oxidation, and large potentials can be required for oxidation - Energy consumption - Electrochemically assisted stripping: Nitrate removal. 	<p>Suitability for mine wastewater treatment is good or potential in electro-oxidation and electrochemically assisted stripping.</p> <p>Electrochemical oxidation technologies can be feasible for selected mine wastewater streams with high chloride and ammonia concentrations. For bulk mine wastewater, a concentration step is required.</p> <p>Electrochemical techniques, which utilize electrochemistry enhanced ammonia stripping, are potentially suited for large flow rate, low concentration wastewater stream analogous to mine site wastewater.</p> <p>Reported removal rate or efficiency: NO_3^-/NO_2^-: 98% NH_4^+: >97% Org. N: 90% Depends highly on the electrochemical method selected.</p>	<p>Approved technologies exist. Electro-oxidation technologies are presently in full-scale use by the mining industry and are suitable for the removal of both NO_3^- and NH_4^+ removal from mine and quarry wastewaters in cold climates.</p> <p>AmmEL is ready technology. A full-scale installation exists. Also ELONITA is commercialized.</p> <p>Electrochemically assisted stripping is at experimental stage, e.g. DesEI has been tested on a pilot scale. Additional research and validation required.</p> <p>Not demonstrated for large flows.</p>

Technology (Reference no.)	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Sorption, precipitation and ion exchange methods [34,38]	<p>Sorption technique is an alternative for the removal of nitrogenous contaminants from aqueous solution. Sorption reactions typically involve surface ion or ligand exchange, and may facilitate precipitation of de novo mineral solids.</p> <p>Numerous materials have been examined for sorption/ion exchange/precipitation of nitrogenous compounds from solution, and natural zeolite minerals, layered double hydroxide minerals and biomass-based activated carbon are among the materials exhibiting the most potential for large-scale application. Some industrial, mining and metallurgical by-products have also demonstrated potential for use as N sorbents; however, by-products are generally not suited to use on industrial scale processes requiring consistent material performance and compliance with regulatory guidelines due to their inherent variability and the potential for release of chemical constituents (e.g. metals and metalloids).</p> <p>Both natural zeolite and biomass-based granular activated carbon are low-cost materials, with relatively low initial capital and on-going operational expenses. Layered double hydroxide minerals, whilst showing substantial promise for the use in small-scale operations, are relatively costly and less stable minerals compared to, e.g., natural zeolite. The layered double hydroxide minerals, which may be generated via precipitation reactions, are fine-textured and not amenable to use as filtration media for large volumes of wastewater. In general, aggregate materials, such as granular zeolite and granular activated carbon, are more suitable for N capture in a fixed bed or column-type configuration than finely-textured materials.</p>	<ul style="list-style-type: none"> + Sorption methods are relatively simple + Removal efficiency varies with sorbent and but can be targeted to specific contaminants + Low to moderate cost + May facilitate precipitation of de novo mineral solids + Low temperature dependence of sorption reactions + Potential for use in combination with other technologies + Commercially available sorbents exist. 	<ul style="list-style-type: none"> - May require disposal of saturated/spent sorbent or waste brine - pH and temperature effects are important - Post-treatment may be required. 	<p>Suitability for mine wastewater treatment is good (zeolite sorption and sorption to carbon-based materials) or potential (sorption to mineral-based by-products).</p> <p>Reported removal rate or efficiency: NO₃⁻/NO₂⁻: 3.5–11 mg/g (HDTMA-zeolite), 60–82 mg/g (Mg/Al LDH), 6–10 mg/g (activated C)</p> <p>NH₄⁺: 6–28 mg/g (zeolite) > 70%.</p>	<p>Adsorption is approved technology, but not for mining applications. Some zeolites, layered double hydroxide (LDH) or hydrotalcite minerals, and carbon-based sorbents examined in laboratory studies have demonstrated potential for large-scale application to remove nitrogenous compounds from wastewaters.</p> <p>Although zeolite has been applied for NH₄⁺ removal from municipal sewage effluents, landfill leachates and similar wastewaters, to date there are no documented full-scale applications using zeolite or surfactant-modified zeolite (SMZ) to attenuate N-enriched mine or quarry wastewaters.</p> <p>Although commercially available activated carbon (AC) is widely used for the treatment of wastewater and contaminated ground water, the examination of N sorption to non-commercial AC or biochar to date has been limited to laboratory and pilot-scale trials. Additional research is necessary to characterize the attenuation of various nitrogenous species by AC or biochar, particularly in the presence of competing ions as are likely to be found in mine and quarry wastewaters, and the long-term stability of the sorbent.</p>

Technology (Reference no.)	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Membranes [34,38]	<p>Water-soluble nitrate and ammonia can be separated by membrane filtration, using nanofiltration (NF) or reverse osmosis (RO) membranes. Nanofiltration can remove ions partially (25–60%) and reverse osmosis almost completely (>96%). RO and NF are both based on osmosis phenomena. Osmosis is defined as a spontaneous movement of liquid solvent from a dilute solution through a semipermeable membrane to a concentrated solution. In RO and NF processes, applied pressure forces water through semipermeable membrane against osmosis force while ions and molecules stay on the other side of semipermeable membrane. The quality of water produced by membrane processes is high compared to other common water treatment technologies, like ion-exchange. (See Sulphate or Metals -worksheets for more information on RO and NF)</p> <p>Due to their high cost and substantial operational requirements, membrane technologies are generally employed for the production of high-quality water. Best performance of membranes is achieved in combined or integrated system.</p>	<ul style="list-style-type: none"> + High quality water + Monovalent ion separation + Compact, modular systems + Suitable for continuous operation + Simple to operate + Requires less energy than other methods generating water of comparable quality + Readily adapted for cold, inorganic and potentially toxic wastewaters + NF: low operation pressure, high flux, high retention of multivalent anion salts and organic molecules, relatively low investment and low operation and maintenance costs. 	<ul style="list-style-type: none"> - Require on-going maintenance - High pressure - High energy consumption - High operation costs - RO: Fouling caused by pore clogging and adsorption of solutes on the membrane surface - NF: Fouling of the membrane - Wastewater pre-treatment recommended to prevent fouling and prolong the membrane life. - Ammonia is only partially withheld by RO membranes and residual concentration is normally above the toxic level for discharge. 	<p>Limited suitability to the treatment of large volumes of mine wastewater (expensive). Reported removal rate or efficiency: NO₃-/NO₂-: 91–99% NH₄+: >90% CN-: 90–95%.</p>	<p>Membrane treatment is not currently used for N removal from mining wastewaters; however, membrane technologies are used in other applications in mining. In addition, membrane filtration is a mature technology used in drinking water treatment and desalination.</p>
Combination of sorption and electrochemical techniques [34,38]	<p>Sorption techniques coupled with electrochemical processes utilizing electrochemistry enhanced NH₄⁺ stripping would potentially suit a large volume, low total N concentration wastewater stream. Sorption can be applied to pre-concentrate nitrogenous compounds and reduce the volume of wastewater requiring electrochemical treatment, Electrochemical processes require only low electrical potential for operation, are relatively temperature-independent, and result in an NH₄⁺ product for reuse as a pure chemical or a fertilizer..</p>	<ul style="list-style-type: none"> + Can be selected and optimized to suit a particular wastewater + Require only low electrical potential for operation, is relatively temperature-independent, and result in an NH₄⁺ product for reuse. 	<ul style="list-style-type: none"> - Research/testing may be required to optimize treatment system for individual applications. 	<p>Suitability for mine wastewater treatment is good. A combination of sorption and electrochemical techniques is potentially the most promising method for the treatment of large volumes of wastewater containing multiple nitrogenous compounds. Reported removal rate or efficiency: NO₃-/NO₂-: variable NH₄+: variable Org. N: variable CN-: variable.</p>	<p>Additional development and optimization of sorption-electrochemical NH₄⁺ capture and reuse, anTabled investigation of system efficiency in full-scale applications is required.</p>

Table 13: State of the art technologies for metals removal

Technology	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Alkaline treatment [1,2,5,7,8,11,15,21,27]	<p>The addition of alkaline agent, such as limestone (CaCO_3), CaO, Ca(OH)_2, NaOH or Na_2CO_3 can be used to raise the pH and to achieve precipitation of metals as hydroxides, oxy-hydroxides or carbonates. Also lime and cement kiln dusts, fluidized bed combustion ash, fly-ash, CaO_2, or seawater neutralized red mud (from bauxite processing) might potentially be used as alkaline reagents. The choice of reagent depends on site-specific criteria.</p> <p>The precipitation of metal hydroxides occurs when a certain pH/solubility limit is reached. Below and above this limit metal hydroxides are in more soluble form. Alkaline treatment can be used to efficiently remove heavy metals such as Cu, Ni, and Zn. Cu and Zn precipitate at the pH 9.5, whereas Ni requires a higher pH, between 10.5 and 11. The neutralization/precipitation process of Ni becomes more difficult if the concentrations of Fe are high. The presence of multiple metals with different precipitation properties emphasizes the importance of pH control.</p>	<ul style="list-style-type: none"> + Well proven technologies + Wide range of different alkaline reagents available + Stable and easily controllable process + Adaptable to changes in water flow and quality + Can be operated on large water volume + Offers permanent results. 	<ul style="list-style-type: none"> - Large amount of sludge is generated - The long-term stability of sludge and possible release of metals is a specific concern - Non-selective process, no possibility for metal recovery; the value of metal hydroxide sludge is low - High operating costs; however, the sludge treatment and disposal costs may be about an order of magnitude higher than the capital and chemical costs - Precipitation processes are relatively slow - Required chemical dosage as well as sludge volume is difficult to predict; stoichiometric amounts of alkalinity are not enough for complete metal precipitation - Pre- and post-treatment (reduction of effluent pH) may be required, an elevated pH is required during operation. 	<p>Applicable for mine effluent waters containing a mix of metals with little or no commercial value.</p>	<p>The "traditional" treatment method, proven technology. Many large-scale applications exist.</p>
Sulphide precipitation [1,19,21,25]	<p>Precipitation or co-precipitation can be used to remove metals as hydroxides, carbonates or sulphides. Sulphide precipitation is applicable for metal containing mine waters when very low effluent concentrations are required or when selective metal removal and recovery are needed.</p> <p>Selective metal precipitation by sulphide compounds (FeS, CaS, Na_2S, NaHS, NH_4S, H_2S and organo sulfides) can selectively remove and recover metals (such as Cu, Ni and Zn) at low pH. The sulphide reagent targets these base metals, but leaves the less valuable metals (e.g. Fe and Al) intact. The solubility of the metal sulphide solids is low, supporting the removal of targeted metals to lower concentrations than with alkaline treatment. Metal sulphide sludges generated by sulphide precipitation are denser than metal hydroxide sludges, and their hygroscopic water content is lower.</p> <p>Can be combined with other treatment technologies. High reactivity of sulphide with metals emphasizes the need for process control and optimization.</p>	<ul style="list-style-type: none"> + Some technologies are relatively simple and proven + A possibility for selective metal recovery + Produces water with low metal concentrations + Offers permanent results. 	<ul style="list-style-type: none"> - Less sludge is generated than with i.e. lime treatment - Need for sludge treatment and disposal - Uncertainty on the long-term stability of the sludges - Reagent costs high in some processes - Mass balance of H_2S is important. 	<p>Very effective treatment technology for many metals, most of the heavy metals removed are able to reach prescribed limits. Is applicable for streams with low metals concentrations ($< 10 \text{ mg/l}$), parts-per-billion final effluent concentrations can be achieved. Reported removal efficiencies: Zn (II) 99.77% Cu (II) 80%.</p>	<p>A proven, large-scale technology. Commercial processes available.</p>

Technology	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Adsorption [16,17,18,20,21,24]	<p>Adsorption is a common method for heavy metals removal from many kinds of waste waters. Removal of metals in AMD can be readily achieved by activated carbon adsorption. However, the price of activated carbon is high and there is a need to find less expensive materials for AMD treatment. There are several studies suggesting alternative sorbents such as natural or synthetic zeolites, clay, natural clinker, fly ash, zero valent iron, agricultural wastes, microbial biomass, activated sludge, collophane, lignite. The regeneration (desorption) of the sorbent is possible for some sorbent materials to allow metal recovery and repeated usage of sorbent. However, less attention to the R&D has been paid on this aspect.</p> <p>The efficiency of metal removal depends on the sorbent material used and the dosage applied. The efficiency is also highly pH dependent; the sorption of metals is often reduced at low pH levels. The effect of elevated ionic strength is similar. In addition, the effects of temperature, metal concentration at initial state, presence of competing ions, and particle size should be taken into account. The pH dependency also enables selective removal of different metals.</p> <p>Note: Also biosorption is discussed below.</p>	<ul style="list-style-type: none"> + Effective, efficient and economical + Possibility for selective metal recovery + Suitable for dilute solutions + Some sorbent materials remove acidity from/ produce alkalinity to the treated water + Not sensitive to toxic substances + Design, scale-up and operation are relatively simple. 	<ul style="list-style-type: none"> - May require disposal of spent sorbent - Adsorbent loses its efficiency over time - Material need for mining water treatment may be large, sorbent costs - The effects of pH, sorbent material properties and dosage, ionic strength, initial metal concentration, particle size, temperature and presence of competing ion are important. 	<p>Applicable for mine effluents containing heavy metals in low concentrations.</p> <p>A preferred method for heavy metal removal, considered as a particularly effective technology. Removal efficiencies of around 90% for Zn and 99% for Cu were determined after 40 min of adsorption in a study in which natural zeolite was used to remove metals from relatively dilute acidic mine water.</p>	Adsorption is proven technology.

Technology	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Ion exchange [3,4,9,11,15,19,21,23,26,28]	<p>Ion exchange (IX) is another form of sorption. In IX process ions are reversibly exchanged between a substrate and its surroundings. The process utilizes a polymer resin packed column for the removal of target species. The resin contains active functional groups, which capture target ions and release an equivalent ion into the solution. Usually the resin can exchange cations or anions, but some (amphoteric) are capable of exchanging both, depending on the pH. The loaded ions (such as metals) are removed from the resin by regeneration. The volume of regenerant solution is considerably smaller than the influent flow, thus resulting in effective concentration of target ions into regenerant.</p> <p>Ion exchange can be applied for the recovery of different metals from AMD. Cu, Ni and Zn have been recovered and purified on an industrial scale by means of IX. It can also be utilized to remove hardness, alkalinity, radioactive constituents and ammonia. IX can be also used as a pre-treatment step to selectively concentrate the dissolved metals before sulphide precipitation. Another aim could be the extension of existing water treatment capacity.</p> <p>IX is best applicable to waters in the pH range of 4 to 8 containing low concentrations of suspended solids, Fe and Al. An efficient removal of metals becomes more difficult as the water solution to be treated becomes more complex.</p>	<ul style="list-style-type: none"> + Removal can be targeted to specific contaminants + Suitable for dilute solutions + Possibility of metal recovery + Low temperature dependence + Not sensitive to toxic substances + Relatively simple treatment systems + Modular configuration possible + Efficiently removes even traces of impurities. 	<ul style="list-style-type: none"> - Need for pre-treatment (e.g. pH adjustment, oxidation, solids removal) - High treatment costs - Applications for AMD still at research/development stage - Limitations in cold conditions - Organic compounds, oxidants or high temperatures can degrade the resin - All resins are not suitable for metal removal - Generally not effective for low pH, and complex mixtures of metals. Also temperature effects are important - Resin regeneration and fouling - Limited pH range for the resins - Competing ions and their effect on removal must be considered. 	<p>Effective method for achieving water quality targets.</p> <p>Reported removal efficiencies:</p> <p>Ni (II): 90%</p> <p>Cu (II): 100%.</p>	<p>Although IX is a technically effective method for removal of heavy metals, it is not widely used in the mining industry at this moment due to the limitations of the method. Few commercially viable methods however exist, e.g., selective IX resins for removal of Cu and Zn are available.</p>

Technology	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Membrane treatment [3,4,9,10,13,19,21,26,27,28,40]	<p>Membrane processes can be used to concentrate and (with further processes) recover metals from mining waters. Different types of membranes can be utilized. The separation is based on sieving effects as well as electrorepulsive forces due to membrane surface charge. Solution pH has a significant impact on membrane performance. An important parameter is the membrane iso-electric point (IEP). At pH values below IEP the membrane is positively charged, and negatively charged elsewhere. Metal rejection has been indicated highest when operating at pH below IEP. Also operating pressure has an impact on the metal separation efficiency.</p> <p>Conventional reverse osmosis (RO) process requires pretreatment (e.g. HDS high density sludge process) of mine water in order to reduce metals concentration to an acceptable level considering membranes. In RO process, a semi-permeable membrane excluding all but pure water is used to separate strong and dilute solutions. By applying an external hydraulic pressure to the saline brine, water is forced to pass through the membrane against osmotic pressure.</p> <p>Nanofiltration (NF) can be used to concentrate and recover metals. In NF process, a hydraulic pressure is used to achieve a diffusion of pure water through a semi-permeable membrane. It is not as fine a filtration process as RO because the pores are larger, close to 1 nm. Compared to other membrane processes, it presents higher fluxes at lower pressure, which reduces capital and operational costs.</p> <p>Electrodialysis (ED) uses electric potential in a separation of dissolved salts and water. ED is based on the migration of dissolved solids (i.e. charged ions) through a membrane. Water molecules cannot pass the membrane and pure water stays on the other side. In electrodialysis reversal (EDR) the polarity of electrodes is periodically changed which reduces, e.g., membrane fouling. In addition, EDR is not sensitive to pH or temperature of the water.</p> <p>Also, liquid membranes can be used to selective recovery of metals from mine waters. After separation, metallic ions are concentrated into a stripping solution. A small amount of selective organic extractant can be used as a membrane.</p> <p>Electrowinning can be used for further recovery of metals.</p>	<ul style="list-style-type: none"> + Wide range of pollutants can be removed, both organic and inorganic + Can remove monovalent ions unlike other treatment methods + Possibility for recovery of valuable resources + Produces high quality discharge water for further use + Low chemical consumption + Small footprint area + Modular configuration possible + Ease of operation + Considered as established technology for mine effluent treatment. 	<ul style="list-style-type: none"> - Need for pretreatment to reduce concentrations of metals, solids, hardness, sulphate etc. to acceptable level to protect the membranes - High operating (electricity, chemicals) and maintenance cost - Disposal costs for brine and pretreatment sludges - Risk of membrane fouling, especially by gypsum formation - The potential toxicity of liquid membranes - Large number of membranes is needed - In cold climates, water temperature controls may be required to minimize water viscosity. 	<p>Reported removal efficiencies:</p> <p>NF: Ni (II): 94% (The preferred membrane technology to be used in cold climates)</p> <p>RO: Cu (II): 99%</p> <p>ED: Ni (II) 69% (Suitable for metal concentrations <20 mg/l, not suitable for metal concentrations > 1,000 mg/l)</p> <p>Membrane electrolysis: Ni (II): 90%</p> <p>Liquid membranes: Up to 99.5% metal removal (e.g. Zn 98%, Cu 64–99.5%).</p>	<p>The utilization of membrane distillation in water recovery as well as acid and metal concentration has been recently demonstrated for mining wastewater. However, as solids are often present in mine water, the implementation of membranes in the mine waste treatment has been slow. Also high costs may hinder the use of this technology.</p> <p>Research regarding the use of membrane technology for mine water treatment is not substantial, and is focused on effluent treatment rather than recovery.</p>

Technology	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
SRB systems (sulphate reducing bacteria) [2,12,33,35,36,37]	<p>Bioremediation of AMD relies on the ability of some microorganisms to generate alkalinity and immobilize metals, thus reversing the reactions taking place in the formation of AMD. The most important alkalinity generating reactions are the reduction of ferric iron and sulphate as they are usually abundant in AMD. After the sulphate is reduced, the produced sulphide reacts with metals to form metal sulphides, which are precipitated and removed.</p> <p>SRB systems can be realized as passive systems or active sulphidogenic bioreactors. Active reactors are constructed and operated to optimize the production of H₂S. SRB systems can also be divided into solid reactant and liquid reactant bioreactors. In solid reactant systems an organic solid substrate is used (e.g. manure, compost, sawdust etc.) whereas in liquid reactant systems alcohol is used as substrate. The systems are operated anaerobically. The pH should be at least 5.5.</p> <p>SRB systems are able to effectively increase pH and remove metals such as Cu, Ni and Zn.</p>	<ul style="list-style-type: none"> + Compact systems + Considered technologically viable method for mine effluent treatment + Possibility for metal recovery + Commercial processes exist. 	<ul style="list-style-type: none"> - High capital and operating costs - Formation of microbial population is time-consuming - Sensitivity to temperature and pH changes - Freezing of solid reactant bioreactors is possible during the winter - Reduction of substrate activity over time. 	<p>SRB systems are applicable for efficient removal of heavy metals from mine waters.</p> <p>Removal efficiencies of >95% for most metals are reported.</p>	Commercial processes exist.
Biosorption [3]	<p>Various biological materials have good metal binding capacities. Biosorption means the removal/binding of metal and metalloid species, compounds and particulates from solution using biological materials. Different mechanisms such as absorption, adsorption, ion exchange, surface complexation and precipitation occur in the biosorption process. Natural and plant materials, together with wastes from industrial processes and agriculture are of particular interest to be used as sorption materials. Inexpensive growth media can be used for the production of biosorbents or industrial by-products can be used. For example, the use of rice husk, bark of Eucalyptus tereticornis, chitin and chitosan is investigated.</p>	<ul style="list-style-type: none"> + Possibility of selective removal and recovery of metals in a wide temperature and pH area + Rapid kinetics + Cost effectiveness, inexpensive sorption materials + Sludge generation is low + Additional nutrients are not needed + Biomass can be used as biosorbent + Biosorbent can be regenerated. 	<ul style="list-style-type: none"> - Loss of efficiency of the biosorbent and need for its treatment and/or disposal. 	<p>Has shown a potential for effective removal of contaminants at very low levels. Reported removal efficiencies:</p> <p>Zn: 77% (Bark of Eucalyptus tereticornis (Smith))</p> <p>Cu: 92% (Bark of Eucalyptus tereticornis (Smith)), 100% (Chitosan).</p>	Mostly on laboratory scale, however, some commercial biosorbents (e.g. BIO-FIX, AMT-BIOCLAIM and AlgaSORB) exist.

Technology	Principle	Advantages +	Disadvantages -	Performance characteristics	Level of technology
Electrocoagulation [39]	<p>Electrocoagulation (EC) technologies use an electrical current to coagulate suspended solids and organic constituents present in the water. The first stage of the process contains an electrolysis treatment of water, in which graphite/stainless steel cathodes together with a metal anode are used. Then, an application of voltage precipitates metals, after which sedimentation or filtration is used to remove them from the water.</p> <p>EC may be suitable for final treatment and polishing of discharge water originating from an HDS water treatment plant, pre-treatment of water prior to filtration or RO, and removal of minor amounts of metals from neutral tailings waters.</p> <p>The most efficient results can be achieved when the water conductivity is high, pollutant concentration is low, and the pH is between 4 and 8.</p>	<ul style="list-style-type: none"> + Potential for metal recovery + Only little maintenance needed + Requires only low electrical current + Sludge generation is low. 	<ul style="list-style-type: none"> - Complex process - High costs - High energy consumption - Regular replacement of electrodes needed - Conductivity, pH, chemical concentrations, and particle size affect the efficiency - Unable to treat acidity or remove sulphate (requires pre-treatment), long retention times are needed to remove metals; implementation on full-scale is challenging - Re-entry of metals is possible. 	<p>Cu, Ni and Zn can be effectively removed. However, small quantities of metals may re-enter the treated water, which reduces the overall efficiency of the technology.</p> <p>Reported removal efficiencies: Cu: 99.9% Ni, Zn: 95–99%.</p>	<p>On a pilot scale. Not a proven technology for treatment of mining waters on a full-scale. Is used in the mining industry to remove coal fines and suspended clay particles from process water.</p>

2.7.1 References

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3. Technological developments

- Responsible partner: LUT.
- Contributors: VTT, LUT, NTNU, LTU, Sintef, and Veolia.

3.1 Research fields covered

The main research targets of this part of the project were to develop and test novel technologies for the treatment of mining waters and compare available methods for the sustainable management of mining wastes. Some of the studied technologies were new emerging ones but some test work has also been conducted for comparison on the already proven technologies. In order to evaluate the feasibility of different processing and technology alternatives, process simulation models were built using HSC Chemistry – a software for selected processes and processing alternatives.

The overall project objective was to develop a proposal with suitable technologies for the concept of “Low-water footprint mine”. In this part of the project, several potential technologies, which either are already proven and implemented under different conditions or are in the development stage, have been experimentally tested by the project partners: VTT, LUT, LTU, NTNU, SINTEF and Veolia.

The main technologies tested by the partners were the following:

- Biosorbents: VTT.
- Precipitation processes: VTT, Veolia.
- Eutectic freeze crystallization and solid-liquid separation: NTNU.
- Electrochemical processes and solid/liquid separation: LUT.
- Membrane processes: SINTEF, LUT, VTT, Veolia.
- Biological processes: Veolia.
- Process modelling: LTU.
- Tailings management: VTT.

Laboratory scale tests were performed both with synthetic and with real mine water samples. Three different recipes for synthetic water samples with low, medium and high ion concentrations were tested in order to perform preliminary tests with each treatment method with similar waters.

The recipe for the preparation of synthetic mine waters was proposed based on the discussions with industrial partners, literature reviews and public reports available from mines. Sulphate limits were chosen based on the average sulphate concentrations

reported for Finnish and Swedish mines. Extreme cases were not taken into account. The final contents of different compounds in the three synthetic water samples are given in Table 14. The main reason for using these kinds of synthetic sample solutions was to verify the comparability of the results obtained by different partners with different techniques. Synthetic waters used in the tests were prepared according to the recipe during the experiments by the partners (see Appendix 1).

Table 14: Compositions of the three synthetic water samples

Ions	Concentration, mg/l		
	Low	Medium	High
SO ₄ ²⁻	1,000	2,000	3,000
NO ₃ ⁻	20	40	60
Cl ⁻	100	200	300
Cu ²⁺	2	5	8
Ni ²⁺	2	5	8
Zn ²⁺	5	10	15
NH ₄ ⁺	10	20	30

Real mine water samples for some tests were obtained from Orivesi and Kevitsa mines in Finland and from LKAB Svappavaara mine in Sweden. Note that the sample characteristics summarized in Table 15 represent only a single batch and are not representative of the water streams in general.

Table 15: Characteristics of Orivesi mine water sample

Compound	Orivesi mine water sample
pH	7.1
Ag, mg/l	0.00001
Al, mg/l	0.468
As, mg/l	0.00138
B, mg/l	0.114
Ba, mg/l	0.0489
Be, mg/l	<0.00005
Bi, mg/l	<0.001
Cd, mg/l	0.00247
Co, mg/l	0.0114
Cr, mg/l	0.00052
Cu, mg/l	0.00999
Li, mg/l	0.0764
Mn, mg/l	3.48
Mo, mg/l	0.00362
Ni, mg/l	0.00727
P, mg/l	<0.02
Pb, mg/l	0.0002
Rb, mg/l	0.0738
Sb, mg/l	<0.002
Se, mg/l	0.026
Th, mg/l	<0.002
Tl, mg/l	0.00016
U, mg/l	0.00583
V, mg/l	0.00013
Zn, mg/l	0.0627
Ca, mg/l	369
Fe, mg/l	0.06
K, mg/l	40.9
Mg, mg/l	88.7
Na, mg/l	503
Si, mg/l	1.42
Sr, mg/l	1.78
S, mg/l	661
Sulphate, mg/l	2,000
Chloride, mg/l	200

3.2 Biosorption studies

3.2.1 Details of the project partner

Biosorption studies for artificial water and Orivesi mine water were conducted by Jarno Mäkinen at VTT.

3.2.2 Summary

Biosorption is a method where dissolved ions, e.g., heavy metals and anions from mine waters, are supposed to be captured and bound by biomass. In this project, *Phanerochaete chrysosporium* white rot fungi was cultivated for biosorption studies. While sulphate was significantly removed (highest adsorption capacity 1 kg SO₄ per 1 kg dry biomass), the adsorption for heavy metals was poor and the actual removal rate was low (< 15% for all contaminants). The cultivation of *P. chrysosporium* directly in the

Orivesi *mine* water sample was successful and was seen to adsorb metals efficiently during the growth. However, throughout the experiments, biosorbent had poor physical stability, resulting in collapse of the structure, greatly hampering the usefulness of the disc shaped biosorbent method.

3.2.3 Process description

In this project, *Phanerochaete chrysosporium* white rot fungi was selected for biosorption studies prompted by the literature survey, which indicated good growth rate and sorption capacity [1–4], but also safety (*P. chrysosporium* is not a known pathogen of humans or animals). It was seen that on industrial scale the safety of the micro-organism is in the key role, both due to economic operation but also due to public response. Many other known and efficient biosorbents, e.g. *Aspergillus niger* are pathogens.

The current state-of-the-art of the biosorption method is moving towards immobilized biomass systems, as freely suspended micro-organisms have strong biofouling effects and uncontrolled growth of biomass as well as low mechanical strength, making industrial scale processes prone to failures [5]. Typical ways to immobilize biomass are different carrier or entrapment materials, such as sodium alginate, polysulphone, polyacrylamide and polyurethane, as well as some natural materials such as wood [1, 2, 5]. The approach in this project was to immobilize the biosorbent without any carrier material by cultivating *P. chrysosporium* into a 3-dimensional disc shape to increase the sorption capacity per volume and weight. The disc shape was found practical for treating AMD semi-passively in pipelines or simple reactor units. Later in the project, a novel approach was drafted, where the biosorbents would be cultivated in the mine water pond itself, adsorbing the impurities passively.

In this project, the experimental work was conducted on a very small and preliminary laboratory scale, with working volumes measured in tens of millilitres of water and grams of biosorbent. Therefore, this technology is only emerging and requires plenty of research to be properly evaluated for industrial level applications.

3.2.4 Research activities

Firstly, *P. chrysosporium* growth and shape manipulation were studied with distilled water and optimal nutrition. The biosorbent discs that were produced were then used to treat synthetic mine water (the most concentrated version). After several experiments, the sorption capacity was determined. After these experiments *P. chrysosporium* was cultivated directly in Orivesi mine water, and simultaneously the water was treated for impurities.

3.2.5 Results and achievements

The *P. chrysosporium* cultivation with distilled water and optimal nutrition was successful with specific biomass production of approximately 6 grams per m² of cultivation surface area per day. The growth manipulation to a 3-dimensional disc shape was successful with

rubber-like composition, providing some mechanical durability as a biosorbent disc. The water permeability of the biosorbent disc was approximately 150 l/m² h.

The treatment of synthetic mine water showed a copper and zinc sorption capacity of 0.6 and 0.4–0.6 grams per kg of dry biosorbent, respectively. Nickel was barely adsorbed. For sulphate sorption, the capacity was clearly higher, 140–1,000 g per kg of dry biosorbent. Other anions were barely adsorbed. Experiments showed only low removal rates for metals (3–7%) and sulphate (15%). The reason for the poor performance was explained by potential dissolution of biosorbent to treated water; the weight loss of biosorbent disc was approximately 60% during the sorption experiments, which naturally disrupts greatly the water treatment capacity.

The direct cultivation of *P. chrysosporium* in real mine water was performed by mixing Orivesi mine water and distilled water equally, and solely with Orivesi mine water. Nutrition was illustrated in all experiments. The biomass growth was slower in these experiments, especially with solely Orivesi mine water; moreover, contaminants were visible (possibly bacterial colonies) in the biosorbent discs. However, cultivation was seen successful. The biosorbents grown in Orivesi mine water were studied with SEM (Figure 7), with the finding that fungal biomass was colonized by bacteria originating from the mine water, which also excreted extracellular polymeric substances (EPS). Moreover, some inorganic crystals were found, illustrating successful biosorption of impurities from mine water.

Figure 7: Biosorbents (1) grown in distilled water, (2) grown in mine water with some bacterial colonization, (3) grown in mine water with heavy bacterial colonization

Note: The red arrows show an example of inorganic crystals.

The biosorbents cultivated in Orivesi mine water were washed with distilled water to remove any free dissolved metals from the mycelium, and then analyzed for metal content with XRF. The copper and zinc concentration was 300 and 200 mg/kg in dry biomass, respectively. These concentrations represent over 100 % sorption yield, but it is noteworthy that this experiment was only indicative. As a comparison, for biosorbents grown in distilled water only, no copper or zinc were detected. The biosorbent discs cultivated were mechanically not stable, and lost their shape already in water washing.

3.2.6 Conclusions and recommendations for future work

The experiments conducted were preliminary and conducted on small scale, which caused some challenges and inaccuracy, especially in analytics. The scale was about to be increased during the project, but the properties of *P. chrysosporium* biosorbent did not allow this. As a conclusion, the metal and anion removal rates and sorption capacities were low. Moreover, cultivation of *P. chrysosporium*, although successful, was very ineffective compared to the amounts needed for industrial processes.

Despite the relatively modest results found in this project, according to the literature higher performance can be expected and the method is studied actively. However, these studies are mainly of low technology readiness level and conducted on small scale. Therefore, industrial insights are needed to direct the future work to achieve actual industrial implementations.

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3.3 Ettringite precipitation process for sulphate removal from mine water

This part of experimental work was conducted mainly in order to 1) compare water treatment results with experiments on emerging technologies (done by project partners) and to 2) produce data on the quality and quantity of solid residues from treatment, which has not been reported previously.

3.3.1 Details of the project partner

This part of experimental research was performed by VTT. Contact person:

- Tommi Kaartinen

3.3.2 *Summary*

Main targets of the research were:

- Sulphate removal from mine waters.
- Monitoring of metals behaviour during the precipitation process.
- Comparison between ettringite precipitation and other treatment methods.
- Stability of the generated solid residues.

Methods used:

- Laboratory scale batch tests with 1) artificial mine water and 2) real mine water from Orivesi mine.

Main results:

- Effective sulphate removal.

Conclusions:

- Ettringite process is a viable option for sulphate removal. Commercial processes already exist (Outotec, Veolia).
- No full-scale plants have been installed yet.
- Aluminium costs increase the operational costs of the process and decrease the attractiveness. Recycling of aluminium could be feasible and should be investigated.

3.3.3 *Process description*

The ettringite precipitation process for sulphate removal consists in principle of the unit operations shown below:

1. Precipitation of gypsum by addition of lime to pH 10.5–12 as a pre-treatment step.
1. Separation of gypsum by filtration or thickening.
2. Al_3^+ -addition in pH 11.5–12 to remove sulphate as precipitated ettringite.
3. Separation of ettringite by filtration or thickening.
4. pH-reduction of the treated water with CO_2 to meet effluent discharge criteria and precipitate CaCO_3 .
5. Second separation of solids (CaCO_3).

Gypsum precipitation occurs when a calcium source, usually lime or limestone, is brought into contact with sulphate-bearing water. Calcium reacts with dissolved sulphate to form gypsum (Eq. 1). The residual sulphate concentrations after gypsum precipitation are controlled by the solubility of gypsum, which is dependent on the composition and ionic strength of the solution. Typically, these residual concentrations are in the range of 1 500 to 2 000 mg/l of sulphate [1].

Ettringite precipitation (addition of lime and Al^{3+}) can be used to remove sulphate and heavy metals. Ettringite ($3\text{CaO} \cdot 3\text{CaSO}_4 \cdot \text{Al}_2\text{O}_3 \cdot 31\text{H}_2\text{O}$) has very low water solubility and therefore the resulting sulphate concentrations are low (Eq. 2).

3.3.4 Research activities

Water samples

All the tests described below were conducted both for 1) artificial mine water spiked with pre-determined components and prepared according to the instructions from project partner LUT (see Appendix 1), and 2) a real mine water sample from Orivesi mine in Finland operated by Dragon Mining. The main purpose was to remove sulphate from these waters, but possibly also to co-precipitate the dissolved metals into solids. Therefore, also metal concentrations were determined both from the feed and the treated waters.

The artificial mine water batch prepared for the studies presented here had the characteristics shown in Table 16. In addition to the shown compounds, the artificial water was also spiked with nitrate, ammonium and chloride. These compounds are not affected by chemical precipitation as performed in this context, so their concentrations are not reported here.

Table 16: Characteristics of the artificial mine water

Compound	Artificial mine water
pH	6.7
Sulphate, mg/l	2,900
Copper, mg/l	3.8
Nickel, mg/l	5.5
Zinc, mg/l	21

The real mine water sample was characterized for a broader range of compounds. Its characteristics are shown in Table 15.

Batch precipitation tests

All of the sulphate removal experiments were conducted at room temperature. The tests were performed as batch tests in titan reactors with 10 l working volume and with continuous mixing. In the first stage, lime was added in order to remove sulphate to gypsum saturation level as well as raise the pH to the level that is favourable for subsequent ettringite precipitation in the second stage. As the ettringite precipitation is performed in a high-pH environment, the pH of the treated water needs to be adjusted to meet the upper limit value for mine effluent pH, typically in Finland around 9 to 10 (see Table 2 in Chapter 2). Figure 8 shows the flow diagram of the precipitation tests.

Figure 8: Flow diagram of ettringite precipitation tests

In the gypsum precipitation tests in batch reactors, 10% lime solution (100 g analytical grade $\text{Ca}(\text{OH})_2$ (>96%) in 1 000 ml) was added to 10 litres of artificial or real mine water to raise and maintain the pH at approximately 12. At the end of the test at 30 minutes, the solution was filtered (0.45 μm) and analyzed for the same components that were present in the feed.

In the ettringite precipitation tests, the lime-treated water was further treated by adding reactive aluminium and precipitating sulphate as ettringite. Extra-pure anhydrous AlCl_3 (>99%) was used as the aluminium source based on its good solubility. AlCl_3 was first solubilized, and added as a solution of 17–25% as a one-time dosage in the beginning of the 30-minute second stage. Al-dosing was calculated based on the sulphate concentration after the first stage (lime precipitation), and a molar ratio ($\text{Al}:\text{SO}_4$) of 1.5 was used. Also lime was added to the second reactor stage to maintain pH at 11.5–12 and to ensure that enough Ca was present for the formation of ettringite according to Eq. 2. At the end of the test at 30 minutes, the solution was filtered (0.45 μm), purged with CO_2 to lower the pH to <10, filtered again to remove formed carbonates, and analyzed for the same components as in the feed.

Characterization of the solids

Solids generated in the ettringite precipitation reactor were characterized for elemental composition (XRF) and for leaching properties (leaching test EN 12457–2) to roughly evaluate the final disposal quality.

3.3.5 Results and achievements

Batch precipitation tests with artificial mine water

Figure 9. summarizes the results of the precipitation tests with artificial mine water.

Figure 9: Behaviour of target components in the ettringite precipitation tests with artificial mine water

Batch precipitation tests with real mine water

Figure 10 summarizes the results of the precipitation tests with real mine water.

Figure 10: Behaviour of target components and aluminium in the ettringite precipitation tests with real mine water

In addition to the parameters displayed for the artificial mine water, the behaviour of aluminium is shown in Figure 10 for the real mine water. The limit value for aluminium concentration in Orivesi mine effluent is 3 mg/l.

Generation, composition and leaching behaviour of generated solids

Table 17 shows the amounts of generated solids in the precipitation process for artificial mine water and real mine water. The dry matter contents of the solids were around 20%.

Table 17: Generated solids in the precipitation experiments

Water	Gypsum precipitation (stage 1), wet weight, g/l water treated	Ettringite precipitation (stage 2), wet weight, g/l water treated	Neutralization, wet weight, g/l water treated
Artificial mine water	-	84	-
Orivesi mine water	1.5	46	1.1

It is noteworthy that only minor amounts of solids were generated in the gypsum precipitation stage, obviously indicating that no gypsum was generated in this step for either of the waters. Artificial mine water had a sulphate concentration of 2,900 mg/l at the start, indicating that sulphate concentrations could have been reduced with lime addition only. However, this did not take place in the experiment, which leads to a conclusion that sulphate was present as a more soluble compound or compounds, such as sodium sulphate. Sodium sulphate was, in fact, the compound in which the majority of sulphate was added to the artificial mine water according to the recipe. Orivesi mine water had an initial sulphate concentration of 2,000 mg/l, being somewhat equal to the solubility of gypsum, and therefore the observations fairly well match the theory in this case.

Only the sludges generated in the ettringite precipitation stages were studied for their composition and leaching behaviour. Table 18 shows the elemental composition of the ettringite sludges formed for chlorine and elements heavier than chlorine, and Table 19 shows the results from the batch leaching test EN 12457-2 performed for the sludges.

Table 18: Semi-quantitative elemental composition (XRF) of sludges from the ettringite precipitation tests. Concentrations of elements are expressed as percentages (%) of dry mass. Typical detection limit of the method is 0.1% (100 mg/kg)

Element, %	Artificial mine water, sludge from ettringite stage	Orivesi mine water, sludge from ettringite stage
Potassium, K	<0.01	0.02
Sodium, Na	26	0.24
Magnesium, Mg	0.05	0.25
Aluminium, Al	2.5	5.4
Silicon, Si	0.02	0.03
Sulphur, S	3.9	7.1
Chlorine, Cl	17	1.9
Calcium, Ca	23	22
Manganese, Mn	0.01	0.01
Iron, Fe	0.02	0.02
Copper, Cu	0.02	<0.01
Zinc, Zn	0.08	<0.01

Calcium, sulphur and aluminium were quite naturally some of the main components in the ettringite sludges. In the case of artificial water, also sodium and usually very

soluble chlorine were somewhat surprisingly present in the sludge of the artificial mine water. The source of sodium in the artificial water was to a large extent sodium sulphate, the purpose of which was to introduce sulphate into the solution. Chlorine came into the system from the addition of an aluminium source, aluminium chloride.

Table 19: Results from batch leaching test performed for the ettringite sludges and comparison to EU-landfill limit values for non-hazardous wastes. Amounts of leached compounds are expressed as mg/kg dry matter

Parameter	Artificial mine water, sludge from ettringite stage	Orivesi mine water, sludge from ettringite stage	EU-landfill for non-hazardous waste (2003/33/EC)
pH	11.0	10.8	>6
Leached compounds, mg/kg dry matter			
As	<0.01	0.08	2
Ba	0.31	0.47	100
Cd	<0.01	0.01	1
Cr	<0.01	0.04	10
Cu	0.02	0.10	50
Hg	-	-	0.2
Mo	0.01	0.39	10
Ni	<0.01	0.03	10
Pb	<0.01	0.02	10
Sb	0.02	<0.02	0.7
Se	<0.01	0.16	0.5
Zn	0.05	0.13	50
Cl ⁻	51,000	25,000	15,000
F ⁻	3.9	2.4	150
SO ₄ ²⁻	24	95	20,000
DOC	22	56	800

The leaching of sulphate, the main compound removed, seems very low from the ettringite sludges in the prevailing conditions. Leaching of the other spiked compounds (Cu, Ni, Zn) also remained at a very low level in the artificial mine water sludge. However, the pH of the ettringite sludge is quite high, around 11, and questions can be raised about the long-term stability of such alkaline conditions. In general, alkaline materials react with atmospheric CO₂ and water to form carbonates from basically all the calcium compounds contained in the material. This also means a transition in the material's pH towards 8 to 8.5, in which an equilibrium state exists between calcium carbonate in the material and CO₂ in the air. The stability of ettringite at a pH close to neutral has not been studied here or elsewhere.

High amounts of chloride exceeding EU limit values for non-hazardous waste (and hazardous waste) landfills were leached from both ettringite sludges. This raises questions about the overall stability of the sludge, but also on the choice of the aluminium source in the ettringite precipitation. Aluminium chloride was chosen for the studies based on its good solubility and reactivity, but the release of chloride both into the treated water and later from the sludge questions this choice. Other, more suitable sources of aluminium could be, e.g. sodium aluminate and some amorphous forms of aluminium hydroxide [2].

Regarding sludge stability, the conclusions that can be drawn from the results for the artificial mine water are limited. More emphasis will be given to the results with real mine water, which will be ready later.

3.3.6 *Conclusions and recommendations for future work*

The main findings of the research presented here can be summarized as follows:

- Sulphate can be effectively removed from mine waters with ettringite precipitation.
- Long-term stability of highly alkaline sludges should be addressed in great detail in the future.
- Recycling options for aluminium in the ettringite process should also be investigated.

3.3.7 *References*

1. International Network for Acid Prevention INAP (2003) Treatment of Sulphate in Mine Effluents Lorax Environmental.
2. Janneck, E., Cook, M., Sommer, K., Dinu, L. 2012. Ettringite precipitation vs. Nano-Filtration for Efficient Sulphate Removal from Mine Water. International Mine Water Association Annual Conference 2012, 206 I-R.

3.4 **Ettringite precipitation process for sulphate removal from mine water with aluminium recovery, $\text{LoSO}_4^{\text{TM}}$**

3.4.1 *Details of project partner*

This part of the experiment was performed by Krüger Veolia. Contact persons Christina Sund, Magnus Nilsson.

3.4.2 *Summary*

Traditionally sulphate is precipitated as calcium sulphate (gypsum). Theoretically a residual concentration of 1,240 mg SO_4/l should be possible to reach; however, in practice because of the stability of calcium sulphate in solution concentrations lower than 1,500–1,800 mg/l is extremely difficult to reach [4].

By combining lime precipitation with a dosage of an aluminium chemical ettringite $3\text{CaO} \cdot 3\text{CaSO}_4 \cdot \text{Al}_2\text{O}_3 \cdot 31\text{H}_2\text{O}$ can be precipitated. Ettringite is a highly insoluble calcium aluminium sulphate mineral and residual concentrations ≤ 50 mg/l SO_4 can be reached at high excess of aluminium. Aluminium salts are fairly expensive compared to, e.g., lime and furthermore sludge volume increases dramatically with aluminium addition. By recovering aluminium from the precipitate and reusing it for renewed precipitation of sulphate both the amount of sludge to be disposed of and the cost for treatment will be reduced.

3.4.3 Process description

The LoSO_4 process differs from other ettringite precipitation processes, as recovery of aluminium (according to Veolia up to 95%) is an integrated part of the concept saving cost for chemicals. Consequently, there will also be lower residual aluminium content in the product to be disposed.

According to Veolia, the different steps of the full-scale process are:

- The first step in the process uses a high-rate lamella clarifier equipped with an efficient mixing system to reduce sulphate by traditional lime precipitation to less than 1,800 mg SO_4/l . The chemical precipitation/adsorption reactions are enhanced by sludge recirculation in the presence of a seed material. The seed material is added only once during start-up to enhance the initial calcium sulphate crystal growth kinetics.
- The first-stage effluent is then treated with calcium and an aluminium-based salt in a second high-rate lamella clarifier system. This second-stage process precipitates sulphate as a highly insoluble calcium sulphoaluminate mineral known as ettringite. This step reduces the dissolved sulphate in the effluent to less than 100 mg/l.
- The excess sludge from the second high-rate lamella clarifier system is pumped to a third smaller high-rate lamella clarifier system, which serves as a chemical regeneration tank. In this step, it is possible to recover up to 95% of the aluminium-based salt from the precipitated sludge for reuse in the treatment process.

Figure 11: Process steps $\text{LoSO}_4^{\text{TM}}$

For high flow rates with lower sulphate concentrations, nanofiltration can be implemented, with the sulphate reduction technology applied to the membrane reject (concentrate). This option minimizes flow to the sulphate reduction process and thereby reduces the cost of the process.

3.4.4 Experimental work

Laboratory tests (1–2 l sample volume per test) have been performed with mine water from Boliden Kevitsa mine (Cu, Ni mine) and LKAB Svappavaara mine (iron mine). For Kevitsa mine, both drainage from the waste rock dump and their combined effluent were tested with LoSO₄TM process. The results for the LoSO₄TM tests on drainage water from the waste rock dump are shown in Figure 12 and for combined mine water in Figure 13.

Figure 12: Residual concentration of sulphate at different dosing ratios for drainage from Waste Rock dump (SO₄ in ratio calculation is the raw water concentration)

Figures 12 and 13 show the relation between dosed aluminium and the residual sulphate concentration for the two streams from Kevitsa. The theoretical Al:SO₄ ratio (g:g) for ettringite precipitation is 0.188 and for the drainage from waste rock dump with nearly 4x higher sulfate content Al requirement was ~110% to the theoretical while for the combined water nearly 50% excess was required.

One result from the test with reuse of aluminium is also shown in both figures 12 and 13. The residual sulphate concentration was slightly higher in this test, which most probably is caused by the uncertainty in weighing sludge used for the recovery of aluminium and the partial loss of Al with the sulfate solution.

Figure 13: Residual concentration of sulphate at different dosing ratios for combined mine water from Kevitsa mine

The process was also tested on clarifier overflow from LKAB Svappavaara mine, Figure 14. The test results show that it is possible to reach a residual concentration of SO₄ in the range of 40 mg SO₄/l, however an Al excess of nearly 300% was required to reach this level. The reason for higher chemical consumption (Al) for the combined streams (both Svappavaara and Kevitsa) could, in addition to the lower initial sulfate content and thereby lower saturation, be that these streams also might contain compounds (i.e. flotation agents) delaying the precipitation of ettringite, calling for higher aluminium concentration to initiate crystallization.

Figure 14: Precipitation of sulphate by LoSO₄™ process. Svappavaara clarifier overflow. Influence of ratio Al: SO₄ (g:g) on sulphate residue

The LoSO₄TM process brings the pH of the liquid phase to a pH of approx. pH 11.5, which means that there will be co-precipitation of metals. Table 20 shows one result from a test with drainage from Kevitsa waste rock dump.

Table 20: Effect on metal content in mine water of LoSO₄TM process.

	Unit	Waste rock drainage	LoSO ₄ treated
Fe	mg/l	0.312	<0.004
K	mg/l	23.4	26.3
Mg	mg/l	424	<0.09
Na	mg/l	34.6	40.8
Al	µg/l	31.3	22.5
As	µg/l	1.03	<1
Ba	µg/l	36.1	75.2
Cd	µg/l	0.149	<0.05
Co	µg/l	186	0.06
Cr	µg/l	1	5.93
Cu	µg/l	16.4	<1
Hg	µg/l	<0.02	<0.02
Mn	µg/l	3,360	1.04
Mo	µg/l	0.855	0.807
Ni	µg/l	4,940	<0.5
Pb	µg/l	<0.5	<0.2
V	µg/l	0.931	0.253
Zn	µg/l	129	<2
SO ₄	mg/l	2,050	293

In order to ensure a non-hazardous residue from the ettringite precipitation process, it is therefore recommended to consider removal of heavy metals, if present, before sulphate removal is performed.

3.4.5 Conclusion and recommendations

The results from the tests performed with mine water from LKAB Svappavaara mine and Kevitsa mine indicate that treating more concentrated streams, i.e. streams with higher sulphate content, are preferable as chemical consumption would be lower. As aluminium is recovered in the process (up to 95% recovery possible), a high consumption would have less financial implication though higher aluminium amounts would require more chemicals for the recovery process. A general recommendation would therefore be to select streams with the highest sulphate content for treatment, or alternatively increase concentration by nano-filtration (NF) and only precipitate sulphate from the concentrate stream produced by NF.

3.4.6 References

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3.5 Evaluation of Eutectic Freeze Crystallization for water treatment

3.5.1 Details of the project partner

The research was performed as a co-operation project between the Norwegian University of Science and Technology (NTNU) and University of Cape Town (UCT). The experimental work was performed at UCT by Professor Jens-Petter Andreassen (NTNU) and research officer Jemittias Chivavava (UCT). The work was led by Jens-Petter Andreassen, assisted by Professor Alison Lewis at UCT, who also performed the thermodynamic calculations and simulations.

3.5.2 Summary

The aim of this project was to investigate the technical feasibility of using Eutectic Freeze Crystallization (EFC) to treat the synthetic minewater brine defined in the Wascious project. A thermodynamic evaluation was performed of the brine with respect to crystallization temperatures and yield of produced water and salts, followed by a short program of EFC batch experiments to investigate the feasibility of the process and verify the predictions from the thermodynamic analysis.

EFC is a water purification technique that allows simultaneous production of purified water (as ice) and salts provided that the concentration of salt in solution is sufficiently high. The Wascious synthetic solution is rather dilute and a substantial up-concentration is required to reach the eutectic point for the main salt, sodium sulphate decahydrate, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ (Glauber's salt). The up-concentration of the water should be performed by a technique that is more economically and technically feasible for water extraction from solutions with low levels of salts, like a membrane separation process. Both the thermodynamic modelling and the experimental work were hence performed on a solution prepared at 10 times the synthetic solution concentration (the most concentrated case) defined in the project.

The thermodynamic modelling confirms that this up-concentration brought the system close to the eutectic point of ice and Glauber's salt, by prediction of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ crystallizing out first at 0.5°C , and then ice nucleating at -1.4°C , where both solids will crystallize in proportions that maintain the eutectic composition.

The experimental investigation showed that a certain supersaturation of the salt was required, as demonstrated by spontaneous crystallization at $-2.6\text{ }^{\circ}\text{C}$ followed by a slight temperature increase due to the release of heat from crystallization. The solution then moved towards the set-point of the cooling medium ($-3.5\text{ }^{\circ}\text{C}$) before the ice crystallized after a significant holding time and the temperature moved up to the predicted eutectic value of $-1.4\text{ }^{\circ}\text{C}$. The system was seeded with ice and salt to avoid a long period of supersaturation build-up, as this will produce crystals of smaller size and with more inclusions. The system was allowed to run at the eutectic conditions and ice and mother liquor were harvested at 30-minute intervals to measure the yield and the purity. Eutectic points for other salts in the mixture will not be reached until more than 90% of the water has been recovered at temperatures as low as $-25.5\text{ }^{\circ}\text{C}$ for $\text{NaCl}\cdot 2\text{H}_2\text{O}$ and -28.75 for NH_4Cl , and these conditions were not considered as feasible. This limits the number of salts that can be produced but also offers the advantage of not getting an impure mixture of salts since their eutectic points with water are that far apart.

The yield of ice produced is directly related to the rate of heat extraction, i.e. the temperature difference between the cooling medium and the eutectic temperature, and the surface area of the cooled surface. For the one-litre batch reactor running at a temperature difference of $\sim 2\text{ }^{\circ}\text{C}$ the amount of ice produced was 4.2 g/minute . The impurities in the ice were either entrained crystals of sodium sulphate decahydrate or from the ions present in the pore volume of the ice filter cake. Washing three times with an amount of water corresponding to half the weight of the wet filter cake removed all impurities from the filter cake and demonstrated that the ice crystals are in themselves without incorporated impurities.

3.5.3 *Process description*

The EFC process is based on cooling down the solution to freeze out the water as ice, which, due to the density difference, floats to the top of the reactor and salts that will crystallize are separated out by gravity due to higher density. When the composition reaches the eutectic point for the specific salt in question, the composition of the mother liquor and the temperature will be constant until the concentration of other salts reaches a eutectic point of lower temperature. This allows for sequential removal of the salts if the eutectic points are well separated, while all the time producing ice that can be recovered and purified by washing with melted ice either on belt filters or in a wash column.

The composition of the synthetic water defined in the project is very dilute and thus it is proposed that the first treatment stage should incorporate a membrane separation process in order to recover water as well as to concentrate the brine prior to the use of EFC (Figure 15). Membrane processes often become of limited use at higher concentrations due to scaling and concentration polarization, and this is where EFC can offer a more efficient separation and allow for production of salts that can represent potential revenue.

Figure 15: Schematics of a combined membrane and EFC process

The feed to the EFC process used in this project is an up-concentrated hypothetical retentate from an upstream membrane separation process as given in Table 21. It is assumed to result in 10 times higher concentration of the salts compared to the original composition of the synthetic solution (the high concentration version):

Table 21: Mine water composition and concentrated version

Chemicals	Original synthetic mine water (high) concentration, g/l	Concentrated mine water concentration, g/l
CuSO ₄	0.02009	0.2009
NiSO ₄	0.02109	0.2109
ZnSO ₄	0.03704	0.3704
Na ₂ SO ₄	4.36609	43.661
NaNO ₃	0.08225	0.8225
NH ₄ Cl	0.08896	0.8896
NaCl	0.39734	3.9734

The material balance for an EFC process based on this up-concentrated water is given in Table 22.

Table 22: Material Balance for the proposed EFC process

	Volumetric flow (1 m ³) Mass in kg
Brine feed	1,050
Water in feed	1,000
EFC process operated at -5 °C	
Ice recovery	878
Na ₂ SO ₄ ·10H ₂ O recovery	98
Waste stream	74
Water	67.4
Salts	6.8
Total water recovery	88%

3.5.4 Research activities

The first part of the project was a thermodynamic evaluation of the up-concentrated version of the synthetic solution defined in the project (10 times the high concentration) with respect to crystallization temperatures and yield of the produced water and salts. The second phase of the study involved a preliminary investigation into the feasibility of the process based on the predictions from the thermodynamic analysis as demonstrated with a short program of EFC batch experiments.

The thermodynamic modelling was performed by Professor Alison Lewis, University of Cape Town (UCT), applying OLI Stream Analyser (OLI Systems Inc, 2015), which uses the revised Helgeson-Kirkham-Flowers (HKF) model for the calculation of standard thermodynamic properties of aqueous species and the frameworks of Bromley, Zemaitis, Pitzer, Debye-Huckel, and others for the excess terms. The EFC batch experiments were performed by Jens-Petter Andreassen in co-operation with laboratory personnel in the IceLab in the Department of Chemical Engineering at UCT. The batch experiments were performed in a one-litre stirred reactor cooled by a cooling medium at a temperature of -3.5 °C, which was found to be optimal for EFC of this water composition in this equipment. This represented a temperature difference of ~2 °C relative to a eutectic point of about -1.5 °C and produced an amount of ice that resulted in a filter cake that allowed for proper washing and at the same time did not allow ice to scale on the reactor walls. The EFC experiments, filtration and washing tests were performed in a refrigerated room maintained around -2 °C. The values of Cu, Zn and Na in the mother liquor as well as in the produced ice were determined by ICP-analysis.

3.5.5 Results and achievements

Table 23 shows the simulated nucleation temperatures for both ice and salts formed in the proposed EFC process for the up-concentrated synthetic solution.

Table 23: Nucleation temperatures for ice and salts formed in the proposed EFC process for the mine water

Major salts	Nucleation temperature (°C)
Na ₂ SO ₄ ·10H ₂ O	-0.5
Ice	-1.5
Secondary salts	Nucleation temperature (°C)
NaCl·2H ₂ O	-25.5
NH ₄ Cl	-28.75

The experimental investigation showed that a certain supersaturation of the salt was required as demonstrated by spontaneous crystallization at -2.6 °C followed by a slight temperature increase due to release of heat of crystallization. The solution then moved towards the set-point of the cooling medium (-3.5 °C) before ice crystallized as a result of seeding after a significant holding time, and the temperature moved up to the predicted eutectic value of -1.4 °C, as shown in Figure 16.

Figure 16: Temperature [°C] versus time [minutes] for spontaneous salt nucleation. The system was seeded with ice at around 90 minutes since it did not spontaneously crystallize at -3.5 °C

By seeding with ice, the temperature increased quickly and stabilized at the eutectic value of -1.4 °C. The ice was harvested from the reactor after 10 minutes because the high supersaturation produced significant amounts of ice during this period. The temperature was increased to melt all the remaining ice before new ice production was carried out. Now the temperature was lowered to just below the eutectic point and ice seeding was performed which resulted in a courser ice product due to lower supersaturation. The salt was left in the bottom of the reactor throughout the ice production periods. Ice production occurred for 30 minutes before the experiment was stopped, and the ice was removed from the reactor and filtered on a Buchner funnel for determination of yield and ice purity of the wet filter cake. A total of three 30-minute ice production experiments were executed. The cake was washed three times with an amount of 0 °C water corresponding to half the weight of the wet filter cake. The amount of impurity ions in the unwashed filter cake as well as after 1, 2 and 3 washes is shown in Figure 17. After the third wash all impurities are removed from the wet cake demonstrating that the ice crystals themselves do not contain any impurities.

Figure 17: The levels of metal ion concentration and the efficiency of water washes represented by copper and zinc (ppb) in the unwashed ice and after 1, 2 and 3 washes of ice on the filter. Cu' and Zn' are the values of the ice produced in the first 30-minute period. Cu''' and Zn''' are the values for the ice produced in the third 30-minute period, from the same batch experiment

3.5.6 Conclusions and recommendations for future work

The ice yield is reproducible and when the process is seeded to remove the kinetic barrier for nucleation, it only depends on the heat removal from the reactor.

The purity of the produced ice can be controlled by the amount of washing of the filter cake.

Experiments should be performed in a continuous scraped surface reactor system at higher heat removal rates to increase the ice production rate and this should be the focus of future research.

3.6 Electrochemical treatment of mine waters

3.6.1 Details of the project partner

Electrochemical treatment of mine waters was performed by a research group from Lappeenranta University of Technology, School of Engineering Science, Competence area of Separation. Doctoral Student Maria Mamelkina mainly performed the research activities. Professor of Solid/Liquid Separation, Antti Häkkinen and Associate Professor Ritva Tuunila provided supervision.

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3.6.2 Summary

Mining waters are known to be very site specific. However, most of them are commonly characterized as containing sulphate in high concentrations accompanied with dissolved metals and other anionic species such as phosphate and nitrate. This part of the research is dedicated to the application of electrocoagulation (EC) as a possible technique for mining water treatment. EC tests were performed using laboratory-scale batch and continuous mode reactors equipped with iron or aluminium electrodes. Synthetic and real mine waters were treated.

The effect of several parameters was studied to investigate the possibility to treat mining waters with electrocoagulation and to determine the most suitable process conditions enabling the most efficient treatment of mining effluent. Among the studied parameters were pH, current density, initial concentration of the contaminants, operational modes and electrode materials.

During the first stage of the research, various experimental conditions were tested by changing the initial pH of the solution, sulphate concentration and applied current to study the EC performance in a batch mode. According to the experimental results, maximum sulphate removal (54%) from synthetic mine waters was achieved at current 3 A after 5 hours of treatment.

The following step consisted of mining water treatment by batch and continuous EC reactors equipped with iron or aluminium electrodes. This part of the research was based on a preliminary study of sulphate removal by chemical coagulation, where the optimal dose of coagulant and operating pH were firstly studied. The results showed the highest removal of sulphate with FeCl_3 at pH 2 and coagulant dose of 1,000 ppm, and for AlCl_3 at pH 5 and coagulant dose of 5,000 ppm. Based on these results new conditions for EC treatment were proposed for continuous treatment of synthetic mining effluent.

The amount of solids originating from the anodes mainly depended on the applied current, electrode material and pH of the solution. The solids formed during the EC treatment with iron electrodes were analyzed. The main detected species determined were iron oxides with associated granulated texture species (Fe, O, S).

Electrocoagulation enables the partial removal of sulphate of high concentrations from mine waters. Dissolved metals and nitrate are confirmed to be removed by EC in both operational modes. Iron electrodes are recommended to be used for sulphate treatment since aluminium electrodes have a tendency to passivate within the long operating time and more coagulant is required to enable the removal of sulphate. The main parameters affecting the treatment of mine waters are applied current and final pH of the solution. No harmful solid compounds were detected to be produced during the EC treatment of mine waters.

3.6.3 Process description

Electrocoagulation is an electrochemical method that has been used for water treatment since 1946 [1]. EC is a method for producing destabilization agents by applying current. These agents induce a neutralization of electric charge for a pollutant

removal. After the particles are charged they bind together to form a mass (Emamjomeh, Sivakumar 2009). The simplest construction of an electrocoagulation reactor is an electrolytic cell with one anode and one cathode (Emamjomeh, Sivakumar 2009). The anode provides metal ions for the system, while the cathode releases hydrogen gas. During the electrocoagulation, aluminium or iron ions are released electrochemically from aluminium or iron electrodes, respectively (Equation 3 and 4), and thus the generation of coagulants in situ takes place [1]. Faraday's law (Equation 5) can describe the amount of solids generated during the EC process.

$$Al(s) \rightarrow Al^{3+}(aq) + 3e^{-}(aq) m_f = \frac{Q}{F} \cdot \frac{M}{z} = Z \cdot I \cdot t \quad F, M, z - const, \quad (\text{Eq. 5})$$

where Q – electrical charge passes, A.s, F – Faraday's constant, 96487 C mol⁻¹, M – Molecular weight, kg mol⁻¹, z – number of electrons involved in the electrode reaction, Z – electrochemical equivalent, g C⁻¹, I – current, A, t – time, s.

Currently, electrocoagulation application lies in the fields of metal recovery, and in treating drinking and process waters. Electrocoagulation finds its application while treating wastewaters generated during tannery, electroplating, dairy and textile processing, as well as from oil and oil-in-water emulsions. In some cases, when wastewaters contain refractory pollutants, electrocoagulation is going to be one of the most efficient and indispensable stages in their treatment. [1]

The review made by Mollah *et al.* [2] shows that electrocoagulation enables the efficient treatment of wastewater containing metals, anionic contaminants, foodstuff, organic matter, polymeric wastes, oil wastes, textile dyes, lignin, chemical and mechanical polishing wastes, phenolic wastes and aqueous suspensions containing ultrafine particles.

Presently, one of the most investigated anionic compounds removed by electrocoagulation is fluoride [3]. In addition, some studies are dedicated to the treatment of wastewater containing cyanide, nitrate, sulphate and phosphate. However, in spite of the considerable success of electrocoagulation for treatment of anionic contaminants in drinking and surface waters, its application for the treatment of mining waters is very rare in the literature. There are very few studies on the elimination of anionic contaminants, especially of sulphate in high concentration, from mine waters by electrocoagulation. No direct studies have been published on sulphate removal from mining waters.

3.6.4 Research activities

Electrocoagulation tests were performed with artificial and real mining waters using reactors of different configurations and operation modes. Treated volumes of mining waters varied from 1 to 75 L. Mainly iron was used as an electrode material. The maximum removal efficiency obtained with Al electrodes was 10% at pH 10 and current 5.3 A for artificial waters with sulphate concentration 1,000 ppm.

A plexiglass jacketed reactor of 1 000 mL was used to study the performance of EC in a batch mode. The reactor was equipped with two pairs of electrodes connected in monopolar arrangement. The electrodes had dimensions of 60x70x2 mm and were placed inside the reactor giving a total anode area of 168 cm². The applied current was 1 A (6 mA/cm²), 2 A (12 mA/cm²) and 3 A (18 mA/cm²). A plastic curved blade turbine was used to provide proper mixing of the treated solution during each test at a speed of 200 rpm, which corresponded to a tip speed of 0.84 m/s. Each experiment took 5 hours. In total 38 tests were performed.

Based on the results obtained from the experiments, a bigger reactor of 75 L was designed and proposed for the efficient treatment of sulphate reach waters. The dimension of electrodes with internal deployment was 300x300x5 mm. Treatment time was 5 h. Solids formed during the EC process were left to settle for 24 hours. The treated water was removed manually. Slurry was filtered using a laboratory Nutsche filter.

Filtration of EC sludge was performed under pressures at 2, 4 and 6 bar (Figure 18). No pH or temperature adjustments were made. The sample volume was 200 ml and the filtration time varied from 7 to 11 minutes.

Figure 18: Cake formed during pressure filtration of EC slurry, 4 bars, pH 7

Continuous mode experiments (Figure 19) were conducted using the installation designed during the research visit to the University of Castille La-Mancha, Department of Chemical Engineering, Electrochemical Laboratory. The main distinctions of designed equipment set-up are low energy consumption, low flow rate to allow simultaneous thickening of solids, slurry recirculation and external electrode placement. Each experiment took from 9 to 92 hours. The electrodes had dimensions of 100x100x2 mm. The applied current varied from 1 to 10 A.

Figure 19: EC continuous mode experiments with solids recirculation

Chemical coagulation experiments were performed to study the physico-chemical characteristics of the sulphate coagulation assisted by Fe and Al. Tests were performed in 250 ml glass vials. The studied volume was 100 ml. Each experiment lasted for 3 hours. The concentration range of the added coagulant varied from 10 mg to 50 g. The operating pH was 2, 5, 9 and 12.

Among the main research activities, collaboration with two WASCIOUS project partners (Lulea University of Technology and Sintef Norway) was established. The University of Castilla La-Mancha was involved in the project to work out the EC continuous treatment concept. Solids analysis and characterization were performed at Lulea University of Technology. Collaboration with Sintef Norway resulted in the development of a concept membrane/EC treatment of mine waters. EC technology was proposed to treat the membrane concentrate.

In this project, EC was proposed as a possible technique to treat concentrate produced during the membrane process. The process scheme is illustrated in Figure 20. The idea of this combined process was to treat the concentrate by EC, and bring the EC treated concentrate back to the membrane process enabling relatively low sulphate concentration in the feed. By applying this process configuration, the total volume of water to be treated with EC would be smaller and thus the size of the equipment needed for the process could be minimized and efficiency of EC improved.

Figure 20: Schematic diagram of a membrane/EC combined process. C_0 , C_1 , C_2 and C_3 are abbreviations for concentrations

Concentrate samples of 1 L were treated using iron electrodes at current 3 A with no pH adjustments. The highest removal of sulphate from concentrate was 40% for an initial sulphate concentration of 3,200 mg/l, when for the concentrate after nanofiltration the sulphate removal of 11% was observed for an initial sulphate concentration of 4,800 mg/l. Based on the results obtained, the treatment of membrane concentrates by EC is effective when the initial sulphate concentration does not exceed 3,500 mg/l.

3.6.5 Results and achievements

Based on the results obtained during the EC and filtration experiments, several main patterns were observed:

- EC is a pH dependent process.
- The presence of other contaminants in low concentrations does not influence the removal of sulphate from mine waters.
- Iron is released in the form of Fe^{2+} .
- Change in conductivity and pH increases with the applied current increased.
- EC enables 54% removal of sulphate, 90% of nitrate and 99% of Zn, Cu and Ni.
- Mainly iron oxide is formed.
- The moisture content of a filter cake varies from 60 to 80%.
- The formed cake is highly porous.

A summary of the work is given in Table 24.

Table 24: Summary of the coagulation experiments

Technology	Water source	Operational conditions	Studied compounds	Achieved results
Electrocoagulation (batch mode)	Synthetic	3A, pH 4 and 10, Fe electrodes	sulphate, Zn, Cu, Ni, nitrate	50% removal of sulphate, 99% removal of Zn, Ni, Cu, nitrate
	Real	2A, pH 7, Fe electrodes	sulphate, Zn, Cu, Ni, nitrate	30% removal of sulphate, 90% of nitrate and 99% removal of Zn, Ni, Cu
Electrocoagulation (continuous mode)	Synthetic	6.25A, pH 2, Fe electrodes	sulphate, Zn, Cu, Ni, nitrate	50% removal of sulphate, 99% removal of Zn, Ni, Cu, nitrate
Chemical coagulation	Synthetic	Coagulant dose 5,000 mg/l AlCl ₃ pH 5, 1,000 mg/l FeCl ₃ pH 2	sulphate, Zn, Cu, Ni, nitrate	AlCl ₃ : 95% removal of sulphate, 0% removal of nitrate, 95% removal of Cu, Ni, Zn FeCl ₃ : 95% removal of sulphate, 0% removal of nitrate, 95% removal of Cu, Ni, Zn
Biosorption (batch mode)	Synthetic and real	<i>P. chrysosporium</i> white rot fungi	sulphate, Zn, Cu, Ni, nitrate	15% removal of sulphate, 0% removal of nitrate, 3–7% removal of Cu, Ni, Zn

3.6.6 Conclusions and recommendations for future work

EC seems to be a promising technology to treat mine waters. However, more studies should be conducted to determine the most suitable operational conditions for continuous EC treatment and a pilot EC-treatment plant is proposed. Solids separation and proper slurry treatment should be a future research focus when developing EC processes.

3.6.7 References

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3.7 Membrane processes in water treatment

3.7.1 Details of the project partner

The research was performed in SINTEF by Marius Sandru Marius.Sandru@sintef.no research scientist and Heidi Johnsen Heidi.Johnsen@sintef.no research manager at SINTEF, Materials and Chemistry, Department of Polymer Particles and Surface Modifications.

3.7.2 Summary

The main objectives of SINTEF Research are to investigate the possibility of integration in the wastewater treatment process from mining industry of new membranes, which are specifically tailored for each particular application.

Initially the literature study was directed towards the removal of heavy metals by using specifically tailored membranes: "The project will investigate the concept of using polymeric membranes and particles modified with specifically tailored complexing agents/chelators targeted towards removal, concentration and recovery of metallic ions of economic interests/critical metals (Cu, Ni, Cr, Au, Ag, etc.)."

The feedback from the mining companies and data gathered on current mining water qualities indicated that the SO_4 ions removal represents the main priority. Consequently, the main direction of research was changed to membrane integration

with other separation technologies such as electrocoagulation (e.g. a pre - concentration step) in a hybrid process for electrocoagulation and solid-liquid separation of ions (SO_4) from mine waters.

An assessment of methods and preparation strategy was performed to improve the separation capabilities of membranes and their stability. Polymeric membranes were prepared and tested for the removal, concentration or pre-concentration of selected components (metals and/or ions) in water from the mining industry. One single synthetic solution having 3,000 mg/l SO_4 ions concentration was used by all partners. Membranes with a defect-free selective layer (0.2–1 μm) coated on porous support were obtained by selection of the porous support of nanofiltration (NF) and ultrafiltration (UF) and polysulphone, fluoro polymers commercially available from Alfa Laval, and selective polymer/material (polyvinyl alcohol, chitosan and polydimethylsiloxane), optimization of concentration and viscosity for the coating solution, and surface modification of the support.

Using the membranes prepared in Norway, tests were carried out on laboratory scale at Lappeenranta University, Finland, using a synthetic aqueous mixture of pre-determined concentrations of sulphate and metallic ions (3,000 mg/l SO_4).

It was concluded that the most promising membranes were NF membranes which reduced the SO_4 concentration in permeate to 30 ppm SO_4 and the surface modified with polyvinyl alcohol (PVA) UF membranes polysulphone (PSF) and fluoro polymer which reduced SO_4 to 1,400 ppm (permeate) and concentrated the feed up to 3,200 ppm.

The results and the research efforts have been presented in a magazine Gemini (<http://gemini.no/2015/09/reenser-gruvevann-uten-kjemikalier/>) and in a poster presentation at NOFS 2016 the 16th Nordic Filtration Symposium in Aug 2016, Lappeenranta, Finland.

3.7.3 *Process description*

A membrane is a selective barrier between two phases controlling the rate of molecule movement which transports selectively one component to the detriment of another based on differences in physical or chemical properties.

The membranes can be used for water treatment as a process itself with separation based on pore size (or molecular weight cut off- MWCO) or affinity for certain elements present in solution.

Based on the literature study for SO_4 ions removal [1–13], it was decided, in addition to using solely nanofiltration membranes, to test surface-modified ultrafiltration membranes (high water flux, more porous) that concentrate the sulphate sufficiently to make more efficient the electrocoagulation process – a hybrid process.

Testing was performed using a high-pressure water permeation set-up at Lappeenranta University by continuously circulating the feed in a loop at a constant flow rate and constant temperature. The feed and permeate were analyzed by ion chromatography for SO_4 ions and atomic absorption spectroscopy for metals. The reduced feed in volume and concentrated in ions was used for further experiments using electrocoagulation.

3.7.4 Research activities

The activities related to the experimental work carried out in SINTEF:

- meetings and discussions with the partners in the project
- literature study regarding membranes used in the mining industry/water cleaning for metal and sulphate removal
- designing a permeation cell and building a small set-up for testing membranes
- selecting commercial membranes (polysulphone, cellulose acetate, polybenzimidazole, etc.) as candidates for surface modification and testing
- preparing 12 different membranes for testing
- testing together with Lappeenranta University the membrane water flux, retention capacity of ions.

A small water permeation set-up was designed and built for the Wascious project. The characteristics of the set-up are the following: flow rates from 2 ml/min up to 2,000 ml/min; temperature 25 °C to 60 °C; pressurized mode (without fluid recirculation) up to 10 bar; possibility of continuous measurements for conductivity, pH and weight of solution.

Figure 21: Water permeation set-up and the membrane cell

The test plan was based on conclusions from data collection on current practice and limit values related to the main contaminants of interest in the mining industry.

The testing was performed in collaboration with Lappeenranta University, Prof. Antti Häkkinen's group and using the synthetic solutions given in Table 14.

The main aim was membrane integration with other separation technologies such as electrocoagulation (e.g. a pre-concentration step) in a hybrid process for electrocoagulation and solid-liquid separation of ions from mine waters.

Polymeric membranes were prepared and tested for removal, concentration or pre-concentration of selected components (metals and /or ions) in water from the mining industry. Membranes having a defect-free selective layer (0.2–1 µm) coated on porous support were obtained by using porous support of nanofiltration (NF) and ultrafiltration (UF) and polysulphone, fluoro polymers commercially available from Alfa Laval and

selective polymer/material (polyvinyl alcohol, chitosan and polydimethylsiloxane). Three types of UF support having different pore size were used for modification: polysulphone with 20,000 MWCO (PSF20), fluoropolymer with 1,000 MWCO (1KF) and fluoropolymer with 10,000 MWCO (10KF). In total 12 different membranes were prepared and tested including the NF and UF membranes without surface modification.

Testing was performed by using a high-pressure water permeation set-up at Lappeenranta University at 5 and 10 bars, and 25 °C, using two feed flow rates of 60 l/h for most of the testing and 217 l/h for some membranes. One single synthetic solution of 3,000 mg/l SO₄ ions concentration was used by all partners. The permeation experiments were run until sufficient permeate was obtained for analysis and for some membranes also until 1 l of permeate was obtained in order to be used for the electrocoagulation experiments. The conductivity of both feed and permeate were measured for selected samples. The feed and permeate were analyzed by ion chromatography for SO₄ ions and atomic absorption spectroscopy for metals.

3.7.5 Results and achievements

Water flux

Table 25 presents the results obtained for water flux at 5 bar, 25 °C. The supports without surface modification showed a proportional flux to the pore size of the UF membranes. From the modified membranes, the highest water fluxes were obtained for those modified with polyvinyl alcohol (PVA). The PSF due to the higher pore size had a certain pore penetration of PVA, which reduced the flux compared to 10KF support. The NF membranes had a flux of 54, 18 L/(m² h).

Table 25: Water flux at 5 bar and 25 °C of tested membranes

1KF (1000 MWCO)	MEMBRANE	FLUX l/h m2
	1KF	91,89
	1KF chit.	18,48
	1KF PDMS	13,30
	1KF PVA	39,28
10KF (10,000 MWCO)	10KF	109,50
	10KF chit.	11,96
	10KF PDMS	no flow
	10KF PVA	56,73
PSF20 (20,000 MWCO)	PSF20	530,79
	PSF20 chit	13,60
	PSF20 PDMS	no flux
	PSF20 PVA	32,52

Sulphate removal

The permeating SO₄ concentration for the UF membranes ranged between 1,400 ppm and 2,500 ppm (from an initial 3,000 ppm SO₄ in the feed).

The most promising membranes beside NF (30 ppm SO₄ in permeate) are the surface modified membranes PSF and 1KF with PVA which reduced SO₄ to 1,400 ppm

(permeate) and concentrated the feed up to 3,200 ppm during the experiment. The nanofiltration membrane results are presented in Figure 22. The permeate concentration remained constant for more than 3 hours in the experiment at 30 ppm SO_4 in permeate and the feed concentration increased due to the reduction of water volume permeating through the membrane in the permeate side.

Figure 22: SO_4 removal/concentration using NF membrane

Metal removal

Table 26 presents the efficiency of membranes for metal removal. All membranes reduced approximatively to half the concentration of Cu, Zn and Ni in the permeate flow. There are small differences between the modified and non-modified membranes, which indicates that the support itself is responsible for ion removal and so much the coating. The PVA coating performed the best as in the case of SO_4 ions removal.

Table 26: Metal ions removal

1KF membrane	Description	Cu, ppm	Zn, ppm	Ni, ppm
	<i>Initial concentration feed</i>	8	15	8
	<i>Concentrate final feed 1KF</i>	10.0	13.1	6.8
	Permeate 1KF	5.5	9.3	3.8
	Permeate CHIT 1KF	6.1	10.1	6.1
	Permeate PDMS 1KF	5.5	9.2	4.0
	Permeate PVA 1KF	5.2	8.9	3.6
10KF membrane	<i>Initial concentration feed</i>	8	15	8
	Permeate 10KF	6.1	10.2	4.3
	Permeate CHIT 10KF	6.2	10.2	4.5
	Permeate PVA 10KF	6.0	9.6	4.0
20 PSF membrane	<i>Initial concentration feed</i>	8	15	8
	<i>Concentrate final 20 PSF</i>	4.3	7.6	3.1

Testing with real mine water

Both NF membranes and the mentioned UF membranes modified with polyvinyl alcohol (PVA) were determined to be promising candidates that can be further tested using real mining water. Based on the results using synthetic mine water, in August 2016, six different membranes were prepared in SINTEF, Norway, and tested at Lappeenranta University at 10 bars, and 25 °C, using feed flow rates of 217 l/h.

The six different membranes tested were:

- two polysulphone ultrafiltration membranes, (20,000 and 50,000 MWCO) surface modified with polyvinyl alcohol (PSF 0 and PSF 50)
- two fluoropolymer ultrafiltration membranes (1,000 and 10,000 MWCO) surface modified with polyvinyl alcohol (1KF and 10KF)
- unmodified nanofiltration membrane from Alfa Laval Denmark (NF).

The permeate flow rate was registered. The composition of both permeate and retentate streams for SO₄ are presented in the table below:

Table 27: Real water testing

Water flux L/(h m²)	Membrane	SO ₄ concentration mg/l	NO ₃ concentration mg/l
107.76 – 1KF membrane	Feed In	2,646.6	217.0
	Concentrate final	3,469.5	186.4
	Permeate final	1,628.2	223.6
136.66 – 10 KF membrane	Feed In	2,477.8	202.8
	Concentrate final	2,989.7	187.8
	Permeate final	1,748.2	185.4
64.07– PSF 50 membrane	Feed In	2,458.3	167.3
	Concentrate final	2,563.6	161.7
	Permeate final	1,874.5	180.9
78.98 – NF membrane	Feed In	2,608.0	171.1
	Concentrate final	3,794.9	67.0
	Permeate final	0.0	270.2

The water flux range was similar to the values obtained using synthetic water. The flux values are higher (see coating using PVA - polyvinyl alcohol) due to an optimized coating procedure leading to a reduced thickness of the coated layer (approximate 0.3 microns). An exception is PSF 50, not tested previously, which had a low water flux taking into consideration that the support on which polyvinyl alcohol was coated is the most porous. An explanation is that the coated layer penetrated the porous structure and that the porous structure compressed and densified under the pressure.

All the membranes reduced the initial sulphate concentration in permeate and concentrated the feed. There are no big differences in permeate composition for the ultrafiltration membranes coated with polyvinyl alcohol (1KF, 10 KF and PSF 50), the

amount of ions in permeate correlate with the pore size of the support. The nanofiltration membranes, as in the case of synthetic mine water, reduced the sulphate concentration in the permeate to zero.

For the nitrate removal it seems that the membrane is not effective because very little change is observed between the initial and final feed concentration and the permeate concentration. For the densest membranes, NF and 1KF, it seems that the membranes concentrate the nitrate on the permeate side. Measurements for each sample were repeated two to three times and average values are reported but in the case of nitrate, there were significant variations between measurements of the same sample – possibly owing to the sensitivity of the instrument or method. This means that the concentrating effect might be due to errors on measurement.

3.7.6 *Conclusions and recommendations for future work*

The most promising membranes beside NF membranes which reduced the SO_4 concentration to 30 ppm SO_4 in permeate are the surface modified membranes polysulphone (PSF20) and fluoro polymer (1KF) with polyvinyl alcohol (PVA) which reduced SO_4 to 1,400 ppm (permeate) and simultaneously concentrated the feed up to 3,200 ppm during the experiment.

Both NF membranes and the mentioned UF membranes modified with PVA are promising candidates and were further tested using real mining water. The results showed that NF are the most effective membranes in sulphate removal even though the low MWCO coated with PVA can concentrate also the sulphate ions for further treatment using electrocoagulation or another technique. Even though the ultrafiltration membrane surface modified with PVA presents a higher water flux, the sulphate could not be reduced under 1,000mg/l in permeate.

Process simulations should be used in order to identify the optimum configuration and process parameters for a successful membrane-electrocoagulation system used for SO_4 removal.

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3.8 Precipitation processes

3.8.1 Ballasted sedimentation Actiflo®

Details of the project partner

This part of the experiment was performed by Krüger Veolia. Contact persons Christina Sund, Magnus Nilsson.

Summary

Mine water contains both dissolved pollutants and minerals attached to the content of suspended solids. Metals are found both in solution and in particulate material in the liquid phase. The particles are basically tiny parts of the mined ore and if exposed to ambient conditions the mineral might be leached and transported into the ecosystem. It is therefore important to remove both the dissolved pollutants and the particles from the mine water before it is discharged into the environment.

A process for the efficient removal of solids was developed by Veolia for the removal of sediments and colloidal material from raw water (river water) used for production of drinking water. The process is called Actiflo® and it has found many applications i.e. where precipitated material is efficiently removed from the water phase together with other particulate matter. It has shown to work well as a precipitation process for a wide range of metals also at low water temperatures [1, 2, 3, 4]. There are approx. 15 working Actiflo® installations in mining operations in Canada and USA and three installations at an open pit European coal mine. The process works

for small flows but also for very big flows, and the capacity can quickly be both ramped up and down, thus meeting the requirements during heavy rainfalls or snow melting. There are operating Actiflo® references with capacities as high as 85,000 m³/d (European coal mine) and 50,000 m³/d (Meadow Bank Gold Mine in Nunavut, Canada) and as low as 1,000 m³/d (Trevali Half Lake Mine, Northern New Brunswick Canada). The short retention time (15–30 minutes) in the Actiflo® system ensures that the effect of changed dosing rates to accommodate change of inlet conditions is implemented with short lag time ensuring that the effluent quality is maintained. In traditional settling systems with hours of retention time, the long lag time makes the system susceptible to both hydraulic and composition changes.

Actiflo® has been tested on real mine water from Boliden Kevitsa mine (Cu, Ni mine) and LKAB Svappavaara mine.

Process description

Actiflo® is a compact process that utilizes micro-sand as a seed for floc formation. The micro-sand provides surface area that enhances flocculation and it also acts as a ballast or weight. The resulting micro-sand ballasted floc displays unique settling characteristics, which allow for clarifier designs incorporating high overflow rates and short overall retention times.

- High efficiency treatment (removal rate of turbidity exceeding 99%).
- Very small footprint process solution compared to conventional clarification processes (reduces civil / construction costs, compact system) 5 to 20 times smaller than conventional systems. According to Veolia, hydraulic loading rates for Actiflo settling is 60–120 m³/m²,h which can be compared to 1–3 m³/m²,h for traditional gravity settling tanks or 10–15 m³/m²,h for traditional lamella clarifiers.
- Flexible (reacts quickly to changing raw water quality), provides consistently high-quality effluent.
- Short start-up time (less than 10 minutes).
- Sludge treatability: the sludge produced can be thickened and dewatered easily.
- Easy to operate and to maintain.

Figure 23: Illustration of the Actiflo® process

In the Actiflo® plant, a coagulant is first added to the polluted water. The coagulant may be a metallic salt, e.g. ferric chloride, aluminium sulphate or poly-aluminium chloride, which reacts with the dissolved substances and converts them into a low-solubility solid substance (as small particles and colloids).

The content of the particles and colloids in the water, partly deriving from the chemical precipitation and partly from the admitted polluted water, can now coagulate to larger primary particles. The precipitation and coagulation processes are performed simultaneously, as they are both very rapid processes. Water flows from the coagulation tank to the injection tank where micro-sand is added and mixed well into the water. The micro-sand is normal silica sand but with a defined particle size. Finally, flocculant (long-chained, charged molecules) is added in the flocculation tank. Through different mechanisms, these polymers bind the micro-sand and the primary particles together and form large and heavy flocks with a high settling velocity.

After flocculation, the water is admitted to the lamella separator. The flocks settle quickly as the micro-sand considerably increases the flock density compared to flocks in traditional precipitation processes. This implies that the hydraulic loading rate of the lamella separator may be 30–80 times higher than in conventional chemical precipitation plants.

The precipitated sludge and the micro-sand are extracted from the bottom of the lamella separator and pumped back to the hydro-cyclone. The recirculated flow is typically 4–8% of the influent, depending on the concentration of suspended solids in the influent. Sand and sludge are mechanically separated by centrifugal forces initiated by the pressure of flow entering the hydro-cyclone. The sand is returned to the injection tank, whereas the sludge flow is treated separately. The sludge flow makes up approx. 3–6% of the total water flow treated. The sludge is made up of precipitated metals as hydroxides coprecipitated with ferric-oxy-hydroxide and some micro sand lost in the Actiflo™ process. About 99% of microsand used in the process is recycled within the process and approx. 1% is lost with the sludge withdrawn.

Experimental work

Veolia's standard jar test procedure for Actiflo® has been applied in all tests. With nearly 1,000 Actiflo® full-scale installations, the test procedure has been validated and shown to give results that are comparable with the performance of full-scale plants.

Tests with water from Boliden Kevitsa Cu and Ni mine

Tests were performed with two different waters from the mine: 1) combined effluent from the mine, and 2) drainage from the waste rock dump. Reference is made to Chapter 4.1 for location of the two streams.

Tests were performed with two different coagulants – ferric chloride and polyaluminium chloride. Anionic and cationic polymers were tested to find the best performing one in the actual water.

Figure 24 compares the results for nickel removal with the two coagulants and at different process pH. Furthermore, the process efficiency for solids removal can be evaluated by comparing filtered and unfiltered samples. As can be seen, nickel requires a pH of ≥ 10 to obtain a concentration $\leq 50 \mu\text{g/l}$ for the actual type of mine water. There is no major difference in the results between aluminium and iron coagulant; however, it should be noted that the molar ratio when using aluminium reagent is approximately double that of iron.

Figure 24: Precipitation of nickel in combined mine water at Kevitsa mine with Actiflo® process using two coagulants

Figure 25: Precipitation of combined mine water at Kevitsa mine with Actiflo® process with and without organic sulphide dosing (Hydrex 6909). Unfiltered samples

The precipitation efficiency of some heavy metals can be increased by the addition of an organic sulphur product specially developed for heavy metal removal. Tests were performed with the sulphide chemical Hydrex 6909 as a complementary precipitation chemical in Actiflo®. In order to precipitate any excess of sulphide, the iron dosage was slightly increased. Figure 25 shows the results. Cd, Cr and Cu were below the detection limit in raw water, but for Co, Ni and Zn the positive effect of organic sulphide dosing can be seen.

Tests were also performed with effluent from the waste rock dump having considerably higher inlet concentrations. The residual concentration did not differ much from precipitation of the more diluted combined mine effluent.

Figure 26: Precipitation of drainage from waste rock dump at Kevitsa mine with Actiflo® process (unfiltered samples)

Tests with water from LKAB Svappavaara iron mine

Actiflo® tests were also performed with mine water from Svappavaara iron ore mine. Water for the tests was taken at the outlet of the sedimentation ponds where the mine water is discharged to an external water body.

Figure 27 shows the results. The metal concentration is generally very low in the untreated water (a few µg/l) and with Actiflo® the content can be reduced by 50 to 80% depending on the element and dosing regime used. Both the dosage of coagulant and the selection of polymer have considerable influence on efficiency of the Actiflo® process and the tests performed have not included a complete optimization.

Actiflo®, however, efficiently reduces turbidity down to approximately 1 NTU, which means that the discharge of solids, potentially containing leachable compounds, is reduced to a high degree.

Figure 27: Precipitation of effluent from clarification pond at LKAB Svappavaara mine with the Actiflo® process

3.8.2 Absorption/co-precipitation of metals in MetClean™ process

Details of the project partner

This part of the experiment was performed by Krüger Veolia. Contact persons Christina Sund, Magnus Nilsson

Summary

- A general tendency is that lower and lower residual concentrations of pollutants are required in water to be discharged from industrial processes into the environment. This also prevails for mining operations globally. Traditionally lime or sulphide precipitation is applied to reduce metal content. However, residual concentrations might not be low enough, or if the water contains metalloids, the removal with traditional lime precipitation is very limited. Furthermore, the traditional precipitation processes produce voluminous sludge, which also requires safe disposal sites.
- A process has been developed by Veolia to try to address these issues, i.e. efficient removal of metals, removal of metalloids and a stable waste product. The process is called MetClean™.

Process description

- MetClean™ technology utilizes the adsorption process in a fluidized bed to remove a wide range of metals from solutions. Experience includes As, Cd, Cr, Hg, Mo, Ni, Se, Zn, Cu, V, Ba and Sr. Treatment efficiency as high as 99% has been experienced for treatment of scrubber liquors from flue gas treatment at power plants and MSW incinerators (ref. Krüger Veolia).
- The characteristic features of the MetClean™ process are:
 - It is possible to reduce the content of metals to a low content – less than 100 µg/l for all metals, and less than 1 µg/l for some metals.
 - Normal silica sand with a defined particle size is used as a matrix for the absorption process.
 - The space requirement (footprint) of the process is small compared to precipitation processes.
 - The waste product, granules, has a water content of less than 10% and takes up less than 10% of the space required for the sludge from conventional precipitation processes.
 - The waste product has a high density, around 2.2 to 2.5 g/cm³ (sun-dried).
 - Like sand, the waste product can easily be dewatered (no special dewatering process is required) and is easily handled.
 - Uses only few and well-known chemicals from international drinking water production, i.e. Fe(II), Mn(II), O₂, H₂O₂ and NaMnO₄, depending on the elements to be removed.
 - The waste product is physically/chemically stable. Sand content in granules is approx. 85%. Leaching tests, according to SS-EN 12457-3 with L/S=2 and L/S=10, have been performed with among others MetClean™ granules from treatment of mine water from Boroo GoldMine in Mongolia. Both leachates passed the EU classification criteria for waste to be disposed on a landfill for inert waste (5).
 - The waste product has high concentrations of metals per volume unit – between 1% and 8% compared to residuals from other BAT technology's 0.1–0.5%, according to the metals removed.

Figure 28: MetClean™ reactor principle

Experimental work

Tests have been performed with three different mine waters:

1. Boliden Kevitsa mine, drainage from the waste rock dump.
2. Boliden Kevitsa mine combined mine water.
3. LKAB Svappavaara mine water effluent from the settling pond.

The results from the tests are presented in Tables 28–30. As MetClean™ mainly acts for dissolved compounds in the water, only filtered samples are relevant for the evaluation of efficiency. The tests marked with higher Mn dosage received approximately a 20% higher Mn dosage. For the waters used in the tests, the manganese regime was selected. However, based on these tests it cannot be concluded that the manganese regime is better when iron regime cannot function.

Due to the low concentration levels, i.e. close to detection limit, some of the elements show a higher concentration after treatment than before treatment, and this might not reflect a real increase but is just an effect of the uncertainty of the analysis.

Table 28: MetClean™ results for drainage from Kevitsa waste rock dump

Element	Sample	Waste Rock drainage	Test 1	Test 2
		Filtered 0.45 µm	Filtered 0.45 µm	Filtered 0.45 µm
pH test			8,86	9,04
Al	µg/l	<2	<2	<2
As	µg/l	<1	<1	<1
Ba	µg/l	29.3	0.551	0.299
Cd	µg/l	<0.05	<0.05	<0.05
Co	µg/l	0.476	<0.05	<0.05
Cr	µg/l	<0.5	0.677	0.998
Cu	µg/l	1.79	<1	<1
Hg	µg/l	<0.02	<0.02	0.0265
Mn	µg/l	1.77	3.35	0.519
Mo	µg/l	<0.5	<0.5	<0.5
Ni	µg/l	4,780	115	37.7
Pb	µg/l	0.948	<0.2	<0.2
V	µg/l	<0.05	0.0968	<0.05
Zn	µg/l	63.6	<2	<2
Reagent			Mn	Mn (Higher dose)

Table 29: MetClean™ results for drainage from Kevitsa combined mine water

Element	Sample	Kevitsa combined mine water	Test 1
		Filtered 0.45 µm	Filtered 0.45 µm
pH test			8,59
Al	µg/l	25.1	<2
As	µg/l	2.96	<1
Ba	µg/l	83	0.235
Cd	µg/l	<0.05	<0.05
Co	µg/l	1.87	0.115
Cr	µg/l	1.1	5.15
Cu	µg/l	2.77	<1
Hg	µg/l	<0.02	0.0273
Mn	µg/l	32.5	0.707
Mo	µg/l	13	4.45
Ni	µg/l	40.2	<0.5
Pb	µg/l	2.74	<0.2
V	µg/l	0.799	0.0514
Zn	µg/l	127	<2
Reagent			Mn

Table 30: MetClean™ results for LKAB Svappavaara mine water effluent settling pond

Element	Sample	Raw water	Test 1	Test 2
		Filtered 0.45 µm	Filtered 0.45 µm	Filtered 0.45 µm
pH test			8.85	9.1
Al	µg/l	10.5	<2	<2
As	µg/l	<1	<1	<1
Ba	µg/l	47.9	<0.2	<0.2
Cd	µg/l	<0.05	<0.05	<0.05
Co	µg/l	<0.05	<0.05	<0.05
Cr	µg/l	<0.5	2.2	0.849
Cu	µg/l	3.91	4.9	<1
Hg	µg/l	<0.02	<0.02	<0.02
Mn	µg/l	0.822	0.297	0.492
Mo	µg/l	15.7	8.49	10.7
Ni	µg/l	3.68	<0.5	<0.5
Pb	µg/l	<0.2	<0.2	<0.2
U	µg/l	8.56	2.17	2.49
V	µg/l	2.36	<0.05	<0.05
Zn	µg/l	17.4	<2	3.94
Reagent			Mn	Mn (Higher dose)

3.8.3 Conclusion

Two different precipitation/adsorption processes (Actiflo® and MetClean™) were tested for mine water from two different mines, one copper/nickel mine, Boliden Kevitsa (sulphide mineral) in Finland and one iron mine, LKAB Svappavaara mine in Sweden.

The mine water from the iron ore mine contains considerably lower metal content than the mine water deriving from sulphide ore mining. Furthermore, drainage from the waste rock dump at Kevitsa contains metal concentrations considerably higher than the combined effluent from the mining operation.

The tests have shown that Actiflo® is capable of efficiently removing suspended solids and colloidal matter whilst at the same time co-precipitating metals with the coagulant used both in diluted and more concentrated mine waters. Metal removal efficiency was also further improved by combining the coagulant with one of the commercial available organic sulphide chemicals. Actiflo® is a proven process operating in many installations for drinking water, storm water and wastewater. However, as every type of water is unique and treatment requirements vary, testing to validate performance is recommended.

Test results show MetClean™ can reduce the metal content to extremely low levels. The residual product containing the pollutant is easy to handle and can in principle be recycled for recovery of the metals in a smelter. When high removal efficiencies or very low residual concentrations (also of metalloids) are required MetClean™ is one of treatment options available. However, test work to define design and operational conditions are compulsory.

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3.9 Biological processes for nitrogen removal from mine water

3.9.1 Details of the project partner

This part of the experiment was performed by Krüger Veolia and the Veolia-owned technology centre for biofilm processes, AnoxKaldnes in Lund Sweden. Contact person Christina Sund, Eva Tykesson.

3.9.2 Summary

Treatment for the removal of metals, nitrogen (ammonia and/or nitrate and nitrite, principally produced by ammonium nitrate explosive used in blasting) as well as chloride, sulphate and/or total dissolved solids (TDS) is increasingly required prior to discharge of mine water to meet regulatory standards.

In connection with detonation, the major part of ammonium nitrate is transformed to nitrogen gas. However, undetonated explosives left on the mineral surfaces can be as much as 5 to 30%. When the rock is in contact with water, this part is washed off and eventually leaves the site by water discharged from the mining area. In a hot climate, this is normally not a major problem as naturally occurring biological processes in the water courses oxidize the ammonia to nitrate, after which the nitrate is denitrified by organic material present in sediments, which results in the release of nitrogen gas to the atmosphere. In cold climate, it is only during the warmest few months of the year when the conditions are favourable for these naturally occurring bacteria to the complete process. Therefore, both ammonia and nitrate might leave the mining site with the discharged mine water. Ammonia and nitrate are toxic to the aquatic environment. Nitrate itself is not toxic, but the intermediate degradation product nitrite (NO_2^-) is toxic.

Biological treatment has been applied for many years to remove nitrogen from municipal effluent, even at cold temperatures. With a growing need for nitrogen removal from tailings ponds, laboratory studies were initially undertaken on mine water from Canadian mines to determine whether nitrification/ denitrification could be sustained at very low temperatures ($<5^\circ\text{C}$) to reflect the local climate conditions [2].

By cultivating these naturally occurring nitrogen oxidizing and reducing bacteria on a plastic media surface (on carriers) in a controlled bioreactor – Moving Bed Bio Reactor

(MBBR), the nitrification and denitrification process can be performed at very low temperatures. Recent tests with Moving Bed Reactor Technology presented in 2016 show that the process can work at temperatures as low as 1 °C [4].

One plant with the MBBR process is in operation in Sweden at Boliden Garpenberg mine, which treats 1,920 m³/d mine water with an inlet concentration of ~20 mg NH₄-N/l and ~30 mg NO₃-N/l down to ≤ 10 mg N_{total}/l in treated effluent. There are also running MBBR plants with nitrogen removal at Canadian mines. Below data from one mine in Canada (owner does not allow publication of the name).

Table 31: Design data for operating MBBR plant for mine water anonymous mine in Canada

Parameter	Unit	Inlet MBBR	Effluent requirement
Ammonia-N	mg N/l	40.2	< 10
Nitrate-N	mg N/l	46.2	< 10
Flow	m ³ /year	500,000	
	m ³ /day	1,500	

The MBBR process has been tested in the Wascious project for mine water from LKAB Svappavaara, which contains mainly nitrate and for wastewater with extremely high ammonia and nitrate content from LKAB's plant for production of explosives (Kimit Sweden).

3.9.3 Process description

Biological wastewater treatment in cold climates with cold water can be a challenge due to the low reaction rates; however, the alternative of heating large flows of wastewater results in significant operating costs.

Using a fixed biomass instead of a suspended biomass allows the process to be operated at much lower temperature as sludge age is no longer a design parameter. The Moving Bed Biofilm Reactor (MBBR) is a preferred example of such a fixed film (or "attached growth") process. Biomass develops on the inner surface of a carrier which is in continuous movement in the reactor.

The MBBR was developed in Norway specifically to achieve nitrogen removal at cold temperatures. Since many Norwegian wastewater treatment plants are inside buildings or underground caverns, a compact alternative to activated sludge was desirable when the requirement for nitrogen removal was implemented for larger wastewater treatment facilities in the 1990's [1].

The MBBR is a biofilm process which utilizes a high-density polyethylene carrier as a biomass support. The carriers provide a highly protected surface area for biofilm development. The preferred carrier, trade name K5, is shown in Figure 29 and it provides a surface area for the bacteria of 800 m²/m³.

Figure 29: Carrier with biofilm

The nitrogen removal rate in a biofilm system, typically expressed as $g\ N_{\text{removed}} \text{ per } m^2$ of protected media surface area per day ($gN/m^2,d$), has been shown to be highly dependent on operating temperature. Typically, the design of the MBBR will be made at the lowest operating temperature to ensure that there is sufficient capacity to achieve treatment under the worst conditions unless some excess heat or other means of heating can be provided to maintain a higher design temperature.

Figure 30: Nitrification and Denitrification process

In Figure 30, the processes involved in ammonia oxidation and nitrate reduction is illustrated. For denitrification, a carbon source is necessary, and as mine water normally does not contain any organics an external carbon source must be added, which is normally ethanol or methanol.

3.9.4 Experimental work

Test performed with effluent from settling pond at LKAB Svappavaara mine

Mine water discharged from the settling pond at LKAB Svappavaara iron mine has a low concentration of ammonia, but the concentration of nitrate is elevated.

Two batches of water sent from Svappavaara mine were used in the continuous MBBR denitrification test, as shown in Table 31.

Table 31: Raw water from Settling pond Svappavaara for MBBR tests

Parameter	Unit	Batch 1	Batch 2
Alkalinity (CaCO ₃)		51	66.1
BOD ₇ TOT	mg/l	<3	-
COD-Cr	mg/l	13.8	9.12
NH ₄ -N	mg/l	0.048	0.289
NO ₂ -N	mg/l	0.097	0.17
NO ₃ -N	mg/l	5.23	13.5
N-TOT	mg/l	5.41	14.2
PO ₄ -P	mg/l	0.021	0.025
P-TOT	mg/l	0.027	0.092
pH TOT		6.5	6.5

Note: Analysis on filtered samples

The test unit was run continuously for 129 days in a one-MBBR reactor system. In this test, methanol was used as the carbon source for denitrification. Ethanol or another easily degradable carbon source could also have been used. Because of the low phosphorous content in the water, phosphorous was added to meet the requirement of the bacteria. As can be seen from Figure 31, the bacteria culture with the capability to denitrify was established fairly fast, and also when the load was doubled the good performance could be re-established within few days.

The residual concentration of NO₃-N obtained was between 1–2 mg NO₃-N/l, i.e. ~ 90% removal in the adopted system. The NO₂-N content after treatment was maintained at more or less the same level as in the raw water feed, approximately 0.1 mg NO₂-N/l.

The applied nitrogen loading rate, after stable operation, which was obtained (mg NO₃-N/m² carrier surface per d), corresponds to what is seen in municipal wastewater treatment working at the same temperature, thus indicating that mine water from the settling pond does not contain substances that inhibit biological nitrification. It should, however, be noted that this mine water contains low concentrations of heavy metals, for example, copper, which at higher concentrations could have a negative effect on the biological process by reducing reaction velocities and treatment capacity.

Figure 31: Nitrogen in and out of the pilot unit

Tests performed with effluent from LKABs explosives factory Kimit

Water from LKAB Kimit's production of explosives was tested in the laboratory for biological nitrogen removal in an MBBR process. The water contains both nitrate and ammonium nitrogen in very high concentration, between 1,000 and 3,000 mg/l of each of the nitrogen fractions (ammonia and nitrate).

Experience of nitrification and denitrification at such high nitrogen levels is limited. The purpose of these experiments was therefore to simulate nitrification and denitrification, to investigate the possible reduction ratio and possible loading rates.

The process tested was a 5-step MBBR process with an initial denitrification followed by two nitrification reactors and another step for the denitrification. As the final step, there was an aerated re-oxidation reactor for the oxidation of residual methanol used as a carbon source for denitrification.

A total nitrogen concentration of more than 3,000 mg/l in wastewater was tested (Table 32) in a continuous operating laboratory set-up, and the target for the test was to reach a treated water concentration in the range of what municipal plants can receive.

Table 32: Inlet nitrogen concentration wastewater from Kimit explosives production plant

Test period	Concentration $\text{NH}_4\text{-N}/\text{NO}_3\text{-N}$
Day 1–54	1,200/1,400
Day 55–107	1,455/1,655
Day 108–192	3,400/3,800
Day 193–247	1,100/1,330
Day 248–278	1,640/1,680

As can be seen from the nitrification and denitrification reactions below, nitrification produces acid and by denitrification alkalinity is partly recovered. This is a challenge at high ammonia concentrations as an imbalance easily occurs, and if the pH drops below pH ~6 the nitrification process is disturbed. By recirculating plant effluent after

denitrification, part of the alkalinity is recovered, which stabilizes the process. Dosing alkalinity (i.e. lime or caustic) can be necessary to maintain system capacity. Furthermore, the bacteria require phosphorous for cell growth and with a P content in wastewater at approx. 0.1 mg/l phosphorous has to be added.

Figure 32 shows the load of the pilot unit including the inlet concentrations of ammonia and nitrate in the feed. As can be seen, the concentrations increase with time along with the adaptation of the system and increase of biomass and treatment capacity. Beyond approximately 3,000 mg total nitrogen dilution before treatment is recommended.

Figure 32: Load conditions for the MBBR pilot system treating water from Kimit

The performance of the system is presented in Figure 33. The figure shows the total content of nitrogen in the effluent, i.e. sum of NH_3 -N, NO_2 -N and NO_3 -N. During the last approximately 30 days of the test, nearly 99% nitrogen removal was obtained with residual concentration of nitrogen of 10–30 mg N_{tot} /l. Running a nitrification and denitrification system with this type of wastewater at very high concentrations in full scale requires very good process control, but also a system allowing for balancing of wastewater volumes to equalize concentration variations.

Figure 33: Performance of pilot unit treating wastewater from Kimit explosives factory

Figure 34: Kimit MBBR tests. Carrier with biomass and magnification of biomass (including free swimming ciliate)

Conclusion and recommendations

Two tests with biological nitrogen removal were performed. One test unit operated for 129 days with mine water from the settling pond at LKAB Svappavaara mine. The ammonia concentration in the mine water was low and the main nitrogen compound was nitrate. Efficient nitrogen removal (~90%) was established with methanol as a carbon source, and the denitrification capacity of the system corresponded to levels seen in, for example, municipal wastewater treatment. The test MBBR system was set up as a single-tank denitrification system; however, a full-scale plant would also need a re-oxidation tank to remove any excess carbon source. The test results are in line with

the experience from running installations and the process can therefore be considered as validated in this application, i.e. mine water with medium to low content of ammonia and/or nitrate. Content of other pollutants like heavy metals, potentially disturbing the biological process, should of course be evaluated before design.

Wastewater from LKAB explosives production site KIMIT is of a completely different nature with extremely high concentrations of ammonia and nitrate (1 000–3 000 mg/l of each). There is very limited experience of biological nitrogen removal at these concentration levels. The adaptation time for the system to handle an undiluted feed of this wastewater was more than six months. However, when the treatment capacity (biomass) was established, and during approximately the last 30 days of the test, the nitrogen removal in undiluted wastewater was 99%. For the actual water, design conditions for full scale facility can be defined based on the tests performed.

A general recommendation is to perform continuous tests for process validation before any full-scale plant design is done.

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3.10 Summary of technology developments

As a main outcome of the laboratory-scale tests performed in this project, a summary of the suitability of different water treatment technologies as observed Table in this project for the studied water samples is given in Table 33.

Table 33: Summary of laboratory scale test results with different technologies for mine water treatment

Technology	Water source	Operational conditions	Studied compounds	Achieved results	Waste characterization
Electrocoagulation (batch mode)	Synthetic	3A, pH 4 and 10, Fe electrodes	sulphate, Zn, Cu, Ni, nitrate	50% removal of sulfate, 99% removal of Zn, Ni, Cu, nitrate	15 g/l containing iron oxides and hydroxides
	Real	2A, pH 7, Fe electrodes	sulphate, Zn, Cu, Ni, nitrate	30% removal of sulphate, 90% of nitrate and 99% removal of Zn, Ni, Cu	10 g/l containing iron oxides and hydroxides
Electrocoagulation (continuous mode)	Synthetic	6.25A, pH 2, Fe electrodes	sulphate, Zn, Cu, Ni, nitrate	50% removal of sulphate, 99% removal of Zn, Ni, Cu, nitrate	
Chemical coagulation	Synthetic	Coagulant dose 5 000 mg/l AlCl ₃ pH 5, 1 000 mg/l FeCl ₃ pH 2	sulphate, Zn, Cu, Ni, nitrate	AlCl ₃ : 95% removal of sulphate, 0% removal of nitrate, 95% removal of Cu, Ni, Zn FeCl ₃ : 95% removal of sulphate, 0% removal of nitrate, 95% removal of Cu, Ni, Zn	
Biosorption (batch mode)	Synthetic and real	<i>P. chrysosporium</i> white rot fungi	sulphate, Zn, Cu, Ni, nitrate	15% removal of sulphate, 0% removal of nitrate, 3–7% removal of Cu, Ni, Zn	
Biological processes	Real	<i>Biofilm process</i> <i>Continuous tests in lab scale during 3 to 6 months. Scale of test adequate for scale up to full scale.</i>	Ammonia, nitrate	At inlet NO ₃ -N ~ 8–14 mg/l residual concentration of 1–2 mg/l was reached. For waste water from explosives factory, 99% ammonia and nitrate removal was obtained	Nitrate removal produces approx. 0.5 g biomass/g NO ₃ -N removed
Coagulation/ Precipitation/ Coprecipitation processes	Real	<i>Physical Chemical Processes</i>	Suspended solids, Metals and Metalloids	Residual concentrations of metals and metalloids for concentrated mine water most metals ≤ 50 µg/l and for more dilute mine water metals ≤ 5 µg/l	Use of caustic as pH controlling agent reduces sludge production to mainly metal hydroxides and coprecipitates with coagulant. Coprecipitation/ Absorption results in compact high- density stable waste product.
Ettringite precipitation (batch mode)	Synthetic	<i>Precipitation process at high pH</i>	Sulphate, Zn, Cu, Ni..	98% removal of sulfate. Residual sulfate ≤ 40 mg/l	wet weight 84 g/l of ettringite
	Real	<i>Precipitation process at high. AlCl₃ active reagent</i>	Sulphate, Zn, Cu, Ni...	≤ 98% removal of sulfate. Residual sulfate ≤ 40 mg/l Coprecipitation of metals	wet weight 1.5 g/l of gypsum, 46 g/l of ettringite
Eutectic freeze crystallization (batch mode)	Synthetic	NaSO ₄ ·10H ₂ O crystallizing out first at 0.5 °C, ice nucleating at - 1.4 °C		Very pure ice crystals could be produced and the amount of ice depends directly on the heat removal from the reactor. The purity of ice could be improved by effective washing of the ice cake.	The impurities from solution crystallize to the bottom of the reactor as pure salts.
Membrane	Synthetic	nanofiltration (NF) and ultrafiltration (UF), 5 and 10 bar	sulphate, Zn, Cu, Ni	NF: 99% removal of sulphate UF: 53% removal of sulphate, 46% removal of Cu, 51% removal of Zn, 61% removal of Ni	Concentrate with high concentration of studied metals and sulphate
	Real				

In this project's laboratory scale experimental work the ettringite precipitation produced the best removal of sulphate. With electrocoagulation and ultrafiltration membranes, the achieved removal efficiencies of sulphate were also rather good. The advantage of electrocoagulation is that no chemical addition is needed compared to the traditional chemical coagulation process, and thus it can be seen as a potential new technology for treating mine waters. Eutetic freeze crystallization is suited especially for waters with high salt concentrations. Biosorption was not found to be a suitable method for sulphate removal in this context.

For metal removal, good results were achieved with eutetic freeze crystallization after 2–3 washing times of ice, ettringite precipitation, electrocoagulation and absorption/co-precipitation. With membranes, about 50% of the metals were removed from the treated waters. Biosorption was not applicable for metal removal.

Further work is still needed, especially with electrocoagulation, freeze crystallization and membranes. In addition, the applicability of different combinations of these technologies should be studied.

Methods used in other application, like a coagulation sedimentation process used in e.g. drinking water treatment and absorption/co-precipitation used for scrubber water from flue gas treatment, have shown that they can be successfully applied to actual mine water from Nordic mines.

4. Aspects of water conscious mine concept

- Responsible partner: VTT.

4.1 Water foot print

A number of tools and metrics have been developed to assess and quantify the impacts of water use. The water footprint aims to quantify the potential environmental impact related to water use, i.e. how the product, service or company affects the ecosystems and society through the use of water. The water footprint relies on life-cycle thinking to measure local impacts as changes in water volume or water quality. An international standard, ISO 14046, has been developed to provide the general methodology for water footprinting based on LCA principles, but a harmonized impact assessment methodology for a consistent application of the standard is still missing.

The ISO 14046 standard was not applied in this study. Further information about the applicability and the experience of the ISO-based water footprinting for a mining operation can be found in [https://www.tekes.fi/en/programmes-and-services/tekes-programmes/green-mining/Green Mining results/Sustainable Acceptable Mining project \(SAM\)](https://www.tekes.fi/en/programmes-and-services/tekes-programmes/green-mining/Green%20Mining%20results/Sustainable%20Acceptable%20Mining%20project%20(SAM)) or <http://virtual.vtt.fi/virtual/sam/english.htm> (see also [1]).

Veolia has developed its own tool “Water Impact Index (WII)” (see Appendix 2) to assess the water impact, but this tool was not tested in this study, because important input data was lacking for the calculation. The WII tool is based on information in the guideline developed by the World Business Council for Sustainable Development for water valuation, which includes all the areas to set the proper value of water in relation to the business (www.wbcsd.org). In this guide, water valuation is a kind of “water-related valuation” by assessing the worth of water to different stakeholders under a set of specific circumstances.

4.2 Water recycling

Large amounts of water are used especially in the flotation process. By recycling water, the need for fresh water can be reduced. To some extent, also flotation chemicals added can be better utilized when water is recycled, and through this water recycling might lower the consumption of chemicals. However, by the recycling of mine water harmful compounds for the flotation process as well as for the equipment may accumulate, which calls for the use of technologies to remove such unwanted

substances. Recycled water contains, for instance, degradation compounds from flotation chemicals, salts, and dissolved organic substances. The impact of these compounds on the flotation process depends on the ore and the metals to be recovered. [2,3]

Potential active technologies for the removal of harmful substances from water are presented in Chapter 2.7.

A tool for simulation of the quality of the water when recycled is presented in Chapter 5.1. Different technologies can be included in the model, and the model enables comparison of different technological solutions.

4.3 Removal of water from tailings

The removal of water from tailings is not very commonly used in the mining industry compared to the conventional tailings disposal methods. Three different methods to remove water are thickening of tailings, paste disposal and filtering of tailings (i.e. dry stacking of tailings). Thickened tailings, paste tailings and filtered tailings can all be seen as a part of the same process starting from segregated tailings with high water content, moving to non-segregated thickened tailings, then shifting to paste tailings and eventually reaching the state of filtered tailings in the form of a solid cake. The principles of these technologies are summarized in Table 34.

Table 34: Principles of different dewatering technologies

Principle	
Thickened tailings	Thickening of tailings basically means the reduction of water content of low solids concentrated tailings slurry. Potential technologies are: high-density methods, gravitational methods, compression and deep cone thickeners, filtering, combination of thickeners and filtering, and manipulation of the chemical properties of the slurry (ref. [4,5,6]. The solids concentration in thickened tailings varies between 60–72% by weight [4,7,8]. The yield stress remains typically between 20 and 100 Pa [5,8].
Paste disposal	The paste is thicker (i.e. has lower water content) than thickened tailings. Potential technologies are: specialized thickeners or ultra-high-density thickeners [4]. The slurry produced is very dense, viscous, and does not have a critical flow velocity [5,9]. The viscosity of the paste can be controlled; in an ideal situation the paste is viscous enough to form a conical pile when deposited, but is still flowing when transported [10].
Filtered tailings	After thickening, the tailings are conducted to the filter (either a belt, disc, press, or vacuum filter, or their combination) [4,11], squeezed to a moisture content between 10 to 15% [11] and to a solids content of >85% by weight [4]. A dry (unsaturated) cake produced is transported using a conveyor or trucks to the deposition area, spread with earth movers, and left either uncompacted or compacted. Seepage waters from the stack are collected and treated. [6,11]

The benefit of these dewatering methods is to reduce the consumption of water. Each dewatering method has varying costs, different risks and their environmental benefits may not be similar. Table 35 provides information of the advantages and disadvantages.

Table 35: Advantages and disadvantages of different dewatering technologie

	Advantages	Disadvantages
Thickening	<p>General advantages of thickened tailings disposal include [e.g. 4,5,6,10,12,13,14]:</p> <p>Small or no embankment is needed when the topography is flat. This leads to structural stability and safety, diminishing the risk of failures. No segregation, which improves rehabilitation potential (good surface for vegetation).</p> <p>Compared to conventional disposal, a smaller surface footprint is required for deposition.</p> <p>Water savings and sustainable water use: reduced water consumption and groundwater pollution; possibility for water recovery and reuse; minimization of seepage, spillage of process water, and evaporation losses; limited amount of free water on site etc.</p> <p>Economic advantages compared to tailings dams, for instance, reclamation costs are lower, no large dams are needed (also diminishes the risk of failure), reduced impoundment needs, possible savings in water and reagent conservation, and lower pumping costs.</p> <p>Minimized environmental risks may help in achieving the social license to operate.</p> <p>Little or no solid/liquid separation prevents the oxygen transport into the tailings which will reduce oxidation of sulphides and thus the formation of AMD from sulphur bearing tailings.</p> <p>Processing reagents as well as soluble economic minerals may be recovered. [E.g. 4,5,6,10,12,13,14].</p>	<p>Disadvantages of the thickened tailings disposal [4,5,13,15]:</p> <p>Dust generation or liquefaction of waste is possible.</p> <p>Higher operating costs.</p> <p>Unproven technology if production rate exceeds moderate.</p> <p>Also relatively unproven method on a global scale.</p> <p>However, compared to the paste technologies, high-rate thickening methods are more proven.</p> <p>Energy consumption is usually higher than in the conventional methods.</p> <p>Suitable implementation is possible only in dry climates.</p> <p>Changes in tailings gradations, ore characteristics, and per cent solids cause operational unpredictability.</p> <p>Requires flat topography.</p> <p>Concerns related to the dynamic stability.</p> <p>Water savings are only marginally higher than in the conventional disposal. [4,5,13,15]</p>
Paste disposal	<p>see above</p> <p>additionally: savings in water</p>	<p>see above:</p> <p>additionally: increase of operational costs</p>
Filtered tailings	<p>These following advantages are especially connected to the dry stacking of tailings [4,16,17]:</p> <p>Considerable amount of water can be saved</p> <p>Suitable for use in a variety of different terrains (e.g. undulating and steep), and in areas of high seismic activity</p> <p>Possibility for progressive rehabilitation causes costs to spread over a longer time period.</p> <p>Higher heights are possible.</p> <p>In cold regions frosting and freezing of pipes may be avoided.</p> <p>More efficient recovery of process chemicals and dissolved metals is possible.</p> <p>Closure and rehabilitation is easier, and compared to the other surface tailings deposition methods a smaller footprint area is required. [4,16]</p>	<p>Disadvantages according to Engels [16]:</p> <p>The dry stacking method is the most expensive of all dewatering methods. High capital as well as operating costs. However, the costs have been decreasing lately due to increased filtration capacities and operational optimization.</p> <p>Upstream diversion systems are essential.</p> <p>High concentrations (low volume) of seepage water may be generated due to sulphide oxidation.</p> <p>No possibility to store water "for a rainy day".</p> <p>Dusting in arid climates due to the low moisture content of dry cakes.</p> <p>High precipitation and seasonal fluctuations may cause operational problems. [16]</p>

Chapter 5 includes a simulation of flows in four scenarios for the management of tailings (conventional, thickening, paste, and filtering options) in an imaginary case study. Information of environmental impact (based on LCA principles) and costs in a selected scenario are discussed.

4.4 Active and passive water treatment technologies at disposal site

Treatment technologies have traditionally been divided into active and passive treatment methods, both of which may include physical, biological and chemical methods. Combinations of several technologies are also often needed to achieve the required treatment results. In active treatment technologies, reagents and/or energy are used and the process usually requires maintenance and monitoring. Passive treatment technologies have generally lower operational costs than active treatment technologies.

This report focussed on active technologies for mine water treatment, which are presented in Chapter 2.7. Examples of passive treatment technologies used in-situ are: wetlands (aerobic constructed or anaerobic constructed compost wetland), limestone/steel slag leach beds, etc. [ref. 18]

The advantages and disadvantages of active and passive treatment technologies are collated in Table 37.

Table 36: Advantages and disadvantages of active and passive water treatment technologies

Technology	Advantages	Disadvantages
Active treatment technology [ref. 19,20,21,22]	Can be designed to tolerate high total acidity loads (i.e. high water flow rate combined with high total acidity including hydrogen ion + mineral acidity). Process controllability and adjustability for changing flow rate and properties. Effective removal of contaminants. Potential for metal recovery. Small area requirement. Not subject to seasonal variations.	Operation costs, e.g. pumping costs, reagents. Requires maintaining/monitoring.
Passive treatment technology [23,24,25,26].	No or low external energy and chemical requirements after construction and commissioning. Self-sustaining processes, no on-going maintenance need, thus suitability also for remote locations without access to utilities. Longevity and low operational costs. Can often be integrated directly to surrounding environment. Use of non-hazardous materials. Landscape, ecological and fauna rehabilitation.	Need for large physical area. Fairly low contamination remediation. Prone to seasonal and other variations in performance due to reliance on biological processes. Need for monitoring, due to lack of day-to-day intervention in treating processes. Sensitivity of biological systems to high concentrations of contaminants, extreme pH conditions, salinity and/or significant changes in hydrologic regime. Relatively high capital costs for construction.

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5. Case studies: Simulation and modelling of flows at mines

This chapter illustrates the use of tools for simulation or modelling of water flows in two mines in order to find feasible solutions for water treatment. In addition, a study of the life-cycle impacts and costs related to tailings treatments is included.

The following case studies are described:

- Simulation of water flows (recycling) for two technologies at conditions in two mines. The aim was to compare and evaluate the impact of different technological solutions on the water quality.
- Cost benefit analysis for use of different technologies at two mines (calculation of OPEX/CAPEX).
- Simulation of flows in four scenarios for the management of tailings (conventional, thickening, paste and filtering options). The aim was to present information of environmental impact (based on LCA principles) and costs in selected scenarios.

It should be noted that the simulation or calculation results shown in this report have been produced merely to illustrate the methodology. The simulation of mine water flow and quality in the case of water recycling and the use of various sets of treatment technologies requires validation of the actual concentrations and flows. Also, the LCA approach used in the imaginary case study on removal of water in tailings management requires further discussion on the boundary conditions used in the calculations as well as the assumptions.

5.1 Modelling and simulations of water balance for mining operation

This part of the research was performed by LTU. Contact person Maria Sinche Gonzales.

The modelling and simulation of water balance for an iron mine (Svappavaara – LKAB) and a sulphide mine (Kevitsa mining operation) were carried out. This approach involved a detailed data collection of raw material and various water quality streams in the whole operation.

Many variables were considered in this study as the water balance is an account of all the water inputs and outputs, changes in pH, temperature, storage and processes.

In addition, seasonal variation in precipitation and evaporation (wet season), changes in production volume and recycling water distribution were included.

The distribution of species in water streams was calculated using the Sim module of HSC Chemistry 7.1 software by solving the set of mass balance equations and transformation reactions of the solid phase, the given water and ore composition, and the percentage of water recirculation for each process unit of a mining operation.

Unlike other water models, this model not only evaluates the water quality, but also simulates changes in solution composition as the minerals dissolve or precipitate by incorporating the reaction path modelling. The user has to define the reaction of the raw material in contact with water, air, gases, reagents or other input components that may react with the ore. The ability to simulate the evolution of water composition in streams along the flow path is a function of the mineralogy of the ore and changes that the water undergoes into process units, where the HSC-Sim provides the thermodynamic reaction state of the completion of no of a defined reaction (progress of reactions).

The predicted water quality of a facility will in part determine what kind of mitigation measures will be taken to prevent pollution in the discharge or negative effect in treatment processes. Therefore, water treatment technologies targeting the main undesirable species in water were considered in the simulation.

5.1.1 *Work description*

Modelling and simulation included:

- Decision on included processes.
- Definition of the modelling level.
- Data collection for volume flow balance.
- Building the circuits for simulations, database with chemical reaction occurring in processes of mineral treatment and tailing disposal.
- HSC Chemistry software trial and general model to be distributed amongst the partners – Decision of model levels: public, confidential.
- Modelling and simulation of water balance and new water treatment processes and reporting.

5.1.2 *Link with other work tasks in the project*

The initial and available data collected about current practices and water qualities was reviewed. This data constituted the initial data used to test a simulated water balance for the LKBA-Kiruna mine. However, the Svappavaara mine was chosen for LKAB as a case study. The other case study was the Kevitsa sulphide mine.

With regard to tailings management, the model and simulation introduce a number of reactions (oxidation, dissolution, precipitation) occurring in the tailing dam, and

consider the time of residence of the water and percentage of recycling water, the temperature, and the rate constant of reaction of raw material.

New water treatment technologies such as electrocoagulation and Actiflo® were tested in the model with the target of reducing sulphates and nickel ions in water, respectively. As a result of the simulation the water quality in all essential process streams of the mine after water treatment installations was obtained.

5.1.3 *HSC Chemistry working principles*

HSC-Sim is a simulation module based on the HSC Chemistry software and databases, which can be used primarily for static process simulation. HSC utilizes an extensive thermochemical database with H (enthalpy), S (entropy) and Cp (heat capacity).

The traditional HSC Chemistry software was designed for various simulation and modelling applications based on independent chemical reactions and process units. The HSC-Sim module expands the possibilities for applying HSC Chemistry to a whole process made up of several process units and streams.

The HSC-Sim module consists of a graphical flowsheet and spreadsheet type process unit models. The reaction approach (mode) was used for the water balance simulation. Reaction-based units contain and calculate user-defined phases and chemical reactions. The units can be used together or separately and the calculations can be Excel or DLL-based. The module permits introducing the solid phase transformation as well as the buildup of species in water. HSC-Sim is a flexible and easy-to-use simulation tool for a number of applications in mineral processing, mineralogy, chemistry, biology, and economics, etc.

5.1.4 *Limitation and assumptions*

- Mineral composition is a regular feed to the process plant and remains constant. The simulation model attempts to operate the mine based on the specified production schedule considered.
- Water flow distribution is used according to the information provided by the companies. Volume and quality of water change with time and seasonal variation.
- The main tailing impoundment receives the bulk of the tailings from the processing plant. In the mines that were modelled, 100% of the solid part of the water stream is stored in the tailings dam, and in Kevitsa 97% of the water is recycled while in Svappavaara the recycled amount is 87%.
- Releases of water from the tailing dam are minimal. A small release can be produced by seasonal conditions. A high fresh water withdrawing occurs mainly during dry season.
- The major components in the model include a detailed representation of the ore processing plant, the water storage ponds and reservoirs within the open pit area, and the tailings impoundment.

- Leakages, infiltrations, runoff and seepages are only partially controlled in the mine. Limited information of some input streams introduced more variability to the simulation.
- An online quality water balance does not exist but it could be implemented in the future.
- Limited information of evaporation, precipitation and raw water from various sources.

5.1.5 Results from modelling and simulation of water balance

Conceptual model

A simplified conceptual geochemical model was developed, which consists of the system components and description of the interaction between components. The model describes the water flows entering into the process system, flowing through the process units, leaving the system to the environment, and recycling from internal and external water sources. The model also represents the system behaviour and describes the reaction approach used by the selected simulation software. In general, the model represents a simplified perception of the system accounting a justified assumption as it was conceptualized by Bear and Verruijt [3].

Figure 35: Conceptual model for water balance simulation

Reaction equations

In the Svappavaara and Kevitsa operations, accelerated reactions occur in the tailing pond (precipitation, dissolution and oxidation) due to the reactions of minerals with liquid and gases and the progression towards chemical equilibrium (Appendix 3, Table 1 and Table 3). In addition, accelerated reactions occur in the pellet plant (oxidation and reduction) in Svappavaara mine (Appendix 3, Table 2). A set of chemical reactions was established after a comprehensive review of the literature. HCS-Sim allows adding a reaction equation within the Distribution Wizard/Chemical reaction model which evaluates the completion of the reaction in terms of H (enthalpy) and K (equilibrium constant) and temperature. In the Svappavaara mining operation, a total of 34 reactions were used for the tailing dam, and 14 on the pellet plant. In the Kevitsa operation, 19 reactions were defined for the tailing storage facility (ion hydroxide reactions are not shown). Most of these reactions have been referenced in order to be used in the database of the HSC software (the tables show the main reactions).

Usually the reaction rate is the first attempt to explain changes in concentration of a product or reactant versus time as a function of liquid, solid and gas composition. However, information on the nature and kinetics of reactions for the major water species is necessary to calculate the progress of the reaction. HSC-Sim gives the alternative to use the option Control, which allows simulations to be run until the equilibrium is reached for a specific species in the water. The link between a kinetic and thermodynamic mass transfer model will be a next step in this work.

Model and simulation of Svappavaara water balance

In Svappavaara iron mine (Figure 36) almost 100% of input water comes from mine water (Gruvberget and Leveäniemi) with sporadic seasonal intakes of fresh water from Nores Dam. This operation has 87% of recirculation of water from internal (thickeners) and external sources (three water impoundments).

Figure 36: Model and simulation of water balance for 3.6 MT pellets production in Svappavaara mining operation

Model and simulation of Kevitsa water balance

Figures 37 and 38 show the water balance of Kevitsa sulphide mine. Simulation of the water balance for the dry and wet seasons in 2015 was carried out. The input water comes from the nearby river Kitinen, the waste rock dam, pit dewatering, seepage, sanitary treated water, rain water and condensation water. This operation uses 97% recycled water from these internal and external sources.

Figure 37: Flowsheet and simulated water balance for a 6.9 MT mineral treatment of Kevitsa mining operation 2015

Figure 38: Flowsheet and simulated water balance of Kevitsa mining operation 2015-wet season

Validation of the simulated water balance was carried out using data from assays of middle streams and discharged water (not used as inputs) and comparing them with the concentration of species calculated by the software within confidence limits. Variability is due to the limitations mentioned in Section 4.1.3, reliable data collection and the fact that the concentration of some species is cumulative and others undergo transformation.

5.1.6 Simulation of the implementation of new technologies

Nickel (Kevitsa) and sulphate (Svappavaara) were identified as the main components in water required to fulfil future government criteria. Moreover, the necessity was mentioned for a predictive water balance model to evaluate variations in water quality due to changes in water management or variations of processes.

Two technologies were modelled and their effect in the whole water balance was simulated. The purpose was to see the functionality of modification and implementation of water treatment units and test an automatic change of the efficiency (in percentage) targeting sulphate (SO_4) and nickel (Ni) concentration reduction. As an example, electrocoagulation with 30% efficiency for sulphate removal is shown in Figures 39 and 40 (see Appendix 3 for Actiflo treatment).

Figure 39: Simulated water balance with implementation of electrocoagulation treatment before electrocoagulation (0% efficiency)

Figure 40: Simulated water balance with 30% efficiency of electrocoagulation treatment

Simulation from the steady-state to dynamic

Precipitation, evaporation and runoff (t/h) were calculated using the monthly precipitation (mm/month) for Svappavaara and water receptor areas. In this way, it was possible to simulate the dynamic variation of water quality fluctuation due to seasonal variation.

Figure 41 shows the annual variation of water flow in Lake water. The volume flow increases in months with high precipitation (June, July or corresponding days in Figure 41) and concentration of SO_4 is decremented due to high dilution.

Figure 41: Dynamic water balance simulation of Svappavaara operation

Benefits

- Measured and calculated flow rates and species from the water model can be displayed on a graphical user interface and in an Excel sheet for easy use and easy learning.
- The HSC water balance in HSC allows modifying and actualizing data.
- The results can be used to implement modifications in operation.
- It is possible to build more detailed processes, e.g. water balance of the process plant.
- It is possible to identify streams needing treatment or affecting processes.

- It is possible to include new units and evaluate various water treatments.
- It assesses to a large number of species and which need at the same time geochemical simulation and transport modelling.
- HSC-Sim gives the quality of water for every element included and below the detection limit of sampling chemical assays.

5.1.7 Conclusion

The model and simulation of the water balance for a sulphide mine and an iron mine developed in HSC-SIM evaluate the quantity and quality of middle stream water, recycled into the process and discharged into the environment.

Modelling and simulation in the cases of Svappavaara and Kevitsa (Brownfield operations) present opportunities to improve water management, water use and water release into the environment. In Greenfield operations, modelling and simulation can be used as a predictive tool.

The simulation allows the evaluation of alternative water infrastructure for water treatment and water supply options in order to meet the requirements for discharge or future mine expansions. It is possible to recognize values out of limits, and fluctuation in the quality and flows due to seasonal variation.

The model sensitivities are a function of the sampling and chemical analysis, but also ore composition, condition reaction and the limitation and assumptions mentioned in this report. Therefore, sampling and quality analysis of water and raw material should be practised as accurately as possible and at the same time.

There is potential to progressively refine the model as relevant mineralogical, geochemical, and hydrological data become available and/or changes in present conditions occur, such as continual operational changes during the active phase of the mine life, or when new technology appears.

5.1.8 References

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Dissemination

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5.2 Case studies with Capex/Opex estimate

This part of the research was performed by Veolia. Contact person: Christina Sund. Mine water composition differs from mine to mine, even if similar ores are mined, due to different production and water management routines. The same applies to raw water source and discharge conditions. The selected cases are intended to serve as inspiration, showing options for treatment and environmental consequences of the location chosen coupled with the financial implication of the option selected. In water impact index (WII), both the quality of water extracted for the operation and the water quality of the receiving water body for any discharges count. The selected cases are

generic, and it is therefore not possible to calculate a related WII. However, based on a Capital Expenditures (CAPEX) cost estimate and an Operation Expenditures (OPEX) estimate, along with an evaluation of the impact on the environmental load, a preliminary cost benefit analysis can be made. All the presented CAPEX and OPEX estimates are indicative and should only be used for the purpose of comparing the different options.

The simplified assessment is based on:

- Effluent quality produced.
- Investment cost for plant (CAPEX).
- Operating expenses (OPEX).
- Total cost. The sum of CAPEX and 10 years of OPEX (no interest included).
- Waste products produced by treatment technology selected.

This type of assessment can help by disclosing where most pollution reduction can be obtained at the lowest total cost, or where the treated water quality required can be obtained at the lowest total cost. This information is also an essential input for calculating the WII for a specific site. Data for the quality of water source and discharge or reuse conditions will complete the WII calculation.

Figure 42: Mass balance for Actiflo® process treating drainage from waste rock dump

Kevitsa Mass balance Actiflo® process treating drainage from Waste Rock dump

Table 37: Results for treatment options for wastewater similar to waste rock drainage at Kevitsa mine

Process	OPEX*		Waste produced		Metals removed		CAPEX		Total Cost	
	Chemicals EUR/m ³	Electricity** EUR/m ³	Maintenance 2% of CAPEX EUR/m ³	EUR k/year	m ³ /y	T/year	Ni%	kg/year Ni, Cu, Co, Zn	EUR M	EUR M
MetClean™ 172 m ³ /h 1 Mm ³ /year	0.166	0.015	0.06	250	60	120	4.25	5,100	3	5.5
Actiflo® 172 m ³ /h 1 Mm ³ /year	0.134	0.006	0.04	200	121	220***	2.25	5,077	2	4

Note: * OPEX excluding manpower.
 ** price assume 0.075 EUR/kWh.
 *** Dewatered sludge assumed 25% Dry solids.

Table 38: Results for treatment options for wastewater similar to combined effluent from Kevitsa mine

Process	OPEX*		Waste produced		Metals removed		CAPEX		Total Cost	
	Chemicals EUR/m ³	Electricity** EUR/m ³	Maintenance 2% of CAPEX EUR/m ³	EUR k/year	m ³ /y	T/year	Ni%	kg/year Ni, Cu, Co, Zn	EUR M	EUR M
MetClean™ 211 m ³ /h 1.3 Mm ³ /yr	0.240	0.015	0.05	400	90	180	0.18	440	3	7
Actiflo® 211 m ³ /h 1.3 Mm ³ /yr	0.079	0.006	0.03	150	105	135***	0.19	365	2	3.5
Actiflo® w. sulphide dosing 211 m ³ /h 1.3 Mm ³ /yr	0.228	0.006	0.03	350	115	150***	0.23	425	2	5.5

Note: * OPEX excluding manpower.
 ** price assume 0.075 EUR/kWh.
 *** Dewatered sludge assumed 25% Dry solids.

When comparing the two locations for water treatment, it is obvious that treating a more polluted stream before it is mixed and perhaps diluted with other streams is financially attractive. An additional advantage is that the waste product produced might present a metal value, making it possible to mix it with mineral concentrate or to recover the metals at a melting plant.

Actiflo® is a less expensive process than MetClean™, also when including 10 years' capitalized OPEX. MetClean™ has, however, a slightly better performance (residual concentration in treated water) and the most important difference is that it produces a chemically stable waste product with low water content (15%), whereas the waste product from Actiflo® is a hydroxide type of sludge (~65% water).

5.2.1 Svappavaara mine: Calculations based on two hydraulic capacities and different discharge strategies

Hypothetical examples used in the calculations are:

- Svappavaara mine wants to recirculate (600 m³/h) of water from the thickener back to the ore processing plant. Treatment of flow is to be recycled. (w. Actiflo® or MetClean™ process).
- The total overflow (1,700 m³/h) from the thickener is to be treated for the removal of metals. (Actiflo® process with and without sulphide precipitation).
- Third option: treat 600 m³/h (Actiflo®) to the quality required for recirculation and 1,100 m³/h to the lowest possible metal concentrations for discharge to the environment (MetClean™).
- Forth option: The total overflow (1,700 m³/h) from the thickener is treated for the removal of metals (Actiflo® process with and without sulphide precipitation). 600 m³/h is recirculated to the ore processing plant, and 1,100 m³/h (volume to be discharged) is post-treated for nitrate removal before discharge (nitrate removal MBBR).

Table 39: Results for treatment options for wastewater similar to Svappavaara mine

Process	OPEX*					Waste produced			Metals removed	CAPEX	Total Cost
	Mm³/year	Chemicals EUR/m³	Electricity** EUR/m³	Maintenance 2% of CAPEX EUR/m³	EUR k/year	m³/y***	T/year	Me%	kg/year Ni, Cu, Co, Zn, U	EUR M	EUR M
MetClean™ 600 m³/h	4	0.19	0.012	0.023	900	340	170	0.85	144	4.5	13.5
MetClean™ 1,100 m³/h	7.3	0.19	0.012	0.025	1,650	620	310	0.85	264	9	25.5
Actiflo® 600 m³/h	4	0.03	0.005	0.01	200	327	234	0.03	76	3.5	5.5
Actiflo® w. Sulphide 600 m³/h	4	0.10	0.005	0.01	500	336	240	0.04	101	3.5	8.5
Actiflo® 1,700 m³/h	11	0.03	0.005	0.009	400	917	654	0.04	210	4.5	9.0
Actiflo® w. Sulphide 1,700 m³/h	11	0.10	0.005	0.009	1,200	025	660	0.04	277	4.5	16.5
Nitrate removal After Actiflo® 1,100 m³/h	7.3	0.015	0.007	0.014****	250	250 Bio-sludge				3	5.5

Note: * OPEX excluding manpower.

** price assume 0.06 EUR/kWh.

*** Dewatered sludge Actiflo® assumed 40% Dry solids. Granules MetClean™ 85% Dry solids.

**** 3% maintenance cost.

The consequence of the above fourth option can be seen in Figure 43, where the combined overflow is treated for metal removal and the part to be discharged from the site is further treated for nitrogen removal.

Figure 43: Mass balance Actiflo® process treating 1 700 m³/h overflow from clarifier and biological nitrate removal process for 1,100 m³/h. Svappavaara mine water

5.2.2 Conclusions

The above examples based on results from tests performed on water samples from the Kevitsa and Svappavaara mines show some of the possibilities for treating mine water for the removal of metals and nitrogen and the consequences thereof. The financial estimates can be used as one factor to consider for ranking of the options. It should be noted that the WII calculations cannot solely be based on this type of estimate and calculation for local conditions (source of water, quality required for use or discharge of treated water) also counts. However, by combining the calculation of WII with the financial estimates, as above, a solid basis for decision can be established.

5.3 Tailings management – Minimum impact concentrator – summary of a conceptual study

5.3.1 Details of the project partner

This part of the research was performed by Outotec. Contact person Kaj Jansson.

5.3.2 Project scope

Tailings management at a typical copper concentration is used here to illustrate the environmental and economic impacts of different solutions for tailings management.

The study is based on modelling using the HSC Simulation tool combined with tools used for lifecycle assessment (LCA).

Minerals processing concentrators are increasingly facing large challenges with the fresh water availability and quality, as well as new environmental limitations both from the old traditional tailings management facilities in addition to the volume and quality of the discharge. The trend of lower grades in mineral deposits is also enlarging the size of tailings management facilities and the water consumption. Furthermore, climate change also has an effect on water supply [1].

The aim of this study was to improve the understanding of the sustainability of a “minimum impact” copper concentrator over an estimated 15-year-long mine lifetime. As background information from earlier studies of a minimum impact Cu concentrator, operational risk results have been used. These operational risks were focused on decreasing water stress, environmental hazards, and possible dam break-up. The main focus of this study was on conceptual evaluation by simulating and calculating the economics of four different tailings management facility methods and their impacts on the site water balance as well as the sustainability assessment.

The selected tailings treatment flowsheets that formed the basis of this study were (i) Case 1: conventional (un-thickened), (ii) Case 2: thickened, (iii) Case 3: paste, and (iv) Case 4: filtered tailings options. Option (iv) also included all the necessary arrangements for safe maintenance of the tailings disposal area, including the drainage water collection systems as well as landscaping of the dewatered tailings piles. All the mass balance calculations were performed using Outotec’s HSC Chemistry simulation tool, which provided the basis for the cost calculation. The costs were estimated based on the Finnish cost basis with an assurance of $\pm 30\%$. For the location of the concentrator, a flat mine site in a temperate climate zone was selected.

Figure 44 shows the estimated seepage amount of these 4 different tailings management facilities, where the highest seepage is related to conventional and thickened ones due to wet physical appearance. As paste and filtered tailings have their water contained in sand locked in by capillary forces, then the only accountable and partly recoverable seepage should come during heavy rain fall.

On the basis of the data in Figure 44, the climate impact on average fresh water demand could be estimated. It can be seen that the highest need of water is for the traditional and thickened tailings management processes. On the other hand, the filtered tailings squeezed out most of the water from the tailings and therefore it has the highest capability for reusing and conserving the water.

Figure 44: Risk related to seepages from tailings management facilities. Monthly fresh water make-up of the plant (a) and the estimated total seepage from the tailings facilities (b)

The LCA calculations showed that the filtered option decreases the water footprint significantly, i.e. from 26.7 to 5.8 kg blue water/kg concentrate produced (or 0.51 to 0.11 kg blue water/kg ore feed) as well as improves the water quality and toxicity indicators. These simulation results were also used to perform an environmental assessment using the GaBi software. There was no significant carbon footprint and acidification potential variation between the four cases was 0.55–0.58 kg CO₂-eq/ca. kg blue water/kg concentrate or about 0.011 kg CO₂-eq/ca. kg blue water/kg ore (when rounded).

5-3-3 Conclusions

Today, new environmental challenges are emerging in the minerals processing sectors. Risks related to poor fresh water quality and scarcity, wet tailings dams and new effluent limitations are growing worldwide. All of these factors are setting new guidelines towards minimum impact concentrators, where the concentrator plant is “carved out” of the surroundings instead being a part of them with minimal environmental effects, whilst rich mineral deposits are diminishing, and large, low grade deposits are dominating the Greenfield mine projects. From this work, the author concluded that:

- Water management of the future lies in more closed water loops and also smaller volumes to overcome higher operational risks.
- For conventional and thickened tailings management, the selected tailings management facilities have a huge impact on the total operational risk.
- Paste thickening is a very good alternative with low operational risk if a backfill option does exist, but it does not solve the water management issues.
- Filtered tailings in this study give the lowest operational risk, with closest to neutral water balance of the four options studied assuming that no specific measures are needed for AMD tailings. The filter investment at the opening of the plant causes a bigger CAPEX for the option, but the net present cost for all constructions during the 15 years of a mine’s lifetime is roughly the same for all options.

- Large, low-grade deposits present challenges in fresh water intake, and the ultimate level of recycling of process water becomes standard design in Greenfield plants. The filtering option (Case 4) shows a significantly lower water footprint and impact, while the carbon footprints of all cases are more or less similar.
- Further details of the LCA study can be found in Appendix 4.

5.3.4 *Reference*

1. IPCC, 2014. Climate Change 2014 Synthesis Report Summary for Policymakers, Fifth Assessment Report (AR5). 32p.

6. Conclusions and recommendations

6.1 Technological development

The main focus of the project was on the development and testing of technologies for mine water treatment. Based on a review of current requirements in mine water permits and data on current discharge levels in Nordic mines, the project group decided to focus in this project on the removal of sulphate, specific metals (Cu, Ni, Zn), and also to a limited extent on the removal of nitrogen compounds. The starting point was a state-of-the-art review on commercially available technologies or proven technologies tested at least with pilot studies.

In the project, several potential technologies for sulphate and metal removal from wastewater were tested and further developed for Nordic conditions and the requirements of the participating research organizations and companies. The technological readiness level (TRL) of the selected technologies varied from research-based to proven technologies. In order to enable comparisons of the performance of the different technologies tested and developed by the research organizations, part of the experimental work was conducted with synthetic mine water samples prepared according to a standardized recipe. However, it must be emphasized that test-runs with real mine water in conditions as close as possible to real ones are crucial for a reliable evaluation/assessment of the applicability of the technology. The pilot test-runs with proven technologies were performed with real mine water and partly real conditions.

In Nordic mines, the requirements on acceptable emissions can be regarded as low for several substances. Therefore, the pollutant levels were rather low both in the synthetic and real mine water samples, which means that the removal efficiency cannot solely be evaluated based on removal percentages. A few combinations of technologies were performed. The following technologies were studied in the project: electrocoagulation, biosorption, chemical precipitation, membrane processes, eutectic freeze crystallization, adsorption and finally biological processes for nitrogen removal.

In this project's laboratory scale experimental work the ettringite precipitation produced the best removal of sulphate. Quite promising results for sulphate removal were also achieved with electrocoagulation and ultrafiltration membranes. The advantage of electrocoagulation is that no chemicals are needed, and thus it can be seen as a potential new technology for treating mine waters. Eutectic freeze crystallization seems to be suited especially for waters with high salt concentrations, but it is still in development stage. Biosorption was not found to be a suitable method for sulphate removal.

Good results were achieved for metals removal with precipitation/coagulation/sedimentation process and coprecipitation processes. Ettringite precipitation, electrocoagulation and Eutectic freeze crystallization (after 2-3 washing times of the ice) also reduced metal content. With membranes tested about 50% of the metals were removed from the treated waters. Biosorption was not applicable for metal removal in this context.

In this study, efficient nitrogen removal could be obtained with the biological fixed film process MBBR.

Further work is still needed especially with electrocoagulation, freeze crystallization and membranes. In addition, the applicability of different combinations of the studied technologies should be investigated.

6.2 Water conscious mining concept studied in this project

Water conscious mining means that all the challenges – water treatment for recycling, tailings dewatering, waste rock storage and process water treatment – must be addressed. The focus of this report was mainly on water treatment technologies for certain key substances. The work also included a literature study on technologies for the removal of water from tailings, and an LCA study on dewatering technologies in a selected a scenario but without including any experimental work.

There are proven water treatment technologies available for the removal of key substances from waters that are generated today in mine processes. The choice of suitable technology depends on the water quality required and especially on the level of pollutants to be removed. The possible use of the treated water as process water or alternatively discharge to the receiving water body determines the goals of water treatment. Often, also a combination of technologies might be needed. The arctic conditions influence on the selection of the treatment concept (i.e. effect of water temperature in physical and biological processes) and also the big variation in flow from winter to spring time with snow melting. In future, the mine water composition or treatment requirements might change calling for new cost-efficient technological concepts for the treatment of waters to achieve low residual concentrations.

The possibilities for water recycling in a mine depend very much on the ore type and thus the substances dissolved. In some cases, water recycling without treatment might lead to an accumulation of unwanted substances and potentially, e.g. gypsum precipitation in pipelines and equipment.

The simulation of different processing and technology alternatives provides important information on both water flows and rough operational costs for comparison. For a feasibility study, also information on CAPEX and OPEX are crucial. In addition to the analysis on the feasibility, an evaluation of the water footprint based on lifecycle principles creates an overview of the sustainability of the water treatment concept.

In this project the simulation of water treatment and recycling was done at two mines which provide information on the impact of treated and recycled water in the full water balance, the removal of species, and the operational costs. It should be noted that the simulation or the calculation results used in this report have been produced merely to illustrate the methodology. The simulation of the mine water flow and the quality in the case of water recycling, and the use of various sets of treatment technologies require validation of the actual concentrations and flows. Furthermore, the LCA approach used in the imaginary case study on the removal of water in tailings management requires further discussion on the used boundary conditions in the calculations as well as the assumptions.

Sammanfattning

Gruvindustrin, som är en stor vattenkonsument, har fokus på en hållbar användning av resurser. En första åtgärd är att öka vattencirkulationen i gruvprocesser för att minska behovet av råvatten. Det är också viktigt att hindra olika typer av vatten på gruvområdet, de som härrör sig från gruvprocesserna och de som inte gör det, från att blandas. I praktiken måste man hitta nya koncept för separering av vattenflöden med olika sammansättningar och för behandling av gruvvatten med nya typer av sammansättning.

Målet med projektet var att 1) göra en studie om nuvarande praxis hos gruvor, samt kartlägga alternativa teknologier för vattenbehandling, 2) identifiera kraven för vattencirkulation och utsläpp, 3) identifiera och evaluera nyckelteknologier för vattenhantering och behandling, 4) kartlägga teknologier för att hantera och avvattna anrikningssand, 5) utveckla och evaluera aspekter som bör beaktas i ett vattensnålt koncept för gruvor, och 6) att säkra ett nordiskt samarbete och forskning.

Arbetet baserar sig på experimentell forskning, litteratur, samt konsortiets expertis och nära samarbete med gruvindustrin. Arbetsuppgifterna uppdelades i olika arbetspaket, som leddes av olika partner i konsortiet.

Genomgången av gängse praxis i de nordiska gruvorna visade på stora skillnader i sammansättningen hos gruvvatten som skall behandlas, samt också på skillnader i kraven för utsläpp till miljön och för vattencirkulation i gruvor. På basis av en kartläggning av nuläget beslöt konsortiet att fokusera forskningen på tekniker för att minska halterna av sulfat, vissa metaller (Cu, Ni, Zn) och till en viss del också kväve i gruvvatten. En utgångspunkt för forskningen var en state-of-art studie som gjorts över kommersiellt tillgängliga teknologier och verifierade teknologier som åtminstone testats i pilotskala.

Följande teknologier studerades inom projektet: elektrokoagulation, biosorption, kemisk utfällning, membranprocesser, eutektisk fryskristallisation, adsorption, och för minskning av kväveföreningar i gruvvatten även biologiska processer. Teknikmognadsgraden hos de utvalda teknologierna varierade från forskningsbaserad till verifierad teknik. Laboratorietester utfördes delvis med syntetiska vatten och delvis med vatten från gruvor som deltog i projektet. Påpekas bör, att för en pålitlig bedömning av en tekniks användbarhet, behövs testkörningar med vattenprover från gruvor som möjligaste mån motsvarar verkliga förhållanden. Några tester utfördes också i pilotskala med redan verifierade teknologier.

Förutom de enskilda verifierade teknologierna, visade också en kombination av forskningsbaserade teknologier goda resultat. Som en sammanfattning av de i laboratorieskala utförda testerna med vatten från gruvor, kan det konkluderas att ettringitutfällning gav låga sulfathalter i det behandlade vattnet. Också elektrokoagulation och ultrafiltration gav tämligen goda resultat. Eutektisk

fryskristallisation verkade vara bäst lämpad för vatten med höga salthalter, men denna teknik är ännu under utveckling. Biosorption fungerade inte som en lämplig metod för att minska sulfathalten i vattnen.

Med utfällnings/koagulations/sedimenteringsprocesser och samutfällningsprocesser för minskning av metallhalter i vattnet erhöles goda resultat. Med ettringitutfällning, elektrokoagulation, eutektisk fryskristallisation (där ren is erhöles efter 2–3 tvättningar) uppnåddes också en reducerad metallhalt. I försök med membraner minskade metallhalterna hos de behandlade vattnen till cirka hälften. Biosorption var inte lämplig för metaller.

I pilotstudien med en biofilm, MBBR, minskade kvävehalten hos det behandlade gruvvattnet till mycket låga halter.

Från det experimentella arbetet kan man konkludera att för att uppnå mycket låga halter behövs i många tillfällen en kombination av processer. Ytterligare forskning om olika processkombinationer rekommenderas.

Datasimulering av vattenbehandlingsprocesser och gruvvattencirkulation utfördes med data från två gruvor. Simuleringsmodellerna gav värdefull information om inverkan av behandlat och cirkulerat vatten på vattenbalansen, reduktionsnivån av olika ämnen i vattnen och de operativa kostnaderna. Användning av simuleringsmodeller i val av tekniker och kombinationer av olika tekniker kan därför rekommenderas.

Idag finns det verifierade teknologier tillgängliga för minskning av halter hos den typ av gruvvatten som nu uppstår i gruvprocesserna. Teknikvalet beror på halten av föroreningar samt vilken vattenkvalitet som eftersträvas samt också på kostnaderna för behandling. Processens effektivitet bestäms av det behandlade gruvvattnets nästa användning, dvs. om det ska cirkuleras av som processvatten eller om det ska släppas ut till ett vattendrag. Behandlingskonceptet påverkas också av de arktiska förhållandena inklusive snösmältning, som ger upphov till stora variationer i flöden från vinter till vår. Det är möjligt att behandlingskraven för gruvvatten kommer att ändras i framtiden, vilket ställer krav på nya kostnadseffektiva teknologikoncept. Detta projekt har gett en inblick i vattensnåla koncept och metoder för hållbarhetsbedömning, vilka kan användas vid utveckling av nödvändig teknologi.

Projektet inkluderade också en litteraturstudie om olika avvattningsmetoder för anrikningssand. Därtill ingick en fallstudie med olika avvattningsskenarier (utan experimentellt arbete) där verkan på kostnader och miljön beräknades. En förenklad kalkyl av effekterna visade en potential för kostnadsinbesparing och möjligheter för att minska risker vid behandling av anrikningssand med avvattningsteknik.

Som resultat av projektet skapades en nordisk forskningsplattform, som kan utnyttjas som nätverk både för att utväxla idéer kring koncept för hållbara och vattensnåla gruvprocesser, och för att bygga upp ett samarbete för projektplanering och deltagande i framtida utlysningar.

Appendices

Appendix 1: The recipe for the preparation of synthetic mine waters

Proposed by LUT, agreed by all project partners

Proposal of the initial concentration levels of ions in the synthetic solutions that will be investigated in the WASCIIOUS-project are summarized in the following table. The proposed levels are chosen according to the water quality information that is publicly available concerning the different waters in Finnish mines.

Table 40: Composition of the three synthetic water samples

Ions	Concentration, mg/l		
	Low	Medium	High
SO ₄ ²⁻	1,000	2,000	3,000
NO ₃ ⁻	20	40	60
Cl ⁻	100	200	300
Cu ²⁺	2	5	8
Ni ²⁺	2	5	8
Zn ²⁺	5	10	15
NH ₄ ⁺	10	20	30

Chemicals and their amounts that are needed for preparing 1,000 ml of synthetic solutions of presented qualities are listed in the following table.

Table 41: Amount of chemicals added for preparation of 1,000 ml of a synthetic water solution

Chemicals	Amount of chemicals, g		
	Low	Medium	High
CuSO ₄	0.00502	0.01256	0.02009
NiSO ₄	0.00527	0.01318	0.02109
ZnSO ₄	0.01235	0.02469	0.03704
Na ₂ SO ₄	1.45847	2.91228	4.36609
NaNO ₃	0.02742	0.05483	0.08225
NH ₄ Cl	0.02965	0.05931	0.08896
NaCl	0.13245	0.26489	0.39734
RO – water	1,000 ml		

Preparation of the solutions

Equipment and supporting elements

Scales, 1,000 ml vial, weighting paper, pipet, 600 ml glass, funnel, spoon.

Chemicals

CuSO_4 , NiSO_4 , ZnSO_4 , Na_2SO_4 , NaNO_3 , NH_4Cl and NaCl . All chemicals are of analytical grade.

Figure 45: Laboratory equipment for preparation of synthetic water for laboratory experiments

Procedure

- Rinse the 1,000 ml vial with pure water before starting.
- Put 400 ml of pure water into the 1,000 ml vial.
- Weight the desired amount of Na_2SO_4 and add it to the 1,000 ml vial. Use the funnel. Carefully rinse paper and the funnel with pure water, add some more water. Mix the solution by turning the vial up and down 40 times. Do not shake.
- Repeat the same actions with all of the chemicals.
- Fill the 1,000 ml vial up to the mark and mix properly.
- Let the solution stay for around 30 min–1 hour.
- Start the experiment.

Note!

Dry chemicals for at least 2 hours in the oven before using. Store dried chemicals in the excicator for 15–30 min to cool them down. Use chemicals at the room temperature.

Appendix 2: Tool developed by Veolia for assessment of Water Impact Index

Text collated by Christina Sund, Veolia

The real value of water is very complex and generally underestimated. “Value” is often used interchangeably with “cost”, but the true importance of water stretches far beyond cost as with lack of water or lack of water of an acceptable quality for the production in question and its employees could result in dramatic consequences for the industry itself. Furthermore, either direct or diffuse pollution downstream of the production might result in the requirement for ceasing the production with unforeseeable economic consequences.

Many companies face substantial business risks related to water, however, without having quantified them. Veolia has sought a comprehensive water footprint indicator that will integrate all the complexities of the water cycle, including water quality and availability in the local environment. No such indicator has previously been available, which compels Veolia to develop a new indicator

The Water Impact Index expands on existing volume-based water measurement tools by incorporating multiple factors such as volume, resource stress and water quality. It provides additional parameters needed to make informed choices about effective water management.

The Water Impact Index WII provides a means of measuring the improvement that industrial investments in treatment infrastructure provide to the local region and community. The Water Impact Index accounts for the impact on water resources generated by a human activity. It allows evaluating how other water users (both humans and ecosystems) could potentially be deprived of this resource expressed in m3-WII-equivalent

Figure 46: Formula for calculation of Water Impact Index

$$WII = \sum_j \left(W_j \times \min_l \left(1; \frac{C_{ref_l}}{C_{j,l}} \right) \times WSI_j \right) - \sum_k \left(R_k \times \min_l \left(1; \frac{C_{ref_l}}{C_{k,l}} \right) \times WSI_k \right)$$

WII = V_{abstracted} * F₁ – V_{released} * F₂

Figure 47: A new metric for assessing water impact

Figure 48: Principle for the calculation of the water impact index

Figure 49: Equation for calculation of water impact

Quality:

$$\sum_j (W_j \times Q_j) - \sum_k (R_k \times Q_k)$$

$$Q = \min_p \left(\frac{C_{ref_p}}{C_p} \right)$$

For each pollutant and we choose the worst quality results

Note: Q = Quality index (no unit).

P = Type of pollutant (COD, BOD, TKN, Pt, SS, DS, pesticides, metals, etc.).

C_{ref} = Reference concentration: concentration that should be reached in water resource to ensure a good ecological status (mg/l).

C = Concentration of pollutant p within water abstracted or release (mg/l).

The quality of the water in both the inlet and the outlet has an effect on the Water Impact Index. This differs from other water footprint methods which only take into account the quality of the effluent. The result of considering both is that the Water Impact Index will decrease if the quality of the inlet is not perfect (using inferior raw water). The quality index is a ratio between the most penalizing pollutant and the reference concentration of that pollutant. The most penalizing pollutant means the pollutant that needs the most water, to be diluted into the reference concentration.

WSI, i.e. Water Stress Index or Water Scarcity Index, is in Nordic region not an issue. There is enough water available, though it can be seen from Figure 50 that Finland and Sweden are classified as having low to medium stress. This does not relate to the amount of water but more to the quality of available water.

Figure 50: Water stress by country

WII can be part of or a contribution to a more comprehensive water valuation exercise. The World Business Council for Sustainable Development has developed a guideline for water valuation including all the areas to set the proper value of water in relation to the business (www.wbcsd.org). The guide aims at assessing the worth of water to different stakeholders under a set of specific circumstances. In this guide, water valuation is a kind of “water-related valuation”.

Veolia’s Water Impact Index, provides insight into the vulnerability of an activity in relation to water resource management, but in the current economic context, decision-makers are looking at an even more pragmatic and straightforward metric: money and risk. Veolia has further developed the assessment of water and named this The True Cost of Water. An evaluation matrix has been developed which includes:

- Direct water costs: Capital and Operational Expenditures of water infrastructures.
- Indirect water costs: existing costs that are usually not attributed to water, e.g. water-related legal costs.
- Financial implications of water risks: costs arising during the lifetime of a plant that were not anticipated.

These elements are organized into four categories: operational (such as water shortages), financial (such as increase in cost of capital), regulatory (such as obligations to meet ecological standards) and reputational (such as temporary loss of license to operate). Especially the financial risks related to water that potentially cause production disturbances are in focus. In connection with evaluation of WII, it is therefore important to address the impact of a water management scheme evaluated from an overall supply risk context.

Appendix 3: Simulation of water recycling: Additional information by LTU, Sweden

*Simulation of water recycling: Additional information. Tables and Figures collated by
Maria Sinche Gonzales, LTU, Sweden*

Figure 42: Main reactions in the slow geochemical processes in Svappavaara tailing storage facility and pellet plant

Process and reaction stoichiometry				ΔH	K
Magnetite oxidation	$4 \text{ Fe}_3\text{O}_4 + \text{O}_2(\text{aq})$	=	$6 \text{ Fe}_2\text{O}_3$	-115.56	5.93E+075
Pyrite oxidation (oxygen path)	$\text{FeS}_2 + 3.5 \text{ O}_2(\text{aq}) + \text{H}_2\text{O}$	=	$\text{Fe}^{2+} + 2 \text{ SO}_4^{2-} + 2 \text{ H}^+$	-336.13	1.42E+216
Pyrite oxid. (ferric iron path)	$\text{FeS}_2 + 14 \text{ Fe}^{3+} + 8 \text{ H}_2\text{O}$	=	$15 \text{ Fe}^{2+} + 2 \text{ SO}_4^{2-} + 16 \text{ H}^+$	-10.53	4.14E+097
Orthoclase oxidation	$\text{KAlSi}_3\text{O}_8 + \text{H}^+ + 7 \text{ H}_2\text{O}$	=	$\text{Al}(\text{OH})_3 + \text{K}^+ + 3 \text{ H}_4\text{SiO}_4(\text{aq})$	2.02	6.95E-003
	$2 \text{ KAlSi}_3\text{O}_8 + 2 \text{ H}^+ + 9 \text{ H}_2\text{O}$	=	$2 \text{ K}^+ + \text{Al}_2\text{Si}_2\text{O}_7 \cdot 2 \text{ H}_2\text{O}(\text{H}) + 4 \text{ H}_4\text{SiO}_4(\text{aq})$	7.25	1.86E-004
Albite oxidation	$\text{NaAlSi}_3\text{O}_8 + \text{H}^+ + 7 \text{ H}_2\text{O}$	=	$\text{Al}(\text{OH})_3 + \text{Na}^+ + 3 \text{ H}_4\text{SiO}_4(\text{aq})$	-2.80	3.07E-001
	$2 \text{ NaAlSi}_3\text{O}_8 + 2 \text{ H}^+ + 4 \text{ H}_2\text{O}$	=	$2 \text{ Na}^+ + \text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2 + 2 \text{ H}_4\text{SiO}_4(\text{aq})$	-15.02	1.44E+010
	$\text{NaAlSi}_3\text{O}_8 + 4 \text{ H}_2\text{O} + 4 \text{ H}^+$	=	$\text{Na}^+ + \text{Al}^{3+} + 3 \text{ H}_4\text{SiO}_4(\text{a})$	-27.36	7.95E+007
Diopside oxidation	$2 \text{ CaMgSi}_2\text{O}_6 + 3 \text{ MgSiO}_3 + \text{SiO}_2 + \text{H}_2\text{O}$	=	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}\text{H}_2$	-23.98	7.38E+014
Actinolite oxidation	$1.5 \text{ Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}\text{H}_2 + 2.5 \text{ KAlSi}_3\text{O}_8 + 3 \text{ CO}_2(\text{g}) + \text{H}_2\text{O}$	=	$2.5 \text{ KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2 + 3 \text{ CaCO}_3 + 12 \text{ SiO}_2$	-51.93	2.72E+009
Ferrous iron oxidation:	$\text{Fe}^{2+} + \frac{1}{4} \text{ O}_2(\text{aq}) + \text{H}^+$	=	$\text{Fe}_3^{3+} + \frac{1}{2} \text{ H}_2\text{O}$	-93.03	7.37E+033
Metal hydroxide precipitation	$\text{Al}^{3+} + 3 \text{ OH}^-$	=	$\text{Al}(\text{OH})_3$	-15.46	3.64E+033
	$\text{Cu}^{2+} + 2 \text{ OH}^-$	=	$\text{Cu}(\text{OH})_2$	-13.21	3.82E+021
	$\text{Fe}^{2+} + 2 \text{ OH}^-$	=	$\text{Fe}(\text{OH})_2$	-4.00	1.48E+014
	$\text{Fe}^{3+} + 3 \text{ OH}^-$	=	$\text{Fe}(\text{OH})_3$	-21.67	3.45E+037
	$4 \text{ Fe}(\text{OH})_2 + 2 \text{ H}_2\text{O} + \text{O}_2(\text{aq})$	=	$4 \text{ Fe}(\text{OH})_3$	-110.36	2.35E+071
	$\text{Ca}^{2+} + 2 \text{ OH}^-(\text{a})$	=	$\text{Ca}(\text{OH})_2$	4.12	2.56E+005
Calcite oxidation	$\text{CaCO}_3 + 2 \text{ H}^+(\text{a})$	=	$\text{Ca}^{2+} + \text{CO}_2(\text{g}) + \text{H}_2\text{O}$	-3.78	7.10E+009
	$\text{CaCO}_3 + \text{SO}_4^{2-}(\text{a}) + \text{H}^+(\text{a}) + 2 \text{ H}_2\text{O}$	=	$\text{CaSO}_4 \cdot 2 \text{ H}_2\text{O} + \text{HCO}_3^-$	-6.40	3.17E+006
	$\text{Ca}^{2+} + 2 \text{ HCO}_3^-$	=	$\text{CaCO}_3 + \text{CO}_2(\text{g}) + \text{H}_2\text{O}$	9.83	7.01E+005
	$\text{CaCO}_3 + \text{H}^+$	=	$\text{Ca}^{2+} + \text{HCO}_3^-$	-6.81	1.01E+002
Chalcopyrite oxidation (oxygen path)	$\text{CuFeS}_2 + 4.25 \text{ O}_2(\text{a}) + 2.5 \text{ H}_2\text{O}$	=	$\text{Fe}(\text{OH})_3 + 2 \text{ SO}_4^{2-} + \text{Cu}^{2+} + 2 \text{ H}^+$	-389.55	4.10E+247
Chalcopyrite oxidation (ferric iron path)	$\text{CuFeS}_2(\text{s}) + 16 \text{ Fe}^{3+} + 8 \text{ H}_2\text{O}$	=	$17 \text{ Fe}^{2+} + \text{Cu}^{2+} + 2 \text{ SO}_4^{2-} + 16 \text{ H}^+$	-12.52	1.30E+108
Andradite oxidation	$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12} + 3 \text{ CO}_2(\text{g})$	=	$3 \text{ SiO}_2 + 3 \text{ CaCO}_3 + \text{Fe}_2\text{O}_3$	-54.51	2.34E+015

Table 43: Main reactions in the fast geochemical processes at Svappavaara pellet plant

Process and reaction stoichiometry			ΔH	K
Magnetite oxidation (oxygen path)	$4 \text{Fe}_3\text{O}_4 + \text{O}_2(\text{g})$	$= 6 \text{Fe}_2\text{O}_3$	-122.90	1.08E+012
Magnetite oxidation (hydrogen path)	$\text{Fe}_3\text{O}_4 + 8 \text{H}^+$	$= \text{Fe}^{2+} + 2 \text{Fe}^{3+} + 4 \text{H}_2\text{O}$	-52.40	7.63E+010
Pyrrhotite hex. oxidation	$\text{FeS} + 2 \text{O}_2(\text{g})$	$= \text{FeSO}_4$	-197.42	8.68E+025
	$4 \text{FeS} + 7 \text{O}_2(\text{g})$	$= 2 \text{Fe}_2\text{O}_3 + 4 \text{SO}_2(\text{g})$	-585.40	3.20E+102
Ilmenite oxidation	$4 \text{FeTiO}_3 + \text{O}_2(\text{g})$	$= 4 \text{TiO}_2 + 2 \text{Fe}_2\text{O}_3$	-27.10	2.19E+109
Biotite (annite) oxidation	$\text{KFe}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2 + \text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12} + \text{O}_2(\text{g})$	$= \text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2 + 2 \text{Fe}_3\text{O}_4 + 3 \text{SiO}_2$	-113.94	7.36E+017
Pyrite oxidation	$4 \text{FeS}_2 + 11 \text{O}_2(\text{g})$	$= 2 \text{Fe}_2\text{O}_3 + 8 \text{SO}_2(\text{g})$	-787.40	5.97E+161
	$2 \text{FeS}_2 + 7.5 \text{O}_2(\text{g})$	$= \text{Fe}_2\text{O}_3 + 4 \text{SO}_3(\text{g})$	-487.62	2.92E+082
Actinolite oxidation	$1.5 \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}\text{H}_2 + 2.5 \text{KAlSi}_3\text{O}_8 + 3 \text{CO}_2(\text{g}) + \text{H}_2\text{O}$	$= 2.5 \text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2 + 3 \text{CaCO}_3 + 12 \text{SiO}_2$	-10.13	1.60E+006
	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}\text{H}_2$	$= 2 \text{CaMgSi}_2\text{O}_6 + 3 \text{MgSiO}_3 + \text{SiO}_2 + \text{H}_2\text{O}$	119.73	3.48E+040

Table 44: Main reactions in the slow geochemical processes in Kevitsa tailings storage facility

Process and reaction stoichiometry			ΔH	K
Pentlandite-Fe dissolution	$\text{Fe}_{4.5}\text{Ni}_{4.5}\text{S}_8 + 10 \text{H}^+$	$= 4.5 \text{Ni}^{2+} + 4.5 \text{Fe}^{2+} + 8 \text{HS}^- + \text{H}_2(\text{aq})$	10.99	3.88E-006
Chalcopyrite oxidation	$\text{CuFeS}_2 + 4 \text{O}_2(\text{aq})$	$= \text{Cu}^{2+} + \text{Fe}^{2+} + 2 \text{SO}_4^{2-}$	-384.64	3.83E+243
Diopside oxidation	$2 \text{CaMgSi}_2\text{O}_6 + 3 \text{MgSiO}_3 + \text{SiO}_2 + \text{H}_2\text{O}$	$= \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}\text{H}_2$	-23.98	7.38E+014
Actinolite oxidation	$1.5 \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}\text{H}_2 + 2.5 \text{KAlSi}_3\text{O}_8 + 3 \text{CO}_2(\text{g}) + \text{H}_2\text{O}$	$= 2.5 \text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2 + 3 \text{CaCO}_3 + 12 \text{SiO}_2$	-51.93	2.72E+009
Albite precipitation and dissolution	$\text{NaAlSi}_3\text{O}_8 + \text{H}^+ + 7 \text{H}_2\text{O}$	$= \text{Al}(\text{OH})_3 + \text{Na}^+ + 3 \text{H}_4\text{SiO}_4(\text{aq})$	-2.80	3.07E-001
	$\text{NaAlSi}_3\text{O}_8 + 4 \text{H}_2\text{O} + 4 \text{H}^+$	$= \text{Na}^+ + \text{Al}^{3+} + 3 \text{H}_4\text{SiO}_4(\text{aq})$	-27.36	7.95E+007
Orthoclase pp and dissolution	$\text{KAlSi}_3\text{O}_8 + \text{H}^+ + 7 \text{H}_2\text{O}$	$= \text{Al}(\text{OH})_3 + \text{K}^+ + 3 \text{H}_4\text{SiO}_4(\text{aq})$	2.02	6.95E-003
Calcite oxidation	$\text{CaCO}_3 + \text{H}^+$	$= \text{Ca}^{2+} + \text{HCO}_3^-$	-6.81	1.01E+002
	$\text{CaCO}_3 + 2 \text{H}^+$	$= \text{Ca}^{2+} + \text{CO}_2(\text{g}) + \text{H}_2\text{O}$	-3.78	7.10E+009
	$\text{CaCO}_3 + \text{SO}_4^{2-} + \text{H}^+ + 2 \text{H}_2\text{O}$	$= \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{HCO}_3^-$	-6.40	3.17E+006
Chlorite-Fe dissolution	$\text{Mg}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8 + 16 \text{H}^+$	$= 5 \text{Mg}^{2+} + 2 \text{Al}^{3+} + 3 \text{H}_4\text{SiO}_4(\text{aq}) + 6 \text{H}_2\text{O}$	-144.75	3.34E+064
Pyrrhotite monoclinic oxid.	$\text{Fe}_7\text{S}_8 + 6 \text{Fe}^{3+}$	$= 4 \text{FeS}_2 + 9 \text{Fe}^{2+}$	-121.75	1.30E+112
Magnetite oxidation	$4 \text{Fe}_3\text{O}_4 + \text{O}_2(\text{aq})$	$= 6 \text{Fe}_2\text{O}_3$	-118.36	8.00E+072
	$\text{NiS} + 2 \text{O}_2(\text{aq})$	$= \text{Ni}^{2+} + \text{SO}_4^{2-}$	-202.25	1.44E+128
Olivine oxidation	$2 \text{Mg}_2\text{SiO}_4 + 2 \text{H}_2\text{O} + \text{CO}_2(\text{g})$	$= \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 + \text{MgCO}_3$	-34.85	1.04E+012
Metal hydroxide precipitation	$\text{Mg}^{2+} + 2 \text{OH}^-$	$= \text{Mg}(\text{OH})_2$	0.57	1.43E+011
	$\text{Mn}^{2+} + 2 \text{OH}^-$	$= \text{Mn}(\text{OH})_2$	-4.32	6.52E+012
	$\text{Cu}^{2+} + 2 \text{OH}^-$	$= \text{Cu}(\text{OH})_2$	-13.21	3.82E+021
	$\text{Ni}^{2+} + 2 \text{OH}^-$	$= \text{Ni}(\text{OH})_2$	-4.52	2.22E+015

Figures 51 and 52 show the major species concentration in mg/l found in water streams. Figure 53 shows the simulated water balance with Actiflo treatment with 92.5% efficiency for nickel removal.

Figure 51: Simulation of species concentration in water in Svappavaara operation

Figure 52: Simulation of species concentration in water in Kevitsa operation

Figure 53: Simulated water balance with Activflo treatment and 92.5% efficiency of Ni removal

Appendix 4: Tailings management – Minimum impact concentrator – a conceptual study

Aim of the study

This part of the research was performed by Outotec. Contact person Kaj Jansson

Project summary

Tailings management at an imaginary copper concentration is here used to illustrate the environmental and economic impacts of different solutions for tailings management. The study is based on modelling using the HSC Simulation tool combined with tools used for lifecycle assessment (LCA).

Minerals processing concentrators are increasingly facing large challenges with the fresh water availability and quality, as well as new environmental limitations both from the old traditional tailings management facilities in addition to the volume and quality of the discharge. The trend of lower grades in mineral deposits is also enlarging the size of tailings management facilities and the water consumption. Furthermore, climate change also has an effect on water supply [5].

The aim of this study was to improve the understanding of the sustainability of a “minimum impact” copper concentrator over an estimated 15-year-long mine lifetime. As background information from earlier studies of a minimum impact Cu concentrator, operational risk results have been used. These operational risks were focused on decreasing water stress, environmental hazards, and possible dam break-up. The main focus of this study was on conceptual evaluation by simulating and calculating the economics of four different tailings management facility methods and their impacts on the site water balance as well as the sustainability assessment.

The selected tailings treatment flowsheets that formed the basis of this study were (i) Case 1: conventional (un-thickened), (ii) Case 2: thickened, (iii) Case 3: paste, and (iv) Case 4: filtered tailings options. All the mass balance calculations were performed using Outotec’s HSC Chemistry simulation tool, which provided the basis for the cost calculation. The costs were estimated based on the Finnish cost basis with an assurance of $\pm 30\%$. For the location of the concentrator, a flat mine site in a temperate climate zone was selected.

Introduction

Water recycling and management in the mineral industry have been studied earlier, for example, by Joe *et al.* [8,9], and energy and water savings in tailings handling have been evaluated by Sellgren [15]. Sustainable disposal of mining waste has been studied by Franks (2011). Studies with full process, including tailings and water management and their impact on the operational risk, economics and water savings have been reported previously by Jansson *et al.* [6]. The Water Footprint Network (www.waterfootprintnetwork.org) has since 2008 provided leadership in the water

footprinting through numerous societal activities. Various studies can be downloaded from this site as well as various references sourced via this portal to understand the impact of human activities on the use of blue, green and grey water (fresh, rain and polluted water respectively) ranging from food production to the impact of energy carriers [1,4,10,].

While there are various studies on the analysis of both the economics and environmental aspects of potable water systems [2,11,12], few studies link not only energy and water, but also material and thus water quality. Van Schaik *et al.* [16] applied a very large system optimization model that linked industry and farming water effluent south of Rotterdam to an industrial water treatment plant in Brabant as well as to the metallurgical processing of residues to maximize resource efficiency.

This study follows a similar approach to Van Schaik *et al.* [16] in that the simulation basis was used to map compounds and total flows with the objective of then performing an environmental analysis to determine the optimal economic solution but also considering the environmental impact [15]. A comprehensive sustainability indicator framework has recently been developed which combines numerous impacts into one simple result while comparing it to a benchmark (Rönnlund *et al.* 2015). Water, energy and materials are thereby combined and evaluated at the same time.

In summary, the objective of this study was to clarify the difference between the whole mineral process operational cost during its lifetime with different layouts and tailings treatment. The focus was put on environmentally friendly solutions, with minimum fresh water usage, effluent volumes, and processes without a wet tailings dam. This paper develops further the concepts presented by Jansson *et al.* [6].

Methodology

The basic water and material balances were calculated for four different mineral process schemes with Case 1: Conventional tailings management, Case 2: Thickened tailings management, Case 3: Paste tailings management, and Case 4: Filtered tailings management following the approach discussed by Reuter *et al.* [13]. In all the mass balance calculations, the fresh water intake was in focus to estimate the amount needed in the process and thus estimate the fresh (blue) water footprint (www.waterfootprintnetwork.org) as well as estimate the effluent volumes from each system. The climate conditions for the selected site were gathered from www.WorldClimateGuide.co.uk. The soil seepage capacity was estimated from data collected from mines near the imaginary location for this minerals processing site. All the data were put into the Outotec HSC simulation tool to calculate the average flows as shown in Figure 54. The simulation tool is a steady-state simulator, and it calculates the situation where all material put into the process also comes out of the process, and does not take into account the normal process variation. These flows were then used as a basis of the cost calculations discussed by Jansson *et al.* [6], and to produce the data used in the environmental footprint software GaBi (www.thinkstep.com) (see Reuter *et al.* [13] for details).

Figure 54: A summary of the methodology: Left the HSC Simulation (www.outotec.com) of the water system for the four cases, and right, the environmental footprint calculation produced from the simulation results by GaBi (www.thinkstep.com) [13]

Project scope

The calculation was based on an imaginary 20 Mt/a capacity copper concentrator (porphyry Cu) with an estimated 15-year life time. The Finnish cost base was used as a turnkey cost basis and the estimated calculation level was around $\pm 30\%$ as net present costs. The concentrator plant is equipped with one SAG mill, two ball mills, two lines with eight flotation cells each, one regrinding HIG mill, one concentrate thickener as well as two PF concentrate filters with a storage system. The project scope includes the total site cost of conventional, thickened, paste and filtered tailings (concentrator + tailings mgmt.. (variable) + water mgmt.. (variable)).

The concentrator was located on a flat area in temperate climate conditions. The fresh water intake was determined to be about 10 km away from the concentrator with a 25-m static head. The tailings area was also located 10 km away from the concentrator with a 25-m static head. A study limitation is that no mine water, freezing conditions, dust control (wind), acid mine drainage (AMD) generated water or earthquakes were taken into account. For operational costs a fresh water price of EUR 0.001 /m³ was used, electricity price EUR 100 /MWh and labour cost EUR 2,960 /month.

Optimizing the operational costs

The fundamental idea of the project was to investigate possibilities to decrease the total operational costs of the minerals processing during its expected 15-year life time. As an illustration, Figure 55 shows the estimated full costs of three alternative process layouts. It should be noted that this figure is simply an illustration of the target setting for the project.

The combined costs of CAPEX and OPEX with the four studied cases are quite close to each other. With the biggest tailings pond options (conventional and thickened tailings options) the investment of pond wall construction is distributed to across the mine's life time. This causes the net present cost to be the same even if the total investment cost in Euros is a bit higher than in the filter option.

Figure 55: Illustration of minimizing the total operational costs over the lifetime of a mineral processing operation

Creating the risk matrix

For estimating the risks allocated to the studied mineral processes, a simple risk matrix, with risk value in EUR versus potential risk level was set up with the basic operational risks today at any typical mineral process. Figure 56 depicts various scenarios for three solution types and shows their respective risk value and level. In Figure 56 the yellow colour indicates conventional tailings management, brown is for paste and blue is for filtered tailings. As seen from this evaluation, the highest operational risks are allocated to conventional tailings management, and the lowest to the filtered tailings. The thickened tailings method was left out due to the clarity issues of the figure, and because it possesses very similar risk to the conventional method.

Figure 56: Simple risk matrix for estimation of operational risks associated with different tailings process

Risks related to the tailings dam wall and its construction

In order to estimate the costs related to tailings dam construction for conventional, thickened and paste options the Upstream, Downstream, Centerline and Modified Centerline dam design constructions were estimated. It should be pointed out that the estimation was made for a completely flat surface (the high-end price). It will be of benefit if there are “bowl” shaped earth structures available, which would lower the estimation towards zero. A naturally formed lake or “bowl” is the cheapest option, but typically it is not part of the options due to strict environmental legislation. For the calculations in this study, the Downstream model was selected to reflect the environmentally sound and sustainable option.

Risks related to the climate conditions and seepages from tailings facilities

Tailings facility seepage is considered as a water consumer. As said before, the concentrator was located in the temperate zone where summers are relatively hot and dry, and autumn to spring is wet with plenty of rain. The average rainfall was 52 mm/month (from 30.4 to 80.6), evaporation 45 mm/month (from 0 to 144). The total water collection area is 725 ha.

Figure 57 shows the estimated seepage amount of these 4 different tailings management facilities, where the highest seepage is related to conventional and thickened ones due to wet physical appearance. As paste and filtered tailings have their water contained in sand locked in by capillary forces, then the only accountable and partly recoverable seepage should come during heavy rainfall.

Based on the data in Figure 57, the climate impact on average fresh water demand could be estimated. It can be seen that the highest need of water is for the traditional and thickened tailings management processes. On the other hand, the filtered tailings squeezed out most of the water from the tailings and therefore it has the highest capability for reusing and conserving the water.

Figure 57: Risk related to seepages from tailings management facilities. Monthly fresh water make-up of the plant (a) and the estimated total seepage from the tailings facilities (b)

Results and discussion

As the basis for the full operational costs calculation, water and material balances had to be fixed and estimated. Four different estimations were made for conventional, thickened, paste and filtered tailings. It should be noted that rainfall, evaporation and seepages are not shown in these simplified process calculations for reasons related to reading clarity (see [6]).

Figure 58a) shows the annual variation of the fresh water needed for the calculated options. Due to the rainfall and evaporation, the need of fresh water in the dry season is more than double compared to the wet season for the conventional and thickened cases (1 and 2). In those cases, the process water circulates through the tailings pond and some of the water evaporates during the dry season. This circulation is removed from the paste (during the dry season) and filtered cases (3 and 4), and therefore the evaporation does not affect the water balance of the plant. In those cases, there is no recoverable water in the tailings area and the evaporation is not a problem. The tailings water lock-in-capability is estimated to be 30%.

The tailings water lock-in-capability is estimated to be 30%.

Case 1: The simulation results with Conventional tailings management effects on fresh water usage

The conventional option is shown in Figure 58a). Using the simulation for sensitivity analysis one can estimate that the average need for fresh water is around 0.6–0.9 m³/t-ore or 1,400 m³/h with a typical 15%, e.g. addition to the calculation. The calculation is a simplification of the real process and all is not taken into account, like process flow variations, and therefore this addition is needed. Operational risks in the conventional tailings are related to the dam risks, seepages, high water usages, and the negative/positive water balances that are drivers for socio-political risks.

Case 2: The simulation results with thickened tailings management effects on fresh water usage

Figure 58b) shows the impact of thickened tailings. A sensitivity analysis with the simulation model showed that the thickened tailings method did not decrease the fresh water usage more than ~200 m³/h to a level of 1,200 m³/h since part of the water is still circulated through tailings area and the rainfall and evaporation in the area will have an effect on the plant water balance. This means an average fresh water usage of 0.5–0.8 m³/t ore. From the risk management point of view, the same risks remain as with conventional tailings management.

Figure 58: Simplified water balance calculations for conventional tailings (a, on the left) and for thickened tailings management (b, on the right). It should be noted that the tailings dam gives the biggest source of variation to the process, by rainfall, evaporation and filtration and of course lock-up

Case 3: The simulation results with paste tailings management effects on fresh water usage

As the paste thickener underflow is estimated to be near 70% and the sand lock-incapability 30%, then very small or no effluent treatment is needed. The fresh water usage is still in the range of 0.45–0.7 m³/h, and the average need around 1,100 m³/h including the +15% needed for the process capacity.

Figure 59a) shows the effect of a thickened paste option. From the risk management point of view, many of the same risks are present as with the conventional and thickened options, although perhaps not as high. If a backfilling option exists, then the operational risks are very low except for the water-related issues.

Case 4: The simulation results with filtered tailings management effects on fresh water usage

This example shows that the big opportunity for lowering the required fresh water amount comes from the removal of wet tailings. In addition, this approach also minimizes the seepage issues and risk through contaminating groundwater, as well as evaporation losses, and rainfall does not impact the dry stacking option in the same ways as in the previous three cases. Thus, there will be lower operational risks than the other options. Under optimal conditions the fresh water usage is estimated to be around 0.1–0.15 m³/t ore and the fresh water flow around 310 m³/h including the +15% as before.

Figure 59: Simplified water balance calculations for paste thickening (a, left) and filtered tailings (b, right)

The disadvantage of the filtered tailings options comes with the requirement for more and “new” equipment and technology. Thus, a significant result of this study shows that the water (blue) footprint is significantly lower for Case 4 (the filtering option) while not impacting significantly the carbon footprint, which will become evident from the next section. The fresh (blue) water consumptions for different cases are 27, 23, 21 and 6 kg/kg concentrate for cases 1, 2, 3 and 4, respectively.

Environmental impact

Figure 60 shows the data that was applied and the flows included in the analysis. The data have been derived from the simulation models that were used to generate Figure 61.

Figure 60: The data used for Case 4 Filter option to perform the GaBi analysis

Figure 61 shows that there is little difference in the global warming and acidification potentials between the four options. However, it is clearly evident that Case 4, due to its lower water usage, has a significantly lower water footprint. In addition, it has a lower impact on water quality, as shown by the eutrophication potential and eco toxicity, noting that the toxicity and eutrophication originate through the various in- and out-flows through the system boundaries (e.g. power, diesel, lime etc.).

Figure 61: The environmental impact analysis for each of the four cases, showing global warming potential (GWP), acidification potential (AP), eutrophication potential (EP-water), Eco toxicity, Water depletion and Resource Depletion (ADP) per kilogram of concentrate

Summary of results

The estimated calculation shows that the lowest total operational risk is achieved with the filtered tailings. If the paste backfill process option exists, then it will have the lowest cost. It should be noted that in these calculations a fresh water price of EUR 0.001 /m³ was applied. If the water price is higher, then the difference of the filtered tailings to the other ones also increases.

It should be clearly evident that the usage of either paste or filtered tailings technology decreases the effluent generation to nearly zero levels.

Conclusion

Today, new environmental challenges are emerging in the minerals processing sectors. Risks related to poor fresh water quality and scarcity, wet tailings dams and new effluent limitations are growing worldwide. All of these factors are setting new guidelines towards minimum impact concentrators, where the concentrator plant is “carved out” of the surroundings instead being a part of them with minimal environmental effects, whilst rich mineral deposits are diminishing, and large, low grade deposits are dominating the Greenfield mine projects. From this work the author concluded that:

- Water management of the future lies in more closed water loops and also smaller volumes to overcome higher operational risks.
- For conventional and thickened tailings management, the selected tailings management facilities have a huge impact on the total operational risk.
- Paste thickening is a very good alternative with low operational risk if a backfill option does exist, but it does not solve the water management issues.
- Filtered tailings in this study give the lowest operational risk, with closest neutral water balance of the four options studied assuming that no specific measures are needed for AMD tailings. The filter investment at the opening of the plant causes a bigger CAPEX for the option, but the net present cost for all constructions during the 15 years of a mine’s lifetime is roughly the same for all options.
- Large, low-grade deposits present challenges in fresh water intake, and the ultimate level of recycling of process water becomes standard design in Greenfield plants. The filtering option (Case 4) shows a significantly lower water footprint and impact, while the carbon footprints of all cases are more or less similar.

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Water Conscious Mining (WASCIOUS)

The main objective of the NordMin WASCIOUS project was to develop a technology concept for water conscious mining, where innovative water and tailings treatment technologies provide good-quality water for recycling and discharge and enable safe disposal or utilization of tailings. The work included a survey on current practices and requirements in Nordic mines and laboratory and pilot scale development of several technologies. Computational simulations of water treatment and recycling practices were performed for a feasibility study of some technology alternatives and technologies for dewatering of tailings were evaluated. As an important outcome of the project, a future Nordic research platform was established related to environmental issues in mining for the Nordic region, enabling exchange of ideas and collaboration in future project calls, and facilitating ideas for future projects.