PASSIVE MINE WATER TREATMENT IN NORWAY

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Abstract
Previous mining history in Norway has resulted in ongoing release of acid mine drainage. Preservation of the historical sites in mining areas does not allow for remediation technologies that result in significant alteration of the historical landscape. Therefore, alternative remediation techniques such as passive mine water treatment have been tested. The climate in Norway varies from mild coastal climates to artic climates, and one of the challenges with passive treatment systems is the cold winter conditions. Anaerobic treatment systems have been built at Kongens Mine near Røros, at Folldal mines, and at Titania's tailings impoundment near Storgangen Mine. These systems utilize sulfate-reducing bacteria that result in the precipitation of metal sulfides. A full- and pilot-scale system at Kongens Mine and Folldal were built in 2006 to remove copper and zinc from typical ARD in an alpine climate. Previous testing with pilot scale systems at Kongens Mine showed that up to 85% copper and 48% zinc could be removed. At Titania A/S the anaerobic system is designed to remove nickel from neutral waters. At this system over 90% nickel is removed when water flow is regulated at a constant flow. Testing shows that the system can function in cold winter conditions, however, optimal metal removal is achieved under warmer temperatures. Temperatures changes by global climatic warming will not adversely affect these anaerobic systems. However, extreme precipitation events and the resulting rapid fluctuations of ARD runoff will provide a challenge for the effectiveness of these systems.

Introduction
Caledonide copper-zinc massive sulfide deposits have been mined in Norway from the 1600's until the 1990's. In many places, the mines and the surrounding mining communities have become a part of the cultural heritage and have historical value. One of these sites, the mining village of Røros and its piles of smelting slag, is a protected UNESCO World Heritage Site.

The massive sulfide deposits stretch from the southwest coast around 60^{o} latitude north, and into the artic Norway near 70^{o} latitude north. This geographic spread of deposits represents a distance of approximately 1,500 km, and ranges from mild and wet coastal climates, to high mountains and artic climates. The resulting hundreds of major and minor abandoned mines release acid mine drainage (AMD) in varying degrees. In some cases, the AMD results in serious environmental consequences for water organisms in salmon rivers, mountain streams and lakes, and in some cases the fjords.

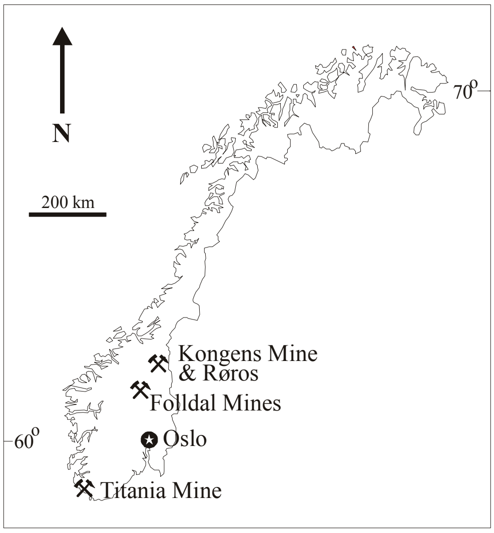

Figure 1. Locations of passive treatment systems in Norway.

During the 1980's the Norwegian Environmental Pollution Control Agency (SFT) prioritized several of the mines for remedial actions. Within the 1990's the goal of a 60 to 90% reduction of AMD was accomplished for most of the sites under the direction of Bergvesenet, the Norwegian Directorate of Mining. Remediation

techniques used during this campaign generally involved capping of the mine sites or removal of the waste rocks dumps.
Due to concern for preserving historical mine sites there has been increased interest for passive mine water treatment that does not involve large changes of the cultural landscape. Since 1999 several passive mine water treatment systems have been constructed in Norway to treat AMD. Presently, a full-scale and a pilot-scale anaerobic passive treatment system is in function at the historic abandoned mine areas at Røros and Folldal in central Norway. Today there are virtually no active metal mines in Norway, with the exception of Titania A/S ilmenite mine near the southwest coast. Leachates from tailings impoundments contain elevated concentrations of nickel. Passive water treatment using a full-scale anaerobic passive treatment system has been successfully implemented at this active mine to remove nickel from the leachates.
Anaerobic treatment systems (or bioreactors) are designed to create an anaerobic environment so that sulfate-reducing bacteria can thrive. These bacteria result in the reduction of sulfate (SO_4^{-2}) to sulfide (S^{-2}). Sulfides can then precipitate metal sulfides that settle to the bottom of the basins. Sulfate reducing bacteria are found in cow manure, therefore, providing a simple source for introducing the bacteria to a constructed treatment system.
This paper presents data and experiences from the use of anaerobic passive treatment systems near abandoned copper mines at Røros and Folldal and the active Titania A/S mine. The systems have been designed for the present climate, and eventual shifts in climate will affect the treatment systems in varying ways.

Kongens Mine, Røros

Kongens Mine (N62°40’17” E11°19’13”) in the northern Røros mining district is one of several mines in this area that produced copper. The mining area lies above tree line at an altitude of approximately 800 meters above sea level. The present weather can be characterized by an alpine climate with an average precipitation of 504 mm. The ARD from Kongens Mine drains to the Orva Creek that is devoid of fish down to its confluence with the Glomma River, Norway’s longest river. An estimated 2.4 tonnes copper and 5.8 tonnes zinc were released during a 12 month period in 1999 and 2000 from Kongens (Iversen and Arnesen, 2001).
In 1999 the first pilot scale system was constructed to treat ARD. The system was comprised of a pre-treatment limestone drain and four anaerobic basins measuring 10 x 1.5 meters and a depth of 1.5 meters. The basins were filled with locally derived organic waste materials, such as rotted hay, sawdust, tree clippings and $CaCO_3$ materials. The basins were inoculated with cow manure and whey from a local dairy was added. It was quickly discovered that the high iron contents clogged the limestone drain, and therefore, other methods for either removing iron or reducing the ferrous iron to ferric iron were tested in the field including iron phosphate precipitation, copper cementation with scrap iron. Field-testing showed that the most effective method to counteract the high iron and low pH problem was to add more $CaCO_3$ into the anaerobic basins, and discontinue the use of pre-treatment. In addition, it was found that materials used, such as the sawdust resulted in too low hydraulic conductivity.
In 2002 a new pilot system was built as one 10 x 10 meter basin with a depth of 2 meters. This basin was constructed with rotted hay mixed with shell sand as a $CaCO_3$ source, and filled with very coarse birch tree materials that are readily available in the region. The ARD passing through this basin was then led to the last two basins in the previous pilot scale system.
Monitoring of the pilot systems showed that up to 85% copper could be removed, whereas up to 48% zinc, 98% cadmium, 82% lead, 71% chrome and 24% nickel could be removed. Examples of the water analyses are presented in Table 1. Over time the monitoring showed that important factors for successful metal removal were retention time, the stability of water flow, seasonal temperature variations and the maturity of the system. Figure 2 shows the removal of copper with respect to water flow (L/min) over time in the new system and old system. These data show that copper removal was best during the warmest months with low and constant water flows. When the water flow was increased during colder months then the removal of copper was drastically reduced.
Black coloured sediments were collected from the bottom of the newer pilot scale system and analysed for the content of metals (Table 1). These sediments show the removal of metals, most likely as metal sulfide particles.
Based on the results from the pilot-scale systems it was decided to construct a full-scale anaerobic system to treat ARD at Kongens. In order to avoid large variations in water flow to the system, two parallel systems were constructed. The first system would receive ARD at a constant rate, and the second system would receive smaller volumes of ARD but varying amounts. The two systems were each built with 4 basins measuring 35 x 10 meters with a depth of 2 meters. Approximately 3,000 m^2 of rotted hay and 6,000 m^2 of coarse tree waste were collected over the previous year from local farmers and lumberjacks. In addition, approximately 40 tonnes of shell sands from the coast of Norway of used. The system was then inoculated with cow manure. All of the system was insulated such that it is frost resistant during the winter. The systems were constructed between August 2006 and November 2006 just in time for the snow. Both systems were filled with water, but only one system was allowed to flow during the winter. The total mine water flow is approximately 40 to 60 L/min during the winter.

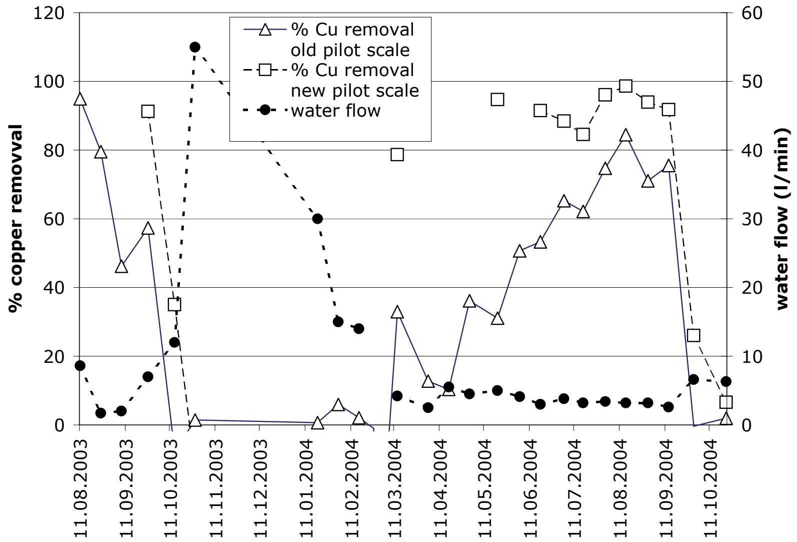

Figure 2. Copper removal vs. water flow in the new and old anaerobic systems.

Table 1. Example water data and sediment data from the Kongens pilot system.

August 15, 2004 Flow: 3.2 L/min						
Sample point		Mine Water	Out : new pilot	Out : old pilot		Sediment Sample
Aluminum	µg/L	34300	25700	22200	mg/kg DM	8700
Cadmium	µg/L	60	25	1	mg/kg DM	12
Copper	µg/L	15200	2360	211	mg/kg DM	5200
Chrome	µg/L	50	35	27	mg/kg DM	28
Lead	µg/L	56	20	<10	mg/kg DM	19
Manganese	µg/L	1210	1140	1180	mg/kg DM	93
Nickel	µg/L	153	124	117	mg/kg DM	16
Zinc	µg/L	34200	24200	17800	mg/kg DM	3900
Sulfate	mg/L	4320	4390	4230	mg/kg DM	12900

As would be expected during a winter start-up, monitoring during the first 3 winter months only show small removal of copper of less than 10%. The second system is expected to be develop anaerobic conditions during the winter, and will be opened during the spring of 2007.

Folldal Mines

The mines at Folldal (N62°08'19" E09°59'27") were first opened in 1745 and mining continued until 1941. During this period approximately 1.5 million tonnes of copper ore were extracted. The mine area is located next to the village of Folldal at an altitude of 700 meters above sea level. The area is just below tree line in a fir tree forest. The present weather can be characterized by an alpine climate with an average precipitation of approximately 360 mm. Runoff from the mine drains to the Folla River, with a total load of approximately 1.7 tonnes copper and 1.4 tonnes sink per year (Arnesen, 1999). Due to the ARD into Folla River there are no trout fish in the river for at least 2 km downstream from the point of emission. The Norwegian Pollution Control Agency (SFT) has required that the maximum copper concentration in Folla River at a sampling point 8 km downstream of the ARD emissions to be less than 10 to 15 µg/L by year 2010.

During the fall of 2006 a pilot scale anaerobic system was constructed to test metal removals from the Folldal mine waters. The ARD at Folldal contains much higher concentrations of copper than Kongens Mine (Table 2). A total of four basins were constructed measuring approximately 8 x 1.5 meters and 1.5 meters deep. The basins were filled with rotted hay, tree clippings dominated by birch and fir, and shell sand as a $CaCO_3$ source. In addition, gypsum was added as an extra sulfur source to the basin. The system was finished right before the first snow fall, and the system was only filled with water and then allowed to rest. During the past months the system was allowed to develop an anaerobic environment.

Monitoring during January 2007 showed that an anaerobic environment is starting to develop with an Eh in the last basin of 147 mV, as compared to an Eh of 678 mV in the untreated mine water. Water collected from the last basin also showed that metals were precipitating in the anaerobic environment (Table 2). During monitoring, abundant black sediment was observed in the first basin. This was sampled and analysed (Table 2).

Table 2. Example water data and sediment data from the Folldal pilot system.

January 23, 2007					
Flow: None					
Sample point		Mine Water	Basin 4		Sediment Sample
Aluminium	µg/L	220000	2600	mg/kg DM	2200
Cadmium	µg/L	200	4.9	mg/kg DM	12
Copper	µg/L	86000	910	mg/kg DM	510
Chrome	µg/L	520	22	mg/kg DM	4
Lead	µg/L	7.0	15	mg/kg DM	<2.1
Nickel	µg/L	750	240	mg/kg DM	27
Zinc	µg/L	57000	1700	mg/kg DM	1700
Iron	µg/L	1200000	42000	mg/kg DM	14900

The water flow was turned on in the basin in January 2007, and it is hoped that the anaerobic environment will be maintained and that metals will continue to precipitate within the basins.

Titania ilmenite mine

Presently, the Titania Mine in southwest Norway has the world's largest reserve of ilmenite and produces approximately 850,000 tonnes ilmenite for the titanium dioxide industry and nickel and copper as a bi-product. Their previous production at the Storgangen Mine (N58°21'40" E06°19'58") generated 8 million tonnes of tailing, of which the coarse fraction was placed in a tailings impoundment. The tailings impoundment is located between 90 and 150 meters above sea level. The site is 5 km from the North Sea and receives an annual precipitation of approximately 1,940 mm with an average temperature of 6°C. Each year approximately 750,000 m^3 of water drains from this tailings impoundment. Although the pH is neutral, the waters contain up to 6 mg/L nickel.

A pilot-scale anaerobic system was tested at this site to remove nickel. Results from this system were presented at the IMWA Congress in Sevilla, Spain in 1999 (Ettner, 1999). Due to the success of this system, in 2003 a full-scale system was built with four basins measuring 35 x 10 meters and 2 meters deep. The basins were filled with rotted hay, coarse tree materials, and inoculated with cow manure. Due to the milder temperatures in this area, the system was not insulated against frost.

Nickel concentrations are monitored by Titania A/S and presented in Figure 2. These data show varying degrees of success for nickel removal. During the first year of operation the system showed erratic removal probably due to a poorly developed anaerobic environment. During the second year the water flow was generally low, and the removal of nickel was over 90%. During the third year of operation the water was allowed to flow freely, and also more tree waste material was added. Rapid fluctuations of the water flow and the disturbance of the anaerobic system have resulted in varying results, especially during extreme rain events during the past two years. It is expected that with a regulated water flow the system should return to high nickel removal during 2007.

Conclusions

Presently, there are two full-scale anaerobic systems and one pilot scale system in operation in Norway. These systems are being tested at sites with varying climates and mine drainage chemistries. These systems and previous pilot-scale systems show that the systems can function and remove metals. By insulating the systems it is possible to maintain an anaerobic environment during the winter, however affectivity may be slightly reduced. In order to effectively remove metals it has been found that the water flows to the systems should be held at a constant flow rate as possible. Climatic warming will probably not negatively affect these passive treatment systems in Norway. However, extreme precipitation events will result in variable ARD releases and will provide a challenge to design treatment systems that can handle rapidly varying amounts of ARD.

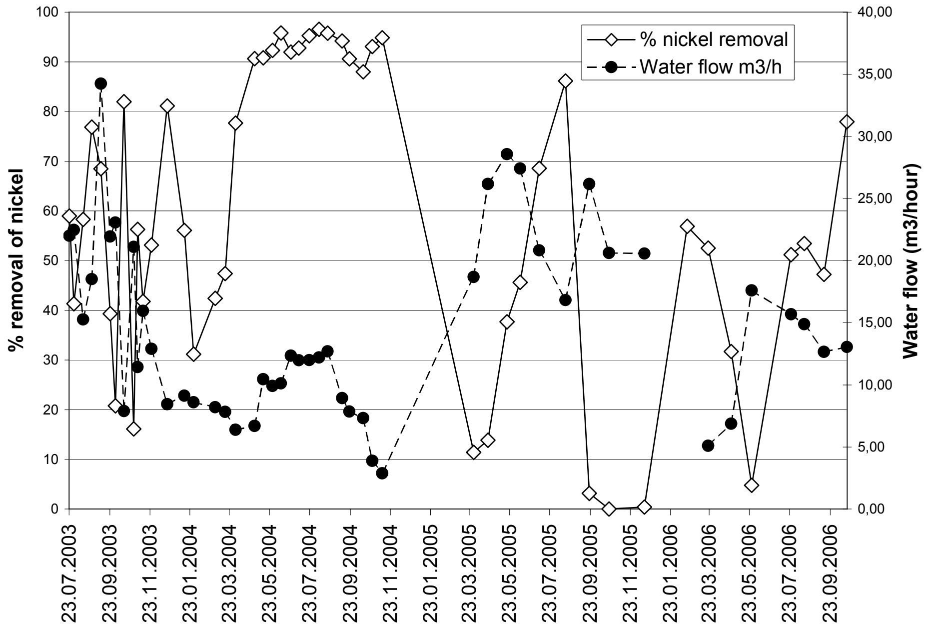

Figure 3. Nickel removal vs. water flow at Titania.

Acknowledgements
This work was supported partly by Skattefunn, Bergvesenet, Folldal Miljøsikringsfond, and Titania A/S. We thank Titania A/S for being able to publish their data.

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