Available online at www.sciencedirect.com

ScienceDirect

Minerals Engineering 21 (2008) 2–9

MINERALS ENGINEERING

This article is also available online at:
www.elsevier.com/locate/mineng

Separation of nutrients from mine water by reverse osmosis for subsequent biological treatment

Katri Häyrynen [a,b,*], Jörg Langwaldt [c], Eva Pongrácz [a], Virpi Väisänen [a],
Mika Mänttäri [d], Riitta L. Keiski [a]

[a] *University of Oulu, Department of Process and Environmental Engineering, Mass and Heat Transfer Process Laboratory, P.O. Box 4300, 90014 University of Oulu, Finland*
[b] *Finnish Forest Research Institute, Rovaniemi Research Station, Eteläranta 55, 96300 Rovaniemi, Finland*
[c] *Geological Survey of Finland, Mineral Processing, Tutkijankatu 1, 83500 Outokumpu, Finland*
[d] *Lappeenranta University of Technology, Department of Chemical Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland*

Received 7 June 2007; accepted 18 June 2007
Available online 31 July 2007

Abstract

Nutrients such as ammonium and nitrate from different sources in mining and mineral processing are often discharged during mining operation to surrounding aquatic environment. The aim of this study was to evaluate the applicability of reverse osmosis (RO) to concentrate ammonium and nitrate from three different mine waters for subsequent removal of nutrients from the concentrate in bioreactors. In initial membrane selection tests, reverse osmosis retained the nutrients and the most suitable membrane was studied for subsequent concentrating tests. The volume reduction factor was up to 20. Ammonium and nitrate were enriched by reverse osmosis 3.6 and 5.7 times, respectively. Total salinity increased about 1.5 times in the RO-concentrate. Iron, copper, zinc, lead and cadmium, potential inhibitors of bacteria, were enriched to the brine of mine water 2. In general, the permeate pH decreased slightly during the reverse osmosis concentration. The produced RO-concentrate was suitable for biological removal of total nitrogen. Prevention of membrane fouling due to suspended solids requires prefiltration of feed prior to reverse osmosis. It was estimated that the total costs for reverse osmosis with prefiltration of feed is about 0.34 €/m^3.

Keywords: Mine waters; Environment; Concentration; Reverse osmosis; Ammonium; Nitrate; Economical analysis

1. Introduction

The major source of ammonium and nitrate in mining and mineral processing is the use of explosives that contain ammonium nitrate. Part of the used explosives remain undetonated and will be transported up from the mine together with extracted rock (Forsberg and Åkerlund, 1999, p. 50). Most of the explosives that are transported from the mine are dissolved in water in wet processes or remain in the barren rock that is separated in dry processes (Forsberg and Åkerlund, 1999, p. 35). Other nutrient sources in mine effluents can be flotation chemicals, cyanide destruction and pH regulation reagents (Langwaldt et al., 2006). The generated wastewaters generally contain also suspended solids, heavy metals, oxidants, reducing agents and salts (Awadalla and Kumar, 1994).

Contamination of mine water with nitrogenous compounds causes environmental problems such as undesirable algal growths in the receiving water bodies (Jørgensen and Halling-Sørensen, 1993, p. 12) and ammonia can be detrimental to fish (Revey, 1996). The promotion of corrosion is an economical issue (Jørgensen and Halling-Sørensen, 1993, p. 12). At the present in the European Union, there are no limits for the discharge of nutrients from mines to receiving waters. The European Union Water Framework

---

[*] Corresponding author. Present address: University of Oulu, Department of Process and Environmental Engineering, Mass and Heat Transfer Process Laboratory, P.O. Box 4300, 90014 University of Oulu, Finland.
E-mail address: khayrynen@mail.suomi.net (K. Häyrynen).

0892-6875/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mineng.2007.06.003

Directive 2000/60/EC demands that member states should aim to achieve the objective at least good water status which means that nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem.

One option for the total nitrogen removal from wastewater is to convert ammonium, nitrite and nitrate into dinitrogen gas by biological nitrification–denitrification. Since the amount of formed mine effluents is extensive, a volume reduction step prior to biological treatment could be economically feasible. For this purpose, membrane filtration is a promising option, since it simultaneously can remove also other pollutants in addition to nitrogenous compounds (Shrimali and Singh, 2001) and requires less energy than many other concentrating processes (Chang, 1996). The molecular weight of ammonium and nitrate is approximately 500 g/mol and, therefore, viable membrane processes for their removal are reverse osmosis and electrodialysis (Shrimali and Singh, 2001). Membrane separation processes are quite simple, the equipments are compact and modular and capable for continuous operation. (Awadalla et al., 1994) In addition, the efficiency and performance of membrane treatment are stable, and predictable with proper feed treatment (Lee and Lueptow, 2001). For this reason, the use of reverse osmosis (RO) was tested to produce a permeate that could be discharged directly to the nature and a concentrated brine including nitrogenous compounds for subsequent treatment in bioreactors (Zaitsev et al., accepted for publication).

Although studies on removal of nitrogenous compounds from wastewater by RO have been published, very few studies have been conducted on separation of nutrients from mine water. Malaiyandi and Sastri (1981 as referred by Awadalla et al. (1994)) reported less than 30% retention of ammonium and nitrate by RO with a cellulose acetate membrane. The Du Pont company (1972 as referred by Awadalla et al. (1994)) reported 80% rejection of ammonium and 85% rejection of nitrate ions from ammonium nitrate and sodium nitrate solutions, respectively, by a hollow fine fiber B-9, polyamide RO membrane. Awadalla et al. (1994) tested four different RO membranes for the removal of ammonium and nitrate from mining effluents with a 99% separation of ammonium and 97% separation of nitrates ions with a crosslinked thin-film composite RO membrane (Toray Ind. Japan). The aim of this study was thus to evaluate the applicability of RO in concentrating ammonium and nitrate from mine waters before the removal of nutrients from the concentrate in bioreactors.

2. Experimental

In this study, water from three different mines was tested for nutrient separation by reverse osmosis. The mines produced gold, chromite and phosphate and samples were entitled mine water 1, 2 and 3, respectively.

For the membrane selection and concentration experiments, a DSS Labstak M20 laboratory equipment was used, manufactured by Danish Separation Systems AS. It can be equipped with flat sheet membranes. The effective membrane area is 0.036 m^2 and it can be increased up to 0.72 m^2 by placing 20 membranes to the packing. Four thin film composite membranes were applied in the bench-scale reverse osmosis equipment (Table 1).

The feed temperature was kept at about 15 °C using a cooler inside the feed tank, to simulate the conditions in the mines. For the pilot scale concentrations, a spiral wound module equipment constructed by Lappeenranta University of Technology was used. The active membrane area depends on the type of membrane used.

Firstly, the feed effluent was filtered through four different commercial membranes. The experiment was carried out in a batch mode, both permeate and concentrate were returned to the feed tank. The operating pressure was raised stepwise from 6 bar to 35 bar and the permeate was sampled. The optimum pressure to be used in the concentrations was chosen based on the measured permeate fluxes and calculated retention based on electric conductivity. The samples from the optimum pressure were further analysed, and based on the analysis results, the most suitable membrane for each mining effluent was selected.

After the most suitable membrane and pressure values were selected, the mine effluents were concentrated by using an effective membrane area of 0.144 m^2. The concentrate was returned to the feed tank and the permeate was gathered in a separate tank. The concentration, to reduce the amount of water, was carried out with five different volumetric reduction factors (VRF).

The volumetric reduction factor was calculated according to the following equation:

$$\mathrm{VRF} = \frac{\text{Total feedwater amount}}{\text{Total feedwater amount} - \text{Amount of permeate}} \tag{1}$$

If the samples from the concentrate could not be returned, the amount of those samples was subtracted from the total feed water amount. A sample from every volumetric reduction factor concentrate was subjected to nitrification and denitrification tests (results not shown).

When the feed is concentrated with high volumetric reduction factors, the osmotic pressure of the effluent

Table 1
Technical data of the studied thin film composite RO membranes as provided by manufacturers

Membrane identification	Supplier manufacturer	Retention (%)	Operating pH range
SW 30 HR	Filmtec Corp.	99.6[a]	2–11
Espa 2	Hydranautics	99.5[b]	3–10
TFC ULP	KOCH membrane systems	98.0[c]	4–11
RO1	Sepro	98.0[d]	3–10

[a] Tested with 32000 mg/l NaCl, 55 bar and at 25 °C.

[b] Tested with 1500 ppm NaCl feed water solution.

[c] Nominal rejection conductivity percent.

[d] Tested with 2000 ppm NaCl feed water, with 8.6 bar pressure at 25 °C.

becomes higher and, therefore, also higher operating pressures are required. Concentration also increases the concentration of elements in the formed permeate, as the feed solute concentration gets higher. Soluble salts, which concentrate to the feed, may to some extent precipitate to the membrane surface, causing fouling and resulting in a decrease of permeate flux (Awadalla and Kumar, 1994).

For the pilot-scale concentration, a spiral wound RO1 membrane, with active membrane area of 1.2 m^2 was used to produce about 0.2 m^3 of RO-concentrate from the mine waters 1 and 2. Volumetric reduction factors were applied based on the biological experiments done on the samples from initial concentration tests. The RO-filtration was operated at nearly constant concentrate flow rate of 800 l/h and permeate flux of 25–33 l/(m^2h).

Membrane fouling was estimated by comparing the water fluxes before and after the filtration to be low when flux difference was 10% or less (Lee and Lueptow, 2001).

The amount of ammonium, nitrate and chloride was measured with Hach Lange DR2800 spectrophotometer. The elemental composition of feed and concentrate was analysed by ICP-AES. The pH and electric conductivity were measured with conventional instruments.

3. Results and discussion

3.1. Characterisation of the different mine waters

All three mine waters were slightly alkaline and the mine water 2 was saline with the chloride concentration of 2400 mg/l (Table 2). The content of ammonium and nitrate varied from 5.5 to 11.8 mg/l and 15.5 to 44.0 mg/l, respectively (Table 2).

3.2. Membrane selection for the concentration of mine waters

In the case of mine water 1, retention based on electric conductivities was more than 90% with all the tested membranes. For further analysis, a sample from 15 bar pressure from Espa 2, TFC ULP and RO1 was chosen based on achieved permeate flux and retention percentage. For SW30 HR, the sample was chosen for an operating pressure of 25 bar, to achieve sufficient permeate flux. Also for mine water 2 the retention of electric conductivity was above 90%. For further analysis of mine water 2, permeate samples from 20 bar pressure from Espa 2, TFC ULP and RO1 membranes were chosen. Using the SW30 HR membrane, the sample was taken at the highest pressure, 35 bar. With mine water 3, retentions of electric conductivity were more than 94% at pressures greater than 6 bar. Based on the fluxes and retention percentages with mine water 3, permeate samples from 20 bar were chosen for Espa 2, TFC ULP and RO1 membranes to be further analysed. For SW 30 HR the analysed sample was from 35 bar pressure. Reverse osmosis filtration resulted in a lower pH in the permeate than in the feed as was also reported in the ammonium removal by RO by Koyuncu et al. (2001). The concentrations of nitrate, ammonium and chloride in feed and permeate were as presented in Table 3.

The RO-membranes Espa 2, TFC ULP and RO1 enabled the highest retention percentages for all the tested waters (Table 3). With mine water 1, permeate fluxes from TFC ULP were the highest. Whereas, for the mine water 2 and 3, RO1 gave the highest permeate fluxes. Awadalla et al. (1994) reported similar results.

Fouling of membranes was below 9%, at all times, with all tested waters. Selection of membranes was based on nutrient retention and permeate fluxes. The TFC ULP membrane was selected for bench-scale concentration tests with mine waters 1 and 2, whereas in the next tests with mine water 3, the RO1 membrane was chosen.

3.3. Bench-scale concentration tests with three mine waters

Bench-scale concentration tests were performed at operational pressures of 15 bar for mine water 1 and for 20 bar for mine water 3. For mine water 2 initially 20 bar pressure was used, however, it had to be raised to 40 to increase the flow.

Sampling of permeate was planned at volumetric reduction factors (VRF) of 9, 10, 12, 15 and 20. The actual sampling occurred at VRF close to the planned VRFs. The retentions of electric conductivity were at least 99.0%, 98.3% and 98.8% for the mine water 1, 2 and 3. These percentages are comparable to the technical data provided by

Table 2
The pH, electrical conductivity (EC) and elemental compositions of the three mine waters

Mine	pH	EC μS/cm	NO_3–N (mg/l)	NH_4–N	Cl	Li	Na	Mg	Al	S	K	Ca
1	7.9	464	15.5	9.53	14.03	<0.01	28.1	15.9	<0.01	14.6	15.0	32.2
2	7.5	6840	20.3	5.5	2400	0.04	834	120	0.59	75.4	76.8	544
3	7.9	988	44.0	11.8	57.6	<0.01	94.1	17.8	0.13	44.9	89.9	52.4

	Mn (mg/l)	B	Fe	Co	Ni	Cu	Zn	As	Cd	Ba	Pb	Cr
1	0.04	0.10	0.01	0.01	<0.01	0.02	0.08	<0.01	<0.01	0.12	<0.01	<0.01
2	0.09	0.40	<0.01	0.04	<0.01	0.03	0.16	<0.01	<0.01	1.62	<0.01	0.02
3	<0.01	0.09	0.02	<0.01	<0.01	<0.01	0.021	<0.01	<0.01	1.68	0.01	0.01

Table 3
Separation of nitrate, ammonium, chloride and sodium chloride of the formed permeates during the membrane selection tests

		Feed	SW 30 HR	Espa 2	TFC ULP	RO1
Mine water 1						
NO_3–N	mg/l	15.6	0.94	0.40	0.36	0.61
	Retention %		93.9	97.4	97.7	96.0
Cl	mg/l	14.0	2.86	<1.30	<1.02	<1.16
	Retention %		79.6	>90.8	>92.7	>91.8
NH_4–N	mg/l	9.53	1.64	0.54	0.81	0.80
	Retention %		82.8	94.3	91.5	91.6
NaCl	mg/l	28.10	1.96	1.60	0.67	1.85
	Retention %		92.0	93.3	96.6	92.4
Mine water 2						
NO_3–N	mg/l	20.8	1.66	1.33	1.94	0.89
	Retention %		92.0	93.6	90.7	95.7
Cl	mg/l	2400	240	152	195	183
	Retention %		90.0	93.7	91.9	92.4
NH_4–N	mg/l	5.50	0.86	0.33	0.60	0.60
	Retention %		84.4	94.0	89.1	89.1
NaCl	mg/l	834	62.2	34.4	65.4	24.7
	Retention %		92.5	95.9	92.2	97.0
Mine water 3						
NO_3–N	mg/l	44.0	1.17	1.76	2.68	3.05
	Retention %		97.3	96.0	93.9	93.1
Cl	mg/l	57.6	1.11	<1.28	1.39	<1.05
	Retention %		98.1	>97.8	97.6	>98.2
NH_4–N	mg/l	11.8	1.07	0.65	0.82	1.64
	Retention %		90.9	94.5	93.0	86.1
NaCl	mg/l	94.1	1.96	4.65	5.63	2.63
	Retention %		97.9	95.0	94.0	97.2

the manufacturers. For mine water 2 and 3, the pH values were lower in the concentrates than in the feed. The concentrate of mine water 1 had higher pH values than the feed. The highest achieved VRF for mine waters 1, 2 and 3 were 20.4, 19.4 and 23.5. With these VRFs, the retentions for ammonium were 82.2%, 71.0% and 68.3% for the mine waters 1, 2 and 3. While retentions were 89.9%, 70.0% and 83.4% for nitrate and 84.7%, 89.6% and 94.1% for chloride with the mine waters 1, 2 and 3. Since the RO-feed became more concentrated during the filtration, the retention percentages are less than reported by Awadalla et al. (1994).

Since nitrifying and denitrifying bacteria are sensitive to salinity, it was monitored during the bench-scale concentration tests. The total salinity increased with VRF and was 4.0, 75.4 and 10.1 g/l at the highest VRF for mine waters 1, 2 and 3. With mine waters 1 and 3 the VRF could be higher than 20 based on biological tests. The obtained total salinity with mine water 2 is relatively high and might decrease the microbial activity in bioreactors. Thus, the VRF should be less than 5 for mine water 2 in the pilot-scale concentration tests. In tests with mine water 1, the heavy metals Cu and Al were enriched to the concentrate. These metals might hinder the microbial activity of the bacteria in bioreactors.

Membrane fouling was 0.4–4.2%, 15.4–20.7% and 30.4–57.2% with the mine waters 1, 2, and 3, respectively. In the case of mine water 3, the increased fouling was probably due to higher permeate flux than with the two other mine waters.

The results of the bench-scale tests were utilized to select the process parameters for pilot-scale concentration of the mine waters 1 and 2. Mine water 3 was not included in these tests.

3.4. Pilot-scale concentrations with two mine waters

The concentration test with mine water 1 was carried out with an initial pressure of 4.5 bar and the final VRF of 17.2 was reached. Since no pre-treatment was applied prior to reverse osmosis, suspended solids affected the filtration. Therefore, the operational pressure was raised during the test up to 35 bar to maintain a sufficient permeate flux (Fig. 1). During the run, the mean flux was about 23.6 l/(m^2h). Additionally, the membrane had to be cleaned chemically, which temporarily improved the situation. The retention of the electric conductivity and permeate pH during the concentration test were as shown in Fig. 2. Initial and final pH values were similar. In the beginning of the

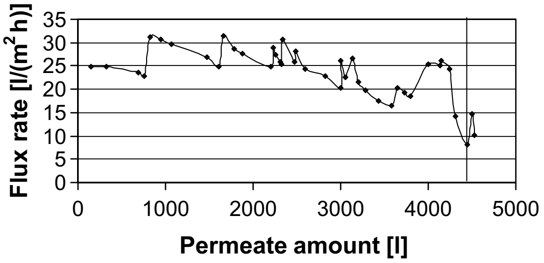

Fig. 1. Development of permeate flux during concentration of mine water 1. Increases in pressure are shown as rapid flux improvements. The chemical cleaning of membrane is marked with a vertical line.

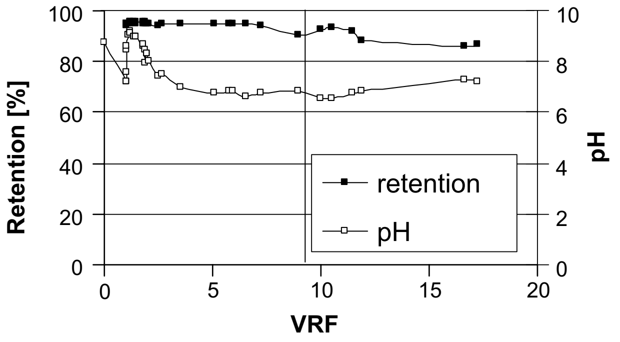

Fig. 2. Development of retention of electric conductivity and permeate pH with increased volumetric reduction factor (VRF) during filtration of mine water 1. The chemical cleaning of membrane is marked with a vertical line.

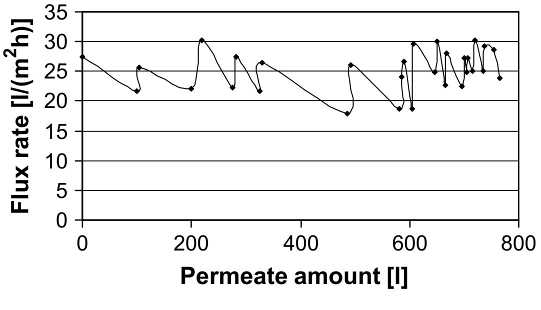

Fig. 3. Development of permeate flux during concentration of mine water 2. Increases in pressure are shown as rapid flux improvements.

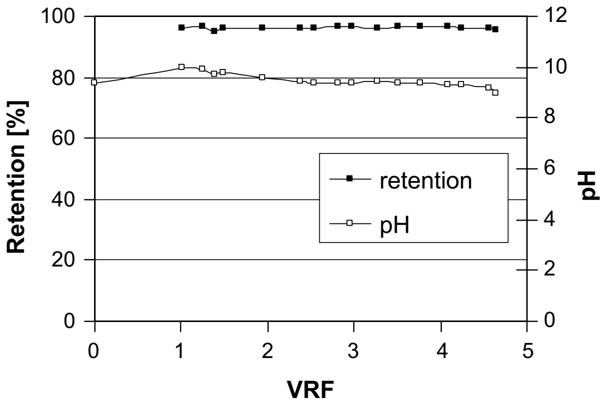

Fig. 4. Development of retention of electric conductivity and permeate pH with increased volumetric reduction factor (VRF) during filtration of mine water 2.

filtration of mine water 1 retentions were above 94%. Retention remained approximately constant up to a VRF value of 7 but, after that, it started to decrease notably, mainly due to the decrease in permeate fluxes caused by fouling. At the VRF value of 8.9, the retention improved temporarily, due to chemical cleaning of the membrane. The reverse osmosis filtration with mine water 2 was started at 12.5 bar. The operational pressure was stepwise increased up to 28.5 bar and the final VRF was 4.7 (Fig. 3). The retention of electric conductivity was stable and over 95%, but the pH decreased during the concentration test (Fig. 4). Comparable to mine water 2, the retention percentages were lower than given by the manufacturers due to membrane fouling. During the run, the mean flux was approximately 25.2 l/(m^{2}h). Ammonium and nitrate were analysed in the feed water of both mine waters and in the final concentrates (Table 4). The membrane retention and the permeate quality was not as favourable as it had been in the small-scale filtrations (Fig. 4). Ammonium and nitrate were analysed in the feed water of both mine waters and in the final concentrates (Table 4). The membrane retention and the permeate quality was not as favourable as it had been in the small-scale filtrations (Fig. 4). For mine water 1, membrane fouling caused smaller concentration increases for ammonium and nitrate as expected from the bench-scale concentration tests. The aim was to keep the feed temperature below 15 °C, however, due to increased temperature of the municipal water used for cooling, the feed temperature of mine water 1 could not be kept below 19.0 °C. The ammonium increase in the concentrate was lower than expected and might indicate biological nitrification of ammonium to nitrate during filtrations. For mine water 2, the feed temperature was 19–21 °C promoting biological nitrification. However, the ammonium content in permeate could not be analysed to quantify the nitrification. The results from the ICP-AES-analyses of the concentrates are presented in Table 5.

With mine water 1, the concentration of arsenic was higher in the feed than in the formed concentrate. This decrease occurred also in mine water 1 membrane selection stage, therefore, penetration of arsenic to the permeate can

Table 4
Ammonium and nitrate content in the reverse osmosis concentrate from the pilot-scale concentration tests

		Mine 1 feed	Mine 1 VRF 17.2 concentrate	Mine 2 feed	Mine 2 VRF 4.7 concentrate
NO_3–N	mg/l	20.7	118	28.1	98.7
	Increase		5.71		3.51
NH_4–N	mg/l	8.56	31.0	3.12	6.03
	Increase		3.63		1.93

Table 5
Elemental composition of the feed and reverse osmosis concentrate obtained from the pilot-scale concentration tests

		Li	Na	Mg	Al	P	S	K	Ca	Mn	B	Fe
Mine 1	mg/l	<0.01	24.5	21.6	0.15	0.07	17.0	17.6	35.6	0.02	0.09	0.03
Mine 1 VRF 17.2	mg/l	0.02	164	169	0.29	0.19	177	82.7	146	0.04	0.15	0.06
	Increase	>2.0	6.69	7.82	1.95	2.58	10.40	4.70	4.10	1.80	1.63	1.78
Mine 2	mg/l	0.03	617	90.4	0.53	0.09	111	94.3	395	0.06	0.27	<0.01
Mine 2 VRF 4.7	mg/l	0.14	2820	386.0	2.03	<0.01	351	425	1440	0.25	0.43	0.41
	Increase	5.19	4.57	4.27	3.83	–	3.16	4.51	3.65	4.44	1.60	>41
		Co	Ni	Cu		Ba	As	Zn	Cd	Pb	Cr	
Mine 1	mg/l	0.02	0.02	0.01		0.16	0.10	<0.01	<0.01	<0.01	<0.01	
Mine 1 VRF 17.2	mg/l	0.05	0.04	<0.01		0.61	<0.01	<0.01	<0.01	<0.01	<0.01	
	Increase	2.10	1.73	–		3.77	–	–	–			
Mine 2	mg/l	0.04	0.01	<0.01		0.19	<0.01	<0.01	<0.01	<0.01	<0.01	
Mine 2 VRF 4.7	mg/l	0.08	0.02	0.39		0.84	<0.01	0.24	0.18	0.10	0.04	
	Increase	2.27	1.94	>39		4.31	–	>24	18	10	>4	

be considered as a characteristic of the RO1 membrane. None of the elements had enriched to a great extent into the concentrate of mine water 1. With mine water 2, the amount of phosphorous was smaller in the concentrate than it had been in the feed and, hence, it has penetrated through the membrane to the permeate. As it can be observed in Table 5, iron, copper, zinc, cadmium and lead were enriched in mine water 2 concentrate. Dalzell et al. (2002) reported 50% inhibition of nitrification by cadmium, copper and zinc at each 15, 30 and 10 mg/l. These IC50 concentrations are well below the metal content in the RO-concentrate of mine water 2, thus unlikely to affect bacteria. Depending on the origin of the nitrifying bacteria, they tolerate different salinities. Koops et al. (1991) described new *Nitrosomonas* species, which show optimal growth at NaCl concentration of 17.5–23.4 g/l. Dupla et al. (2006) studied extensively the denitrification of seawater, 28–30 g NaCl/l, and achieved good denitrification at 10 °C. Thus, the salt content in the RO-concentrates is not expected to significantly inhibit the biological nitrification or denitrification of the RO-brine.

When concentrating mine water 1, fouling percentage for the RO1 spiral membrane was 98% because suspended solids were not removed prior to RO. Therefore, it has been concluded that a prefiltration step would be needed before treating mine water 1 with the RO-module. With mine water 2, the fouling percentages to the membrane were from 6.4% to 18.9% depending on the pressure. The 10% limit of low fouling is exceeded, however, the fouling percentages are still tolerable. Notwithstanding, a prefiltration step is recommended also in this case.

3.5. Process economics

An estimate of the process economics can be calculated. The calculations were done for a plant capacity of

Table 6
Estimated total costs for processing 250000 m^3/a and 1000000 m^3/a of mine water

	Used parameters		250000 m^3/a, VRF 20	1000000 m^3/a VRF 5
	Plant capacity 250000 m^3	Plant capacity 1000000 m^3		
Energy	• Energy price 7.20 c/kWh • Pump efficiency 70% • Average operating pressure 9 bar	• Average operating pressure 20 bar	0.03 €/m^3	0.07 €/m^3
Chemicals	• The prices 3.73 €/kg (used as 1% solution) and 2.86 €/kg (used as 0.5% solution) • Two chemical cleanings per year		0.002 €/m^3	0.002 €/m^3
Membrane and pre-filtration cartridge changes	• 678 modules, 218.24 € a piece • Membrane life expectancy 4 years • Pre-filtration cartridges changed once a week • 7 cartridges, 18 € a piece	• 2283 modules, 218.24 € a piece • 22 cartridges, 18 € a piece	0.17 €/m^3	0.15 €/m^3
Labour	• 75 h in a year		0.006 €/m^3	0.002 €/m^3
Capital costs	• 30 years amortizing time, 5% interest rate		0.13 €/m^3	0.11 €/m^3
Total			0.34 €/m^3	0.31 €/m^3

250 000 m^3/a at VRF 20 and for a plant capacity of 1 000 000 m^3/a at VRF 5. Estimated capital and operational cost are listed in Table 6.

The operational costs are formed from membrane replacement, energy consumption, cleaning chemicals purchase and labour costs. The calculations were done for a spiral wound module with a membrane area of 1.2 m^2 in one module. The incoming flux rate was assumed to be 700 l/(m^2h) and the permeate flux from one unit 33.3 l/(m^2h). The pretreatment unit before the reverse osmosis unit is considered to be cartridge filters. By using larger RO modules, the costs for the membrane changes would be much lower, since the price for membrane square meter is lower. The energy consumption depends mainly on the operational pressure and, therefore, the energy costs are higher with a larger plant capacity and higher operational pressures. The calculations were done considering two chemical cleanings per year. The estimated labour hours would form from turning the plant on and off, recording the flow and pressure, maintaining the log (Taylor et al., 1989) and performing the chemical cleaning.

According to Awadalla et al. (1994), the membrane costs typically represent about 20–30% of system costs for an aqueous separation system. In the present calculation, membrane costs were assumed to be 30% of system costs. With amortizing time of 30 years and with an interest rate of 5% the capital costs would be 0.13 €/m^3 of processed feed with the lower plant capacity and 0.11 €/m^3 with the larger plant capacity.

Based on these considerations the total estimated total costs was calculated to be 0.34 €/$m^3$of processed feed with the plant capacity of 250 000 m^3/a and with VRF 20. For a plant capacity of 1 000 000 m^3/a and VRF 5, the total estimated costs are 0.31 €/m^3. This is considerably less than the \$0.95 to \$1.06/m^3 total costs of ammonium removal by RO from surface water estimated by Koyuncu et al. (2001).

4. Conclusions

All the tested RO membranes retained ammonium and nitrate acceptably in the membrane selection stage. Espa2, TFC ULP and RO1 were clearly the best membranes for all tested mine waters, with the retention value of above 90.7% for NO_3–N and above 86.1% for NH_4–N. The concentration of the mine waters deteriorated the permeate quality compared to the permeate formed in membrane selection stage, however, the retention for ammonium and nitrate were satisfying. For the part of the reverse osmosis process, the mine effluent could have been concentrated by higher volumetric reduction factor than 20 but, because the processability of the concentrate in a bioreactor defines the highest possible VRF, it can not be very high, especially for mine water 2 when the salt content in the feed water is high.

For pilot-scale concentration, the results were poorer than expected due to higher feed temperature and membrane fouling. However, concentration on a large-scale is possible and, using adequate pretreatment it should give similar results as the smaller-scale concentration.

According to the economical analysis, the estimated cost for the treatment of the tested mine effluents with reverse osmosis would be from 0.31 to 0.34 €/m^3. This is a reasonable price for a water treatment plant, however, for a mine, the overall costs are high.

Acknowledgements

This study was carried out in the framework of the KAIRA-project funded by the European Regional Development Fund, the Finnish Funding Agency for Technology and Innovation TEKES and industrial partners. We acknowledge the technical support in water sampling generously provided by the mine personnel.

References

Awadalla, F.T., Kumar, A., 1994. Opportunities for membrane technologies in the treatment of mining and mineral process streams and effluents. Separation Science and Technology 29 (19), 1231–1249.

Awadalla, F.T., Striez, C., Lamb, K., 1994. Removal of ammonium and nitrate ions from mine effluents by membrane technology. Separation Science and Technology 29 (4), 483–495.

Chang, L., 1996. An industrial wastewater pollution prevention study: Evaluation of precipitation and separation processes. Environmental Progress 15 (1), 28–36.

Dalzell, D.J.B., Alte, S., Aspichueta, E., de la Sota, A., Etxebarria, J., Gutierrez, M., Hoffmann, C.C., Sales, D., Obst, U., Christofi, N., 2002. A comparison of five rapid direct toxicity assessment methods to determine toxicity of pollutants to activated sludge. Chemosphere 47 (5), 535–545.

Dupla, M., Comeau, Y., Parent, S., Villemur, R., Jolicoeur, M., 2006. Design optimization of a self-cleaning moving-bed bioreactor for seawater denitrification. Water Research 40 (2), 249–258.

European Union Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities. 22.12.2000 (referred 31.5.2006) p. 72. Accessible from http://europa.eu.int/eurlex/pri/en/oj/dat/2000/l_327/l_32720001222en00010072.pdf.

Forsberg, H., Åkerlund, H., 1999. Nitrogen and the residues of explosives in ore-, waste rock- and production flows of LKAB. (Kväve och sprängämnesrester i LKAB:s malm- gråbergs- och productflöden.) M.Sc. thesis. Luleå University of Technology, Luulaja, (in Swedish) p. 87.

Jørgensen, S.E., Halling-Sørensen, B., 1993. Nitrogen compounds as pollutants. In: Halling-Sørensen, B., Jørgensen, S.E. (Eds.), The removal of nitrogen compounds from wastewater. Elsevier Science Publishers B.V., Amsterdam, pp. 3–40.

Koops, H.-P., Böttcher, B., Möller, U.C., Pommerening-Röser, A., Stehr, G., 1991. Classification of eight new species of ammonia-oxidizing bacteria: *Nitrosomas communis* sp. nov., *Nitrosomonas urea* sp. nov., *Nitrosomas aestuarii* sp. nov., *Nitrosomonas marina* sp. nov., *Nitrosomas nitrosa* sp. nov., *Nitrosomonas eutropha* sp. nov., *Nitrosomas oligotropha* sp. nov., *Nitrosomonas halophila* sp. nov. Journal of General Microbiology 137 (7), 1689–1699.

Koyuncu, I., Topacik, D., Turan, M., Celik, M.S., Sarikaya, H.Z., 2001. Application of the membrane technology to control ammonia in surface water. Water Science and Technology: Water Supply 1 (1), 117–124.

Langwaldt, J., Mattila, K., Zaitsev, G., 2006. Biological removal of nutrients from mine waters. Materia 63 (1), 47–49.

Lee, S., Lueptow, R.M., 2001. Membrane rejection of nitrogen compounds. Environmental Science and Technology 35 (14), 3008–3018.

Malaiyandi, M., Sastri, S.V., 1981. Reverse Osmosis Separation of sulphate, nitrate and ammonia from mining effluents. Separation Science and Technology 14 (4), 371–376.

Permasep Technical data Separation/Concentration of ammonium and Nitrate ions, Technical Bulletin 403, Du Pont Permasep Permeators, 1972.

Revey, G.F., 1996. Practical methods to control explosives losses and reduce ammonia and nitrate levels in mine water. Mining Engineering 48 (7), 61–65.

Shrimali, S., Singh, K.P., 2001. New methods of nitrate removal from water. Environmental Pollution 112 (3), 351–359.

Taylor, J.S., Mulford, L.A., Durenceau, S.J., Barrett, W.M., 1989. Cost and performance of a membrane pilot plant. Journal AWWA 81 (11), 52–60.

Zaitsev, G., Mettänen, T., Langwaldt, J., accepted for publication. Removal of ammonium and nitrate from cold inorganic mine water by fixed-bed biofilm reactors. *Minerals Engineering*, special issue Bio and Hydromet ’07.