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Review

# Gold acid mine drainage treatment by membrane separation processes: An evaluation of the main operational conditions

Alice O. Aguiar, Laura H. Andrade, Barbara C. Ricci, Wadson L. Pires, Gisele A. Miranda, Míriam C.S. Amaral *

*Department of Sanitary and Environmental Engineering, Federal University of Minas Gerais, P.O. Box 1294, ZIP 30.270-901, Belo Horizonte, MG, Brazil*

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ABSTRACT

Acid mine drainage (AMD) is an effluent characterized by low pH and high concentrations of sulfate, metals, and metalloids. AMD treatment by membrane separation processes (MSP), specifically nanofiltration (NF) and reverse osmosis (RO) is particularly interesting; as these processes can retain divalent ions efficiently to produce high quality permeate for industrial reuse. This study aimed to evaluate the main operational conditions of the gold AMD treatment by MSP, and conduct a preliminary capital and operational cost evaluation. The results showed that the NF had a higher potential to treat the AMD than the RO, as the NF had higher permeate flux and satisfactory solutes retention efficiency. The NF90 membrane had the highest retention efficiency among the NF membranes, while the NF270 membrane had the highest permeate flux. Effluent pH affected both the solutes retention efficiency and the membrane-fouling tendency. The best combination of membrane type and feed pH was the NF270 at pH 5.5. The maximum water recovery rate at this condition was 60%, when a sharper decrease in the retention efficiency and the permeate flux was observed. The estimated capital cost of the UF-NF unit considering an effluent volumetric flow rate of 15 $m^3/h$ was US$ 131,250.00, and the operational cost was 0.263 US$/$m^3$ of effluent.


**Contents**



* Corresponding author.
*E-mail address:* miriam@desa.ufmg.br (M.C.S. Amaral).

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## 1. Introduction

The oxidation of sulfide minerals in mining waste, tailings, and structures of active or abandoned mines can cause the formation of acid mine drainage (AMD). AMD is recognized as one of the most difficult environmental problems confronting mining companies; because of the ecological consequences of AMD, the difficulty of controlling it once it has started, the large volumes involved, the high associated treatment costs, and the perpetuity of the process [1]. AMD is characterized by low pH and high concentration of sulfate, as well as high concentrations of metals and metalloids [2].

Membrane separation processes (MSP) are the most promising technologies to reduce effluent discharge, and minimize water requirement through wastewater reclamation. MSP have high efficiency, high reliability, ease of operation, high adaptability to changes in feed flow, low operation times, and modular design [3]. Both nanofiltration (NF) and reverse osmosis (RO) processes can retain salts and metals from the feed solution and, therefore, show high potential for AMD treatment aimed at water reuse [4]. RO membranes are permeable to water but substantially impermeable to salts; therefore, they are suitable to separate ionic species, dissolved metals, and organic molecules of low molar mass [5]. On the other hand, NF membranes are an intermediate between RO and ultrafiltration (UF) membranes. The NF membranes have higher permeate fluxes than RO membranes and can retain multivalent ions and dissolved molecules, with a molecular weight between 200 and 1000 DA [6]. However, NF and RO are highly susceptible to membrane fouling, which is caused by the deposition of organic and inorganic matter and/or the formation of biofilms on the membrane surface. Although membrane fouling in MSP is inevitable, the rate and extent of fouling can be influenced by feed characteristics, membrane properties, and operational conditions [7]. It is essential to control membrane fouling to ensure an economically feasible operation.

The membrane surface properties, such as hydrophobicity/hydrophilicity, surface roughness, and membrane charge density and charge polarity directly influence the fouling tendency of the membrane. The surface properties of the membrane depend on the polymeric material of the membrane, the manufacturing process, and the added functional groups, as well as the conditions to which the membrane is exposed. The feed solution pH, for example, has a significant effect on the membrane charge and the distribution of solute species, since it can protonate and deprotonate the membrane functional groups and/or the molecules in the solution; and consequently, influences the process efficiency [6]. On the other hand, operational conditions, such as feed pressure, temperature, and feed flow rate, influence the convective transport of foulants toward the membrane surface [7]. One of the most important operational conditions for designing NF/RO systems is the water recovery rate (RR). Higher RR implies higher system productivity and lower retentate production, which, consequently, influence the treatment capacity and the investment in equipment [8].

Al-Zoubi et al. [9] studied the treatment of two synthetic AMD solutions with NF (NF99-Alfalaval and DK-GE-Osmonics) and RO membranes (HR98PP-Alfalaval). These authors evaluated the effects of pressure, temperature, and feed flow rate on pollutants rejection and permeate flux. The results showed that NF was more suitable for AMD treatment at low temperatures because of its higher permeate flux. The rejection of heavy metal ions by NF (NF270-Dow membrane) was further investigated by Al-Rashdi et al. [10] pertaining to the effects of feed pH, pressure, and metal concentration on cations rejection and permeate flux. These authors observed that metal rejection was higher at feed pH below the membrane isoelectric point, attributable to the positive charge on the membrane surface. Tests were also carried out on non-synthetic AMD solutions. Sierra et al. [2] treated mercury AMD with the NF-2540 (FILMTEC™) membrane. They studied the effects of pressure and volume reduction factor and observed that the permeate flux was similar to the pure water flux up to a pressure of 10 bar, which suggests low concentration polarization. Moreover, the rejection of pollutants increased with the pressure and, at 10 bar, sulfate rejection was 88%. Mullett et al. [11] investigated the treatment of copper AMD with two NF membranes (NF 270-Dow and TS 80-TriSep). They conducted feed pH and water recovery tests; however, non-synthetic effluent was used only on the feed pH test with the NF 270 membrane. The results for this tests showed that sulfur ($S^{-2}$) rejection increased and cations ($Ca^{+2}$, $Cu^{+2}$, $Mg^{+2}$, and $Mn^{+3}$) rejection decreased with higher pH. Moreover, all the rejections were higher than 88%.

Evidently, membrane separation processes showed high potential for AMD treatment, with high pollutants retention efficiencies. However, a thorough evaluation of AMD treatment in relation to all the main process characteristics was still needed. Therefore, the aim of this study was to optimize the treatment of gold AMD with MSP in relation to commercial membrane types, pH adjustment, and maximum water recovery; simultaneously evaluating the effects of each factor on the main pollutants retention and on membrane fouling potential. With these conditions optimized, a more realistic cost assessment was obtained.

## 2. Materials and methods

### 2.1. Analytical methods

Multi-element analyses of liquid samples were performed by ion chromatography (Dionex ICS-1000 ion chromatography, equipped with column type IonPac AS22 and IonPac CS12A). The other parameters analyzed were pH (pHmeter Qualxtron QX 1500), conductivity (Hanna conductivity meter HI 9835), turbidity (Hach 2100AN turbidimeter), and solid fractions. All analyses were performed in accordance with the *Standard Methods for the Examination of Water and Wastewater* [12].

### 2.2. Gold acid mine drainage characterization

AMD was collected at a gold mining company site in the state of Minas Gerais, Brazil. The company has two underground gold mines and an industrial processing plant. AMD was collected at one of the underground mines, at the fourth level below ground. The AMD characteristics vary throughout the year, and the effluent properties of greatest interest to the present study are presented in Table 1. Other metal concentrations in the raw AMD were also analyzed (values not shown here). However, the concentration of calcium, magnesium and sulfate were at least $10^1$ orders of magnitude larger than those, and, therefore, these 3 were selected to evaluate the retention efficiency of the membranes.

Each batch of experiments used the same AMD collection sample to enable the comparison of the results.

### 2.3. Membrane separation processes

#### 2.3.1. Ultrafiltration

The raw AMD was ultrafiltrated prior to NF and RO experiments. UF was performed in order to prevent severe damage to the NF membranes caused by the presence of suspended solids from the raw effluent. UF used a commercial submerged membrane (ZeeWeed) module, with a filtration area of 0.047 $m^2$, average pore diameter of 0.04 μm, and a PVDF-based polymer. UF was carried out at 0.7 bar up to a recovery rate of 60%.