Seawater desalination using forward osmosis process

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ABSTRACT

This study aims to evaluate the feasibility of the forward osmosis (FO) process for seawater desalination. The leakage of boron from the seawater into the draw solution was also studied. According to the WHO guideline, the maximum permissible limit of boron in drinking water is 2.4 ppm. Preliminary results of boron rejection by forward osmosis membrane were found to be 60–70%. Minimal fouling of the FO membrane was observed in the experimental run spanning over 70 days. Under the given set of test conditions, flux of $1.4 \, \text{L m}^{-2} \, \text{h}^{-1}$ was found throughout the run and there was no significant decline in the flux. With a flux recovery of 40% which is the same as that of the reverse osmosis (RO) process, FO could be potentially utilized for seawater desalination applications.

Key words | boron rejection, forward osmosis, membrane fouling, scaling, seawater desalination

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INTRODUCTION

The current scenario of global water crisis demands innovative and novel technologies that not only provide elevated throughput and productivity, but also ensure optimum energy efficiency at the same time. Today, the most consistent and reliable technology to extract fresh water from seawater is the reverse osmosis (RO) process (Elimelech & Phillip 2011). However, the energy consumed by this process, including the pressure exchangers at the brine stream is roughly 3–$4 \, \text{kWh m}^{-3}$ of water produced (Mezher et al. 2011). Furthermore, it also faces the issue of membrane fouling.

At the turn of the new century, scientists have shown keen interest in electro-deionization technologies, forward osmosis (FO) process and nanofiltration using carbon nanotubes, in order to address the challenges faced by the RO process (Shea 2009). The FO process is a viable prospect for seawater desalination by extracting water molecules from the seawater into a draw solution. In addition to the applications of FO available in the literature (Cath et al. 2006), it could be prudently employed for seawater desalination due to its low energy consumption and lower fouling propensity. Reports (Kessler & Moody 1976) suggest that a flat sheet FO membrane made from cellulose triacetate

(CTA) could draw about 5 L of potable water from seawater using 1 kg of glucose–fructose draw solution. It was intended to commercialize seawater desalination to produce a stand-alone emergency water supply on lifeboats. Recently, other draw solutions such as ammonium bicarbonate (McCutcheon et al. 2005) have been experimented with for their potential use in solute extraction and reusability. In these tests, 0.5 M NaCl representing seawater was used as the feed while 6 M ammonium bicarbonate was employed as draw solution. Preliminary results substantiated that FO membrane helped produce higher flux compared to RO membrane. A recent research article (Phuntsho et al. 2011) reported using fertilizer solutions as draw solutions for seawater desalination using the FO process.

Earlier research on seawater desalination using the FO process was generally concerned with the choice of draw solution and flux recovery (Kravath & Davis 1975; McGinnis et al. 2007) However, fouling propensity of seawater on the FO membrane, the necessity for any seawater pretreatment prior to passage through the FO membrane, and boron rejection by the FO membrane have not been studied in detail. Recently, Jin et al. (2011) investigated boron passage through the FO membrane in two

membrane orientation modes, namely the dense layer facing the feed solution and the dense layer facing the draw solution. Under simulated test conditions, artificial seawater (i.e., 0.5 M NaCl) was tested at batch scale with the addition of boron solution. Boron rejection was better for the dense layer facing the feed solution mode due to effective and efficient rejection of boron. Furthermore, it was reported that the boron rejection increased with increasing membrane water flux.

Nevertheless, there is a necessity to use actual seawater and run it in continuous mode to investigate the boron flux and hence its rejection by the FO membrane. Fouling due to seawater exacerbates the plant throughput, thus affecting the water production efficiency. As far as the RO process is concerned, fouling in seawater desalination is basically due to particulate matter, organic compounds and biological growth (Magara *et al.* 2000). Furthermore, Huertas *et al.* (2008) have investigated the impact of biofouling on RO membrane boron rejection. It was observed that the boron rejection dropped by 45% for RO membrane fouled by *P. aeruginosa* PAO1. The decrease in boron rejection was attributed to biofilm growth that enhanced concentration polarization of salts, including boron, near the membrane surface. Generally, a decrease in boron rejection is observed when biofouling occurs. Therefore, research is necessary into membrane fouling, boron rejection by the FO membrane, impact of pretreatment of seawater using the microfilter (MF) membrane and overall recovery of the system for seawater desalination. Tapping the osmotic gradient energy of the highly concentrated sodium sulphate as a draw solution in the FO process, seawater was desalinated at laboratory scale in this study. Studies on flux performance, fouling and boron rejection of the FO membrane were carried out.

MATERIALS AND METHODS

Surface seawater with pH of about 8.1 and total dissolved solids of 32,500 ppm was used. It had a nominal silt density index (SDI) of 4, turbidity of 1–2 NTU and total organic carbon of about 4–5 ppm. Sodium sulphate solution with a concentration of 1.15 M was employed as the concentrated draw solution. Sodium sulphate is used as a suitable draw solution due to its high osmotic pressure obtained at low solute concentrations, comparatively lower cost, low toxicity and ease of reconcentration through low pressure systems, such as nanofiltration. Nanofiltration technology is used for the separation of water molecules from the concentrated draw solute.

The FO flat sheet membrane used was purchased from HTI Inc., USA. A 0.45-μm polyethersulphone (PES) MF membrane was used to treat seawater prior to filtration with FO membrane.

The experimental set-up (Figure 1) consisted of submerged FO membrane modules in seawater, with the draw solution circulating inside it. The draw solution tanks were placed on a weighing scale to measure the change in the weight of the draw tank, from which the membrane water flux was calculated. Two types of seawater feed were tested simultaneously, one pretreated with MF and the other with no pretreatment. This helped study the effects of pretreating the seawater before the actual FO filtration process. A seawater retention time of 3 days was maintained in the FO reactor tanks.

Boron determination in seawater feed and subsequent seepage into the draw solution were measured using ICP-OES (inductively coupled plasma optical emission spectrometry) method at 249.772 nm as per ASTM-3120 B protocol. An ion chromatogram was used to monitor the ions present in the seawater and draw solution. Turbidity, SDI and pH of the feed seawater solutions were measured intermittently. A nephelometer (Hach 2100 N Turbiditimeter, USA) was used to measure solution turbidity. GE Osmonics' (USA) SDI kit was used for measuring the SDI of feed seawater solution. The SDI is a measure of the capacity of any feedwater to foul RO membranes. The SDI is determined from the fouling rate of a 0.45-μm filter at a pressure of 30 psi and is described in the ASTM standard method D4189 (Eaton *et al.* 1997). At the end of the experiments, the FO membrane was subjected to destructive testing to investigate the degree of fouling on its surface using scanning electron microscopy (SEM-XL-30-FEG, Philips, Germany). Prior to taking the SEM images, membrane samples were prepared by freezing the membrane at −50 °C in a chiller for 2 hours followed by freeze drying at −70 °C and 0.01 mbar (vacuum conditions) for 7–8 hours. This was done in order to keep intact the foulant layer of the
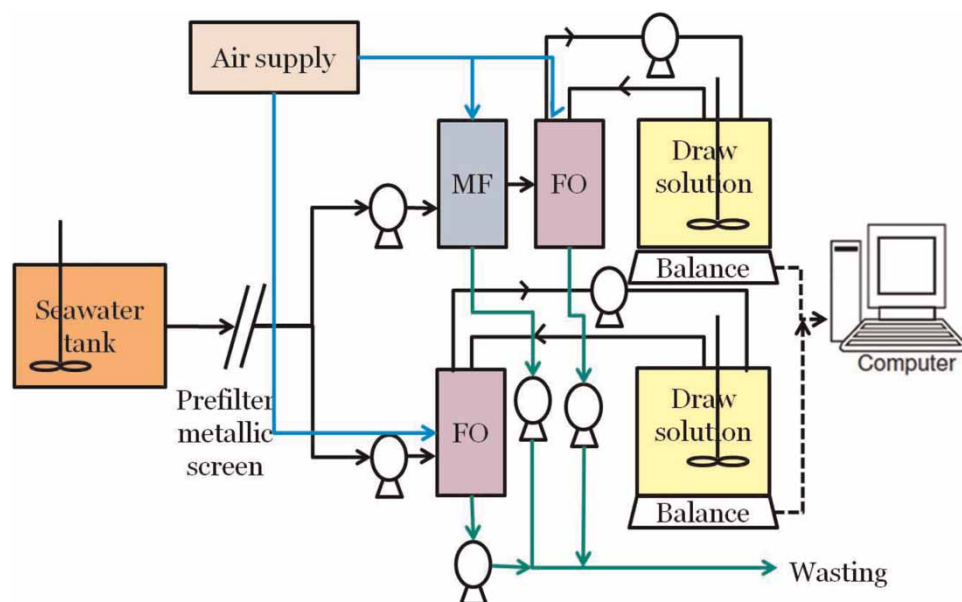
Figure 1 | Submerged membrane reactor set-up.

membrane, without the formation of cracks upon direct drying.

RESULTS AND DISCUSSION

Over 70 days of the experiment run, no cleaning of the membrane was required, since the FO water flux decline was negligible over the entire period of the experiment. The water flux was maintained at around $1.4 \text{ L m}^{-2}\text{h}^{-1}$.

Effects of MF pretreatment

In theory, MF pretreatment should impact the membrane fouling tendency since it can remove fine particles larger than 0.1 μm, thereby reducing the fouling tendency of the feed water. The MF pretreatment thus aids in the removal of suspended particulate matter to alleviate fouling and ageing, and reducing the frequency of intermittent cleaning for the downstream membrane process – FO process in this study. SDI and turbidity are indicators for the quality and efficiency of pretreatment of a feed water sample. Generally, SDI less than 3 is preferable for RO influent (Greenlee *et al.* 2009), while feedwaters with SDI greater than 4 need a suitable pretreatment. Similarly, turbidity values less than

0.2 NTU are mostly beneficial as RO influent. It is to be noted that these parameters are mere indicators of a typical feedwater's fouling potential and may not be singled out as the only cause of fouling. In this study, results on turbidity and SDI showed reduction in each parameter to a considerable extent. The SDI_{15} of raw seawater and MF-pretreated seawater were 4.2 and 3, respectively. The raw seawater turbidity was about 1–2 NTU, while that after MF treatment was about 0.5 NTU. Figure 2 shows the photographic images of SDI filter strips tested for raw seawater and MF-pretreated seawater. Thus, MF pretreatment did help in reducing the turbidity and SDI of the feed seawater significantly.

Seawater fouling of FO membrane

As reported in the literature, RO membranes are highly vulnerable to biofouling. In addition, the compact cake layer so formed is difficult to remove unless chemical cleaning is initiated. However, in the case of FO membrane, the degree of cake formation would be less compact since no hydraulic energy is used to force the feed seawater across the membrane (Mi & Elimelech 2010). The draw solution on the other side of the membrane 'sucks' water from the feed side across the FO membrane, thus imparting less
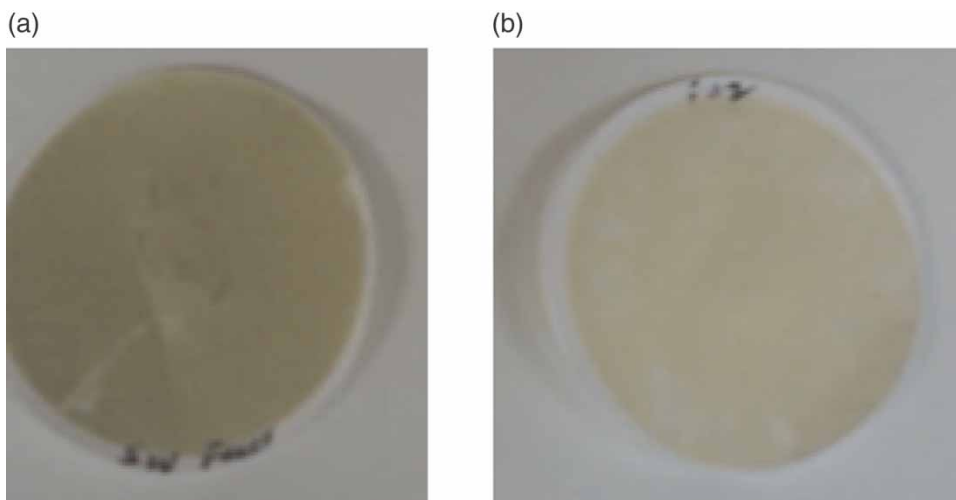
Figure 2 │ SDI$_{15}$ filter strips after testing for (a) feed seawater, (b) MF-pretreated seawater.

pressure on the foulants on the feed side and making the foulant layer less compact and easily removable. The water flux decline and normalized flux profile of the membrane was also monitored in this study (Figure 3). It is observed that the flux decline was not significant for both with and without MF pretreatment. This could be due to the hydrophilic CTA make of the membrane that prevented excessive fouling on the membrane surface, thereby causing significant flux decline. In addition, due to operation of the membrane in the FO mode, the dense layer facing the feed seawater solution side avoided fouling effectively.

Furthermore, the experimental flux obtained was lower than the critical flux above which fouling occurred. However, a slightly higher flux was observed for the FO membrane subjected to MF-pretreated seawater. Hence, the seawater with MF pretreatment helped to improve the FO water flux, but the effects were not very significant in this study due to very low experimental water fluxes obtained.

After the completion of 70 days of continuous operation, the FO membrane surface was analysed using SEM with energy dispersive X-ray spectroscopy (EDX) to identify the
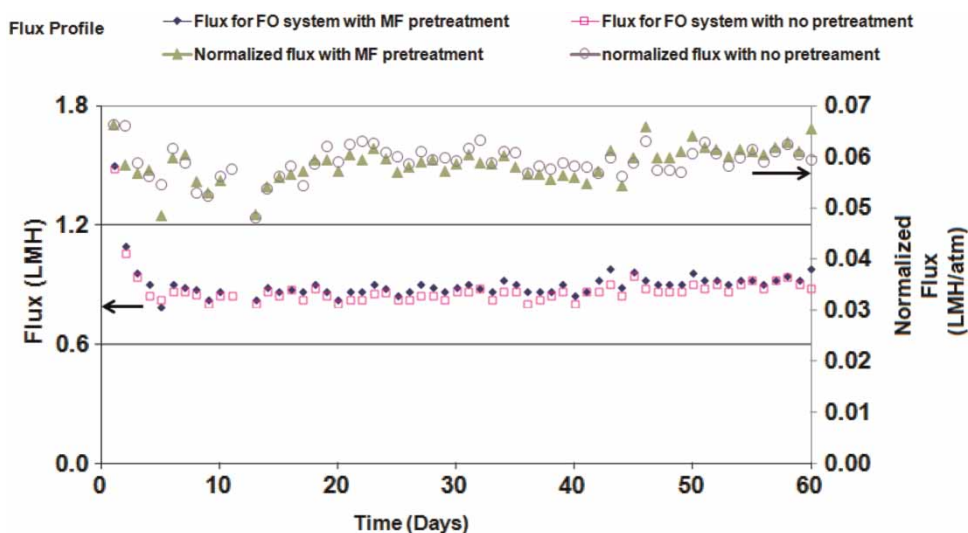

Figure 3 │ Effect of MF pretreatment on flux and normalized flux.

elemental group composition. The FO membrane subjected to direct raw seawater showed signs of scaling deposits on its surface. Figures 4(a)–4(c) show the SEM images of the FO membranes treating MF-pretreated seawater and raw seawater, respectively. At 200× magnification, scaling over the FO membrane surface was much greater for the FO membrane subjected to non-pretreated seawater. This scaling on the FO membrane surface subjected to non-pretreated seawater could be due to the precipitation of calcium sulphate or calcium carbonate crystals. EDX analysis of the scaled membrane surface (Table 1) confirmed the presence of calcium. The reason for the excessive scaling observed on the FO membrane surface that was subjected to non-pretreated seawater could be due to the excessive organic fouling during the initial stages that further led to inorganic fouling (i.e., scaling) similar to the 'cake enhanced concentration polarization' effect (Hoek & Elimelech 2003). However, for the FO membrane pretreated with MF, the extent of organic fouling was low, preventing further scaling

on its surface. It is to be noted that although there were signs of scaling on the FO membrane surface for the FO membrane subjected to non-pretreated seawater, it was not significant enough to reduce the membrane water flux. Figure 4(d) shows the photographic image of the FO membrane subjected to non-pretreated seawater. The extent of fouling on the membrane was not severe.

Boron rejection

Seawater contains boron with a concentration as high as 5 ppm. When seawater is desalinated by the membrane process, leakage of boron can be significant. For natural seawater of pH 8, boron rejection by the FO membrane is low, around 60–70%. Since boron in potable water (i.e., drinking water) is fatal to the human body, it is a serious challenge to prevent boron leakage into the permeate side. In the RO process, raising pH in the second pass is one of the viable options to reduce boron leakage. Boron specific
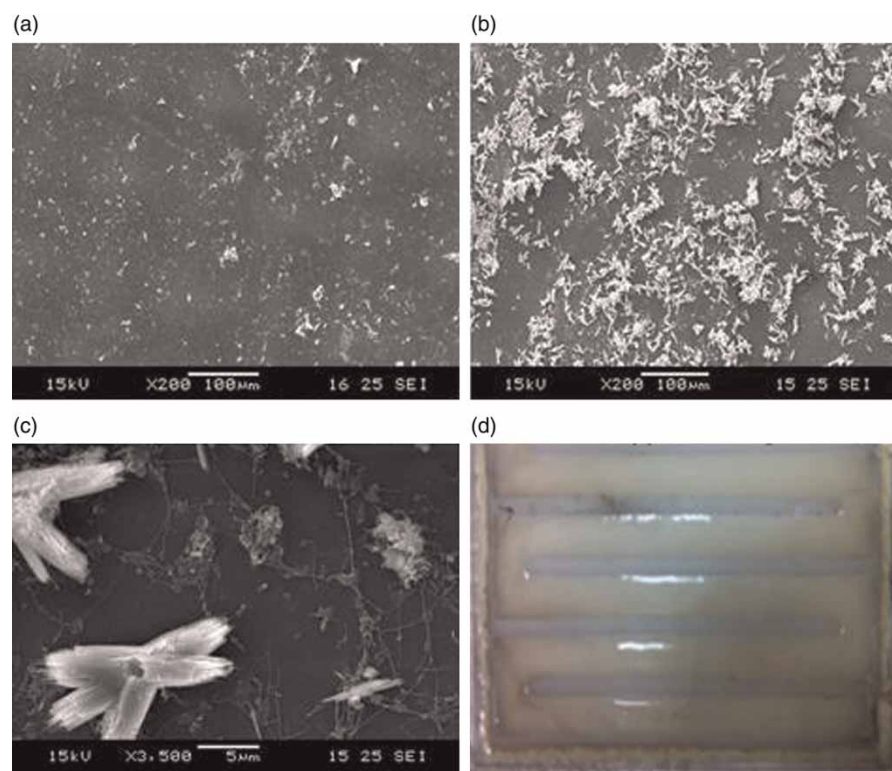

Figure 4 │ SEM images of (a) FO membrane treating MF-pretreated seawater – less fouling; FO membrane treating seawater with no pretreatment – excessive scaling 200× (b) and 3,500× (c); and (d) photographic image of FO membrane treating seawater with no pretreatment.

Table 1 │ EDX analysis for scaling on FO membrane surface subjected to non-pretreated seawater

Elements	wt%
C	7.40
N	Negligible
O	76.51
Na	0.22
Mg	0.10
Al	0.30
P	0.24
S	0.23
K	0.07
Ca	**14.46**
Fe	0.61

ion exchange resins have also been used. The FO membrane could not reject all the boron effectively, with an overall boron rejection of 60%. Figure 5 shows the concentration of boron in the FO reactors and draw solution tanks. It was observed that the concentration of boron kept increasing over the experimental run, owing to its accumulation in the draw tank. Comparing the boron concentrations in draw solutions, it was observed that the boron leakage was slightly greater when non-pretreated seawater was used, unlike the case when MF-pretreated seawater was used in the FO reactor. Thus with MF pretreatment, a better boron

rejection was obtained (Figure 5(b)). This could be attributed to the fact that fouling could reduce boron rejection by hindering back-diffusion of boron into the bulk feedwater, resulting in rising boron concentration near the FO membrane surface, thus enhancing the boron passage into the draw solution (Huertas et al. 2008). As a result, boron concentration in the draw solutions for the FO system with non-pretreated seawater was slightly higher. It is also to be noted that a decreasing trend in the FO membrane boron rejection is due to the accumulation of boron in the draw tank. Nevertheless, it is concluded that MF pretreatment of seawater could enhance boron rejection of the FO membrane.

Salt rejection

The overall FO membrane rejection for chloride was constant at about 97% at the end of the experimental run (Figure 6).

CONCLUSION

The FO process, in conjunction with a post-treatment process, could be potentially utilized for seawater desalination, provided that the issue of boron rejection could be tackled effectively. As far as fouling is concerned,
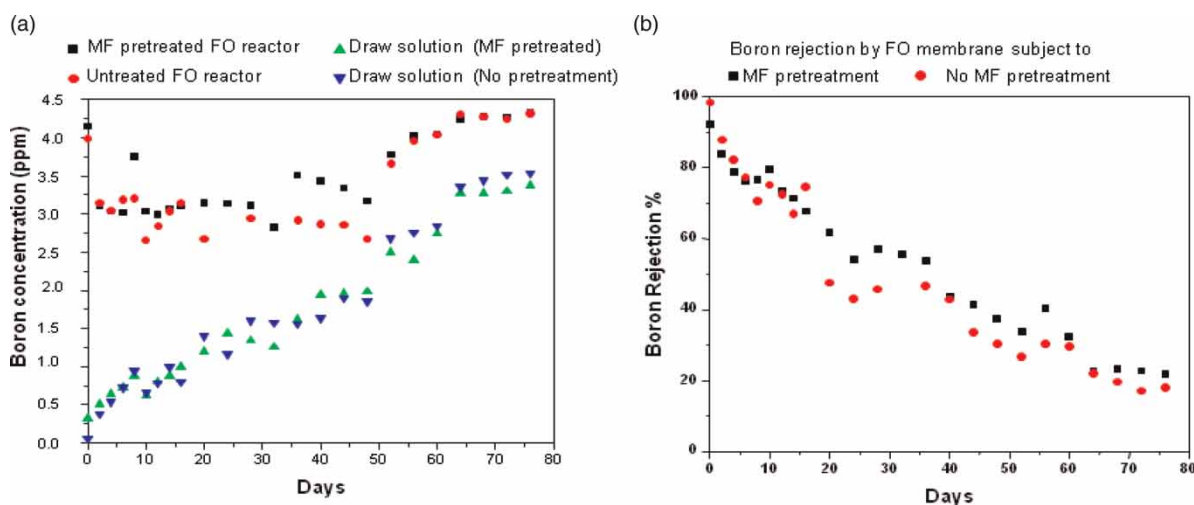
Figure 5 │ Boron (a) concentration profile and (b) rejection percentage by FO membrane subject to MF-pretreated seawater and seawater with no pretreatment over the experimental run of 70 days.
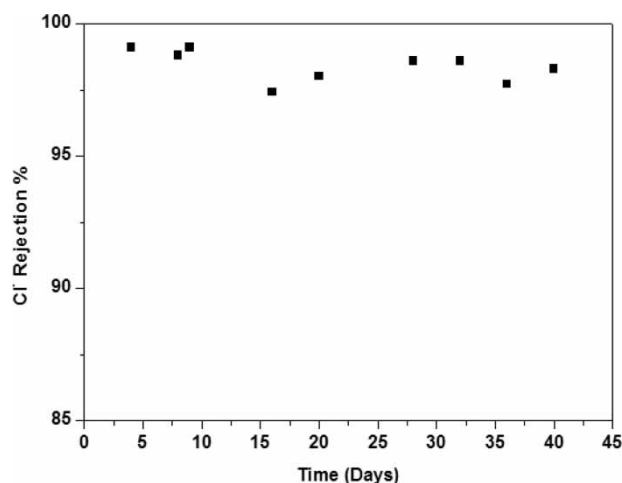
Figure 6 | FO membrane chloride (Cl^-) rejection profile.

the FO process has an added advantage since minimal deposition of foulants occurred. MF pretreatment of seawater reduced the FO membrane water flux decline slightly compared to non-pretreated seawater. The normalized flux decline profile affirmed that the FO membrane was able to withstand fouling to a significant extent. The low flux conditions and the CTA FO membrane's inherent hydrophilic nature had led to minimal fouling or scaling on the membrane surface. The overall boron rejection by the FO membrane was about 60–70%. In order to produce potable water within boron regulation, post-treatment of the diluted draw solution is necessary.

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