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Evaluation of forward osmosis backwash in a pilot-scale seawater reverse osmosis (SWRO) desalination system

MinJin Kim[a], JunYoung Park[b], KiTae Park[a], PooReum Kim[a], HyungSoo Kim[a], JiHoon Kim[a,*]

[a]*Graduate School of Water Resources, Sungkyunkwan University, Suwon, Korea, Tel. +82-31-290-7647; Fax: +82-31-290-7549; email: jjtt23@skku.edu (J.H. Kim)*
[b]*Environmental Technology Development Team, Hyundai Steel, 1480 Bukbusaneop-ro, Songak-Eup, Dangjin, Chungnam, Korea*

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ABSTRACT

Forward osmosis backwash (FOB) can actively control membrane fouling through the effect of physical cleaning that is generated by the diffusion resulting from the osmotic pressure difference between the influent and the treated water in the reverse osmosis process. Thus, to determine the operating characteristics of seawater reverse osmosis (SWRO) processes when applying the FOB using the real seawater, 110 m^3/d SWRO pilot plant was operated in 2 different conditions. Firstly, it was operated as a control group with conventional methods, and secondly, as an experimental group application of FOB for comparison. Cleaning in place was performed twice for the control group during the same operation period. For the experimental group, the long-term operation was performed with a pressure increase rate of less than 10%. Also, both SWRO pilot plants in the control and experimental groups were operated at the same operating pressure in the early phase, but the overall difference in operating pressure reached approximately 5 bar with time. Based on this result, it is considered that energy consumption in the experimental SWRO pilot plant was reduced compared to the control group.

Keywords: Desalination; Forward osmotic backwash (FOB); Seawater reverse osmosis (SWRO); Fouling control; Maintenance cleaning.

1. Introduction

For the last decade, the amount of available water resources has been decreasing due to environmental issues such as population growth and global warming. This led to a rapidly growing interest in developing alternative water resources. In particular, seawater desalination technologies have been receiving the most attention as a method to produce potable water from almost infinitely available resources [1]. Among different desalination technologies, seawater desalination technologies using seawater reverse osmosis (SWRO) have achieved faster technological growth than other technologies. This is because SWRO is easily operated with relatively lower production cost compared to the existing evaporation methods [2]. However, membrane fouling is inevitable in seawater desalination methods using reverse osmosis (RO) membranes [3–5]. Organic matter, inorganic matter, and microorganisms in seawater cause fouling, which can be accelerated by the high operating pressure. Fouling can cause problems such as increased operating costs and poor quality of produced water [6].

Membrane fouling in SWRO processes is indirectly expected by water quality treated in pretreatment processes or monitored only by differential pressure in RO processes

* Corresponding author.

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and quality of produced water. Cleaning cycles are determined by the results. Currently, cleaning in place (CIP) is the most commonly used method of cleaning to control the fouling in the RO process [7]. However, CIP requires to periodically stop the operation, which could cause life-shortening and environmental problems due to excessive use of chemicals [8].

Thus, forward osmosis backwash (FOB) has been continuously studied as an alternative method that is environmentally-friendly, and capable of delaying the development of fouling in RO processes [9–11]. FOB is performed when the operating pressure becomes lower than the osmotic pressure ($\Delta\pi$) of the feed. FOB can remove fouling by sheer force of circular flow because foulants swell up on the membrane surface or become isolated when permeate water is diffused to the concentration polarization layer through RO membranes [11–14]. Periodic FOB can delay not only irreversible fouling but also inorganic fouling by controlling the reversible fouling of RO membranes [15,16]. However, in order to effectively apply FOB, it is necessary to consider the effects of operational factors such as pressure, shear velocity, feed water properties, and concentration [17–19].

Moreover, FOB can have effects on the recovery rate with the use of produced water, and issues on the commercialization potential have been raised because FOB has rarely been used in SWRO plants. Therefore, there is a need for a pilot-scale demonstration to establish optimal FOB conditions. In this study, 110 m^3/d SWRO pilot plant was operated as a control group with general operating conditions and as an experimental group with the application of FOB to investigate the operating characteristics of SWRO processes with FOB. This study also examined the effects of FOB by changing various conditions such as the salt concentration of influent feed water, cleaning period, frequency of FOB cycle, and pretreatment processes to effectively apply FOB.

2. Materials and methods

2.1. Principle of forward osmosis backwash

As shown in Fig. 1, if the high pressure in the feed side is removed, the RO permeate with low concentration will move towards the feed side with higher concentration due to the osmotic pressure gradient. The foulants on the RO membrane is compressed by high pressure, but it can be easily removed using the permeate moving back towards the feed side. The basic principle of this phenomenon is the main principle of forward osmosis process. Therefore, the concept of backwashing the membrane using the osmotic pressure difference can be called FOB in the SWRO process. During FOB, the foulants that are compressed on the RO membrane surface, due to the driving force of the RO, swell up. Previously, Qin et al. [9,14] have confirmed that during the FOB process, there would be a strong driving force to lift and sweep the foulants from the membrane surface. In this case, reversible fouling can be controlled, in a similar way that reversible fouling is controlled in low-pressure membrane microfiltration/ultrafiltration (MF/UF) processes through physical cleaning, and periodical application of FOB can slow down the generation of irreversible fouling.

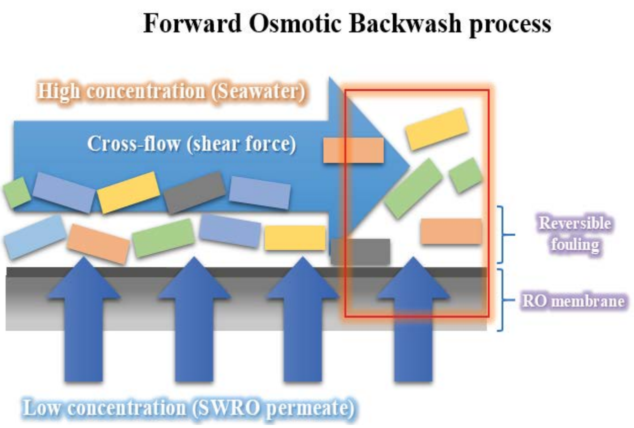


Fig. 1. Schematic of forwarding osmosis backwash process.

2.2. Description of the pilot plant

Fig. 2 shows the schematic diagram of the SWRO pilot plants used in this experiment. Two pilot plants with a capacity of 110 m^3/d were built to analyze and compare the data with and without the application of FOB. They both used first-pass RO, and operating programs were set to control and maintain the constant cross-flow rate. An energy recovery device (ERD) was installed to improve the efficiency of high-pressure pumps. Furthermore, a feed tank, permeate tank, inlet pump, high-pressure pump, digital pressure gauge, and flowmeter were added to automate the FOB. The plant was operated continuously, and the FOB and data logging were automatically operated through human machine interface program. The high-pressure pump, pipes, and accessories were made of Duplex to prevent corrosion from high-salinity feed water. The facilities also included a CIP process.

During the FOB process, the pressure in the vessel was reduced by controlling the Hz and the decompression valve without stopping the operation of high-pressure pumps and booster pumps. The FOB operating program was made so that it was possible to control the flux and flow rate of influent feedwater with the desired range by controlling the Hz of the feed water pump's when pressure decreases. Moreover, pretreated seawater was flown to the feed side in the RO vessel as a draw solution for FOB. The produced water was stored in a separate FOB tank during the SWRO filtration process and is designed to flow through the pipe of permeate during the FOB process.

2.3. SWRO membrane

An 8-inch spiral wound polyamide membrane was used in this experiment as an SWRO membrane with allowable pressure of up to 8.2 MPa and 99.8% of salt removal efficiency. The total effective membrane area was 287 m^2, and the pilot plant test was performed by installing seven elements to one vessel. In this experiment, two types of SWRO membranes manufactured by different companies were selected for the pilot plant test to determine the effects on the SWRO membranes. Table 1 shows the specifications for the RO membranes used in this experiment.

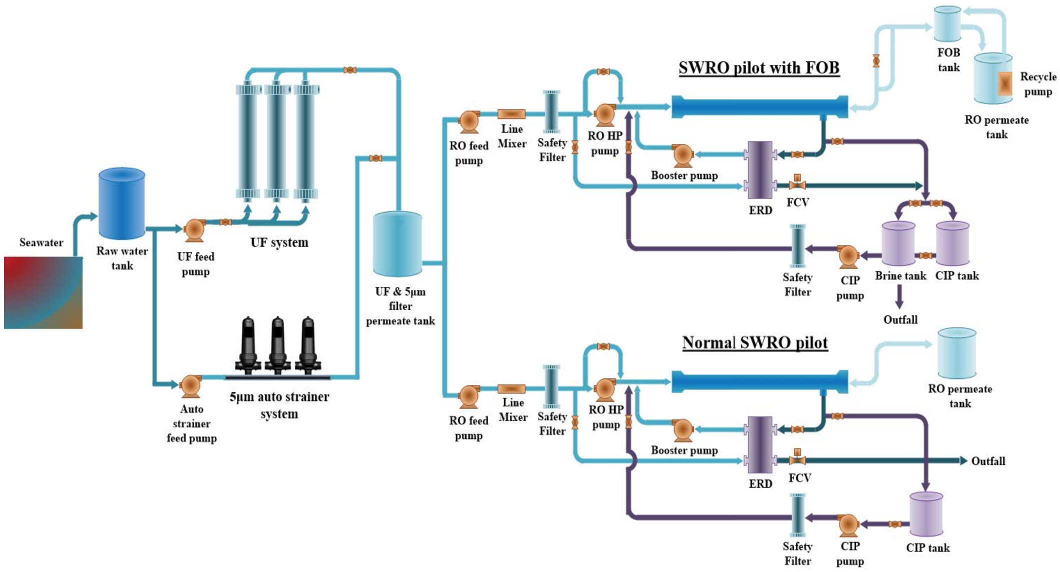


Fig. 2. Schematic of the SWRO pilot plant for seawater desalination.

Table 1
Characteristics of SWRO membrane

Maker	Model	Effective membrane area (m^2)	Permeate flow rate (m^3/d)	Stabilized salt rejection (%)	Maximum applied pressure (MPa)	Membrane material
DOW	SW30HRLE-440i	41	30.2	99.8	8.3	Polyamide
LG	SW 440 GR	41	31.2	99.85	8.27	Polyamide

2.4. Seawater sources

The thermally discharged seawater from Gwangyang Steelworks, which was originally used as the cooling water within the plant, was used as the feed water. Gwangyang Steelworks is located in Gwangyang city of South Korea. When thermally discharged seawater is used as the feed, there could be many restrictions on the operation conditions (i.e. use of coolants, pre-chlorination, etc). The quality of seawater (aquaculture) and salinity may also vary for the thermally discharged seawater which could greatly affect the operation and efficiency of the RO process. In particular, the feedwater used in this study was taken using the surface intake method, and the temperature of the feed greatly varied depending on the operation of the power plant. The characteristics of the feed water can be found in Table 2.

Table 2
Qualities of seawater

pH	7.9–8.2
TOC (mg/L)	1.5–2.0
TDS (mg/L)	32,000–33,000
Turbidity (NTU)	4–10
UV_{254} (cm^{-1})	0.07–0.09
SS (mg/L)	5.0–10.0
Temperature (°C)	24–32

2.5. Experimental operation of SWRO pilot plants

In this experiment, comparative tests were performed by operating two 110 m^3/d SWRO pilot plants. The first one was a control group to be compared with the existing SWRO operating conditions and the second one was an experimental group with FOB technologies applied. To more accurately determine the operational factors and conduct reliable comparative analyses, the same operating conditions were used except the FOB process. The operating conditions of the SWRO pilot plants were calculated with consideration of the inflow rate, the application range of the flow rate of concentrated water, the maximum allowable pressure in RO membrane vessel, and operating manuals provided by manufacturers. Moreover, the SWRO pilot plants were operated at an operative recovery rate of 45% and 50% by controlling the constant flow rate with the cross-flow method. This study aimed to derive the optimal conditions by measuring changes in the mixing rate of ERD and treated water quality capable of affecting operational data, and comparatively analyzing them. Table 3 shows the operating conditions of the SWRO pilot plants set in this experiment.

2.5. Analytical methods

For analysis of water quality, this study analyzed the temperature, electrical conductivity, pH, turbidity, and silt density index (SDI) for each unit process using a portable measuring device on-site; and analyses other than the

Table 3
Operating conditions of SWRO pilot plant

	Parameters	Values
Typical common operating conditions	RO capacity water (m^3/d)	110
	Recovery rate (%)	50
	Flux (LMH)	15.8
	RO feed pressure (bar)	55–63
FOB operating conditions	Draw solution	Sea water or brine
	RO feed pressure (bar)	1–2
	RO feed flow (m^3/h)	4–5
	FOB operating time (min)	5, 10, 15

aforementioned categories were done by the analysis agency. Also, water quality analysis was cross-checked by not only performing on-site analysis but also checking online measuring device items installed in the SWRO pilot plants. Organic matter causing membrane fouling in desalination processes was analyzed using total organic carbon (TOC-V CPH, SHIMADZU, Japan) and UV/VIS spectrophotometer (DR 6000, Hach, USA) at Sungkyunkwan University located in Suwon city of South Korea.

3. Results and discussion

3.1. Effects of FOB by pretreatments

Prior to the full-scale experiments on the SWRO pilot plants, lab-scale SWRO test units were constructed to examine the effects of FOB according to the pore size of pretreatment in RO processes. A vessel with one spiral wound SWRO element having an effective membrane area of 1.1 m^2 was used in the 2.5-inch lab-scale SWRO test unit. In order to get data similar to the real pilot plants, the lab-scale SWRO pilot plants were built so that it was possible to continuously provide inlet feed water. According to general SDI_{15} value presented by membrane manufacturers, inlet feed water does not cause serious fouling when SDI_{15} value is less than 3 and it causes severe fouling when SDI_{15} value is more than 5. Moreover, water pathways can be clogged, which can result in damage for the module, when silty materials flow into a standardized spiral wound RO membrane modules, because of the narrow pathway on the inlet side.

Thus, pretreatment was performed using 1 and 5 μm filters to consider only the effects of silty materials, and SDI_{15} values for each treated water were measured. However, as shown in Table 4, the pretreated water using 1 and 5 μm filters showed SDI value (SDI_{15} > 5) that is not suitable for a draw solution for SWRO processes. Therefore, in this study, the possibility to control membrane fouling by FOB was evaluated with the application of inappropriate feed water (SDI_{15} > 5) as a draw solution for SWRO processes.

In this experiment, seawater was pretreated using 1 and 5 μm cartridge filters and then used as inlet feed water. The constant-pressure operation was performed using a cross-flow method at a pressure of 40 bar. In general, CIP is performed when the normalized permeate flux decreases by 10%–15%, and it is commonly considered that irreversible fouling is formed. Thus, it can be assumed that irreversible fouling is formed when a flux decline rate (FDR) reaches 15% in the lab-scale SWRO experiment. This study examined the efficiency of FOB according to the pore size of cartridge filters by performing FOB when FDR of permeate flux decreases by approximately 12% before the CIP timing expected to be able to perform physical backwashing.

Table 4
Comparison of SDI values according to the nominal pore size of prefilter

Parameters	Pretreated by 5 μm filter	Pretreated by 1 μm filter
SDI5	18.44	17.93
SDI_{10}	SDI value of seawater was not measurable	
SDI_{15}		

Fig. 3 shows that the pretreatment with a 5 μm cartridge is more effective than that with a 1 μm cartridge. This results from the loosening of the compaction between the large particles and the foulants on the membrane surface when applying a 5 μm cartridge filter. Therefore, it is considered that long-term operation is possible if FOB is done continuously within the range of reversible fouling, even if the suspended matter gets into the draw solution for SWRO processes.

3.1.1. Results of operation of SWRO pilot plants with application of water treated by 5 μm auto disk filter

The experiment on SWRO pilot plants was performed by dividing them into the experimental and control groups, and inlet feed water was used as an RO draw solution after being treated by a 5 μm auto disk filter. It was impossible to measure the SDI_{15} value of water treated by a 5 μm auto disk filter, and this suggests that it is inappropriate to be used as a draw solution for SWRO processes. However, as seen earlier, because the effects of FOB increased when 5 μm filter was used for pretreatment in the pilot-scale SWRO experiment was still performed to evaluate the possibility of membrane fouling control with FOB.

Fig. 4 shows the FOB efficiency with the application of water treated by a 5 μm auto disk filter in the SWRO pilot plants. FOB was performed for 15 min once a day according to the above-mentioned method without stopping the device. With regard to the results from the control group, the operating pressure reached 70 bar when performing the continuous operation for approximately 100 h (for about 4 d). Although the continuous operation was performed again after flushing for about 2 h, the operating pressure reached 70 bar in less than 24 h. It is considered that these results were caused not by membrane fouling but by the inflow of silty materials such as mud. Unlike the feed water raw feed water, it was difficult to remove it with a 5 μm auto disk filter attached to the SWRO pilot plants because particulate matter such as mud increased. When a large amount of mud (more than 30 mg/L suspended solids) flows in, large-sized particulates could flow in because the plate between the disks got wider. On the other hand, it was possible to operate the SWRO pilot plant in the experimental group for a long time by performing FOB once a day even though particulate matter flows in, and this can be seen in Fig. 4.

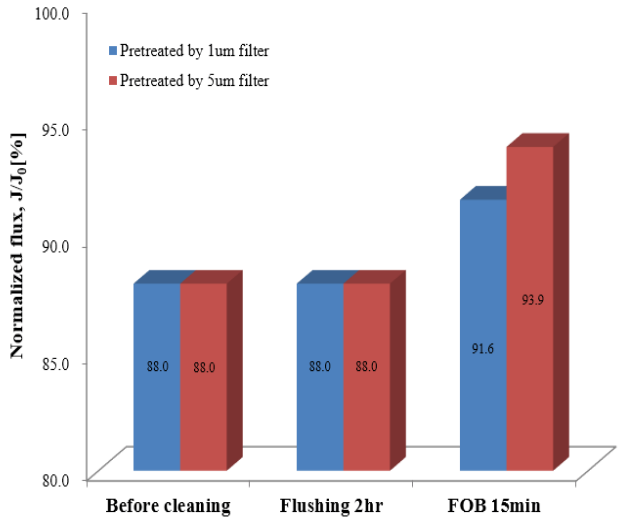


Fig. 3. Comparison of FOB efficiency according to the pore size of pretreatments.

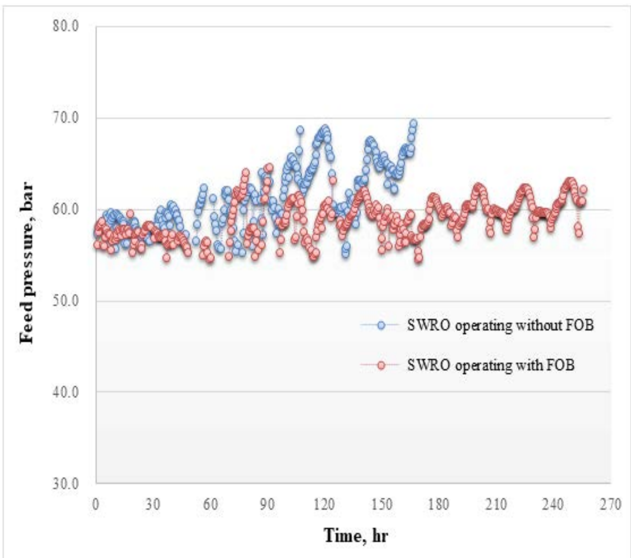


Fig. 4. Changes in operating pressure of SWRO pilot plants with water pretreated by 5 μm auto disk filter: Frequency of FOB - 15 min/d.

Fig. 5 shows the changes in the flow rate of RO permeate flux and the turbidity of RO draw solution with time when FOB is applied. The RO permeate flux showed the highest flow rate at the start of FOB and then dramatically decreased. Subsequently, it showed a tendency to slowly reduce the flow rate until the water completely ran out. Sagiv and Semiat [16] reported that these phenomena were caused by dilution of concentration polarization layers. Also, the turbidity of the RO draw solution was the highest when the flow rate was the highest. Thus, it is considered that the largest effect will appear within a few tens of seconds after the start of FOB. In order to obtain more reliable operational data, the SWRO

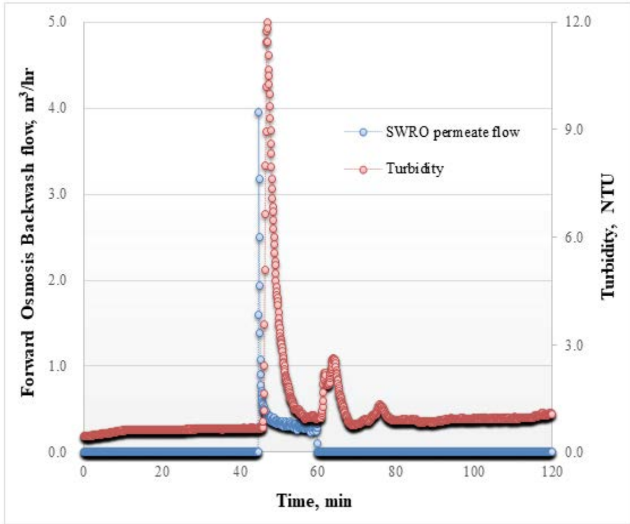


Fig. 5. Changes in the flow rate of SWRO permeate flux and turbidity of draw solution with time.

pilot plants were operated to apply FOB technologies using UF pretreated water as the feed water.

3.1.2. UF results of operation of SWRO pilot plants with application of UF treated water

This experiment was performed in the same manner as the previously performed experiment, and UF treated water was applied as RO draw solution. Before the full-scale experiments on the SWRO pilot plants, experimental errors were minimized by checking the automatic operation values of the SWRO pilot plants and calibrating the measuring equipment. Continuous operation with the cross-flow method was conducted until FDR of permeate flux reached 10% or until the pressure was increased by approximately 15% compared to the initial operating pressure. Also, the RO operating mode was set so that the recovery rate would reach approximately 50% while maintaining a certain flow rate. This study examined changes in values of early operating pressure, electrical conductivity of permeate flux, and permeate flux quality based on the long-term operation of the SWRO pilot plants. For the SWRO pilot plant in the experimental group, FOB was performed for 15 min once a week according to the above-mentioned method without stopping the operation.

Fig. 6 shows changes in the operating pressure of the SWRO pilot plants in the experimental and control groups. CIP was performed twice for the SWRO pilot plant in the control group during the operating period of approximately 70 d. As previously mentioned, CIP was carried out when FDR of normalized permeate flow reached approximately 10% or normalized pressure increased approximately 15% compared to the initial operating conditions. For the SWRO pilot plant in the control group, normalized pressure increased approximately 15% after 35–40 d.

On the other hand, regarding the SWRO pilot plant in the experimental group, the long-term operation was performed with maximum pressure increase rate of 10% for

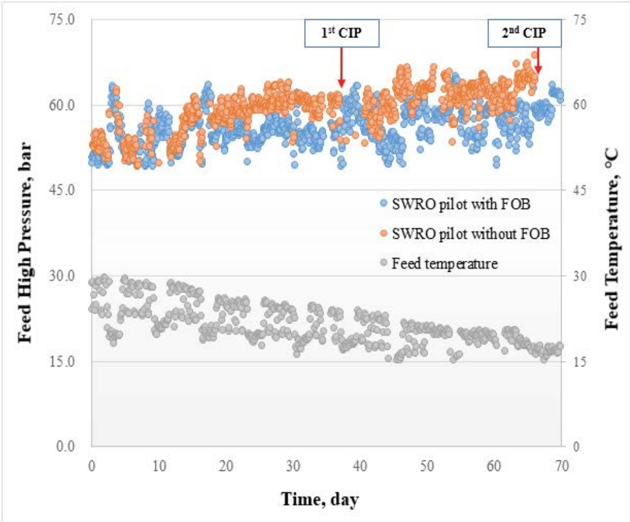


Fig. 6. Changes in operating pressure and temperature of SWRO pilot plants: SWRO feed water - UF pretreated water; Frequency of FOB - 15 min/week.

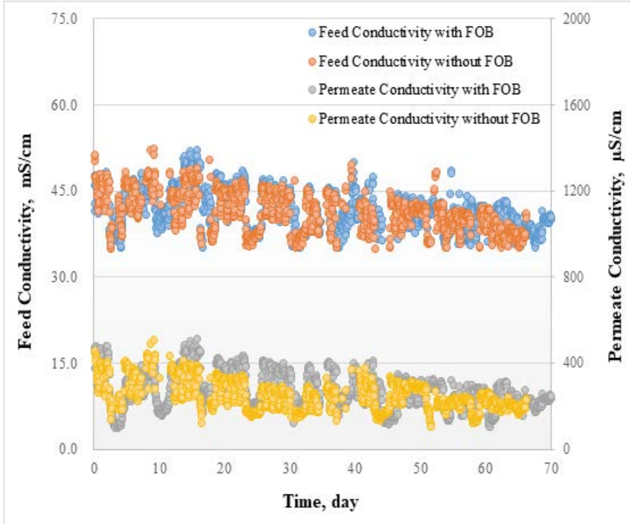


Fig. 7. Changes in conductivity of SWRO feed water and permeate with time.

about 70 d. Furthermore, although the both SWRO pilot plants were performed at the same operating pressure in the early stage, over time it showed an operating pressure difference of about 5 bar. Thus, it is can be said that the energy consumption of the SWRO pilot plant in the experimental group decrease compared to that in the control group. These results were obtained under of the same operating conditions such as quality of feed water and RO membrane specifications where the only difference was the application of FOB. Therefore, it can be seen that the resulting differences are due to the application of FOB.

This study also examined the changes in operating pressure with changes in temperature of the SWRO pilot plants because thermal discharge used as feed water showed rapid changes in temperature with or without operating power stations. Fig. 6 shows that operating pressure gradually increases with decreasing temperature of the draw solution. It is considered that the decrease in temperature of draw solution partly contributed to the reaching of the maximum operating pressure for the SWRO pilot plant in the control group. Although operating pressure increased with decreasing water temperature in the experimental group as well, it is thought that the results are caused by FOB because operations were performed with maximum pressure increase rate of 10%.

Fig. 7 shows the changes in the electrical conductivity of draw solution and permeate flux of the SWRO pilot plants. As shown in the graph, the electrical conductivity of draw solution for the SWRO pilot plants in the experimental and control groups had the same range, and their values decreased with decreasing temperature. The electrical conductivity of permeate flux was less than 500 µS/cm and met the standards for quality of drinking water at the early stage of both processes. Subsequently, electrical conductivity values showed a tendency to decrease with decreasing feed water concentration, which decreased with water temperature and with passage of time.

In general, although CIP is supposed to be performed when salt flux increases by 15%, CIP was conducted twice for the SWRO pilot plant because pressure increased by approximately 15% in the SWRO pilot plant in the control group. The salinity did not change much during the period, and it is considered that it showed rapid changes in temperature because it was more affected by temperature changes while operating at higher flux and higher recovery rate than the existing SWRO processes.

Fig. 8 shows the changes in the turbidity of feed water and the flow rate of SWRO permeates with time when applying the FOB mode. According to the graph, operating pressure gradually decreased with the start of FOB, and the decrease in pressure was delayed for a certain period at around 30 bar. This is to prevent water flow by osmotic pressure from gradually moving from the side of permeate flux to the side of feed water in advance and to maximize the efficiency of FOB by discharging instantaneous pressure in a certain pressure section (at the level of seawater osmotic pressure). Subsequently, the flow rate of SWRO permeate showed the highest flow rate at the start of the FOB and then dramatically decreased. Also, it showed a tendency to slowly reduce the flow rate until the end of FOB process. Thus, it is considered that the largest effect of FOB will appear within a few tens of seconds after the start of FOB because the turbidity of RO feed water showed the highest value in the section with the highest flow rate.

However, there is a need to increase reliability in this cleaning technology by obtaining data on the cleaning efficiency even in the section where the flow rate of SWRO permeates slowly reduces after the point when the flow rate of SWRO permeate rapidly decreases in FOB.

3.2. Effects of FOB with different conditions

3.2.1. Results of operation of SWRO pilot plants according to an operative recovery rate

This experiment was performed to examine the effects of FOB by monitoring changes in operating pressure when applying different operation recovery rates in both groups.

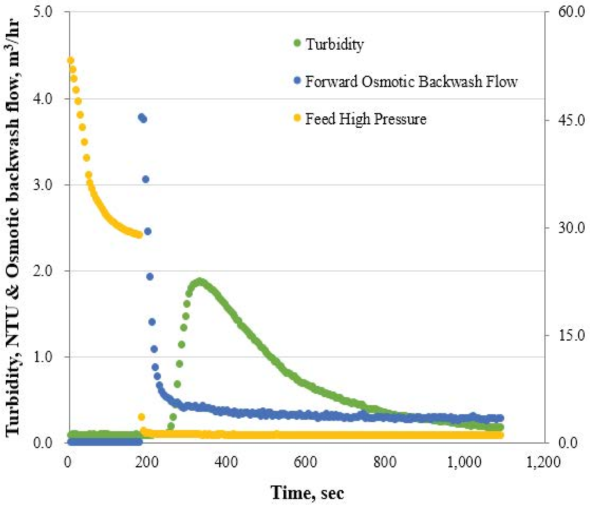


Fig. 8. Changes in turbidity, high pressure, and osmotic backwash flow with time in FOB.

This experiment was performed in the same manner as the previously performed experiment, and UF pretreated water was used as the feed water. Before the full-scale experiments, errors of experimental data were minimized by checking and controlling changes in flow rate and ERD mixing rate according to changes in the recovery rate both groups in advance. Also, the RO was set so that the recovery rate of the experimental group and control group would reach 50% and 45%, respectively, while maintaining a certain flow. This study examined the effects of FOB by monitoring changes in early operating pressure based on the long-term operation of the SWRO pilot plants. With regard to the SWRO pilot plant in the experimental group, FOB was performed for 15 min once a week according to the above-mentioned method without stopping the operating.

Fig. 9a shows the changes in the operating pressure of the SWRO pilot plants in the experimental and control groups. CIP has performed both groups due to the emergency shutdown during the operating period for approximately 60 d.

Based on the operation results of groups, long-term operations were performed with a maximum increase rate of 10% for the pressure. They were operated in the same pressure range even though they had different set recovery rates. It is because they are operated in the same pressure range since the operating recovery rates were calculated by fixing the amount of permeate in both groups while increasing the amount of inflow in the control group. It was confirmed that the recovery rate only has a slight effect when the amount of permeate is the same. For more accurate analysis, this experiment was performed using different recovery in both groups with a fixed amount of inflow.

Contrary to expectations, Fig. 9b shows that the SWRO pilot plants in both groups are operated stably at the same pressure range. It was expected that the lower recovery rate would result in lower operating pressure when inflow is fixed in both groups because the lower recovery rate would result in less amount of permeate. However, as seen from the graph, the cleaning efficiency of FOB had an effect when they were operated in the same pressure range. The difference in the operating pressure was approximately 5 bar with or without FOB in both groups under the same operative recovery rate (50%).

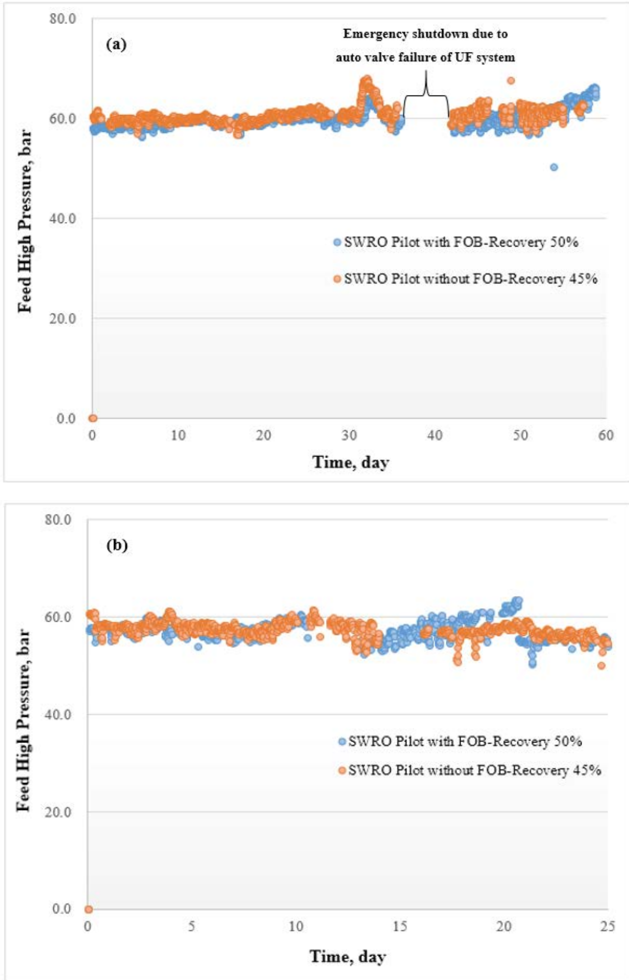


Fig. 9. Changes in operating pressure according to the operative recovery rate of SWRO pilot plants: (a) Calculation standard of recovery rate - fixed RO permeate flux and (b) calculation standard of recovery rate - fixed inflow amount of time.

As the results of this experiment, it is considered that the pressure range was stable compared to the control group since the previous experiment with fixed permeate water was carried out the periodic osmotic cleaning. Subsequently, when different operation recovery rates were applied by fixing the amount of inflow, it seemed that the SWRO pilot plant of the experimental group was stably operated in the same pressure range as the control group because the operating pressure was maintained by FOB as shown in the above graph.

However, the mixing rate of the ERD and changes in feed flow rate due to the change of the operation recovery rate may affect the operation pressure change, thus there is a need to secure long-term operational data for more accurate data analysis.

3.2.2. Evaluation of cleaning efficiency with application time in FOB processes

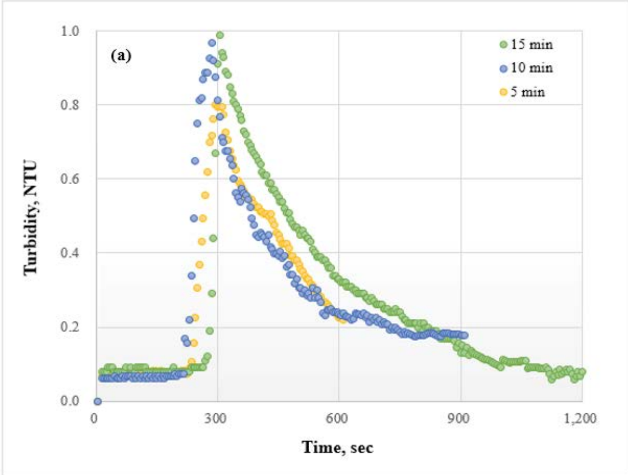
The experiment was performed by dividing the application time of FOB into 5, 10, and 15 min to examine the cleaning efficiency for a different application time of FOB in the SWRO pilot plant process. It was confirmed that long-term operations were possible with 15 min of FOB. Thus, to increase the overall recovery rate, the experiment was conducted by shortening the application time of FOB to less than 15 min. According to previous researches related to FOB, FOB is performed when the operating pressure becomes lower than the osmotic pressure ($\Delta\pi$) and the permeate can dilute salinity and clean fouled layers on the membrane surface.

Also, this kind of FOB is performed in two broad stages. In the first stage of FOB, the instantaneously high flow rate is found due to the high osmotic pressure. This stage finishes when salinity caused by concentration polarization becomes lower than that of bulk salinity. In the second stage, permeate water diffuses to the side of a provision in proportion to salinity on the side of the draw solution. In this stage, it is confirmed that the salinity on the side of the draw solution keeps decreasing and becomes slower than that in the first stage of FOB [14–16].

Based on the results of these papers, it is considered that the highest cleaning efficiency will be found in the first stage. However, it was suggested that different results would be obtained due to the effects of the actual hydrostatic pressure and mixing ratio of bulk layers. The cleaning efficiency in actual FOB is determined by total dissolved solids (TDS) concentration of draw solution, cleaning time, and cleaning cycle. There is a need to analyze the operating characteristics for each condition by preliminary experiments because these vary depending on the target feed water, process, operating characteristics. Therefore, this study examined the effects of FOB time on the cleaning efficiency of SWRO membranes by experiments on the efficiency with application time in the FOB mode.

The above graph shows the changes in turbidity of the SWRO draw solution and accumulated flow rate of backwash water according to the operation time when applying the FOB. As previously explained, the flow rate of SWRO permeates flux showed the highest flow rate at the start of the FOB, which then dramatically decreased. Subsequently, it showed a tendency to reduce the flow rate slowly until the water completely ran out. The same tendency was found in all the experiments performed previously, and the changes in the turbidity of the SWRO draw solution also showed the highest turbidity in the section with the highest flow rate.

Thus, it was considered that the cleaning was the most effective at the start of FOB. However, Fig. 10a shows that turbidity on the side of draw solution returns to the normal turbidity about 15 min after it increased up to approximately 1 NTU when applying the FOB mode. Thus, it is considered that the proper cleaning time of the FOB mode should be more than 15 min. Also, according to the graph in Fig. 10b, about 1.5 L/min element flow rate was required because approximately 150 L of permeate flowed in for the 15 min cleaning. Assuming that the weekly permeate usage is 150 L, the annual use (52 weeks) is calculated.



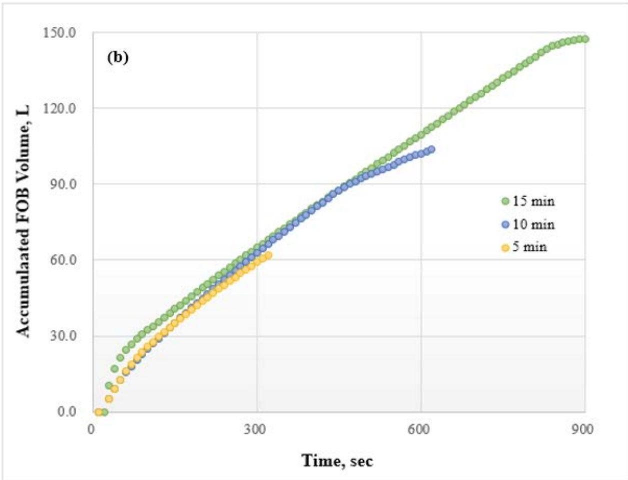


Fig. 10. Changes in turbidity of draw solution and accumulated FOB volume according to FOB time: (a) Variation of turbidity and (b) variation of accumulated FOB volume; draw solution = UF treated seawater; FOB operation time = 5, 10, 15 min.

As a result, approximately 7.8 m^3/year is required, and this effect can be obtained using about 0.02% of the total permeate flux (calculated based on 110 m^3/d: 40,150 m^3/year).

3.2.3. Evaluation of cleaning efficiency withdraw solution in FOB processes

It is expected that the cleaning efficiency of FOB will be increased with increasing osmotic pressure, where conductivity and concentration of TDS of the draw solution is the determining factor. Therefore, to determine the cleaning efficiency depending on the draw solution, FOB was conducted using the concentrate from the SWRO pilot plant as the draw solution. For the FOB experiment using the concentrate as the draw solution, the valve placed before the pump for the feed-in SWRO was used to collect the concentrate during the regular SWRO process and release it when the cleaning is done. Other conditions were identical to the FOB experiment using the UF pretreated water.

The above graph shows the changes in the accumulated flow rate of backwash water and turbidity of RO draw solution with time when concentrate as the draw solution (DS) was used in FOB. According to Fig. 11a, it showed a similar tendency to the FOB with the application of raw feed water as the DS. Turbidity increased up to approximately 1.5 NTU and rapidly decreased compared to FOB using the raw feed DS. It is thought that this is caused because a large number of membrane foulants were desorbed by a relatively large amount of backwash in the early cleaning stage. This graph also shows that turbidity returns to the same range as the early stage about 15 min after the application of FOB.

Thus, it is considered that the proper cleaning time of the FOB mode should be at least 15 min. According to Fig. 11b, the accumulated flow rate showed a similar tendency until a few tens of seconds after the start of the FOB and then gradually showed a difference. When accumulated backwash flow rate was compared between the raw feed DS and the concentrate DS, the accumulated backwash flow rate with concentrate DS required 3.6 L/min element (approximately 380 L for 15 min), which is twice as much compared to the raw feed DS. (150 L and 1.5 L/min element). Thus, it is considered that cleaning efficiency will also increase when concentrate DS is

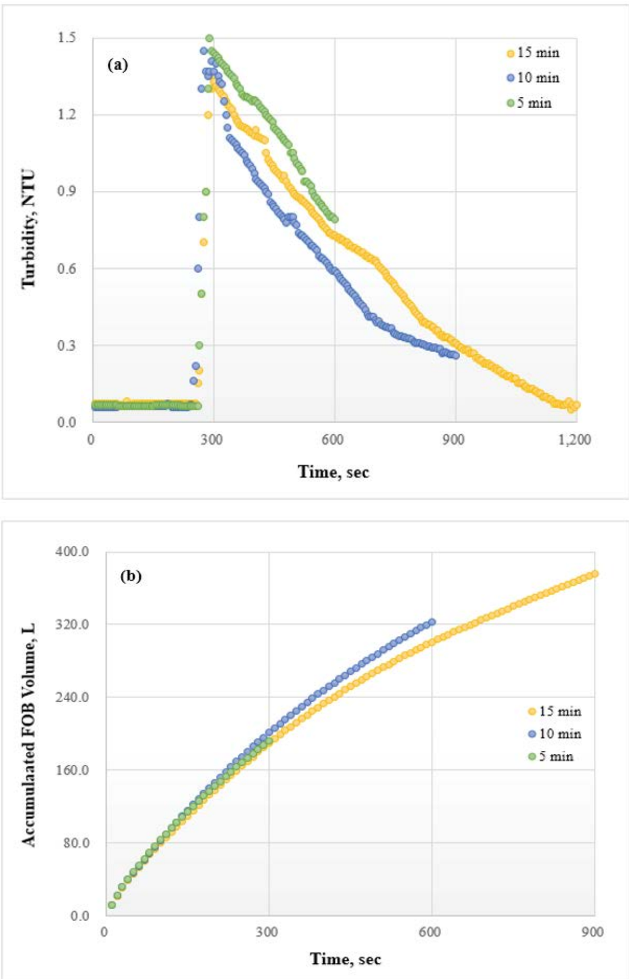


Fig. 11. Changes in turbidity of draw solution and accumulated FOB volume according to FOB time: (a) Variation of turbidity and (b) variation of accumulated FOB volume; draw solution = concentrated seawater; FOB operation time = 5, 10, 15 min.

used because of its high osmotic pressure resulting from high salinity of the concentrate DS in FOB.

However, there is a limitation in increasing the cleaning efficiency due to the existence of membrane fouling and limited cleaning capacity of FOB even with increasing inflow rate. Nevertheless, FOB using concentrate as DS can maintain a higher recovery rate because it does not use UF treated water, and it has the advantage of reducing the concentrated water by recycling it. Thus, it will be necessary to consider it when applying FOB processes in the future.

3.3. Evaluation of relative energy consumption

This study calculated electrical consumption using more than two kinds of energy estimation to examine the energy reduction efficiency with the application of FOB. Although electricity meters capable of measuring power consumption for each SWRO pilot were attached, it is considered that they are less reliable to be used for comparing actual measured values because they were produced to measure energy consumption not only by the SWRO pilots but also by peripheral equipment. Therefore, this study calculated relative electrical consumption according to differences in operating pressure for each SWRO pilot using electric consumption calculation simulation and theoretical calculations. The software of ERI and DORIS Energy Consumption Calculator were used to simulate the estimate of electrical consumption, and the calculation method presented by. Sassi and Mujtaba [20] was applied to estimate the theoretical electrical consumption.

According to the data of the previously performed experiment (Fig. 6), SWRO pilot plants in both groups were operated under the same conditions, but the overall difference in operating pressure reached approximately 5 bar with time. Based on this result, it is considered that there was a reduction in energy consumption in the experimental SWRO pilot plant compared to the control group. As shown in Fig. 12, this study examined the results obtained by the simulation and theoretical calculation. The electrical consumption with constantly increasing pressure and the average electrical consumption per unit pressure was approximately 0.034 kWh/m^3. It is estimated that approximately 0.17 kWh/m^3 of electricity will be reduced. The method of estimating electrical consumption applied in this study may differ from the actual electrical consumption because it was used to calculate only relatively important elements.

3.4. Analysis of SWRO membrane damage by FOB

Autopsy analysis was also conducted by collecting the SWRO elements used in both groups to analyze the damage of SWRO membranes caused by FOB and membrane foulants. The outside and inside (membrane surface) damage, telescoping, and channeling of the SWRO elements were observed as a visual inspection. As an analysis of SWRO membranes, foulants detected from the membrane surface, the elemental composition of deposits, and membrane surface were analyzed using scanning electron microscopy-nergy dispersive X-ray (SEM-EDX) analysis as shown in Fig. 13.

As a result of the autopsy, there was no major exterior and interior damage overall. Telescoping on the inlet side and

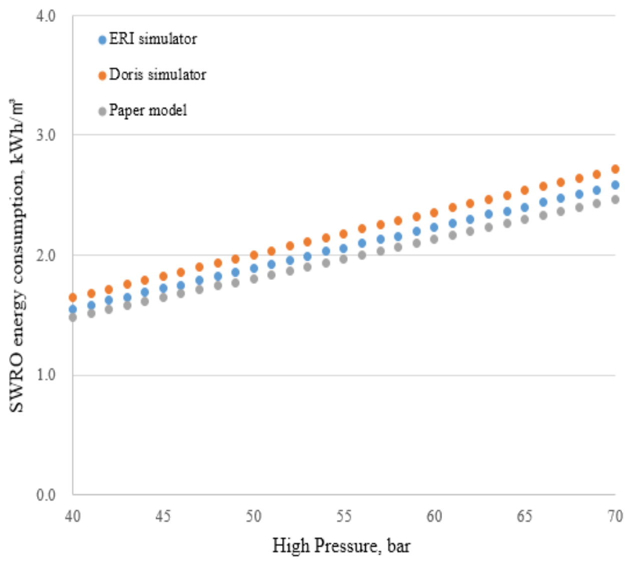
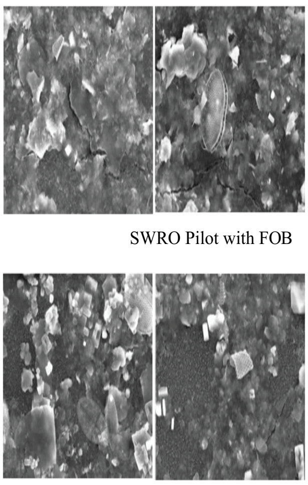


Fig. 12. Changes in electrical consumption according to operating pressure.



NO.	Line	Wt %	
Model		(a)	(b)
1	C	40.19	37.59
2	O	36.10	29.09
3	Na	3.97	9.03
4	Mg	0.69	1.07
5	Al	3.76	2.75
6	Si	5.08	4.03
7	Cl	6.41	12.36
8	Ca	1.53	2.60
9	Fe	2.28	0.87
Total, %		100	

Fig. 13. SEM-EDX analysis of SWRO membranes.

mesh displacement outside the concentrated side was not found. Although it was difficult to make an accurate judgment of foulants because fouling consisted of the mixture of organic and inorganic matter, it is considered that complex compound was formed due to the existence of organic and inorganic foulants.

Moreover, it was hard to compare the cleaning efficiency of the experimental and control groups with FOB based on the autopsy results because they showed a similar form of fouling. Membrane damage may have variables because it was analyzed by collecting some RO membrane specimens from the overall SWRO elements. However, it is considered that is possible to confirm the membrane is not damaged by the FOB, which can be proved by the data from the operating pressure and permeate quality, described above.

4. Conclusions

This study evaluated the effects of FOB by comparatively operating 110 m^3/d SWRO pilot plants. Although CIP was performed twice for the SWRO pilot plant in the control group during the same operation period, long-term operations were performed with maximum pressure increase rate of 10% for the experimental group. Also, SWRO pilot plants in both groups were operated at the same operating pressure in the early phase, but the overall difference in operating pressure reached approximately 5 bar with time. It is estimated that approximately 0.17 kWh/m^3 of electricity can be saved using FOB. Furthermore, this study conducted an autopsy analysis of SWRO elements with FOB and an analysis of permeate quality.

As a result, there was no membrane damage caused by FOB. The application of FOB makes it possible to obtain these effects using about 0.02% of the total permeate flux (calculated based on 110 m^3/d:40,150 m^3/year). In SWRO processes, FOB cleaning time and the cycle can vary depending on feed water quality. Thus, there is a need for additional experiments with various feed water conditions and cleaning conditions to apply FOB in the future.

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