Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2016.1168582

57 (2016) 26518–26528
November

Taylor & Francis
Taylor & Francis Group

Role of pressure-retarded osmosis (PRO) in the mega-ton water project

Masaru Kurihara[a,*], Hideyuki Sakai[b], Akihiko Tanioka[c], Hiroki Tomioka[d]

[a]*Toray Industries, Inc., "Mega-ton Water System" Funding Program for World Leading Innovation R&D on Science & Technology (FIRST) (FY2010-2013), 2-1-1 Nihonbashi-muromachi, Chuo-ku, Tokyo 103-8666, Japan, Tel. +81 3 3245 5716; email: Masaru_Kurihara@nts.toray.co.jp*
[b]*Kyowakiden Industry Co., Ltd, 10-2 Kawaguchi-machi, Nagasaki-shi 852-8108, Japan, Tel. +81 95 848 7788; email: hidesakai@kyowa-kk.co.jp*
[c]*Department of Organic and Polymeric Materials, The Osmotic Power Research Center, Tokyo Institute of Technology, Mail Box S8-27, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan, Tel. +81 3 5734 2059; email: tanioka.a.aa@m.titech.ac.jp*
[d]*Toray Industries, Inc., 3-2-1 Sonoyama, Otsu, Shiga 520-0842, Japan, Tel. +81 77 533 8407; email: Hiroki_Tomioka@nts.toray.co.jp*

Received 21 January 2016; Accepted 13 March 2016

ABSTRACT

Reverse osmosis (RO) membranes have been widely applied to seawater desalination and wastewater reclamation, and many large RO plants (>100,000 m^3/d) have been constructed since 2000. Energy efficiency is indispensable for large plants, especially for future mega-ton scale seawater reverse osmosis (SWRO) plant (1,000,000 m^3/d). In order to reduce energy demand in RO operation, high-efficient low-pressure RO membrane, energy recovery device (ERD), and pressure-retarded osmosis (PRO) which would recover power from salinity gradient between freshwater and concentrated brine were studied in the "Mega-ton Water System" project. A PRO hollow fiber membrane module was newly developed, and a practical continuous operation has been examined at a prototype plant for one year. The maximum 13.5 W/m^2 of membrane power density using 10-inch module was established at our prototype PRO plant. As the results of the plant cost estimation and the financial impacts on the energy saving operation at the mega-ton scale SWRO plants, not only 20% energy reduction by the high-efficient low-pressure RO membrane and the ERD but also further 10% energy saving was possible by using the PRO system.

Keywords: Seawater desalination; Reverse osmosis (RO); Energy saving; Low environmental impact; Energy recovery device (ERD); Pressure-retarded osmosis (PRO); Concentrated brine; Hollow fiber module; Treated sewage; Fouling; Concentration polarization

*Corresponding author.

Presented at the IDA 2015 World Congress (Desaltech 2015) 29 August–4 September, 2015 San Diego, CA, USA

1. Introduction

Although water is taken for granted, it is our most precious finite resource and is confronted with a critical situation today. Human race has been consuming huge amount of water resources and has been polluting them since the industrial revolution. While the world population tripled in the twentieth century, global water consumption has risen almost sixfold [1]. Nowadays, a lot of countries and regions are under water stress or water scarcity, especially in Middle East, North Africa, South Asia, China, and so on [2,3]. Furthermore, water withdrawals is projected to increase by 44% by 2050 due to growing demands from manufacturing, thermal power generation, agriculture, and domestic use [4]. Regarding water pollution, an estimated 90% of all wastewater in developing countries is discharged untreated directly into rivers, lakes, or the oceans [5], and there are more than 700 million people relying on unsafe drinking water sources in the world [6,7]. Therefore, the water issue is one of the most serious worldwide problems as well as global warming. Water treatment technologies for securing sufficient and safe water sources are strongly required. Membrane technology for water treatment is regarded as indispensable in this century for it can provide high-grade and sustainable water supply. In particular, RO membranes have been widely applied in the desalination field to not only seawater desalination but also brackish water desalination including industrial and sewage wastewater reclamation, and the market of RO membranes has been rapidly growing. Energy saving and improvement of water quality have always been two major subjects in seawater reverse osmosis (SWRO) desalination. At the point of energy saving, the average energy consumption in SWRO plants has been reduced to one-fifth for these 40 years and current energy consumption in total desalination process and RO pass are, respectively, 4 and 2–3 kWh/m^3 [8–10]. However, innovative advancement of RO membrane technology for further energy saving is continuously required in order to satisfy the growing water demand.

2. Overview of "Mega-ton Water System" project [11–15]

As stated above, RO technology is widely used all over the world to secure sustainable water source and to solve the water issues. It is interesting to note that the size of water treatment plants with RO technology shows a certain trend. Fig. 1 shows the productivity of top 20 RO plants constructed in each year. According to the advancement of technologies, plant scale has been getting larger for a few decades, and huge water treatment plants capable of producing more than 100,000 m^3 of freshwater per day (equivalent to the daily supply for around 400,000 people) have been built after the 2000s. However, water problems continue to worsen, and even larger plants with producing capacity of 1,000,000 m^3/d will be required in the foreseeable future. This has led to urgent needs of developing innovative water treatment systems which address the problems caused by the construction of mega plants, such as massive energy consumption and environmental destruction [11–13]. Compared to small plants, it is possible to design an optimum layout through effective accumulation of components in the mega plants. This layout can decrease total foot print of the plants, increase energy efficiency, and decrease environmental impact. Therefore, technological developments for mega plants were required. In 2010, FIRST (Funding Program for World-Leading Innovative R&D on Science and Technology) program "Mega-ton Water System" started. "Mega-ton Water System" project, which was a cutting-edge research and development project in Japan, and was carried out to develop twenty-first century key technologies on water treatment for sustainable management of water environment and for low-carbon path [11–15]. The project aimed at developing innovative water treatment technologies, which are necessary for realizing mega plants such as biofriendly pretreatment, low-pressure multistage RO system, low-pressure SWRO membrane, highly efficient energy recovery device (ERD), high-pressure resin pipes and proposing a system for mega plant. The summary and noteworthy outcomes of this project were as follows:

(1) Vision & Mission of "Mega-ton Water System" Vison is realization of sustainable desalination and reclamation. Missions are as follows: (1) 20–30% Energy reduction, (2) Low environmental impact (less chemical consumption), and (3) 50% Water productions cost reduction.
(2) Water cycle in "Mega-ton Water System" It is composed of seawater RO system and wastewater treatment system as shown in Fig. 2. Pressure-retarded osmosis (PRO) system is included in SWRO system. Integration of advanced materials, equipment, and system technology are shown in Figs. 3 and 4.
(3) Noteworthy outcome 1: Low-Pressure SWRO Membrane Technology.

Regarding the surface morphology of SWRO membranes, it was hypothesized that protuberance structure on the membrane surface would largely contribute to water permeability of the membranes. However, the conventional SEM analysis methods had

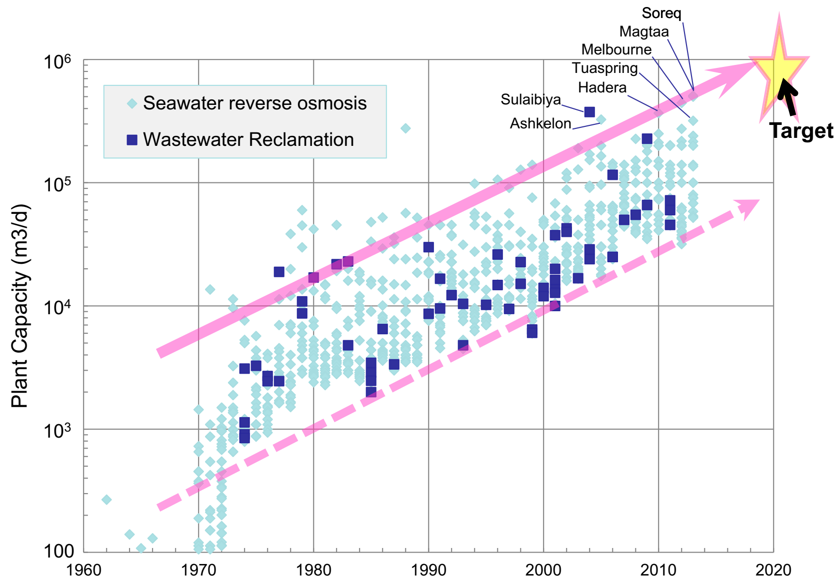


Fig. 1. Change in size of SWRO plant and WW reclamation RO plant.

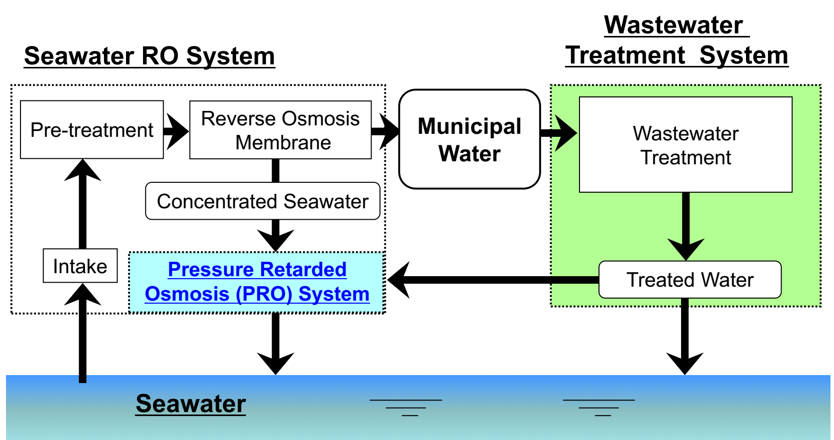


Fig. 2. Water cycle in "Mega-ton Water System."

provided limited information from an appearance as shown in Fig. 5(1) (left-hand). It was not completely clear how the protuberance structure took part in the performance of SWRO membranes. In order to obtain reliable information, more precise estimation of the protuberance structure was needed. In this study, a modified treatment procedure that enabled to detect the fine protuberance structure as measuring in wet condition was developed. It seemed that the shape of the protuberances treated by the modified method was well kept even in a high vacuum environment for microscopic analyses as shown in Fig. 5(1) (right-hand) while a change of shape in the case of the conventional method was found.

Transmission electron microscope (TEM) was used to analyze the cross section structure of RO membranes. Membrane samples for the observation were prepared with a special technique to preserve the shape of the protuberances. Analyses by TEM gave clear images as shown in Fig. 5(2) (left-hand). TEM images indicated that the protuberances had a cave-like inside structure and enabled to quantitatively analyze the surface morphology of RO membranes. Surface area of RO membrane was estimated from the ridgeline length of the protuberances, and thickness of the polyamide layer was estimated as thickness of the protuberance skin. Additional analyses by a scanning transmission electron microscope with electron energy

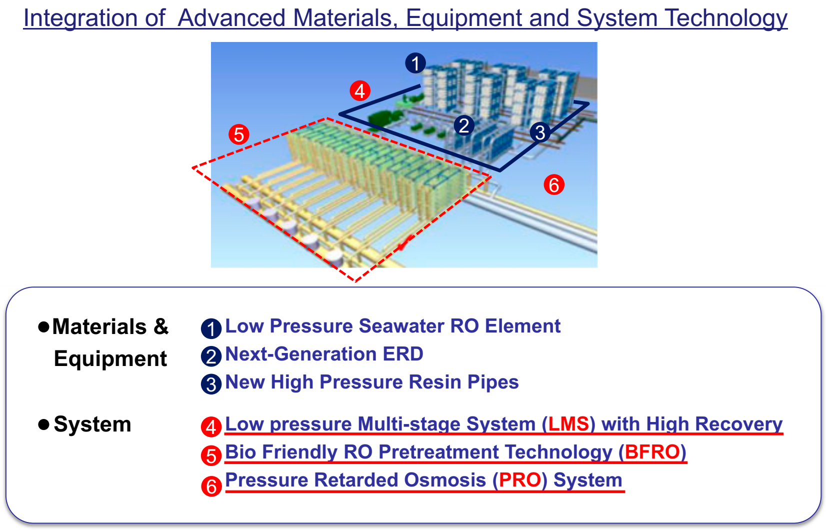


Fig. 3. "Mega-ton Water System" Technology.

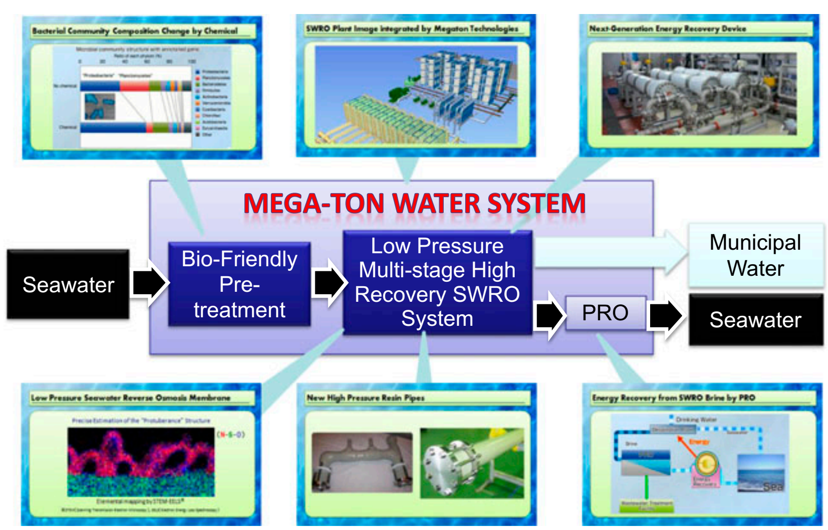


Fig. 4. Indispensable key technologies of "Mega-ton Water System" for twenty-first century.

loss spectroscopy (STEM-EELS) provided an elemental mapping image as shown in Fig. 5(2) (right-hand), which enabled to confirm that polyamide does not exist inside of the protuberances. It was found that the skin part of the protuberances is a real polyamide layer which is about 200 nm in height and 20 nm in thickness.

Through the TEM analyses, two structural parameters, i.e. surface area and thickness which contribute to RO membrane performance were obtained [11,12,16,17]. With the comparison of morphologies between RO membranes having different water permeability, membrane with a larger surface area or smaller thickness showed higher water permeability. Furthermore, the number of the protuberances also affected the surface area and water permeability. Thus, the correlation between the morphology of protuberance structures and water permeability of RO membrane was revealed. Utilizing the relationships, the ultimate membrane microstructure which maximized not only water permeation but also salt rejection was pursued in this project [18]. The pore structure with an appropriate size and number for effective salt removal and the protuberance structure with a larger surface area and smaller thickness for higher water productivity were desired. Membrane fabrication process, particularly the step of interfacial polycondensation reaction to form polyamide layer,

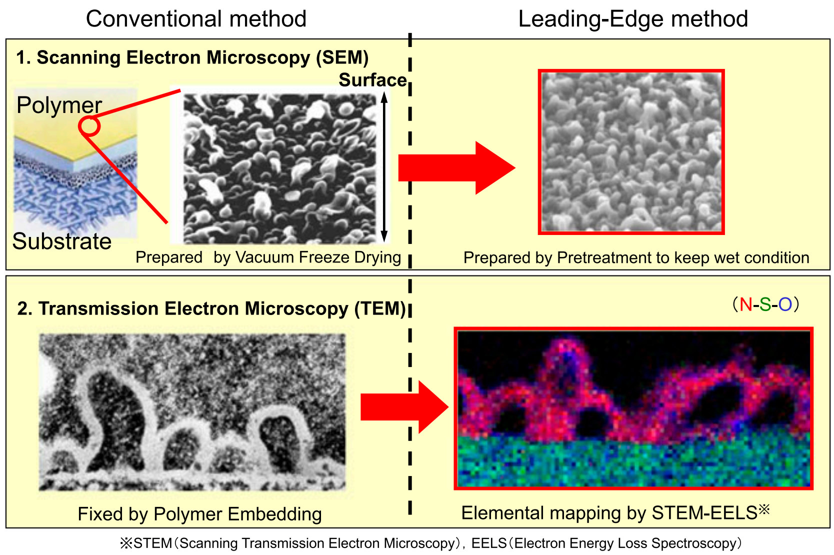


Fig. 5. Progress of "Protuberance" structure analysis by scanning election microscopy (SEM) and transmission electron microscopy (TEM).

was studied for realizing the desired structure. The interfacial polycondensation reaction was affected by various conditional factors such as monomers, solvent, additives, temperature, pH, and support layer. A fine polycondensation technique had been successfully established by precisely controlling the conditional factors, and an innovative low-pressure SWRO membrane was prepared in this project.

With the above-mentioned knowledge based on the fundamental analytical researches, the structure of the polyamide layer for further excellent performance was designed. Energy saving effect of the new membrane was estimated in comparison with Toray's standard SWRO membrane as shown in Fig. 6. The standard SWRO membrane was manufactured by the conventional fabrication method and it was commercially available. The performance of each SWRO membrane itself was measured without energy recovery in the laboratory test. The conventional SWRO membrane needs more than 6.0 MPa as an operating pressure to show the membrane performance of 99.85% salt rejection and 1.0 $m^3/m^2/d$ water permeability for the desalination of 3.5% seawater. On the other hand, new membrane shows similar excellent performance at the feed pressure lower than 5.0 MPa, and the result indicates that the new SWRO membrane will contribute to significant energy reduction in seawater desalination process.

(4) Noteworthy outcome two: Low-pressure Multistage Inter-boosted Seawater Desalination System (LMS).

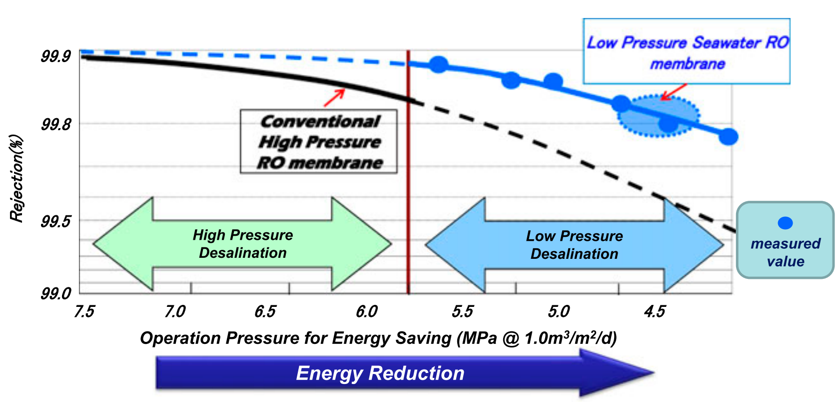


Fig. 6. Comparison of SWRO membrane performance in high- and low-pressure desalination.

A highly effective SWRO system for energy saving was also studied by Hitachi Ltd [13]. Low-pressure multistage inter-boosted seawater desalination system (LMS) was proposed to reduce the total water cost while keeping high quality of the produced water. LMS is a two-stage RO process as shown in Fig. 7. Brine from the first stage RO is pressurized and fed to the second stage RO for increasing water recovery. In the case of applying new low pressure SWRO membrane to LMS process, it is estimated that the total energy consumption in SWRO plant will be reduced by 20% compared to the combination of conventional single-stage SWRO process and conventional SWRO membrane.

3. PRO system in the "Mega-ton Water System"

SWRO is one of the promising processes to solve the water shortage problem, because it claims lower cost and less energy. However, there are still several concerns such as concentrated brine released from SWRO plant, sometimes causing environmental problems. And SWRO plants with more cost effective and less energy consumption are demanded, especially on the megascale SWRO plant. In the "Mega-ton Water System," PRO was focused on as a process that could recover energy from the salinity difference between the concentrated brine and freshwater and, simultaneously, as a candidate to solve the environmental problem caused by the SWRO brine released back into the sea. PRO was proposed by Loeb et al. 40 years ago [19–22]. They conducted experiments of the PRO process at the Dead Sea in Israel [22] and the Great Salt Lake in the USA [23], where both concentrated saline and freshwater were available. Their results were not so good because these experiments employed semi-permeable membranes that were not for forward osmosis, but for SWRO. Dr Takeo Honda of National Institute of Advanced Industrial Science and Technology (AIST) showed that net output power from PRO, generated power minus consumed power, would be positive if membrane module is properly modified [24]. Recently, some research teams, especially from Europe, are studying the process to recover salinity gradient power such as WETSUS in the Netherlands [25]. In Japan, Kyowakiden Industry Co., Ltd, since 2002, has conducted fundamental and operational research with the cooperation of Kyushu University, Nagasaki University and Tokyo Institute of Technology. In 2002, a PRO bench scale plant using membrane modules was constructed near Fukuoka SWRO Facility. From 2007 to 2009, PRO possibilities were investigated and the first prototype plant of PRO using commercial type membrane module was constructed under the support of NEDO, New Energy and Industrial Technology Development Organization. In 2010, the prototype PRO plant joined the "Mega-ton Water System" project [26,27]. In the project, the maximum membrane power density per surface area was reached to 13.5 W/m^2 using 10-inch module at the prototype PRO plant in Fukuoka, and 17.1 W/m^2 in the laboratory-scale experimental using 5-inch module with freshwater as feed solution and concentrated brine (ca.7%) as draw solution. In particular after the Great East Japan Earthquake on 11 March, 2011, PRO was paid much more attention than before as new "Renewable Energy." The summary of PRO in this project was as follows:

(1) Target and current status of PRO The recent reports and discussions related to PRO are very confusing. Thus, target and current status of PRO are clearly shown in Table 1. The relation between energy source and target is divided into three groups. The Statkraft project which was recently suspended belongs to the item one. On the other hand, hot discussion

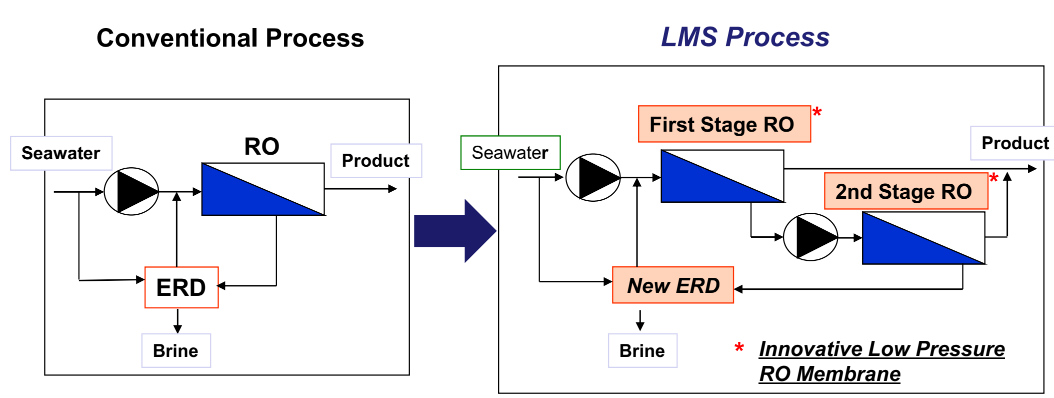


Fig. 7. Comparison of flow diagrams of conventional process and LMS process.

Table 1
Target and current status of PRO

	Energy source	Target	Player	Membrane	Current status
1	Low-salinity water (Seawater)–River water	Power production	Statkraft	PA Spiral and plate	Suspension
2	High salinity water (SWRO brine)–Treated waste water	Energy recovery and environment friendly	"Mega-ton Water System" project (Japan)	CTA hollow fiber	Near to commercial plant
			GMVP (Korea)	PA spiral and plate	National project start
3	Ultra high salinity water (Dead sea)–River water	Energy recovery and power production	Dr S. Loeb	–	–

has grown in item two, and "Mega-ton Water System" project is much contributed to the progress of PRO technology in this item, in which the current status will be near to commercial plant. Dr S. Loeb proposed the importance of item three, but no progress technologically nowadays.

(2) PRO energy recovery system and process flow diagram is shown in Fig. 8. Renewable energy recovered by PRO process is (1) no heat emission, no chemical reaction, (2) stable under any weather condition, around-the-clock operation, (3) populated city gives good resources for PRO as treated wastewater and concentrated seawater outline of PRO energy recovery system. The PRO plant can be constructed near or in urban area. The PRO process diagram is shown in Fig. 9.

(3) Prototype PRO plant Prototype PRO plant was constructed and operated using eight pieces of 10-inch PRO module (Toyobo CTA Hollow Fiber) as shown in Fig. 9. Brine from the SWRO facility was used as draw solutions (DS: 460 m^3/d), and low-salinity water from the regional wastewater treatment facility was used as feed solution (FS: 420 m^3/d) after removing potential foulants of the membranes using UF unit and chemical, before introducing into PRO units.

(4) Achieved power density at prototype plant and laboratory-scale plant. The prototype plant has achieved 13.5 W/m^2 of the maximum membrane power density per surface area using 10 inch membrane modules. On the other hand, laboratory-scale plant showed 17.1 W/m^2 with 5-inch module as shown in Fig. 10.

(5) Long-term operations at PRO prototype plant Long-term test operations at the PRO prototype plant was carried out over one year as shown in Fig. 11. The osmotic flow rate through mem-

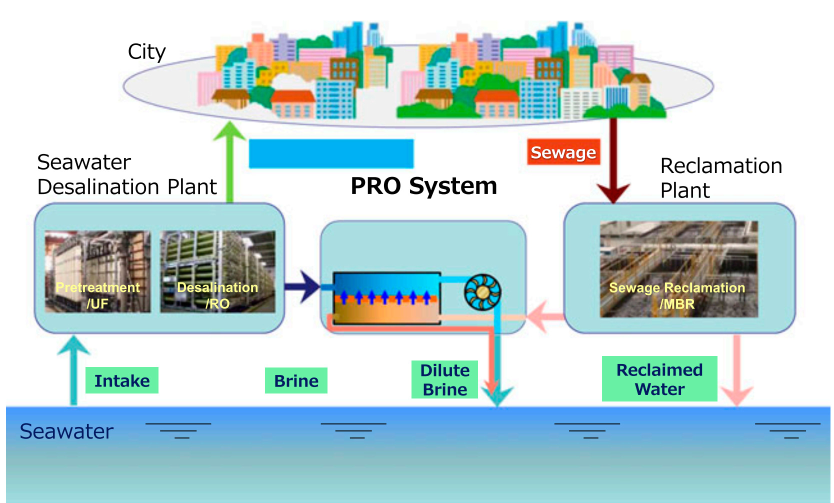
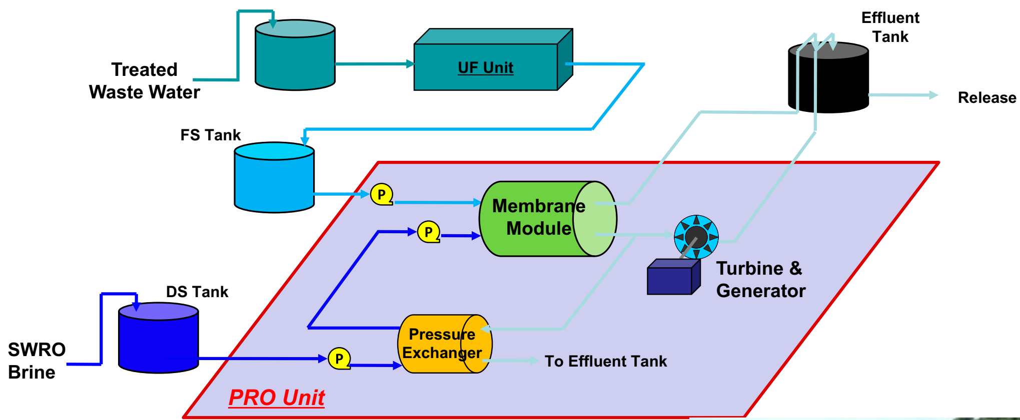


Fig. 8. Pressure-retarded osmosis (PRO) system.



RO Product and Brine Flow (m^3/d)	Waste Water Flow (m^3/d)	Energy Reduction Rate (%)
500	390	2
20,000	13,000	6
1,000,000	730,000	10

Fig. 9. PRO system flow.

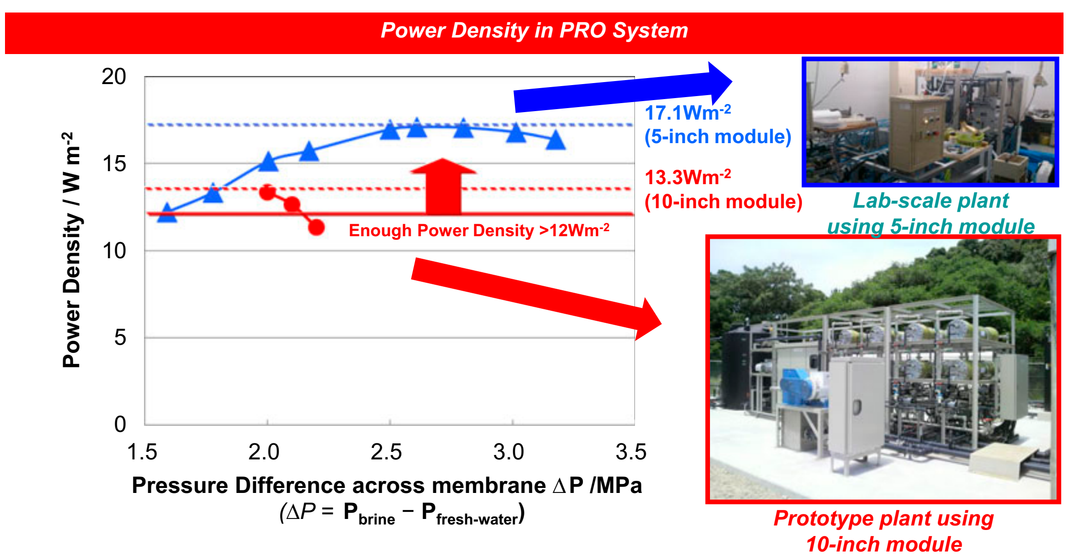


Fig. 10. Achieved power density at prototype plant and laboratory-scale plant.

brane was found to depend on the temperature, which seasonally varied as traditional membranes. Also found was little decline in osmosis flow rate between the beginning and one year after the test launch, even though continuing the same membrane modules. This means that we have successfully produced freshwater from the treated wastewater of enough quality for the PRO system, employing some traditional pretreatment method and that commercial scale operation would be possible for long period.

(6) Input and output energy of PRO Generated power and consumed power at PRO plant were shown in Fig. 12. Generated power was found

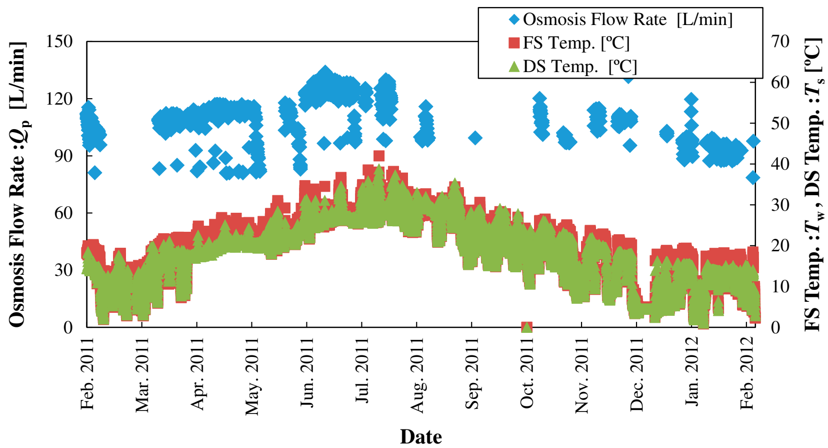


Fig. 11. Long-term prototype PRO plant operation over 1 year.

to be maximum at draw side hydraulic pressure 2.5 MPa; net output power, generated power unit minus consumed power was also found to be maximized at draw side hydraulic pressure 2.5 MPa, at which PRO operation would optimized.

(7) Energy reduction by Mega-ton Water Technology Specific energy consumption rates in case of 3.5% seawater as total dissolved salts concentration are compared in the process: (1) conventional process, (2) Mega-ton Water System without PRO, and (3) Mega-ton Water System including PRO as shown in Table 2. About 20% energy reduction is established in (2) and 30% energy reduction in (3) compared to (1).

(8) Trend of energy reduction in SWRO Trend of energy reduction in SWRO since 1970 is shown in Fig. 13, in case of total energy consumption and first RO pass consumption [8].

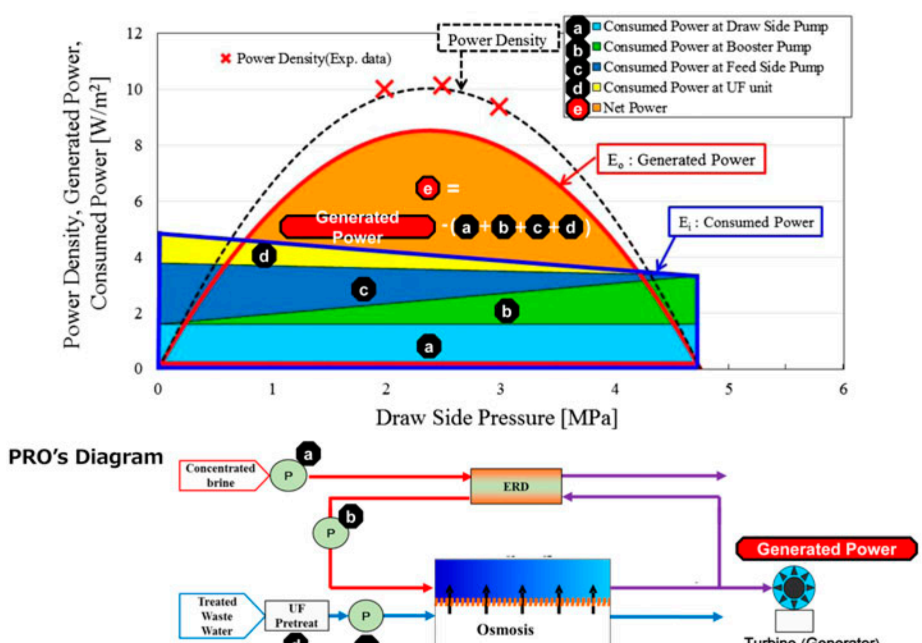


Fig. 12. Input and output energy of PRO.

Table 2
Energy reduction by mega-ton water technology

Process <Seawater conc. = 3.5%>	Membrane	ERD	Pump efficiency (%)	PRO	SEC rate (%)
Conventional (*R* = 45%)	Conventional	Turbo	70–85	–	100
Mega-ton (*R* = 60%)	Megaton technology	New ERD	90	–	80
Mega-ton (*R* = 60%) with PRO				PRO[a]	70

Notes: Energy reduction is 20% by megaton technologies.
Energy reduction is 30% by megaton technologies with PRO.
[a]This is under final verification stage in Japanese seawater conditions.

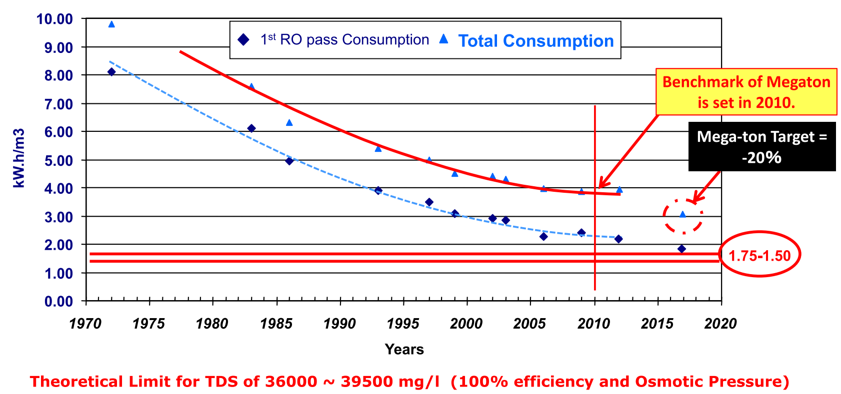


Fig. 13. Trend of energy reduction in seawater RO.

4. Conclusion

(1) Morphology analyses of polyamide SWRO membranes focused on protuberance structure on the membrane surface were conducted to reveal the parameters influencing water permeability of the membranes. According to TEM analysis, it was shown that the water permeability of RO membranes depended on the surface area and thickness of protuberances. An innovative low-pressure SWRO membrane was obtained by the precisely controlled preparation technique based on the analytical research. The new membrane will contribute to energy saving and low environmental impact for realizing mega plants in the near future.

(2) A new RO system LMS that enables high RO recovery rate (under 65%) is developed. High recovery operation makes it possible to reduce water production cost.

(3) (1) About 20% energy reduction target is established by low-pressure SWRO membrane and new ERD in the LMS process without PRO. (2) About 30% energy reduction is also possible in the LMS process including PRO.

(4) Low environmental impact on disposal of brine is suggested by PRO energy recovery system.

Acknowledgement

This research is granted by the Japan Society for the Promotion of Science (JSPS) through the "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)," initiated by the Council for Science and Technology Policy (CSTP). The author's deep appreciation goes to NEDO that supports "Mega-ton Water System" project.

References

[1] UNESCO International Hydrological Programme, World Water Resources and Their Use a Joint SHI/UNESCO Product. Available from: <http://webworld.unesco.org/water/ihp/db/shiklomanov/1999>.

[2] Managing Water Under Uncertainty and Risk, The United Nations World Water Development Report 4, vol. 1, UNESCO, 2012.

[3] The United Nations World Water Development Report, Water and Energy, vol. 1, UNESCO, 2014.
[4] World water day, Advocacy Guide, UN-Water/United Nations University/UNIDO, 2014.
[5] E. Corcoran, C. Nellemann, E. Baker, R. Bos, D. Osborn, H. Savelli (Eds.), SickWater? The Central Role of Wastewater Management in Sustainable Development, A Rapid Response Assessment, United Nations Environment Programme, UN-HABITAT, GRID-Arendal, 2010.
[6] The Millennium Development Goals Report, UN Department of Economic and Social Affairs, 2014.
[7] Progress on Drinking Water and Sanitation, WHO/UNICEF, 2014, update.
[8] M.A. Sanz, Energy as motor of seawater reverse osmosis desalination development, in: Oral Presentation in Mega-ton Symposium New Energy and Industrial Technology Development Organization, (NEDO), 21–22 November 2013, Tokyo, 2013.
[9] M. Kurihara, Membrane research for water treatment facing the age of global mega competition & collaboration, in: Oral Presentation in Project Leader's Summit at IWA-ASPIRE 2011, Tokyo, October 3 2011, 2011.
[10] D&WR, 16(2) (2006) 10–22.
[11] M. Kurihara, M. Hanakawa, Mega-ton Water System: Japanese national research and development project on seawater desalination and wastewater reclamation, Desalination 308 (2013) 131–137.
[12] M. Kurihara, T. Sasaki, K. Nakatuji, M. Kimura, M. Henmi, Low pressure SWRO membrane for desalination in the "Mega-ton Water System", Desalination 368 (2015) 135–139.
[13] N. Kishizawa, Low pressure multi-stage RO system developed in "Mega-ton Water System" for large-scaled SWRO plant, Desalination 368 (2015) 81–88.
[14] M. Kurihara, The pursuit and progress of future membrane technology, in: Oral Presentation in the IDA World Congress International Desalination Association, (IDA), 20–25 October 2013, Tianjin, 2013.
[15] M. Kurihara, Membrane research for water treatment facing the age of global mega competition & collaboration, in: Oral Presentation in IUPAC World Polymer Congress Polymer and Polymer-based Membranes for Energy and Environmental Applications II, 24–29 June 2012, Blacksburg, 2012.
[16] M. Kurihara, M. Henmi, H. Tomioka, T. Kawakami, Advancement of RO membrane for seawater desalination and wastewater reclamation, in: Oral Presentation in International Congress on Membranes and Membrane Processes (ICOM), 13–18 July 2008, Hawaii, 2008.
[17] T. Uemura, K. Kotera, M. Henmi, H. Tomioka, Membrane technology in seawater desalination: History, recent developments and future prospects, Desalin Water Treat. 33 (2011) 283–288.
[18] M. Kurihara, M. Henmi, H. Tomioka, High boron removal seawater RO membrane, in: Oral Presentation in Advanced Membrane Technology III: Membrane Engineering for Process Intensification, 11–15 June 2006, Italy, 2006.
[19] J. Bartram, Improving on haves and have-nots, Nature 452 (2008) 283–284.
[20] S. Loeb, Production of energy from concentrated brines by pressure-retarded osmosis, J. Membr. Sci. 1 (1976) 49–63.
[21] S. Loeb, Production of energy from concentrated brines by pressure-retarded osmosis, J. Membr. Sci. 1 (1976) 249–269.
[22] S. Loeb, Energy production at the Dead Sea by pressure retarded osmosis: Challenge or chimera? Desalination 120 (1998) 247–262.
[23] S. Loeb, One hundred and thirty benign and renewable megawatts from Great Salt Lake? The possibilities of hydroelectric power by pressure-retarded osmosis, Desalination 141 (2001) 85–91.
[24] Takeo Honda, Fred Barclay, "The Osmotic Engine", The membrane alternative, The watt committee on energy Report Number 21, 13 (1990) 105–129.
[25] S.E. Skilhagen, Osmotic power—A new, renewable energy source, Desalin. Water Treat. 15 (2010) 271–278.
[26] K. Saito, Power generation with salinity gradient by pressure retarded osmosis using concentrated brine from SWRO system and treated sewage as pure water, Desalin. Water Treat. 41 (2012) 114–121 March.
[27] M. Kurihara, "Mega-ton Water System"-including PRO system, in: Oral presentation first International Symposium on Innovative Technologies, 1–3 September 2014, Seoul, 2014.