Prof. Shoji Kimura's contribution to Desalination around the world

12th July 2023

President of (NPO) Japan Desalination Association
Dr. Hideo Iwahashi

Table of Contents

1-1 Introduction (self-introduction)

● Born in 1954, 69 years old tomorrow
1980 Completed master's degree at Kimura Laboratory, University of Tokyo
(master's thesis: Separation of solutes by reverse osmosis membrane)

● 1980 Joined Mitsubishi Heavy Industries, Ltd.
Retired as Chief Desalination Engineer (2018)
⇒ Consistently develop, plan, design, operate and troubleshoot of seawater desalination plants (evaporation method and membrane method)
Engaged in dealing with Ordered plant in charge All KSA AJ-2, MT-1, Jeddah RO-1 & 2, MY-2 RO, Rabigh IWSPP Phase-1, Shuqaiq IWPP

● Mitsubishi Corporation for four years from October 2018, now Toyobo MC Co., Ltd.
⇒Senior advisor (technical advisor) in the field of water treatment

● Association activities
⇒Board member of International Desalination Association (Past) and Asia Pacific Desalination Association (Past)
⇒President of NPO Japan Desalination Association (Present)

1-2 Introduction

August 1979, Sado Island

November 1980, Yugate

Master's thesis : Separation of solutes in reverse osmosis

The abstract is shown below (Japanese)

逆浸透法における溶質排除の解析

（東大生研） 0 （正）岩橋英夫※（学）中尾真一（正）木村尚史
（日東電工） （正）湯本恵視

I. 緒　　言

逆浸透法の溶質分離に関する定量的解析法には，未だ確立されたものがない。NaCl等分離のよいものに対しては，$\sigma \sim 1$ と考え，kimura-Sourirajan のＢ値で解析して，妥当な結果を得る事ができるが[1]，排除の悪い溶質系に対しては，実験データも少なく定量的な取り扱いは，殆どなされていない。そこで本研究では，非対称酢酸セルロース膜を用いて，排除の悪い電解質群及びアルコール群について，逆浸透実験をおこないSpiegler-kedemの式による解析，検討をおこなってみた。

II. 実　　験

装置のフローシートはFig. 1。熱処理温度を変化させて，膜性能の異なる五本の非対称酢酸セルロース膜を製作し，直列につないで用いた。流量一定で圧力を変化させる実験及び圧力一定で流量を変化させる実験を行った。液温は25℃，使用溶質は$NaCl$，$LiNO_3$，$NaNO_3$，KNO_3，NaI，$NaClO_4$，尿素，n-propanol，iso-propanol，tert-butanol。

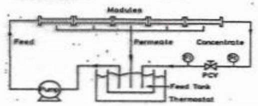


Fig. 1

III. 解析及び結果

＜濃度分極の影響＞

逆浸透実験から求まる溶質の排除率は，

$Robs = \frac{Cb - Cp}{Cb}$ で与えられるが，膜面では濃度分極の影響で溶質濃度がCbより高い値となり，実際の排除率は，

$R = \frac{Cm - Cp}{Cm}$ であらわされ，Cmを知る必要がある。

$$Jv = k \ \ln \frac{Cm - Cp}{Cb - Cp} \quad \cdots\cdots (1)$$

(1)式から，Cmを求めるためにはｋを知る必要があり，流速変化法[2]によって求めた。このようにして求めたｋは，円管内乱流におけるDeisslerの相関式

$$Nsh = 0.023 NRe^{0.875} Nsc^{0.25} \quad \cdots\cdots (2)$$

に良く一致した。一例をFig. 2 に示す。従って，排除率の悪い溶質に対しても，ｋを求めるのに，Deisslerの相関式が有効である事がわかった。

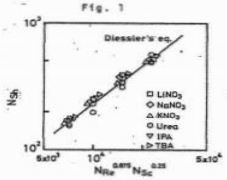


Fig. 2

＜溶質分離の定量的取り扱い＞不可逆過程の熱力学によると，溶質の膜透過は次のようにあらわされている。[3]

$$Jv = Lp(\Delta P - \sigma \Delta \pi) \quad \cdots\cdots (3a)$$

$$Js = W \Delta \pi + (1 - \sigma) Jv\bar{C} \quad \cdots\cdots (3b)$$

（３ｂ）中の$\bar{C}$は，膜両側溶液の溶質濃度平均だが，逆浸透の場合，両側溶液の濃度差が著しいので，Ｃの決め方が問題となる。

Spieglerとkedem は，膜の微小部分に対し，（３ｂ）が成り立つと考え，それを積分して，次の結果を得た。[4]

$$R = \frac{\sigma \left[1 - \exp\left\{-\frac{(1-\sigma)Jv}{P}\right\}\right]}{1 - \sigma \exp\left\{-\frac{(1-\sigma)Jv}{P}\right\}} \quad \cdots\cdots (4)$$

(4)式中のσ，Ｐを膜性能パラメータと考え，圧力変化の実験より得られたJv，Ｒのデータに対し，(4)式をカーブフィッティングしてσ，Ｐを決定した。その結果，電解質では，すべての$\sigma \fallingdotseq 1$と考えてよい。Fig. 3は，陰 ion が硝酸根の１－１電解質に対するＲvs１／Jvのグラフだが，これから求まるのも，ほぼ１となる。従ってＲの差は，Ｐの差に起因している。この場合には，Li^+，Na^+，K^+ のＰの大小（$P_{LiNO_3} < P_{NaNO_3} < P_{KNO_3}$）は，各 ion の水和半径の大小（$r_{Li^+} > r_{Na^+} > r_{K^+}$）と逆の関係にあることがわかった。

また，Fig. 4は，アルコール群に対するもので，このグラフから排除率の差は，σ，Ｐの両方に効くが，σの差の方が大きく効いている事及びUREAと NPAでは同程度の排除率だが，σとＰにわけると違いがあり，それを従来のように，排除率の差を１つのパラメータに帰因させている限りは，この差がでなかった事がわかる。

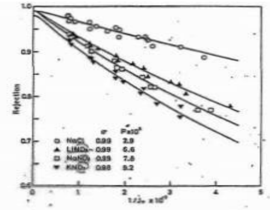


Fig. 3

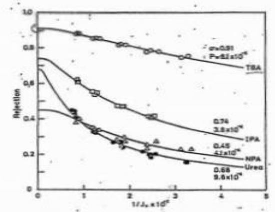


Fig. 4

IV. 結　　論

① 物質移動係数を求めるのに，排除の悪い溶質に対しても，Deisslerの相関式が有効である。
② 逆浸透の定量的データを，Spiegler-Kedemの式のσ，Ｐで整理できた。
③ 電解質の場合，排除率が悪いものでも，σは１と考えてよい。又，排除率の差はＰの差に起因する。
④ アルコールの場合，排除率の差は，σとＰの両方に起因するが，σの差が大きく効いている。

《記　　号》

σ：反射係数〔－〕，Ｂ：溶質の透過係数〔$\frac{gr}{atm \cdot sec}$〕，Robs，Ｒ：みかけの排除率，真の排除率〔－〕，Cb，Cm，Cp：バルク濃度，膜面濃度，透過液濃度〔ppm〕，

Jv，Js：体積流束，溶質流束〔$\frac{gr}{cm^2 \cdot sec}$〕，ｋ：物質移動係数〔$\frac{cm}{sec}$〕，

Lp：純水の透過係数〔$\frac{gr}{atm \cdot sec \cdot cm^2}$〕，$\Delta P$，$\Delta \pi$：機械的圧力差，浸透圧差〔atm〕

Ｗ：溶質の透過度〔$\frac{gr}{cm^2 \cdot sec \cdot atm}$〕 Ｐ：溶質の透過度〔$\frac{cm}{sec}$〕

《引用文献》

1）SHOJI KIMURA. 4th inter. Sympo. on Fresh Water from the Sea. Vol. 4. 197～206. 1973
2）JUN NAKAZAWA et. al.，化工協会第12回秋季大会講演要旨集．355～356．1978.
3）O. KEDEM et. al.，J. Geme Physi. Vol. 45. 143～179. 1961
4）K. S. SPIEGLER et at Desalination. 1. 311～326. 1966

RB2IWH105 ※現在，三菱重工業㈱

RB2IWH105

1-3 Introduction

Experiences of MHI / Seawater Desalination Plants

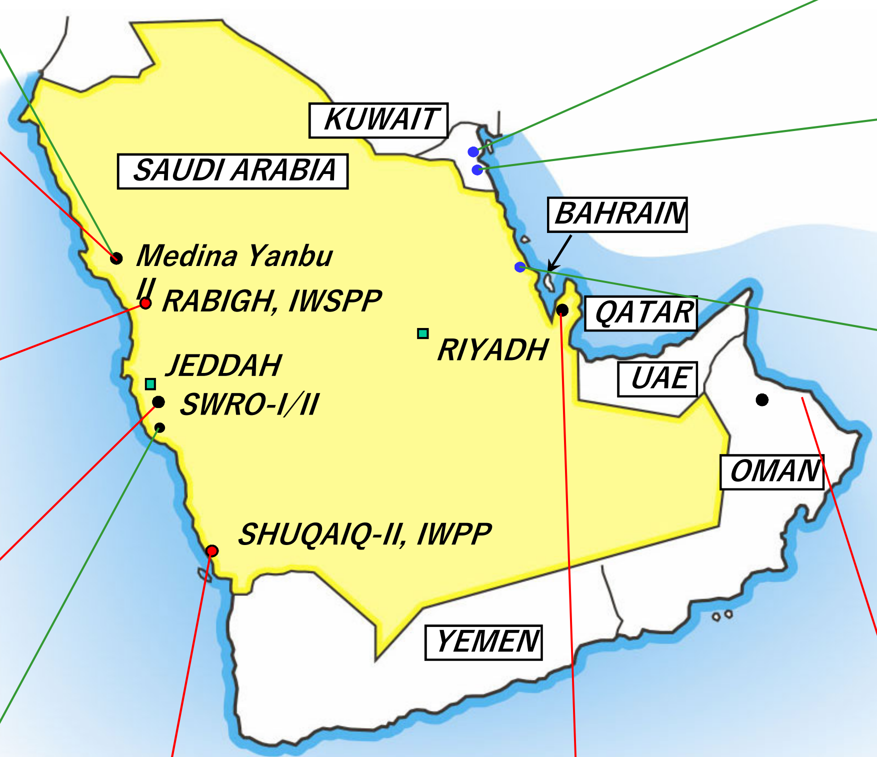
Yanbu
MSF : 110,000m³/d
Start : Nov 1981

Medina Yanbu II
SWRO : 127,800m³/d
Start : Sep 1998

Rabigh IWSPP
Power : 120MW x 5
SWRO : 192,000m³/d
Start : Oct 2007 (SWRO)

Jeddah SWRO I/II
SWRO : 113,600m³/d
Start : May 1989 & Mar 1994

Shoaiba
MSF : 223,000m³/d
Start : Sep 1989



Doha West
MSF : 393,120m³/d
Start : Mar 1985

Az Zour
MSF : 262,080m³/d & 109,104m3/d
Start : Jun 1989 & Oct 1998

Al-Jubail I/II
MSF : 611,000m³/d
Start : Apr 1982 & Aug 1983

Green : MSF (Multi Stage Flash)
Red : RO (Reverse Osmosis)

Shuqaiq-II IWPP
Power : 340MW x 3
SWRO : 216,000m³/d
Start : Dec 2009 (SWRO)

QATAR Pilot Plant
SWRO : 200m³/d
Start : Jan 2005

OMAN Pilot Plant
SWRO : 200m³/d
Start : Oct 2003

1-3 Introduction

Al Jubail 2 Plant

MSF : 455,000m^3/d
Start : Aug 1983

1-3 Introduction

Jeddah SWRO I&II / Saudi Arabia

Pioneer of Large Scale SWRO

Capacity : 113,600 m3/day (56,800 m3/day x 2 phase)

Plant Completion : May 1989 & March 1994

Jeddah SWRO I Phase-1 / Saudi Arabia

1. Capacity & number 1.5 MIGPD x 10 trains (56,800m^3/day)
2. Seawater salinity 43,000ppm as TDS
3. Product water quality 625ppm as Cl^-
4. Conversion ratio 35%
5. Design temp. 24°C
6. RO modules Hollow fine fiber modules
7. Plant completion May, 1989

Medina Yanbu II / Saudi Arabia

World's Largest SWRO in 20th Century

Capacity : 127,800 m3/day (8,520 m3/day x 15 trains)

Plant Completion : September 1998

Pilot Plant / Dukhan, Qatar

Challenge against Gulf water by SWRO

Capacity : 200 m3/day

Seawater Salinity : 59,400 ppm as TDS(approx. 9 ppm as Boron)

Product water quality : 5 ppm as Cl^- / 0.5 ppm as Boron

Plant Completion : January, 2005

1-3 Introduction

Rabigh IWSPP Project / Saudi Arabia

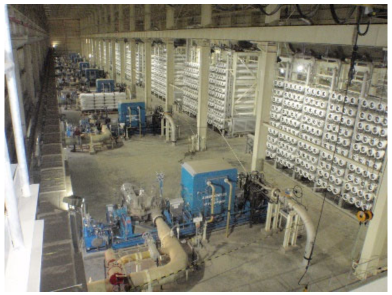
World's First Full 3 Pass SWRO

Power : ST 120MW x 5, Boiler 470t/h x 9
Capacity : 192,000 m^3/day (12,000 m3/day x 16 trains)
Seawater salinity : 41,200 ppm as TDS
Product water quality : less than 5 ppm as Cl^-
Plant Completion : June, 2008

Shuqaiq IWPP Project / Saudi Arabia

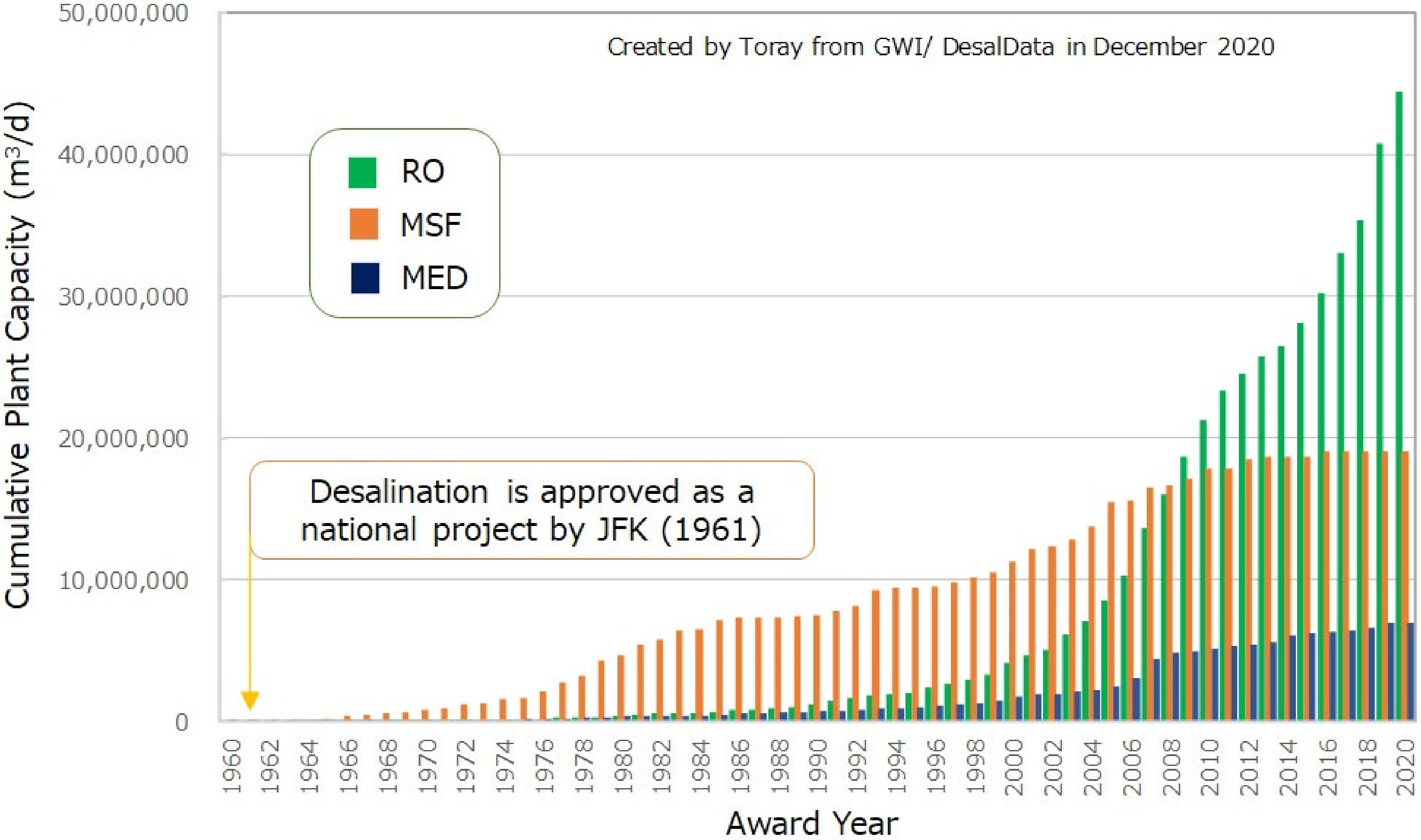
Boron Removal by MHI Original Process

Power : ST 340MW x 3, Boiler 1,080t/h x 3
Capacity : 216,000 m^3/day (13,500 m3/day x 16 trains)
Seawater salinity : 44,080 ppm as TDS
Product water quality : 14 ppm as Cl^- / 0.5 ppm as Boron
Plant Completion : Feb, 2011



2-1 History of seawater desalination plants

Technology transition from distillation to membrane



2-2 History of seawater desalination plants

Taweelah Independent Water Project, Abu Dhabi, UAE

WATER DESALINATION REPORT

Capacity: 909,000 m³/d

Area is equivalent to 50 soccer grounds

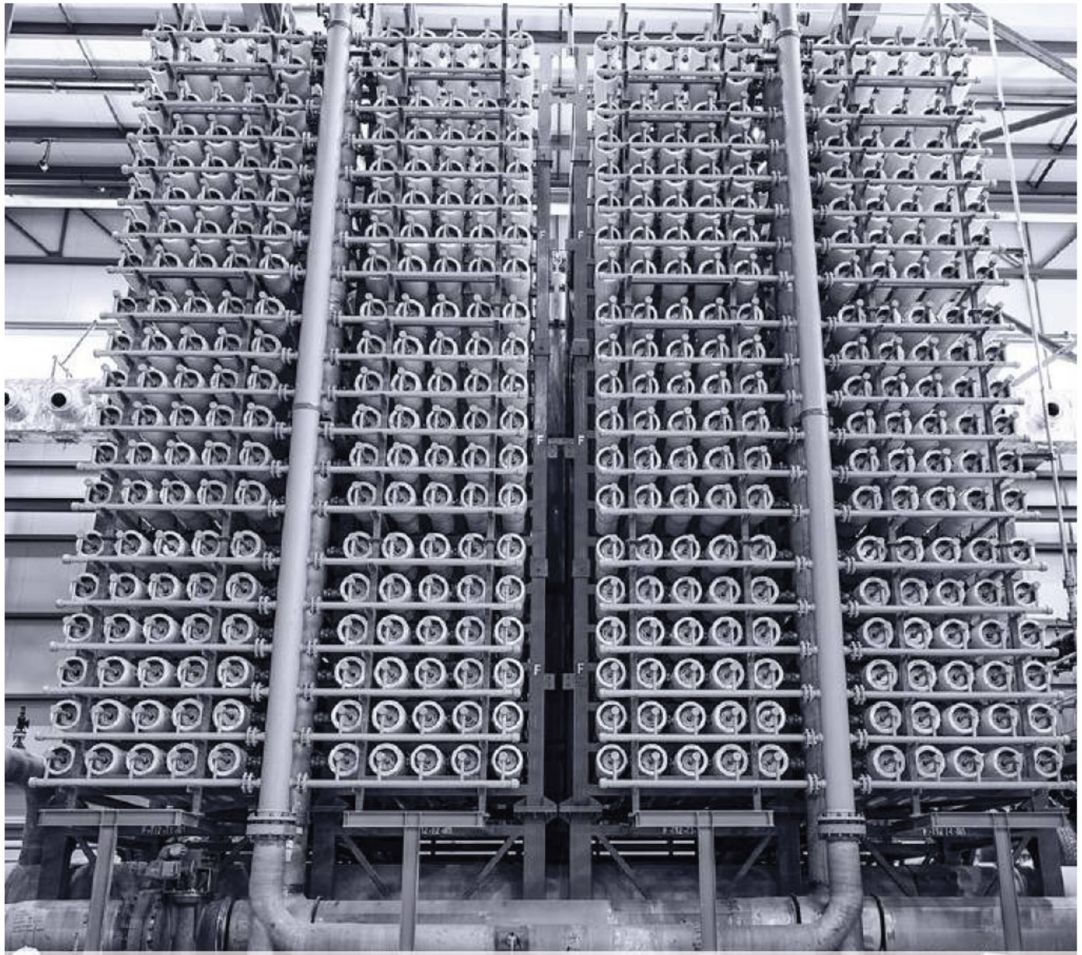
WDR Volume 57, Number 44, 13 December 2021

2-2 History of seawater desalination plants

TAWEELAH IWP, ABU DHABI

The world's largest operational membranedriven desalination plant, with an unprecedented capacity of 909,000m^3/d, located in the emirate of Abu Dhabi and capable of supplying potable water to more than 350,000 households. The seawater reverse osmosis (RO) plant features a 50MW onsite solar PV power generation facility and was delivered as an independent water project (IWP) under the build-own-operate model.

The Taweelah IWP was delivered by a development team comprising Taqa and Mubadala (60%) alongside ACWA Power (40%), with an EPC team comprising Abengoa (desal) and Sepco III and Power China (civil works) for the client, Abu Dhabi's Department of Energy. Toray supplied the plant with RO membranes for the ROPV pressure vessels, alongside Flowserve pumps, TALIS valves, ERI energy recovery devices, and a Siemens control system.



The Taweelah RO plant in Abu Dhabi is the largest membrane desalination installation ever to be built

Global Water Intelligence Magazine, p70, Volume 24, Number 3,March2023

2-3 History of seawater desalination plants

Latest Mega-SWRO Projects of over 400,000 m^3/d as of April 2023

No	Country	Project name	Capacity (m^3/d)	Award Year	Developer	Plant Supplier (Desal)	Membrane Supplier (RO)
1	SA	Jubail 2 Replacement Plant	1,000,000	2022	~EPC~	Metito	
2	UAE	Taweelah IWP	909,000	2019	Mubadala Development & ACWA Power	Abengoa	Toray
3	UAE	Umm al Quwain IWP	681,818	2019	ACWA Power	Veolia Sidem	Toray
4	Israel	Soreq 2	670,000	2020	IDE Technologies	IDE Technologies	DuPont W. S.
5	SA	Khobar 2 replacement SWRO	630,000	2019	~EPC~	Acciona Agua	LG Chem
6	Israel	Soreq	624,000	2010	IDE Technologies & Hutchison Water	IDE Technologies, Hutchison Water	Hydranautics / DuPont W. S.
7	SA	Rabigh 3 IWP	600,000	2019	Saudi Brothers & ACWA Power	Abengoa	Toray
7	SA	Rabigh 4 IWP	600,000	2023	ACWA Power, HAACO & Almoayyed		
7	SA	Jubail 3a IWP	600,000	2020	Gulf Investment & ACWA Power	Abengoa, Lantania	Toray
7	SA	Shoaiba 5 (SWCC)	600,000	2020	~EPC~	Advanced Water Technology	Toray
7	SA	Shoaiba 3 Conversion Project	600,000	2022	ACWA Power	Doosan Heavy Industries	
12	SA	Jubail 3b IWP	570,000	2021	ENGIE, Nesma Water & Ajlan Bros	Acciona Agua	
13	Algeria	Magtaa	500,000	2009	Hyflux	Hyflux	Toray
14	SA	Shuqaiq 3 IWP	450,000	2019	Marubeni, Acciona Agua & Almar Water	Acciona Agua	LG Chem
14	SA	Yanbu 4 IWP	450,000	2021	ENGIE, Nesma Water & Mowah	Doosan Heavy Industries	
16	Australia	Victorian Desalination Plant	444,000	2009	Thiess Contractors, Suez & Macquarie	Degremont	Hydranautics
17	SA	Shoaiba 4 (ex Jeddah 4)	400,000	2017	~EPC~	Doosan Heavy Industries	Toray
17	SA	Jubail 1 replacement SWRO	400,000	2020	~EPC~	Metito	
17	SA	Shuqaiq 4 (SWCC)	400,000	2020	~EPC~	Al Rashid Trading & Acciona Agua	
17	India	Chennai 4 (Perur)	400,000	2023	~EPC~	Metito & VA Tech Wabag	

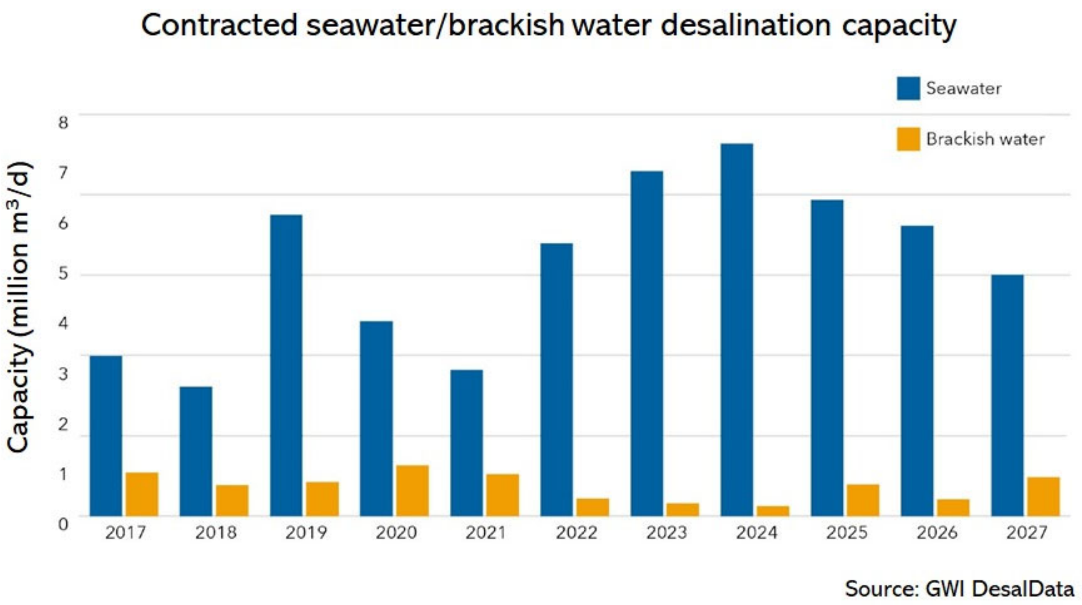
Note: Created by Toray based on GWI/DesalData

2-3 History of seawater desalination plants

Desalinated water price in Mega-SWRO and Desalination market forecast

• Rabihg 3	(Saudi Arabia)	600,000 m^3/d	$0.53/$m^3$
• Shuqaiq 3	(Saudi Arabia)	380,000 m^3/d	$0.51/$m^3$
• Taweelah	(UAE)	909,200 m^3/d	$0.49/$m^3$
• Jubail 3A	(Saudi Arabia)	600,000 m^3/d	$0.41/$m^3$
• Soreq 2	(Israel)	672,000 m^3/d	$0.40/$m^3$
• Hassyan	(UAE)	545,000 m^3/d	$0.39/$m^3$

Source: GWI/18 September 2018
GWI/WDR, 3 Dec 2018
GWI/DesalData, 23 January 2019



Source: GWI DesalData, Desalination market forecast, Desalination 2022 Q4 Market Update

3-1 Prof. kimura's contribution to the development of RO desalination

AIChE Journal Vol.13, No.3, 1967

Analysis of Data in Reverse Osmosis with Porous Cellulose Acetate Membranes Used

SHOJI KIMURA and S. SOURIRAJAN
National Research Council, Ottawa, Canada

Reverse osmosis experimental data for some inorganic salts with the porous cellulose acetate membrane used were analyzed to obtain their diffusivity in the membrane. A parameter including the diffusivity was found constant for each film in the concentration range investigated for a particular solute at a particular pressure. This parameter was also independent of feed flow rate. The effect of operating pressure on the parameter was found to depend on the film shrinkage. Mass transfer coefficient between the membrane and the feed solution was also obtained by the analysis, and this value was independently checked by the diffusion current method. Coincidence of these coefficients shows that the ordinary mass transfer coefficient can be used in reverse osmosis with the appropriate driving force. These facts facilitate the prediction of solute separation and membrane throughput rate in reverse osmosis.

ANALYSIS

The situation to be analyzed is shown in Figure 1. By the action of mechanical pressure applied, both the solute and the water tend to permeate the membrane. But because of the low value of the solute diffusivity in the

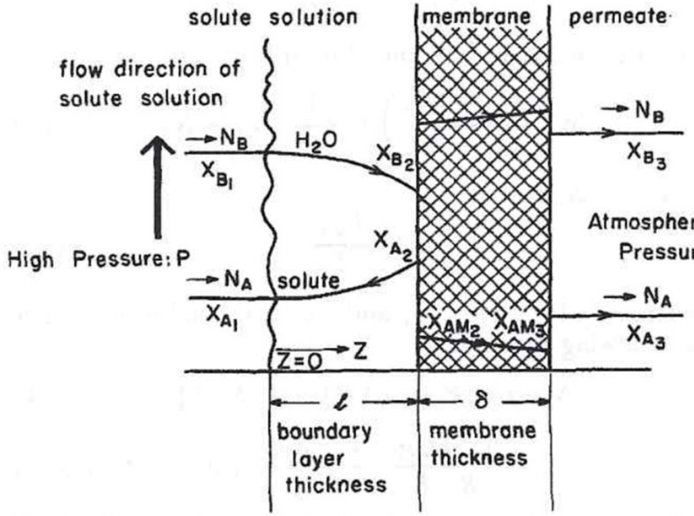


Fig. 1. Concentration distribution in the boundary layer and the membrane.

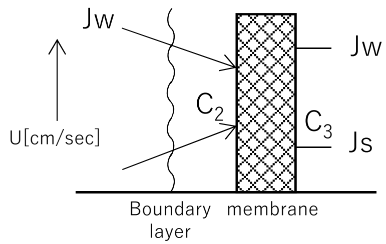
3-2 Prof. kimura's contribution to the development of RO desalination

Transport equations in microscopic parts of membrane (solution – diflusion type)

$Jw=A(\triangle P - \triangle \pi)$ A:Pure water permeability constant [mole・H2O/cm2・sec・at m]

$Js=B(\triangle C)$ B:solute permeability constant[cm/sec]

Concentration polarization in boundary layer and the membrane



$$\frac{C_2-C_3}{C_1-C_3}=e(Jv/k)$$

$Jv=Jw+Js\simeq Jw$

$k\propto u^a$

k:mass transfer coefficient [cm/sec]

u:velocity [cm/sec]

$a\simeq 0.6\sim 0.8$

Jw and Js are calculated given the operating pressure P, the predetermined concentration Cl and the velocity u

A=function (T, t, Fouling factor, etc.)
B=function (T, t, Fouling factor, etc.)
Both A and B value determined for each membrane

Prof Kimura's greatest achievement in RO plant's design was to organize the membrane transport equations in a simple and easy-to-understand form which has been very important thing for customers.

3-3 Prof. kimura’s contribution to the development of RO desalination

Advancedness of the Fukuoka Seawater Desalination Plant

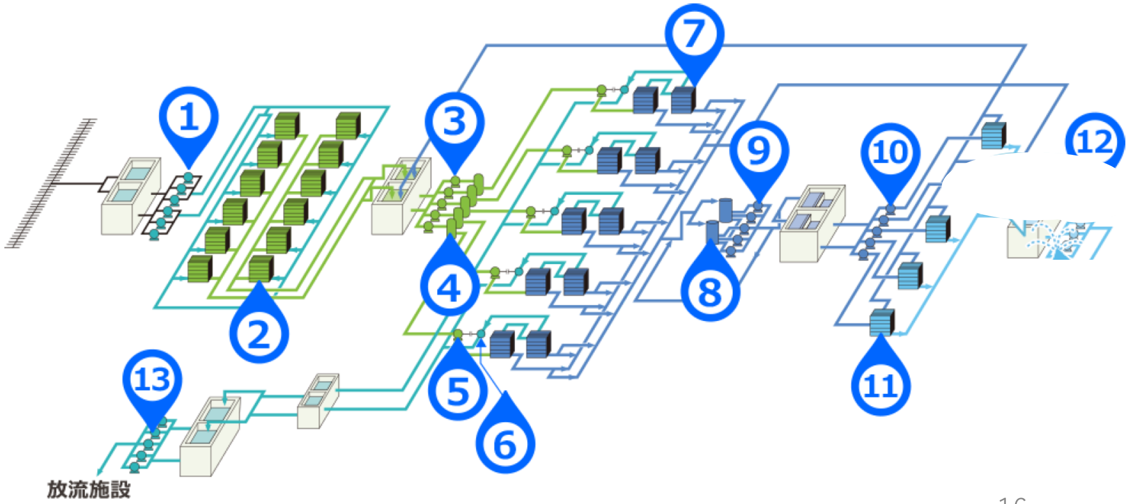
1) 60% Recovery Ratio
2) Infiltration seawater intake
3) UF + RO

1:Water intake pump
2:UF membrane unit
3:Filtered seawater pump
4:Cartridge Filter
5:High pressure RO pump
6:Power recovery device

7:Seawater RO membrane unit
8:CO_2 removal unit
9:Permeate transfer pump
10:Low pressure RO pump
11:Brackish water RO membrar
12:Product water transfer pumr

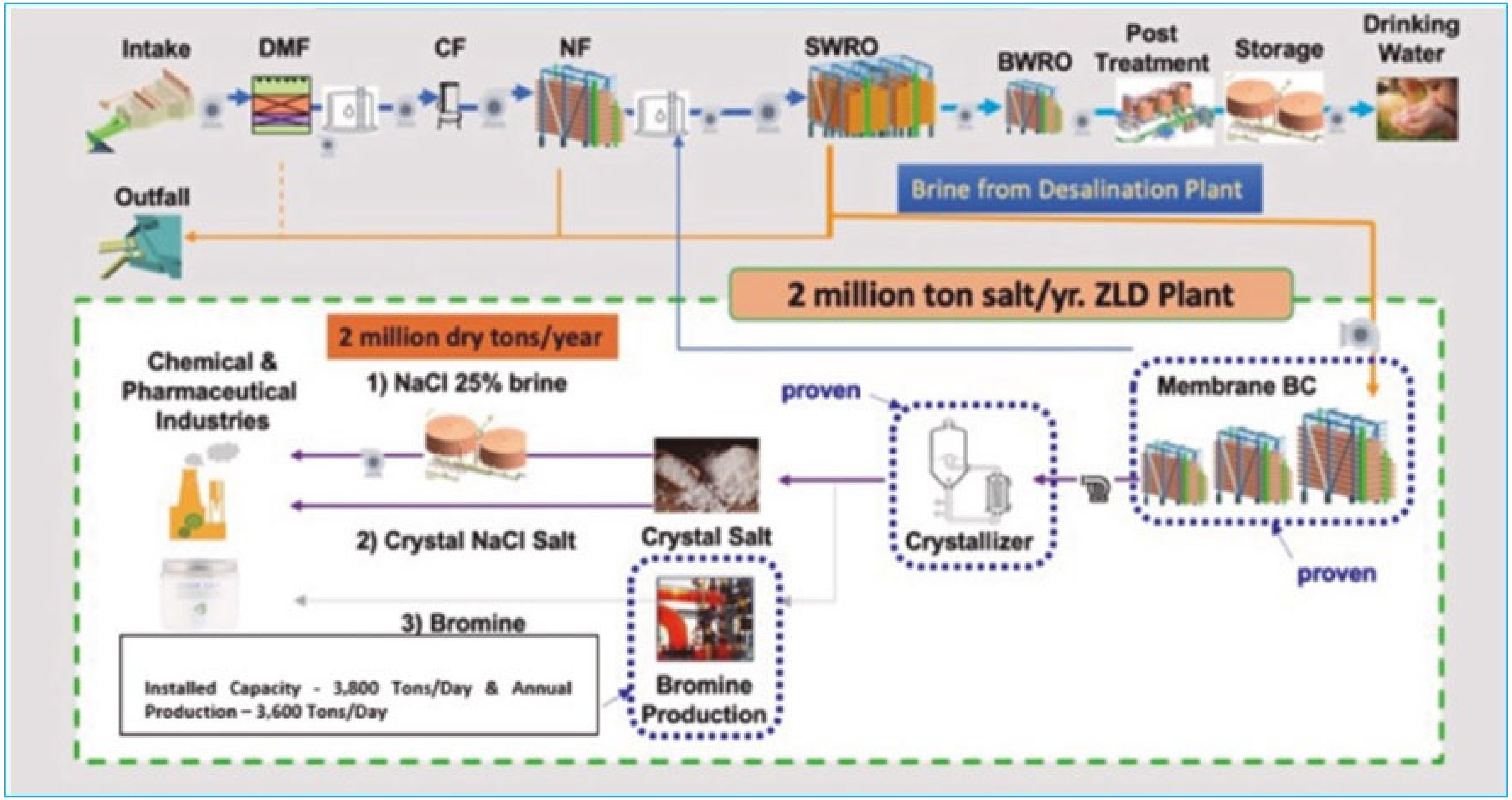
Seawater desalination plant overall flow

Introducing the desalination system.



4-1 Future Prospects of RO Desalination Plants

General Schematic of the Brine Mining Plant for NaCl and Br



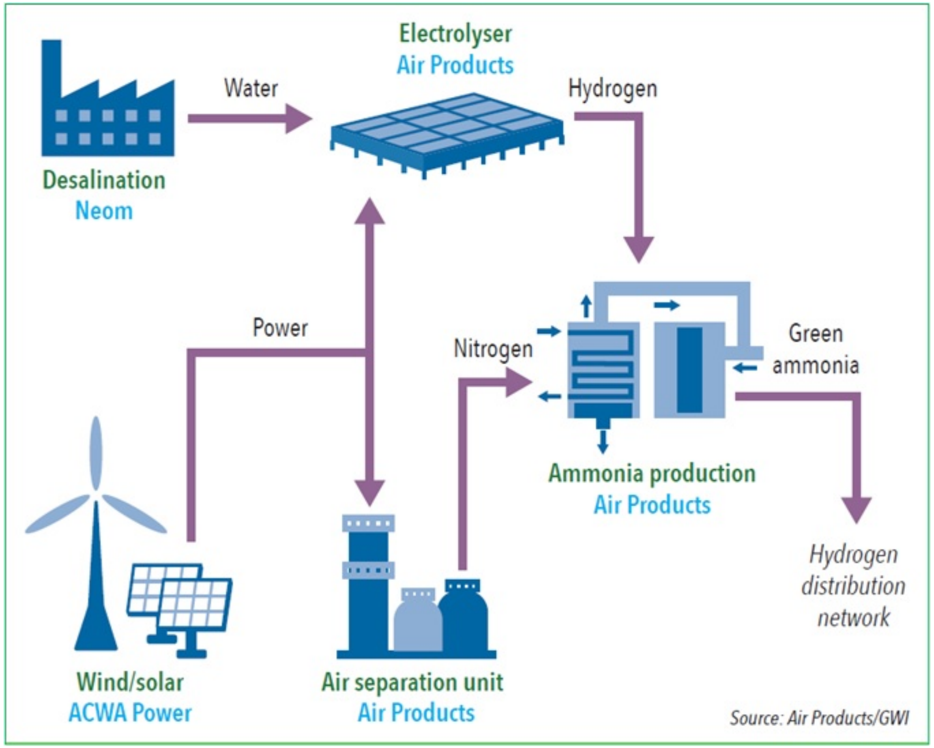
IDA GLOBAL CONNECTIONS, Fall, p21-24, 2021

4-2 Future Prospects of RO Desalination Plants

Smart City & Green Energy – NEOM in Saudi Arabia

Projected site of Neom development

BBC Feb.22, 2022



NEOM's future city desal, "a new model for urbanization and sustainability", which is related to water and green hydrogen for sustainable future.

GWI Magazine, 44, July 2020

5 Last Word

March 1995 , Final lecture

July 2018 , Group photo at Prof. Kimura's home visit

Thank you very much for your kind listening

Contact : hideo.iwahashi@japandesalination.onmicrosoft.com