MARKET MAP

Configurations and smart optimisation make the difference in advancing RO

The potential of radical material science taking reverse osmosis to new heights is yet to be realised, and other innovations are taking centre stage. Novel staging and arrays of RO, as well as digital solutions, are forging ahead to meet demands of higher recoveries.

As hype around radical new material science for reverse osmosis starts to tone-down, methods of optimisation and new configurations are instead taking centre-stage, shaking up the RO water production market.

With the majority of radical material science developments being held up by obstacles in up-scaling and meeting required salt rejection, the main suppliers in the RO market are focusing on optimisation rather than overhaul, while novel system configurations such as semi-batch RO are seeing increasing commercial traction. There is also potential for these configurations to see growth beyond brackish water applications, where most efforts have been to-date, and see entry into the SWRO market.

These configurations are more evolutionary than revolutionary and make use of proven technologies and off-the-shelf components, focusing on achieving higher recovery, high reliability, and greater flexibility with the least radical changes. With the world's largest private desalination developer ACWA Power also adopting an R&D focus on RO process optimisation with data and machine learning, it is a good time to ask: what do the next few years hold for optimisation of this vitally important and widespread water production technology?

In the highly competitive market for RO desalination, strong opportunities exist for those who can provide reliability, efficiency, flexibility, and customisability in their solutions.

Drivers for process optimisation

From a technical performance perspective, the maximisation of recovery rates is one of the most promising, and fastest growing areas of RO development, and a key target for new RO configurations. Demand for higher RO recovery rates stems strongly from the industrial sector, with reductions in water abstraction and wastewater volume being the key drivers. In the seawater and brackish water desalination markets too, higher recovery rates have strong drivers. Increased recovery allows for downsized intake and pretreatment systems, reducing total system capex, and a report released by GWI DesalData in June 2020 found that higher recovery rates have played a key role in bringing down EPC prices to record low levels at SWRO plants in the Middle East.

Of the configurations that aim to address this and increase recovery rates, there are two primarily seeing current growth in the market: semi-batch configurations and high-pressure RO.

Semi-batch surge

In a semi-batch process, feedwater is ▶

READINESS OF RO DEVELOPMENTS

Graphene and carbon nanotube based membranes have yet to make any commercial entrance in the RO market and there is no clear indication as to when, or if, this will occur. However, aquaporins developed by eponymously named Aquaporin A/S are seeing some commercial traction in small-scale point-of-use applications and brackish water applications. Meanwhile, the most mature and immediately promising developments are configurations and digital innovations which aim to optimise the RO process rather than overhaul it.

Innovation	Brackish water market	Seawater market	Readiness level
Machine learning software	Well established with numerous references (particular SW focus)		**TRL 9:** Actual system proven in operational environment
DTRO	Established in niche application	No market	
Closed Circuit RO	Well established with numerous references	Currently seeing potential for market entry	
3D-printed membrane spacers	Early-stage with a few small-scale references	Pre-commercial	**TRL 8:** System complete and qualified
CFRO	Established with few references	Early stage but growing numbers of references	
Semi-batch RO	Early-stage with a few small-scale references	No market. Potential market entry if CCRO is successful	
Spiral-wound UHPRO	Early-stage with a few small-scale references	Early stage	
The Barrel	Not the main focus	Early stage pilot testing	**TRL 7:** System prototype demo in operational environment
Aquaporins	Early-stage with a few small-scale references	Pre-commercial	
Chlorine-tolerant membranes	Pre-commercial		**TRL 6:** Technology demonstrated in relevant environment
Graphene-based membranes	Pre-commercial		**TRL 4:** Technology validated in lab
Batch RO	Pre-commercial		
3D-printed TFC membranes	Pre-commercial		**TRL 3:** Experimental proof of concept
Carbon nanotube membranes	Pre-commercial		

Source: GWI

passed normally through the membrane but is then cycled back to the start of the stage where it mixes with a continuous feed stream. Circulation continues until desired recovery or reject conditions are met, when the system is flushed to begin a new batch. Semi-batch RO makes recovery a function of the time each batch is run for, rather than of the number of physical stages. Whereas a conventional, continuous RO plant might need multiple stages to reach the desired recovery, a semi-batch system may have just one. This offers a number of advantages including more customisable recovery, better flux distribution, stronger resilience to fouling and scaling through salinity and pressure cycling, and greater flexibility to variable feedwater conditions This makes semi-batch processes particularly suited to brackish water and wastewater applications where feedwater conditions can vary significantly. Current examples of semi-batch configurations include Desalitech's Closed Circuit Reverse Osmosis (CCRO) and IDE Technologies' MAXH2O Pulse-Flow RO (PFRO).

Semi-batch RO is seeing growing numbers of commercial references, particularly in BWRO and industrial applications, where there tends to be lower resistance to new technologies. "In brackish and industrial markets, plants are often smaller so owners feel more comfortable experimenting with new technologies," observed Rick Stover, Gradiant's VP of Technology.

These plants are typically awarded on the basis of total cost of ownership, where new technology usually has a better chance than in the multi-bid-round approach used by many municipalities where new technologies can meet technical qualifications but are knocked out on capital cost.

Among semi-batch developments, CCRO in particular has seen the most widespread commercial success, with more than one hundred references in various brackish water and industrial applications, particularly in the food and beverage sector, and more recntly, the oil & gas and mining sectors. Historically, Desalitech has focused on these markets for CCRO, with the typically large-scale plants in the seawater market driving strong conservatism that has impeded commercial traction of new technologies in that space. However, earlier this month, Singapore's national water agency PUB awarded a three-year grant to DuPont Water Solutions, Desalitech's parent company, to investigate the potential of CCRO in improving the efficiency, flexibility, and reliability of seawater desalination. DuPont has said this grant could enable it to further optimise CCRO's value for the SWRO market, a statement echoed by Mike Boyd, regional director at Desalitech, in an interview with GWI.

The grant marks a step towards opening the door for future opportunities in the seawater desalination space and performance of the CCRO system will be keenly observed by the industry. Speaking to GWI, DuPont's global technology director for water solutions, Gary Xuqing Gu, highlighted the membrane supplier's interest in the semi-batch approach: "We're excited about the synergistic benefits and potentials we can bring to the customers through combination and optimisation of membranes, elements, and process innovations under CCRO conditions."

Desalitech has recently completed its first large-scale BWRO plant, with a capacity exceeding 10MGD (37,854m^3/d), at a per- and polyfluoroalkyl substances (PFAS) mitigation project in Alabama. Although at a smaller scale, IDE Technologies is also seeing commercial traction with its PFRO design receiving a contract award in late 2020 for a 5,450m^3/d high-recovery system as part of Cherokee Metropolitan District's water reuse project. Although they will not fully replace continuous RO configurations anytime soon, with growing uptake in the wastewater reuse and industrial sectors, high suitability for the challenges of BWRO, and the potential to break into the large SWRO market, the future opportunities look bright for semi-batch.

While not a semi-batch process, Rotec/AdEdge's Flow Reversal RO design (FRRO) which also uses a novel configuration to increase recovery and avoid fouling, has too seen early commercial traction. Rotec/AdEdge have had a small-scale FRRO installation operating at an undisclosed US industrial plant since mid-2020.

Batch to the future?

In a batch process, feedwater is stored ▶

THE DYNAMICS OF THE RO MARKETS

Opportunities for new RO technologies particularly lie in the brackish and industrial spaces where the markets are less hostile to new developments, while seawater applications hold strong potential for digital optimisation.

Brackish water	Seawater
Innovation obstacles	
• Projects often gated by engineering companies with a preference for legacy technologies.	• Typically more risk averse due to generally larger plants.
Innovation opportunities	
• Often smaller projects mean greater comfort with experimentation. • Strong variability of feedwater chemistry is an opportunity for flexible processes like semi-batch RO. • Importance of brine disposal costs make high recovery an important goal.	• Typically larger, more energy intensive plants offer strong opportunities for digital optimisation.

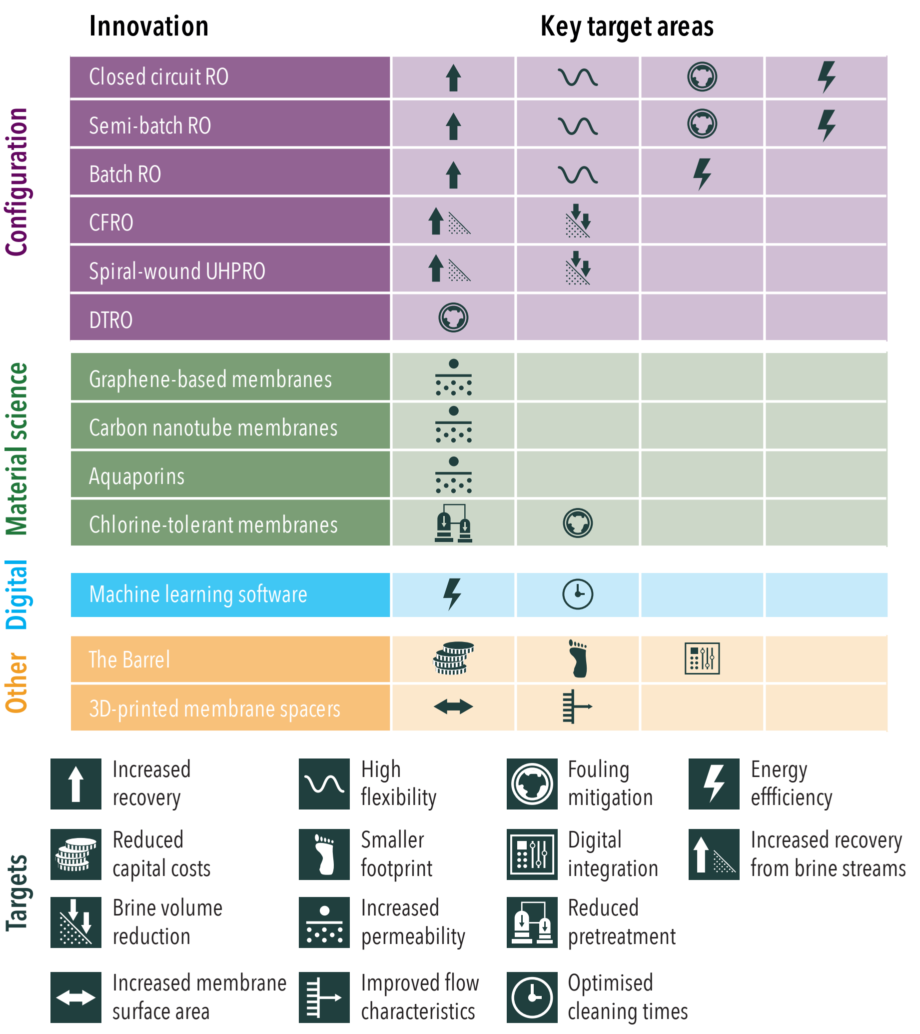
Municipal	Industrial
Key market dynamics	
• Common approach of an initial round of technical solicitations followed by a second round only considering price favours the lower initial cost of legacy technologies.	• Many industrial plants are awarded on total cost of ownership, which new technology usually has a better chance in. • Fiercer competition and greater emphasis on cost reduction, drives faster uptake of machine learning. • Importance of brine disposal costs make high recovery an important goal.

Source: GWI

> "In brackish and industrial markets... owners feel more comfortable with new technologies.
>
> Rick Stover, Gradiant Corporation

THE KEY AREAS OF IMPROVEMENT

Reverse osmosis is seeing development in multiple areas with higher recovery rates, fouling mitigation, flexibility, and increased energy efficiency being key targets for improvement.



Source: GWI

in a feed tank, is passed through the RO membrane and is then cycled back through the feed tank and membranes again until the desired percentage of water is recovered. Theoretically, batch RO has the potential to offer high recovery while reaching the lowest practical energy consumption of any RO configuration. However, it is at a much earlier stage of development and still has mechanical challenges to be addressed. Currently, development of batch RO is being pursued by MIT spin-off, Harmony Desalination, which is designing a system with a variable-volume bladder to pressurise the feedwater. The technology is also seeing progress at the academic level. Three papers have been published since February this year, proposing promising new designs for batch RO systems.

Increasing the pressure

In contrast to batch and semi-batch processes, ultra-high pressure RO aims to achieve higher recovery rates and reduce concentrate volume by increasing the pressure of the process. Traditional RO has a maximum operating pressure of up to 1200 psi, which is a limiting factor to further increasing recovery. By contrast, ultra-high pressure RO, which can operate at pressures more than 40% higher, at up to 124 bar (1800 psi), allows more feedwater to be squeezed through the system and for a higher recovery rate to be achieved. As well as its potential for improving technical performance, UHPRO also has the advantage that it can be used as a "bolt-on" process. UHPRO can be added as a module to an existing plant that needs higher recovery, without the need for a plant redesign, or additional pretreatment or intakes.

UHPRO has existed for many years now, with a focus on small-scale brine concentration and niche industrial applications such as leachate treatment using a novel disc-tube (DTRO) configuration. However, UHPRO that utilises modern high-pressure spiral-wound membranes and energy recovery with the goal of increasing fresh water production, is a new development of the last few years that has only seen a small number of commercial references so far, primarily in industrial applications such as the food and beverage sector. However, modern UHPRO is now seeing increased interest in the market with several new approaches to the technology targeting municipal and potable water industrial applications.

With the much higher pressures involved, the UHPRO process demands more durable and resilient membranes than conventional RO. However, unlike material science developments that aim to replace polyamides, such as graphene-based membranes, UHPRO membranes do not demand a revolution in membrane chemistry, and still fundamentally use the same polyamide design. UHPRO membranes are offered or under development by almost all membrane companies with Hydranautics, Toray, and DuPont taking the lead. Hydranautics' membranes were used in North America's first commercial UHPRO installation, in Canada-based Saltworks' XtremeRO UHPRO system.

Two energy recovery companies ▶

Mitigating fouling

Resistance to biofouling is another target for some of the novel system configurations under development in the market. In the case of semi-batch processes, the mixing of concentrate with feedwater results in very high salinities which have a damaging effect on organisms in the feedwater, reducing the chance of biofouling.

Meanwhile, mitigation of scale-formation in high-salinity waters is also a target for configurations. CFRO, Flow Reversal RO and PFRO all aim to kinetically resist scale-formation by cycling the system more quickly than the induction time of scale formation. This allows operation with higher salinity feedwater while avoiding fouling.

have also shown activity in the UHPRO space: FEDCO and Energy Recovery Inc. (ERI). FEDCO's multi-stage, multi-turbo (MSMT) system operates by using turbochargers as booster pumps with the aim of increasing recovery. MSMT saw its first commercial reference in 2019, using Hydranautics high-pressure membranes, a 360m^3/d SWRO plant in Mexico that operates at 60% recovery. Meanwhile, ERI has just introduced its Ultra PX energy recovery device (ERD), which operates similarly to ERI's standard PX ERD but at pressures of up to 120 bar. ERI is targeting both high recovery SWRO, and ZLD markets in China and India, and has already seen orders for several industrial installations. Use of UHPRO has also been made more viable with the approval in 2021 of a new 'Code Case' by the American Society of Mechanical Engineers (ASME), meaning UHPRO systems will soon be able to use ASME validated pressure vessels.

However, although increased recovery rates reduce capex by cutting down the size of required intakes and pretreatment, the higher energy demands of UHPRO mean that the value offered varies from case to case. The best value is offered in areas with high water scarcity or high brine disposal costs, where high recovery is most important.

What of CFRO?

Alternatively, developments such as Gradiant's CFRO offer another method for increasing recovery rates by "bolting-on" to an existing brine stream. Similarly to UHPRO, CFRO has historically been a technology focused on applications where brine minimisation was the primary goal. However, from 2019 to 2020, Gradiant used their CFRO technology at Sawaco's South Jeddah Corniche (SoJeCo) SWRO plant in Jeddah, Saudi Arabia, to treat the brine stream with the goal of increasing overall system recovery. On the back of the data collected from the demonstration unit, two full-scale units are now under construction with a combined production capacity of 5,000m^3/d of potable water, and Gradiant has an extensive sales pipeline lined up to increase recovery for numerous further SWRO projects both inside and outside Saudi Arabia.

"Increasingly, we are seeing demand for brine treatment in seawater desalination," Stover observed to GWI. "At existing seawater facilities, we can increase permeate output without new intake or pretreatment works. For new SWRO facilities, membrane brine concentration has made recovery rates of 60-75% viable, shifting long-standing design paradigms."

Integrating AI and big data

Optimising RO is not just a matter of improving process design and overcoming technical performance challenges but also of using a system in an intelligent and informed manner. Extensive data collection and machine learning integration are two areas that are currently an important opportunity for improving RO plant performance.

With the wide range of feedwater conditions found in desalination, and the otherwise unattainable level of optimisation offered by machine learning and predictive analytics, there are strong opportunities for those who can offer effective and easy to use optimisation software. Canadian firm Synauta for example has adopted an approach of desalination software-as-a-service, using machine learning to provide daily set points and recommend cleaning times while integrating with existing SCADA systems. Synauta aims to reduce both energy and chemical usage by as much as 20% and has already seen energy savings of 9.7% over a six month period at a 4,000m^3/d SWRO plant in Australia. Pani Energy, meanwhile, uses cloud-based machine learning software to provide real-time guidance to a plant's O&M teams, and reduce opex and downtime.

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>
> Mike Dixon, Synauta

Going forwards, the market for digital technologies and machine learning in RO looks set to see strong growth. Speaking to GWI, Synauta's CEO Mike Dixon anticipated that: "In 5-10 years, there will be a lot less guesswork for owners and operators about their plants. Data will be more accessible and people in the industry will have more awareness of how to leverage machine learning and IoT to augment ▶

WHO ARE THE INNOVATING PLAYERS?

Innovations in RO are under development by a number of players from major equipment suppliers to start-ups pursuing more radical approaches such as aquaporins and 3D-printed spacers. The development of graphene and carbon nanotube-based membranes in RO water production applications, however, remains limited to academia. Although New York-based Mattershift was previously engaged in scaling up CNT membranes for seawater desalination, it has since shifted its focus to other areas.

	Innovation	Key players
Configuration	Semi-batch RO	Desalitech (DuPont), IDE Technologies
	Batch RO	Harmony Desalination
	CFRO and FRRO	Gradiant Corporation, Rotec/AdEdge
	UHPRO membranes	DuPont, Hydranautics, Toray
	UHPRO ERD	ERI, FEDCO
Material science	Aquaporins	Applied Biomimetics, Aquammodate, Aquaporin A/S
	Chlorine-tolerant HF membranes	NALA Systems, Toyobo
Digital	Machine learning software	Pani Energy, Synauta
	Smart connector	Veolia Sidem
Other	The Barrel	Veolia Sidem
	3D-printed membrane spacers	Aqua Membranes

Source: GWI

their roles. In a similar timeframe there will be a filtering of what machine learning and IoT technologies are delivering business wise and how they are able to be deployed at scale."

Currently, both BWRO and SWRO markets are seeing machine learning uptake, with large-scale, high-energy usage SWRO plants offering particularly strong opportunities for the opex savings provided. "We're seeing a lot of traction with large SWRO plants – when energy costs are 40-60% of your opex you want to find savings," observed Dixon. Meanwhile, fiercer competition and a greater emphasis on cost reduction is driving faster uptake in industrial markets compared to municipalities.

However, to get the most out of AI, sufficient data is required, otherwise a machine learning process has nothing to learn from. The value of data and efficient machine learning in optimising RO is such that the development of new sensors to provide better data collection is a key R&D focus of the worlds' largest private desalination developer, ACWA Power in its collaboration with KAUST. Speaking with GWI, ACWA Power's VP of Innovation & Water Technology Thomas Altmann highlighted the importance of getting this right in the desalination sector: "Deploying AI in highly complex desalination plants requires foresight and planning and can't be a spur-of-the-moment decision. Without plenty of quality data for the key parameters, the plant is at risk of becoming less efficient because the algorithm may be selected and tuned based on inaccurate or insufficient information." One notable development in this area is Veolia Sidem's Barrel approach, which uses a smart interconnector between elements, allowing for permeate salinity and temperature to be digitally measured for each individual element.

It is also important to have data in a usable state. "I would say further development is needed by plants to get their data healthy and collected in a format that makes it machine learning ready," noted Dixon. "There are still many plants wrestling with unwieldy Excel sheets, which we want to help transition away from."

The art of flexibility

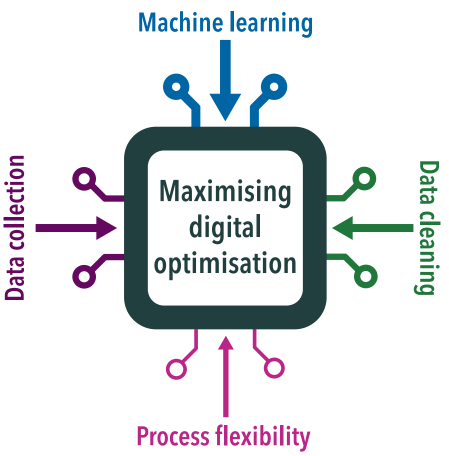
Another angle to getting the most out of machine learning is process flexibility and fine control. Although not a requirement for the use of machine learning, processes that offer adaptability in their operation, along with easily fine-tuneable metrics, can allow software to more effectively make the changes it needs to. "More flexible RO plants in general should see better savings when using machine learning," Dixon observed. "In plants with maximum flexibility we see closer to 10% energy savings, while in plants with less flexibility, for instance with no VFDs and older energy recovery devices, the energy savings might be more like 5%. Systems like batch and semi-batch RO might see even more enhanced savings given they can have more flexibility."

This is a key driver in the development of new configurations across the market and an important long-term advantage of semi-batch RO. Desalitech's Mike Boyd highlighted this to GWI, stating: "The biggest value in CCRO is the ability to use standard components while harnessing the power of big data and IoT software to drive efficiency, reliability and overall performance."

Semi-batch processes such as Desalitech's CCRO configuration have a number of features that offer increased control and customisability, and open the door for future advances in digital technology and AI. One of these features is having dedicated components for each typical design metric. "The [CCRO] system decouples recovery, flux rate and crossflow, which are all independently controlled. As a result each metric can be easily fine-tuned, allowing for greater control and optimisation of the system," explained Boyd. Combined with the ability of semi-batch processes to adjust recovery as a function of time, this approach allows for real-time adjustments to varying feedwater conditions. Currently, Desalitech's standard CCRO products use an IoT based software, however future plans will fully integrate AI. "The holy grail is a self-learning RO system that has the team's knowledge built into it," said Boyd.

KEY TO DIGITAL DESAL

Digital optimisation of an RO plant is not a one-step process. Alongside the invaluable machine learning software, having sufficient, clean data is crucial to making best use of it, while a flexible process enables maximum effect.



Source: GWI

> "I have some doubt that current polyamide-based chemistry will achieve the goal [of chlorine tolerance]. We may need totally different membrane chemistry.
>
> Hoon Hyung, LG Water Solutions

Chlorine tolerant membranes

Biofouling mitigation is an important area for RO. One key approach to addressing biofouling is to improve the chlorine resistance of the membrane to make the use of chlorine as a biocide more cost effective. "Chlorine tolerant membranes, even with slightly poorer permeability or rejection than current polyamide membranes, could be the holy grail of RO," enthused Hoon Hyung, head of LG Water Solutions.

Currently there are several companies pursuing new chlorine resistant membranes. However, none have seen commercial application yet. Toyobo has offered a chlorine tolerant hollow-fibre cellulose triacetate (CTA) membrane for over 30 years. Although the CTA does allow the use of chlorine, its low flux with correspondingly higher energy requirements, greater pretreatment requirements, and lack of interchangeability with the industry standard 8-inch spiral-wound elements have greatly limited its use. However, US-based startup NALA Systems is currently developing a chlorine resistant membrane based on a novel polymer, and is looking to install pilot-scale production equipment in the near future.

In the longer term, chlorine resistance is also an area where a more radical approach to membrane chemistry may offer advantages. "I have some doubt that current polyamide-based chemistry will truly achieve the goal," Hyung told GWI. "We may need totally different membrane chemistry.

Carbon nanotube or graphene-based membranes might be an option to overcome the issue but I think there is a long way to go before the technology could be ▶

commercialised and applied at industrial scale."

One approach that could offer a smoother, less disruptive market entry for these more radical innovations is in their use as additives to existing membrane chemistry. "We would embrace these technologies and support their industrial explorations and commercialisation. They won't necessarily blow away the existing polyamide-based TFC membranes but it would be possible to use them as additives to the membrane structure" said DuPont's Gu. One example of progress from this angle is a patent, submitted in mid-2020 by Nitto Denko for a chlorine tolerant membrane using a protective graphene oxide coating. Although this approach is still far from being market-ready, chlorine tolerance is an area where use of more radical developments like graphene as additives could have potential.

> "We would embrace these technologies and support their industrial explorations and commercialisation. They won't blow away the existing polyamide TFC-based membranes but it would be possible to use them as additives to the membrane structure.
>
> Gary Xuqing Gu, Dupont Water Solutions

Form factor and project delivery

Not all the approaches to improving RO focus on improvements to technical performance. One of the most promising RO developments is a shift in project delivery approach. 'The Barrel' from Veolia Sidem represents a novel approach to RO that focuses on standardisation. The Barrel utilises conventional components in a traditional continuous configuration but aims to provide a self-contained, factory assembled package. The market for such a standardised approach looks to primarily lie with mid-to-large sized systems where standardisation can most meaningfully reduce complexity and capital cost.

The Barrel could also offer a potential new future for an older RO development. Historically, larger RO elements were considered a promising future for desalination. 16" elements in particular, with their much higher effective per-element membrane area, looked to offer strong advantages in both capital and lifecycle cost. However, there are several difficulties that prevented widespread adoption of 16" elements. Firstly, 16" elements require the same tooling as 8" elements, meaning that production comes at the cost of capacity for the proven 8" design. Secondly, the increased weight of the elements makes them difficult for plant workers to handle. Thirdly, the larger pressure vessels required a significant increase in capital cost. An approach like The Barrel has the potential to nullify some of these drawbacks, particularly issues of pressure vessel size, and could allow for an efficient and cost-effective way to utilise the benefits of larger RO elements. If this would prove to be a successful combination, this could give a new lease of life to larger-sized RO elements and open the door for renewed opportunities for the companies that offer them.

Smaller membrane spacers offer a further route by which to optimise the form factor of an RO system. Efficiently designed thinner spacers can allow for more membrane to be packed into the same volume, thereby reducing overall system footprint. DuPont's Gu gave GWI his view on the potential of spacer innovation: "We see promising opportunities from new spacers, such as those created by 3D printing. Element designs may benefit from increased membrane packing density and improved element efficiencies. These spacers can also impact operational costs for customers through reductions in organic fouling, biofouling, and scaling. The challenge is to scale up the 3D printed spacers and achieve a cost of manufacturing that reaches the inflection point for disrupting conventional spacers."

3D-printed membrane spacers are currently under development by US-based Aqua Membranes. Additionally, 3D printing is not limited to membrane spacers; research underway at the University of Connecticut shows that 3D printing may offer some performance advantages in manufacturing full-size polyamide membranes, and Singapore's Nanosun has already developed 3D-printed MF membranes although they are still at an early stage. ■

Terminology

Aquaporin membrane: A membrane process that uses membrane proteins that selectively conduct water molecules in and out of a cell.

Biofouling: A process where microbial cells in feedwater become attached to the membrane surface, forming a biofilm that impedes membrane performance and lifespan.

Brine concentration: An application where the goal is to maximise concentration of dissolved solids in the brine stream of a treatment process, primarily with the goal of reducing volume for disposal.

Carbon nanotube membrane: Process that aims to utilise the narrow diameter of carbon nanotubes to permit free water flow, while excluding larger molecules.

Graphene membrane: A novel membrane process that utilises graphene-oxide with very fine pores as the membrane element. When feedwater is passed through these membranes, nanoparticles and dissolved salts are filtered out.

IoT: The concept of connecting any electric device with an on and off switch to the Internet, and consequently, to each other.

Machine learning: The science of training computers to improve their learning over time in autonomous fashion by feeding them data and information in the form of observations and real world interactions. Machine learning makes computer processes more efficient, cost effective and reliable.

Polyamide: A molecular chain polymer made of amide linkages used in the construction of thin-film composite reverse osmosis membranes.

Recovery: In reverse osmosis processes, recovery indicates the amount/percentage of product water recovered from the feed stream.

Reverse osmosis: A method of separating water from dissolved salts by passing feedwater through a semipermeable membrane at a pressure greater than the osmotic pressure of the feed solution.