# Forward Osmosis Applied to Evaporative Cooling Make-up Water

*Peter Nicoll, Neil Thompson, and Victoria Gray*


## ABSTRACT

Modern Water is in the process of developing a number of forward osmosis based technologies, ranging from desalination to power generation. This paper outlines the progress made to date on the development and commercial deployment of a forward osmosis based process for the production of evaporative cooling tower make-up water from impaired water sources, including seawater.

Evaporative cooling requires significant amounts of good quality water to replace the water lost by evaporation, drift and blowdown. This water can be provided by conventional desalination processes or by the use of tertiary treated sewage effluent. The conventional processes are well documented and understood in terms of operation and power consumption. A new process has been successfully developed and demonstrated that provides make-up water directly, using a core platform 'forward osmosis' technology.

This new technology shows significant promise in allowing various raw water sources, such as seawater, to be used directly in the forward osmosis step, thus releasing the use of scarce and valuable high grade water for other more important uses. The paper presents theoretical and operational results for the process, where it is shown that the process can produce make-up water at a fraction of the operational expenditure when compared to conventional processes, in particular regarding power consumption, which in some cases may be as low as 15 % compared to competing processes. Chemical additives to the cooling water (osmotic agent) are retained within the process, thus reducing their overall consumption. Furthermore the chemistry of the cooling water does not support the growth of *Legionella pneumophila*. Corrosion results are also reported.


## INTRODUCTION

The use of evaporative cooling towers is set to increase across the world, driven by both economic and environmental concerns, with a corresponding increase in the demand for make-up water. Usually, this make-up water needs to be of high quality and, where there is an appropriate supply, this water has traditionally been supplied from rivers and mains water supplies, depending on the geographical location. Where these sources are not available, or not available in sufficient quantity, the cost of providing suitable make-up can be costly both in energy and financial terms. This can prevent the installation of an evaporative cooling system in a particular location. Make-up water has also been provided directly as seawater and more recently treated sewage effluent.

In the Middle East region, water for evaporative cooling has mainly been supplied using desalinated water, with the occasional use of seawater when the infrastructure and physical location of the site were suitable. As the waste water infrastructure has developed and with the ever increasing demands on desalinated water, treated sewage effluent has become one of the favoured sources for make-up water. This is particularly prevalent in the district cooling sector, where for instance in Dubai [1] and Abu Dhabi, legislative changes prohibit the use of mains supplied water for new installations.

In California the use of open seawater intakes for once-through cooling of power stations is being actively discouraged [2], primarily driven by the need to protect the marine environment, leading to some debate about suitable economically viable alternatives.

It is in this climate, with increasing demands on our resources, that a new and ground-breaking technology has been developed for the preparation of make-up water from impaired water sources, ranging from seawater to treated sewage effluent. This process uses forward osmosis, a low pressure and low energy process, to produce desalinated/permeate quality make-up water. This new technique allows the economic use of water sources that otherwise would not be considered for make-up and therefore extends the applicability of evaporative cooling and just as importantly allows desalinated water substitution, thus freeing up valuable potable water or treated sewage effluent for more appropriate use.

## FORWARD OSMOSIS

In order to explain the process, first let us consider the principles of manipulated osmosis. In the industry most people are familiar with reverse osmosis (RO), where high quality permeate is separated from a feed solution such as seawater or brackish water by a selectively permeable membrane. When the hydraulic pressure of the feed is greater than its osmotic pressure (a property of the solution), essentially pure water flows through the membrane. It can then be collected and used for various purposes, the most common application being the production of fresh water suitable for human consumption or irrigation. This is a high-pressure, high-energy process.

"Forward osmosis", "manipulated osmosis" or just "osmosis" are the terms used to describe the natural phenomenon whereby a solvent flows from a region of lower osmotic pressure across a selectively permeable membrane to an area of higher osmotic pressure (Figure 1). A good example of this in nature is the mechanism whereby plants take up moisture in their root systems and become turgid.

We can manipulate two fluids with differing osmotic pressures to exploit this natural phenomenon so that, for instance, we can make essentially pure water flow out of seawater across a selectively permeable membrane to dilute a solution with a higher osmotic pressure. It is important to note that this process takes place without any significant applied pressure, all that is required is to overcome the frictional resistance on either side of the membrane (typically 2–3 bar). This is markedly different to the case for reverse osmosis, where very high pressures may be applied, generally up to 83 bar. High osmotic pressure solutions may be made safely and easily, without any impurities or foulants, by dissolving in water a suitable salt or combination of salts, of which there are many.

Successful "real-world" applications of this phenomenon are emerging. One example of these applications has been developed by Hydration Technology Innovations (HTI) in the USA. HTI's emergency sugar drink [3] can be produced from contaminated water simply by placing a pouch fabricated from a selectively permeable membrane in the available water. The sugar solution inside the pouch has a high osmotic pressure and, over time, clean water flows from the contaminated side to the sugar side to produce an energy drink. Two examples on an industrial scale are Modern Water's multi-patented manipulated osmosis desalination process, which produces drinking water [4], and evaporative cooling make-up water system, the subject of this paper.

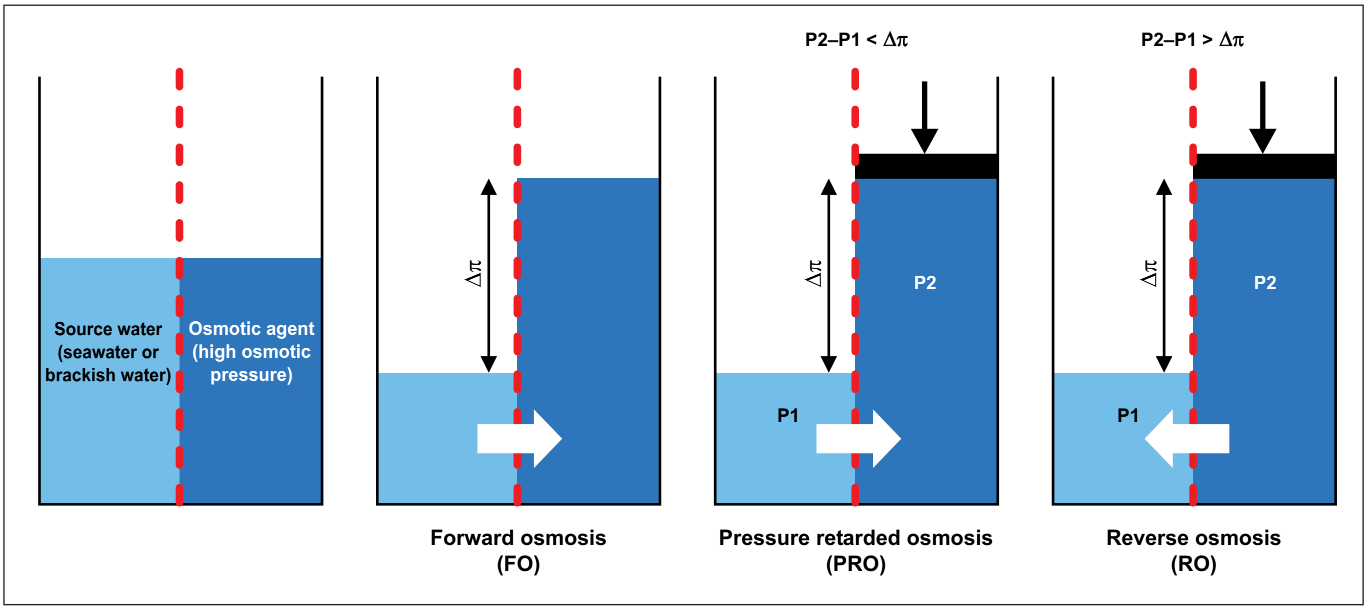


Figure 1:
Manipulated/forward osmosis.

## FORWARD OSMOSIS AND EVAPORATIVE COOLING

Having established the basic principles of manipulated osmosis, we can now look at how it may be simply applied to the production of evaporative cooling make-up water. There are two ways it could be applied: as a complete desalination process producing low total dissolved solids (TDS) water (using a two-step process) [4] or as just a single forward osmosis step, which is what is considered here.

The process is very simple in concept. To draw in water, to replace that lost by evaporation drift and blowdown, the cooling water chemistry is changed to increase its osmotic pressure above that of the feed water. This high osmotic pressure solution may be known as an "osmotic agent" or "draw solution". A portion of the high osmotic pressure cooling water is introduced to one side of a selectively permeable membrane and on the other side we have a feed water such as seawater, brackish water or treated sewage effluent. The natural process of osmosis takes place and essentially pure water flows into the recirculating cooling water replacing that lost in the process. Figure 2 illustrates a typical arrangement.

Like any membrane process a certain amount of pre-treatment is required, which may include screening, multimedia filtration or other suitable systems. Given the inherently low fouling potential of the membranes, less conservative design values for these systems could be used compared to conventional membrane plant.

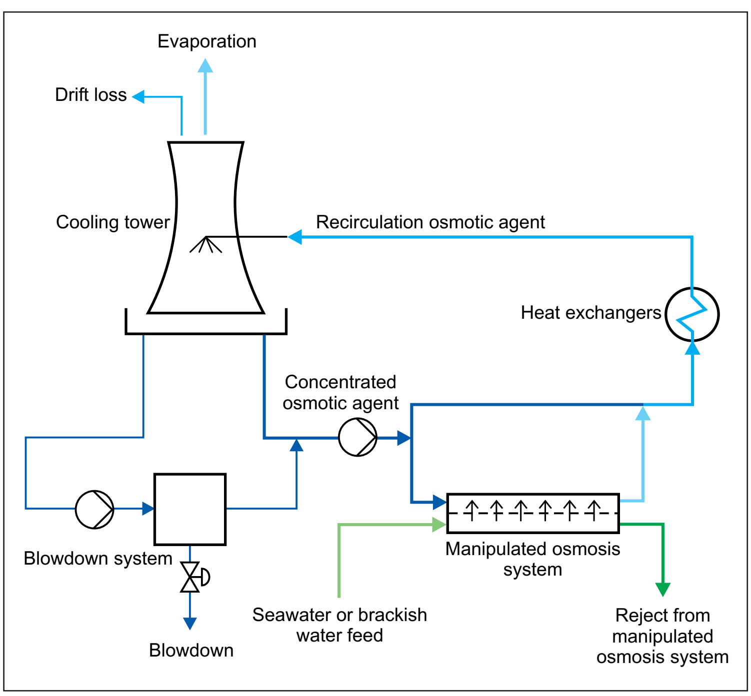


Figure 2:
Evaporative cooling make-up water process.

### Forward Osmosis Membranes

These membranes operate at low pressure, typically 3–4 bar on either side of the membrane with minimal pressure loss. Recovery on the feed water side is similar to that of a reverse osmosis plant, with similar limitations based on scaling depending on the feed water source.

The membrane chemistry is suitable for use with oxidising biocides used in cooling water systems, unlike most conventional reverse osmosis membranes, which are not chlorine resistant. The membranes are contract manufactured to specific design requirements for forward osmosis. It is worthy of note that there have been a number of design/specification improvements over the last three years, with significant improvements in the bulk permeability. The details are commercially sensitive and so are not presented here.

### Osmotic Agent

The question that is often asked is: 'What is the osmotic agent or draw solution?' The composition is proprietary but what we can say is that it is based on a safe, economical, readily available commodity chemical which is not corrosive to all normal heat transfer surfaces.

Like any cooling water system there is a need for chemical conditioning of the recirculating osmotic agent (cooling water), to minimise biological material and to ensure the metallic materials are suitably protected from corrosion.

As part of the ongoing development of the process and in particular the chemistry and it's compatibility with both the forward osmosis membranes and just as importantly the common materials found in cooling water circuits, a detailed investigation was undertaken to measure the corrosion rates of various metals that may be used in cooling water systems.

These tests were done on the operational demonstration unit, with seawater used as the raw water and an osmotic agent (cooling water) with an osmotic pressure of 55 bar, using both corrosion test coupons and real time on-line corrosion monitors. The materials tested were carbon steel, 304 stainless steel, 316 stainless steel and copper. The results indicated little or no corrosion of the stainless steels and copper, with some corrosion of the carbon steel. The corrosion rates of the carbon steel were significantly reduced after the addition of a corrosion inhibitor based on a blend of phosphonates and carboxylic acids.

Further work has been done to determine whether bacteria hazardous to human health were able to grow in the untreated osmotic agent, specifically *Legionella pneumophila* and *Pseudomonas aeruginosa*, which are commonly found in cooling towers. Tests were undertaken at different concentrations of osmotic agent (without any biocide) to determine the minimum inhibitory concentration (MIC). It was found that *Legionella pneumophila* was unable to grow, but *Pseudomonas aeruginosa* was able to grow and multiply. Results for the *Legionella pneumophila* are presented in Table 1 and graphically in Figure 3. For ease of data analysis, 1 000 colony-forming units (CFU) per ml has been designated for too numerous to count (TNTC). The data shows average colony counts of *Legionella* for various osmotic pressures at 24, 48 and 72 h. Figure 3 clearly demonstrates a MIC equivalent to an osmotic pressure of 3.6 bar.

The fact that the *Legionella* was unable to grow at these low osmotic pressures is particularly significant given its potential to harm human health.

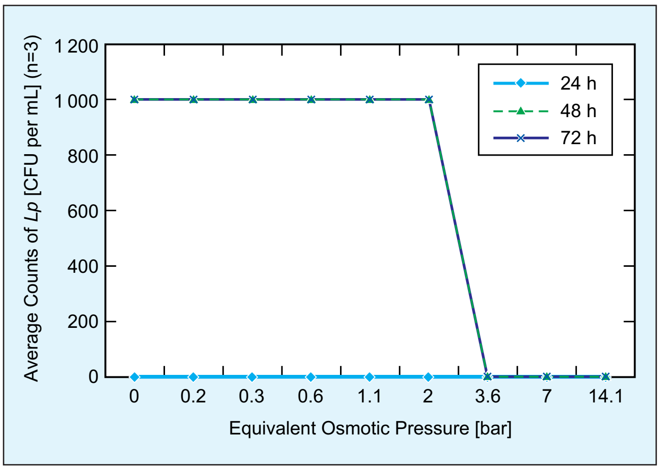


Figure 3:
Growth of *Legionella pneumophila* (*Lp*) at various osmotic pressures employing the agar (charcoal-yeast extract) plate minimum inhibitory concentration (MIC) method.

**Blowdown**

Like any evaporative cooling system the dissolved solids are lost via drift and blowdown, so in the case of manipulated osmosis there could be a loss of the main chemical base of the osmotic agent unless a recovery system is incorporated. A patented system has been developed that recovers and reuses the osmotic agent in the blowdown stream to minimise the loss of chemicals and therefore further improve the economics. There is clearly a loss to the atmosphere via drift, however with modern drift eliminators this is insignificant.

The blowdown system is primarily membrane based using 'loose' membranes because of the nature and molecular weight of the osmotic agent. It has the added advantage that any large molecular weight additives used in the cooling water are retained and therefore a significant reduction in chemical usage can be achieved. This is an area of ongoing work and may be reported in a future paper.

| Osmotic pressure of solution [bar] | Average counts of *Legionella pneumophila* (NCTC 11378) as CFU per mL (n=3) | | | Relative colony size at 72 h* |
|---|---|---|---|---|
| | 24 h | 48 h | 72 h | |
| 0.0 | 0 | TNTC | TNTC | 5 |
| 0.2 | 0 | TNTC | TNTC | 4 |
| 0.3 | 0 | TNTC | TNTC | 4 |
| 0.6 | 0 | TNTC | TNTC | 3 |
| 1.1 | 0 | TNTC | TNTC | 2 |
| 2.0 | 0 | TNTC | TNTC | 1 |
| 3.6 | 0 | 0 | 0 | 0 |
| 7.0 | 0 | 0 | 0 | 0 |
| 14.1 | 0 | 0 | 0 | 0 |

Table 1:
Growth of Legionella pneumophila at various osmotic pressures.

* Relative colony size demonstrated good colony size (5) to very poor minute colonies (1). No growth was valued at 0.

CFU colony-forming units
NCTC national collection of type cultures
TNTC too numerous to count

## INPUT FROM FORWARD OSMOSIS DESALINATION APPLICATION

At the heart of this process is the same forward osmosis technology that has been successfully applied on challenging feed waters at a number of locations across the world. This significant experience has helped the body of knowledge as to how these systems perform in real-world conditions.

In September 2008, the world's first manipulated/forward osmosis desalination plant located in Gibraltar on the Mediterranean Sea was commissioned. The local water utility, AquaGib, completed rigorous testing procedures of the product water and on 1 May 2009, water was exported and put into the public water supply. The export of water has continued since that time.

A year later, in September 2009, a larger seawater plant was installed in the Sultanate of Oman at the Public Authority of Electricity and Water's (PAEW) site at Al Khaluf, shown in Figure 4. PAEW selected this site because of the extremely challenging seawater, taken from a very shallow open seawater intake which was sometimes exposed at low tide. The plant shares a common pre-treatment with an existing similarly sized seawater reverse osmosis facility, thus providing a unique opportunity to trial the two technologies on a like-for-like basis.

The results from the Al Khaluf plant [3] were significantly better than expectations, in particular on resistance to fouling and product water quality. Despite the atrocious feed water conditions at Al Khaluf, the forward osmosis membranes have not required cleaning in over two years. This contrasts with the conventional reverse osmosis plant, which has required cleaning every two to four weeks and has had a number of membrane changes. This clearly demonstrates the inherent low fouling of the forward osmosis based processes.

## DEMONSTRATION PLANT

Further confidence in the operation of the system has been obtained following the operation of a demonstration/pilot plant. This facility allows the process to be trialled at different client sites. A pre-requisite was that the design of the plant should not interrupt the operation of an existing cooling water system, so that there was little or no risk to the client. In order to do this, the plant is completely self-contained and equipped with its own evaporative cooling system. A separate heat exchanger is installed between the heat load supplied by the host.

The demonstration unit is housed in a 6.1 m (20 ft) container, with an external packaged evaporative cooling tower with a nominal cooling capacity of 50 kW.

Feed water can be supplied from any appropriate source ranging from treated sewage effluent to seawater. The plant incorporates a full pre-treatment system for the raw water, based on multi-media filtration. Other systems include the manipulated osmosis membranes and the osmotic agent blowdown recovery system. Hence all aspects of the process can be demonstrated on a client site.

The plant is currently being trialled on a petrochemical plant in Sohar, Oman (Figure 5).

Figure 4:
Forward osmosis based desalination plant, Oman.

Figure 5:
Demonstration plant, Sohar, Oman.

## CAPITAL EXPENDITURE AND OPERATIONAL EXPENDITURE

The capital cost of a system will be similar to that of a conventional reverse osmosis plant designed to operate on the same feed water. Unlike a conventional plant, which may use exotic super duplex stainless steels, the manipulated osmosis based system makes extensive use of lower cost plastic components because of the low operating pressures.

Let us make the assumption that capital expenditure costs are the same for the manipulated osmosis (MO) and reverse osmosis (RO) processes and consider the differential operational costs for each process. In the case of reverse osmosis we will consider only electricity and in the case of manipulated osmosis, electricity and the cost of osmotic agent lost via drift and blowdown.

### Power Consumption Comparison

This comparison is based on the following assumptions:

- Feed water temperature 25 °C
- Pre-treatment requirements the same for MO and RO
- Pump overall efficiency 70 %
- Energy recovery efficiency 70 %
- Pressure loss across MO membrane systems including pre-treatment 3 bar
- Maximum conversion with MO limited to 30 % (very conservative)
- Conversion for RO, 80 % – 41 % depending on feed total dissolved solids (TDS)
- Cooling tower concentration ratio 5

Figure 6 shows the significantly better power consumption of manipulated osmosis when compared to reverse osmosis, across the spectrum of differing feed waters. This is particularly true with seawater, which is typically 35 000 – 45 000 $mg \cdot L^{-1}$ TDS.

### Power and Chemical Operational Costs

It is interesting to note that in the case of manipulated osmosis, without using the osmotic agent recovery system on the blowdown stream, the power consumption does not vary with feed TDS. Indeed the economic advantages of the process increase the more challenging the feed water source.

We now consider the same technical assumptions and the following economic assumptions:

- Power US$0.075 per kWh (low)
- Osmotic agent US$75 per 1 000 kg

Figure 7 shows very clearly the significant economic advantages of the manipulated osmosis process for supplying make-up water. These figures are conservative for manipulated osmosis because we have fixed the conversion (make-up water to feed water ratio) of the process to 30 % across the range of feed water TDS, where in fact the process would have a similar conversion to reverse

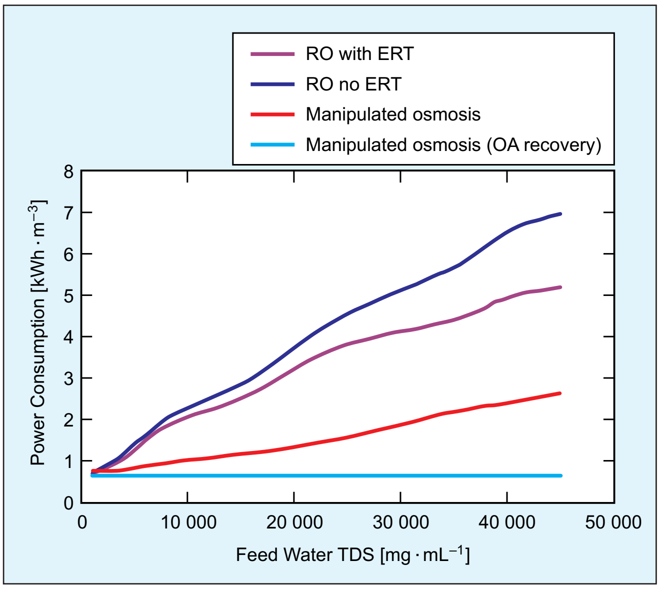


Figure 6: Power consumption comparison.

ERT energy recovery turbine
OA osmotic agent

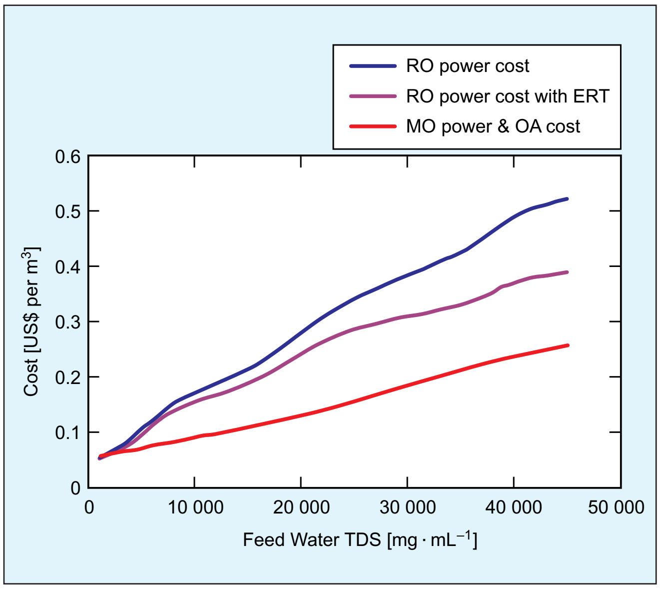


Figure 7:
Operational cost comparison.

osmosis. Therefore for any particular case, the process economics are better than illustrated.

It will be clear that the manipulated osmosis process becomes increasingly economically attractive the higher the cost of power and the more challenging the feed water. This does not take account of the other advantages when compared to a reverse osmosis based process, including: an increased availability, fewer membrane replacements and lower chemical cleaning costs.

## DEPLOYMENT OPPORTUNITIES

This innovative technology provides an additional consideration when siting evaporative cooling towers and the supply of make-up water. Clearly where there is an abundant supply of low cost water of a suitable quality, the process would not be cost effective. However as soon as alternatives are considered, whether seawater cooling with its inherent challenges, or the treatment of seawater, brackish water or treated sewage effluent, it is clear that forward osmosis provides an economical and technically attractive solution.

The process is unlikely to be suitable for hyperbolic natural draft cooling towers because of the high drift losses associated with such installations, however it is ideally suited to forced draft towers with appropriate drift eliminators.

The system can be easily retrofitted to existing installations where a suitable source of raw water is available to feed the process. An important consideration is that it is quite easy to revert back to a conventional make-up source in the very unlikely event of plant failure, which of course can be minimised with appropriate design measures. The simplicity of such a switch is illustrated in Figure 8, where initially the cooling tower uses potable water for make-up to increase the sump level followed by a simple switch to forward osmosis, which then maintains the level replacing the evaporation, drift and blowdown losses.

### Other Make-up Water Sources

The forward osmosis process is a new process that provides an alternative solution to traditional water sources and clearly has distinct economic and technical advantages in particular situations. For ease of comparison the process is compared with seawater and treated sewage effluent water sources in Table 2, both of which have a role to play depending on local conditions.

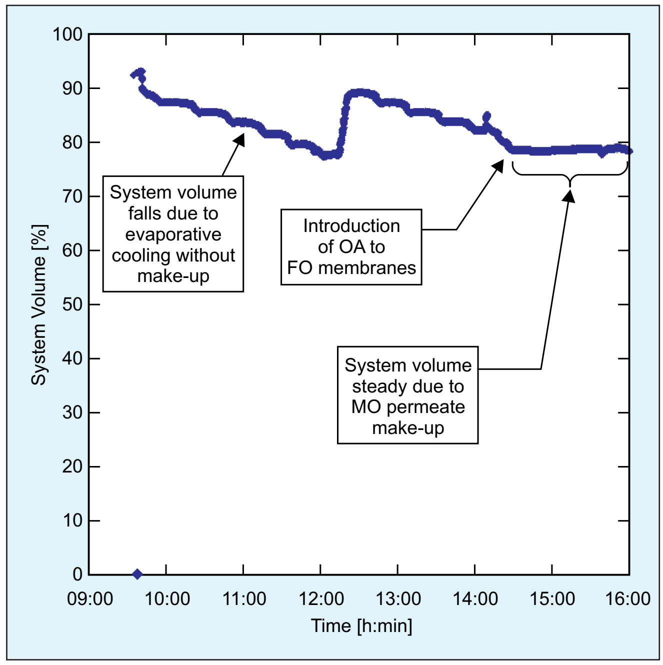


Figure 8:
Manipulated osmosis operation.

## CONCLUSIONS

'Desalination' is not always about producing low TDS water using what is normally an energy intensive process. The manipulated/forward osmosis process has an important role to play in delivering water in a form that is 'fit for purpose', in this case providing a source of low TDS make-up water to a recirculating cooling water acting as an osmotic agent (draw solution). The economics and robustness of the process are quite compelling, however as this application of the process is completely new and has not been factored into developers' planning, it will take some time to become accepted.

While this application for the technology is new, there have already been several years of operation of forward osmosis based processes in very challenging environments, using the same key components. All three of these operational forward osmosis based plants have demonstrated that the process is far less prone to fouling than reverse osmosis, and therefore there can be a high degree of confidence in the robustness and reliability of the core aspect of the process.

The particular osmotic agent selected does not support the growth of *Legionella* at the osmotic pressures generally required to operate the process. Furthermore through the deployment of an osmotic agent recovery system on the blowdown stream, not only is the osmotic agent retained but also large molecular weight cooling water additives, with the potential for significant cooling water dosing chemical reductions.

| | Seawater | Treated Sewage Effluent | Manipulated Osmosis |
|---|---|---|---|
| Feed water availability | Unlimited but requires proximity to the sea | Limited availability, transport of effluent to the point of use, subject to seasonal and population effects | Unlimited but requires a source of feed water (seawater, brackish water, treated effluent) |
| Cycles of concentration | 1.2–1.5 | 2.0–2.5 | 4–5 |
| Materials | Special materials required for pipework, heat transfer surfaces (titanium, copper-nickel, etc.) | No special materials required for heat transfer surfaces | No special materials required for heat transfer surfaces |
| Chemicals | Requires significant quantities of chemicals including continuous use of oxidising biocides | Careful monitoring required to ensure biological and corrosion controls remain in place, due to wide variability of incoming sewage effluent | Requires replacement of lost osmotic agent to maintain concentration in cooling water. Blowdown recovery system minimises this loss and that of other chemical additives to the cooling water |
| Drift | Salt laden drift requires careful selection of the site, can cause corrosion damage to surrounding structures and may affect local flora and fauna | Public perception issues associated with airborne treated sewage water | No detrimental effects on surrounding structures and flora and fauna |
| Other issues | Introduction of solids and biological materials from the marine environment, with potential detrimental effects on heat transfer and tower fill materials | Public perception. Disposal of blowdown due to high phosphates and nitrates. | Membranes not prone to fouling |

Table 2:
Alternative make-up water sources.

This low-energy, low-fouling membrane based process has the potential to open up evaporative cooling to sites where up until now it has been considered uneconomical.

The process lends itself to being retrofitted to existing installations, especially if there is an existing reverse osmosis plant supplying the make-up water, as all the intake and pre-treatment systems will already be in place.

Clearly the opportunities for the economic deployment of the process are site specific and will depend on the availability of a suitable feed water and the cost of power at the site. Where the cost of power is high, the advantages of using this system become greater relative to desalinated or tertiary treated effluent, if these are being considered.

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## THE AUTHORS

**Peter Nicoll** (BSc, Mechanical Engineering, University of Glasgow, UK) leads the multi-disciplined technical team at Modern Water plc, where he has been instrumental in the planning, development, deployment and implementation of the company's patented forward osmosis processes. He has extensive experience in the design and operation of large desalination plants, business development, sales of capital equipment and professional services throughout the world. Peter Nicoll is a Chartered Engineer and a Fellow of the Institution of Mechanical Engineers. His previous experience includes Business Development Director for Fichtner Consulting Engineers, and he has held a number of senior roles both technically and commercially at Weir Westgarth Ltd.

**Neil Thompson** (M. Eng., Mechanical Engineering, Imperial College of Science, Technology and Medicine, London, UK) is a Chartered Engineer who started his career working in the Power Generation Division of Mott MacDonald, where he specialized in the analysis of the technical and commercial performance of power and cogeneration plants, particularly for large independent water and power projects. He joined Modern Water plc in 2008, and became technical development manager in 2009. Neil Thompson has had a key role in the successful transfer of Modern Water's membrane-based technologies from the university laboratory to the field, including forward osmosis desalination facilities for both potable water production and industrial use. He is currently based in the UK working as a senior consultant for Fichtner Consulting Engineers Limited.

**Victoria Gray** (BSc, Microbiology, Ph.D., University of Swansea, UK) joined Modern Water in 2008 and played a substantial role in developing a university spin out technology utilizing bioluminescent biosensors to monitor real-time water toxicity. She also supports ther activities within Modern Water with her expertise in microbiology.

## CONTACT

Peter Nicoll
Modern Water plc
Bramley House
The Guildway
Old Portsmouth Road
Guildford
GU3 1LR
United Kingdom

E-mail: peter.nicoll@modernwater.co.uk