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Innovative Spiral-Wound Membrane Elements for High Temperature Desalination Applications

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ABSTRACT

Water desalination has become one of the most important methods of alleviating water shortages and meeting stricter environmental regulations across the world. While spiral-wound reverse osmosis (RO) and nanofiltration (NF) membrane elements have proven very successful in a variety of desalination applications, more and more applications are emerging that require spiral-wound membrane elements capable of handling high temperatures or extreme cleaning conditions. Because industry-standard RO and NF water elements are limited to a maximum operating temperature of 45°C (113°F), membrane manufacturers are investigating alternative materials to build high temperature elements for applications where standard RO and NF elements cannot be used.

This paper explains how data is used to determine when more robust element components (i.e. materials of construction) such as feed spacers, permeate carriers, permeate tubes, and outerwraps are needed to develop elements that can handle different levels of elevated temperatures. Elements constructed with these alternative materials fall into four categories based on temperature tolerance:

- Warm temperature operation (up to 60°C / 140°F continuous)
- High temperature operation (up to 80°C / 176°F continuous)
- Heat-sanitization (sanitization up to 90°C / 194°F)
- Extreme cleaning at high pH and high temperature (up to pH 13 and 75°C / 167°F)

Overall, this paper focuses on why high temperature spiral-wound elements are needed, which applications require these types of elements, and how different element components can be combined to tackle an even broader range of applications than ever before.

INTRODUCTION

Spiral-wound reverse osmosis (RO) and nanofiltration (NF) membrane elements are the most commonly used desalination technology available today. RO and NF elements are used in a variety of applications, including desalination for wastewater reclamation and reuse, potable use, high purity water, ingredient water, and much more. Due to increasing water shortages and stricter environmental regulations, the number of desalination applications continues to grow. However, because industry-standard RO and NF spiral-wound elements are manufactured using predominantly plastic materials, these elements have defined pH, pressure, and temperature limitations for operation and cleaning processes. Specifically, these standard thin-film composite RO and NF elements are limited to a maximum operating temperature of 45°C (113°F). While exposure to temperatures over 45°C may not result in immediate damage to the element, it may cause certain plastic materials to soften or deform and negatively affect the element's performance and lifetime. As a result, this temperature limitation has largely restricted the direct use of RO and NF for treatment of high temperature streams including hot evaporator condensates, laundry wastewater, boiler blowdown, high purity streams, produced water, and more.

With the rising demand for membrane elements that can operate on high temperature streams, it is important to understand how the temperature limit of 45°C was established for industry-standard RO and NF elements and why these elements cannot handle higher temperatures. This paper explains when more robust materials are needed and how they may be combined to develop elements that can handle different levels of elevated temperatures. In addition, this paper discusses how these advanced elements built with alternative materials fall into four categories based on the temperature needed for particular applications. Overall, this paper will give the reader an understanding of why high temperature spiral-wound elements are needed and how different materials can be combined to tackle an even broader range of applications than ever before.

MEMBRANE TEMPERATURE LIMITS

Industry-standard thin-film composite RO and NF membrane elements have a maximum operating and cleaning temperature of 45°C. To understand how this temperature limit was derived and established for industry-standard RO and NF elements, first it is important to recognize the temperature limits of the membrane itself.

CELLULOSE ACETATE MEMBRANES – Cellulose acetate (CA) membranes, originally developed in the early 1960s, were the first type of membrane used in commercial RO desalination plants. After CA membranes are cast, the membrane is annealed in a hot water bath to form the small voids underneath the dense barrier layer (Figure 1.1). During operation, CA membranes are limited to a maximum operating temperature of 30-32°C (86-90°F) (Suez, 2019 and MICRODYN-NADIR, 2019). This is because temperatures above 35°C (95°F) will further anneal the membrane, resulting in a much denser material that is difficult to force water through. Operation at higher temperatures may also lead to hydrolysis of the membrane (or the chemical breakdown of the membrane due to its reaction with water), leading to degradation of the membrane (Kucera, 2015).

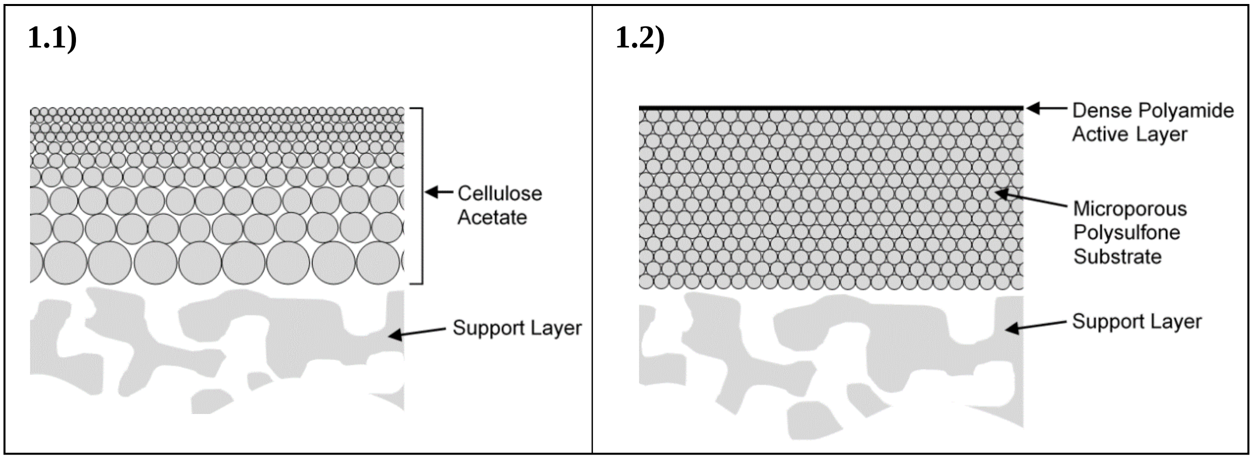


Figure 1: Comparison of cellulose acetate (1.1) and thin-film composite membrane (1.2).

Because CA membranes are limited to a maximum temperature of 32°C (90°F), these membranes cannot be used in high temperature applications. Fortunately, due to the low temperature tolerance, narrow pH range, and high feed pressures of CA membranes, researchers created the next generation of RO membrane that would be able to tolerate a wider range of operating conditions.

THIN-FILM COMPOSITE MEMBRANES – In the late 1960s, thin-film composite (also referred to as thin-film or polyamide) membranes were developed. Thin-film membranes comprise three layers: a thin, dense polyamide barrier layer (from which the term "thin-film composite" was derived), a microporous polysulfone substrate and a support layer (as illustrated in Figure 1.2). The microporous substrate layer acts as additional support that along with the non-woven polyester support layer, allows the membrane as a whole to be highly resistant to mechanical stresses and chemical degradation.

Thin-film membranes proved to surpass CA membranes in membrane flux and rejection, operate at a lower pressure, and can tolerate a wider operating pH and temperature range. Industry-standard spiral-wound thin-film RO and NF elements are commercially advertised to operate at temperatures as high as 45°C (113°F) and within a pH range of 2-11.

While industry-standard spiral-wound RO and NF elements can operate at up to 45°C, thin-film flat sheet membrane can perform at higher temperatures. However, temperature does influence membrane flux and rejection performance. Assuming constant pressure, water flux is linearly proportional to water temperature (Kucera, 2015). So, at higher temperatures, the permeate flux increases. In fact, water flux increases about 3% per 1°C increase (Al-Mutaz, 2001). This occurs because the viscosity of water is reduced at higher temperatures, allowing the water to flow more readily through the membrane. Salt rejection decreases slightly with increasing temperature due to the higher diffusion rate of salt through the membrane.

Exceeding temperatures of 45°C may cause a thin-film membrane to undergo a permanent annealing process, making it denser. This physical change causes the thin-film membrane to have lower flux and higher salt rejection. Despite these changes in flux and rejection, there are a variety of applications where the economic benefit of high temperature operation or heat sanitization greatly outweighs the costs of these effects on membrane performance. For example, by using high temperature elements for treatment of hot streams such as boiler blowdown, industrial plants can reduce the size of their cooling system or are able to avoid cooling the feed stream entirely. By eliminating the need to cool down the stream, the plant may save significant capital and operating costs on heat exchangers that far outweigh the fact that the membrane has annealed.

Despite the effects of annealing of the flat sheet membrane at temperatures above 45°C (113°F), the maximum operating temperature for thin-film membranes is a function of pH (see Table 1). Thin-film membranes can tolerate higher operating temperatures so long as the pH remains more neutral. For example, thin-film membranes can operate at temperatures up to 80°C (176°F) and pH 3-8 (DuPont, 2017). A combination of high temperature and extreme pH (especially high pH) may cause damage to the polyester support and polyamide layers (Kucera, 2015).

Table 1: Operating temperature as a function of pH for thin-film composite membranes.

Temperature	pH Range
25°C (77°F)	1 – 13 [1]
35°C (95°F)	1 – 12 [1, 2, *]
45°C (113°F)	2 – 11 [2, *]
60°C (140°F)	2 – 10 [3]
70°C (158°F)	3 – 9 [4]
80°C (176°F)	3 – 8 [2]

[1] Kucera, 2015.
[2] DuPont, 2017.
[3] TriSep Corporation (now MICRODYN-NADIR), 2014.
[4] Suez, 2015.
* Maximum temperature for continuous operation above pH 10 is 35°C (95°F); only temporary operation is advisable at these temperatures above pH 10.

Because thin-film composite membranes can operate at temperatures up to 80°C, it is evident that the membrane is not the limiting factor when it comes to maximum temperature restraints for thin-film composite RO and NF spiral-wound elements.

WHY INDUSTRY-STANDARD ELEMENTS CANNOT HANDLE HIGH TEMPERATURES

When industry-standard RO and NF elements are exposed to higher temperatures, several things may happen that may adversely affect the element’s performance. The most common include:

- Intrusion
- Material deformation
- Feed spacer migration

INTRUSION – Intrusion generally occurs when the element is subjected to a combination of very high pressure and temperature. Because the polymeric components of a spiral-wound element tend to soften at elevated temperatures, intrusion is far more common in applications where the feed temperature is above 35°C (95°F). The term "intrusion" is used because the membrane is being pushed (or intruded) into the channels of the permeate carrier. When this happens, the channels of the permeate carrier where the permeate flows to the permeate tube are partially blocked, thus hindering flow and creating a permeate-side pressure drop. This results in lower permeate flow, which is irreversible. Additionally, with intrusion, there may be some membrane damage from deformation of the membrane over the weaves of the permeate carrier. When membrane from an element affected by intrusion is removed and cell tested, it will typically have higher flux (and often higher salt passage) than the element. Intrusion causes the entire element to lose efficiency.

Elements that have experienced intrusion typically have concave scroll ends. When the membrane leaf gets pushed into the channels of the permeate carrier, the result is an element with concave scroll ends at both the lead and tail ends of the element (Figures 2.1 and 2.2). This is not to be confused with an element that has experienced membrane telescoping, where the affected element's lead end is concave and tail end is convex (Figure 2.3). Membrane telescoping is usually the result of excessive pressure drop from the feed to concentrate, or operation without a pressure vessel thrust ring.

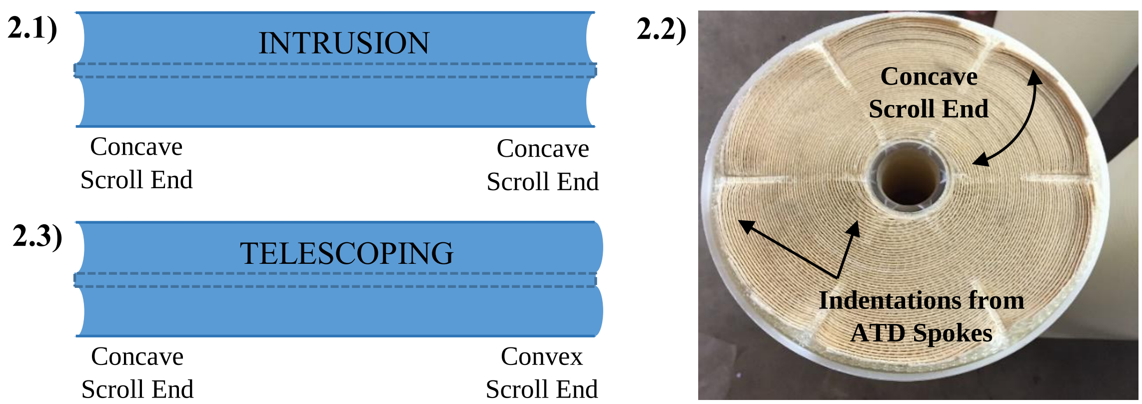


Figure 2: Elements that experience intrusion have concave scroll ends at both ends (2.1 and 2.2). Elements that experience telescoping are usually concave at one end and convex at the other (2.3).

MATERIAL DEFORMATION – Spiral-wound elements are made from layers of flat sheet membrane, feed spacer, permeate carrier, a single perforated permeate tube, adhesives, and an outerwrap. Industry-standard RO and NF elements are made using materials that can handle a maximum temperature of 45°C (113°F). If exposed to higher temperatures, some of these materials may soften and deform.

> <u>Membrane Backing</u> – While it has been proven that the membrane can handle operation at higher temperatures, the polyester membrane backing (the support layer) has a limited pH range, which is exacerbated by high temperature. In fact, a combination of high temperature and high pH (particularly outside the values listed in Table 1) will cause the polyester support layer to disintegrate and lose its supportive structure, as shown in Figure 3.

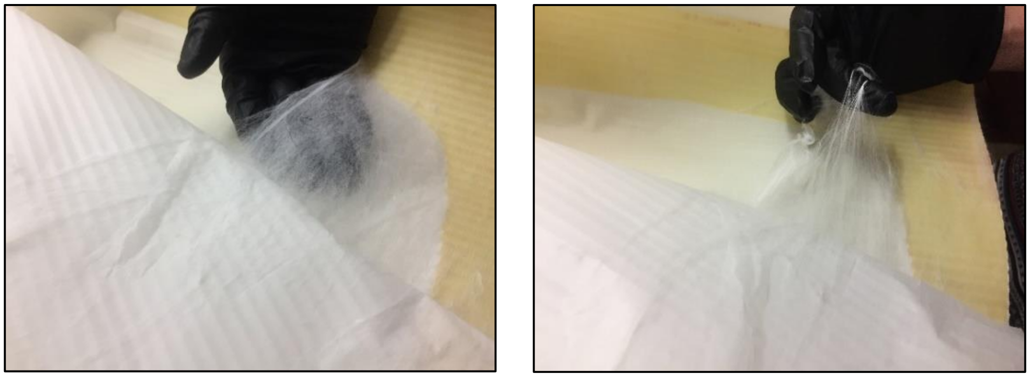


Figure 3: Polyester backing disintegrates when exposed to high temperature and high pH.

Permeate Carrier – The permeate carrier (sometimes called a permeate spacer) is a tricot mesh spacer material, typically made of polyester, that is inserted between two layers of flat sheet membrane (Figure 4). This spacer is comprised of parallel channels that help direct the permeate water toward the central perforated permeate tube, hence the term "permeate carrier". When an industry-standard RO or NF element is exposed to temperatures exceeding 45°C (113°F), the polyester permeate carrier loses rigidity. As soon as pressure is applied, the softened permeate channels collapse, leading to restricted permeate flow. In fact, it is because of the potential collapse of the permeate carrier's channels that temperature limitations are coupled with pressure limitations (Franks, 2017). This is one reason why industry-standard brackish water RO elements are limited to a maximum temperature of 45°C and maximum pressure of 41 bar (600 psi).

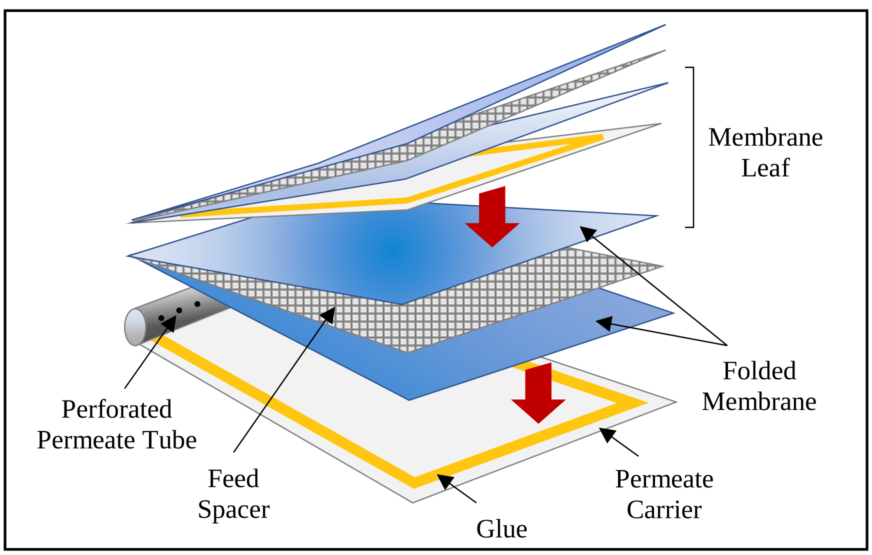


Figure 4: Membrane leaves separated by feed spacers.

Permeate Tube – The permeate tube collects all the water that has permeated through the membrane. The permeate tube used in industry-standard brackish water RO and NF elements is typically made of arcylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), or noryl materials and is another component that is affected by temperature and pressure. Exceeding the temperature and pressure limits of the permeate tube material can cause the tube to deform and collapse. Again, the pressure limits of the permeate tube are a function of temperature. As temperature increases, the pressure limit of the tube decreases.

Adhesives – General adhesives are also sensitive to temperature, pH, and pressure. Exceeding limits can cause the glue to soften at high temperature, weakening the adhesion between the membrane leaves, and allowing them to pull apart. This may lead to the possibility of leaking feed water into the permeate.

FEED SPACER MIGRATION – Most industry-standard RO and NF elements are built using polypropylene feed spacers. While polypropylene material can handle high temperatures, feed pressures, and a wide pH range, thin polypropylene feed spacers are still subject to soften and weaken when exposed to high temperature. With the addition of pressure (or high pressure drop), the weakened feed spacer may deform further or migrate. Feed spacer migration refers to the feed spacer moving through the element, sometimes past the scroll end of an element, as shown in Figure 5. Feed spacer migration may lead to physical damage to the membrane surface (Andes, 2013).

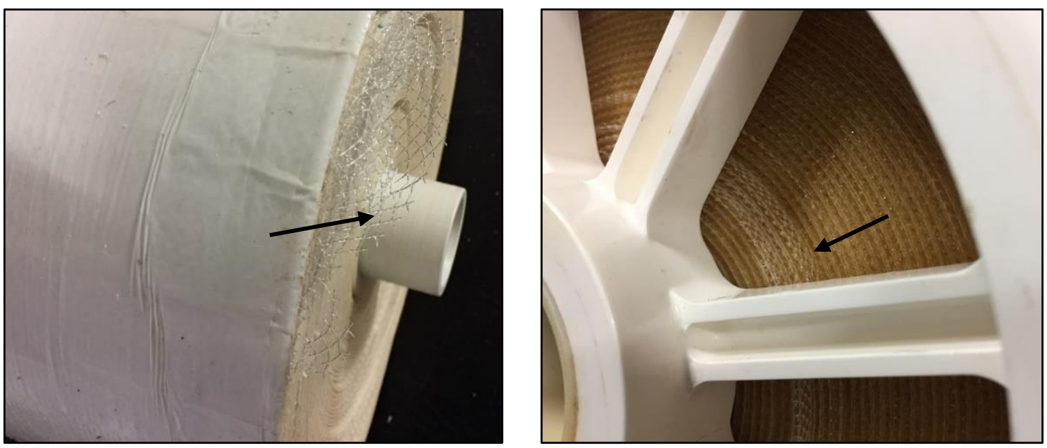


Figure 5: Feed spacer migration through two different elements.

Since many of the materials used in industry-standard RO and NF elements soften, weaken, and deform at elevated temperatures, it is apparent that it is the materials of construction that limit the element's operating and cleaning conditions, not the membrane. More robust materials are needed to build sturdier elements for use at temperatures above 45°C (113°F).

WHEN IS A MORE ROBUST ELEMENT CONSTRUCTION NEEDED?

A growing number of desalination applications require elements that can handle higher feed temperatures. Treatment of high temperature streams including hot evaporator condensates, laundry wastewater, boiler blowdown, produced water, and high purity streams for pharmaceutical and semiconductor production, for example, require advanced or even customized membrane elements. In order to select the proper element construction for these applications, it is important to understand the Wagner Unit as well as the different temperature requirements for each application.

WAGNER UNIT – Coined by Jørgen Wagner, Wagner Units are used to consider the limits of different element constructions (Wagner, 2012). Wagner Units are calculated by multiplying the operating temperature in degrees Celsius and the operating pressure in bar as shown in Eq. (1) below:

$$\text{Wagner Unit} = \text{Temperature (in °C)} * \text{Pressure (in bar)} \qquad (1)$$

When the feed temperature and pressure are multiplied to determine the Wagner Unit, the graph in Figure 6 is helpful in determining when an advanced or custom element is necessary for a specific application. For example, an application with a 60°C (140°F) feed and pressure of 20 bar (290 psi) has 1200 Wagner Units and falls into the "High Temperature Construction" category in the graph. This means that an element with high temperature construction is recommended for these specific operating conditions. Similarly, an application that requires a feed temperature of 20°C (68°F) and pressure of 80 bar (1160 psi) has 1600 Wagner Units and falls into the "Ultra-High Pressure" category in the graph. In this case, an element with ultra-high pressure construction is recommended.

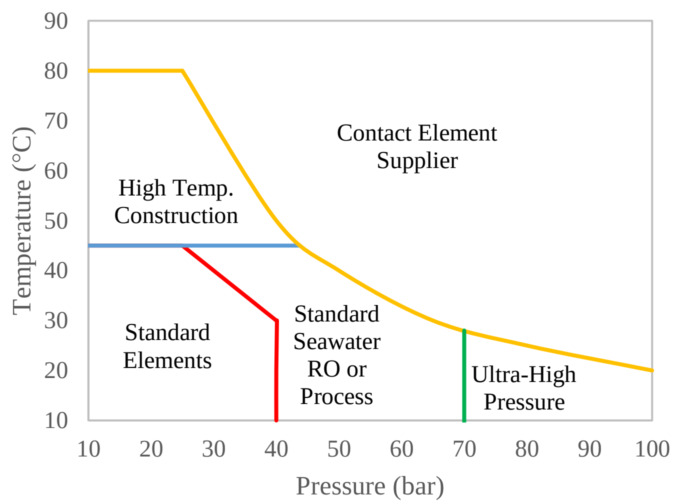


Figure 6: Wagner Units are used to consider the limits of different element constructions.

HIGH TEMPERATURE SPIRAL-WOUND ELEMENTS

While the Wagner Unit has proven a very helpful tool in determining which element construction is necessary for certain operating conditions, it does not differentiate between distinct high temperature element constructions based on different levels of elevated temperatures. Today, spiral-wound elements fall into four categories based on temperature tolerance (differences between these elements are summarized in Table 2):

- Warm temperature operation (up to 60°C / 140°F continuous)
- High temperature operation (up to 80°C / 176°F continuous)
- Heat-sanitization (sanitization up to 90°C / 194°F)
- Extreme cleaning at high pH and high temperature (up to pH 13 and 75°C / 167°F)

Table 2: Typical operating and cleaning conditions for high temperature spiral-wound elements.

Element Type	Operating Temperature	Cleaning Temperature	Cleaning pH	Sanitizing Temperature	Outer Wrap
Industry-Standard Fiberglass Elements	45°C (113°F)	45°C (113°F)	1.0 – 12.0	-	Fiberglass
Warm Temp Elements	60°C (140°F)	50°C (122°F)	1.0 – 12.0	-	Fiberglass or Sanitary Outerwrap
High Temp Elements	80°C (176°F)	50°C (122°F)	1.0 – 12.0	-	Sanitary Outerwrap
Heat-Sanitizable Elements	50°C (122°F)	50°C (122°F)	1.0 – 12.0	Up to 90°C (194°F) at 1.7 bar (25 psi) maximum pressure	Sanitary Outerwrap
High pH / High Temperature Elements	60°C (140°F)	75°C (167°F)	1.0 – 13.0	Up to 85°C (185°F) at 1.7 bar (25 psi) maximum pressure	Sanitary Outerwrap

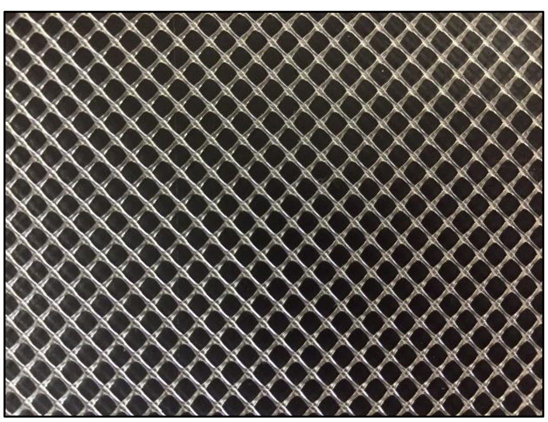
WARM TEMPERATURE ELEMENTS – Warm temperature elements are spiral-wound elements that can handle continuous operating temperatures up to 60°C (140°F) but are cleaned at standard cleaning conditions (up to 50°C / 122°F and pH 1-12). These elements are useful for several desalination applications including treatment of laundry wastewater, boiler blowdown, warm well water, paper mill wastewater, and produced water streams, as well as various other process applications where the feed stream is warmer, specifically up to 60°C. Using spiral-wound elements that can handle warmer feeds allows users to avoid cooling the feed stream, resulting in considerable capital and operating cost savings.

While the membrane used in warm temperature elements is the same RO and NF membrane used in industry-standard RO and NF elements, the warm temperature element does require other robust materials to allow for operation up to 60°C. They typically use a sturdier permeate carrier. Instead of an ABS, PVC, or noryl permeate tube, warm temperature elements customarily use a polysulfone (PSF) permeate tube. Polysulfone is an amorphous polymer that keeps its excellent strength properties over a wide temperature range—it can tolerate higher temperature and pressure limits (Microspec, 2019). High temperature adhesives are also used so that the membrane leaves do not pull apart during operation. While industry-standard RO and NF elements typically use a 31-mil diamond feed spacer, thicker feed spacers (e.g. 34-mil diamond) may also be used in warm temperature elements to help reduce pressure drop through the element, preventing feed spacer migration (Figure 7.1). Lastly, warm temperature elements available on the market today can be fiberglass wrapped, net wrapped, or have a patented sanitary hard shell for use in many diverse applications.

HIGH TEMPERATURE ELEMENTS – Spiral-wound elements that can operate at temperatures up to 80°C (176°F) continuously (at near neutral pH; refer to Table 1) and cleaned at standard cleaning conditions (up to 50°C and pH 1-12) are called high temperature elements. These elements are advantageous in applications where feed temperatures exceed 60°C and where it does not make economic sense, or is not feasible, to cool the stream before processing. As such, most high temperature elements are used in very distinct process applications including the concentration of sugars or other specific food & dairy streams.

Like warm temperature elements, the membrane used in high temperature elements is the same membrane used in industry-standard RO and NF elements; however, high temperature elements require even sturdier materials that will not soften or deform at 80°C (176°F). High temperature elements typically use a stronger permeate carrier that will not deform at high temperature and will prevent the membrane from intruding into the permeate carrier (as seen in Figure 2.2). It is also common to use a bigger feed spacer to minimize pressure drop through the element and avoid feed spacer migration. A 47-mil parallel feed spacer, for example, is thicker, more rigid, and provides more open space between individual strands compared to a 34-mil diamond feed spacer (Figure 7). With additional open space that the parallel (or ladder) geometry offers, the feed water has more room to flow through the feed channels and lowers potential fouling. This minimizes the pressure drop through the element, and the potential for feed spacer migration is drastically reduced. Similar to the warm temperature elements, high temperature elements also use polysulfone permeate tubes as well as high temperature adhesives. Since high temperature elements are primarily used in process applications, they are typically available with a net wrap or sanitary hard shell outerwrap.

7.1)



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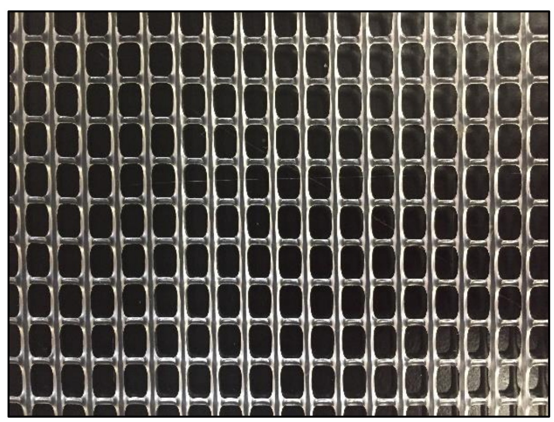

Figure 7: A comparison between 34-mil diamond (7.1) and 47-mil parallel feed spacers (7.2). A more open feed spacer provides more space for feed water to travel through the feed channels. This minimizes pressure drop and drastically reduces the potential for feed spacer migration.

HEAT-SANITIZABLE ELEMENTS – Heat-sanitizable elements are ideal for applications that demand ultrapure water including dialysis, pharmaceutical, and semiconductor rinse water.

These elements deliver high purity water while also being able to withstand sanitization with hot water (up to 85-90ºC, or 185-194°F), eliminating the need for chemical sanitizers. Heat-sanitizable membranes have high water permeability before they have been heat-set, or pre-conditioned (i.e. exposed to hot water). After heat-setting, the elements attain their specified flow and salt rejection performance during operation at normal temperature (up to 50°C / 122°F). After the heat-setting procedure, the membrane's performance remains stable regardless of additional sanitization cycles (DuPont, 2015).

These elements can endure these heat-sanitizations, or periods of high temperature, due to the materials used in the element construction. Heat-sanitizable elements are typically made using a durable permeate carrier, a polysulfone permeate tube, and high temperature adhesives. Because these elements are operated and cleaned at standard conditions (up to 50°C during operation and up to 50°C and pH 1-12 during cleanings), these elements are not as likely to exhibit feed spacer migration. As such, these elements can be built with varying feed spacer thicknesses and geometries.

HIGH pH / HIGH TEMPERATURE ELEMENTS – While high pH / high temperature elements are used primarily in process applications like food & dairy rather than desalination applications, it is important to understand how their function and construction differs from warm temperature, high temperature, and heat-sanitizable elements.

High pH / high temperature elements are used in systems where chlorine use is restricted or undesirable due to concerns with chlorinated byproducts in wastewater streams. As such, these systems are cleaned using alkaline cleaning solutions at high pH and high temperature. The elements in these systems must be able to withstand a cleaning pH range of 1-13 and cleaning temperatures up to 70°C (158°F), and must be heat-sanitizable at up to 85°C (185°F). Cleaning at such extreme conditions puts standard polyester membrane backing and polyester permeate carrier at immense risk for disintegration; as a result, the membrane used in these elements requires sturdier support layer and permeate carrier materials. Consequently, the membrane used in high pH / high temperature elements is commonly cast onto a polypropylene support layer rather than polyester. Additionally, a special permeate carrier is used to allow for high pH and high temperature cleanings.

Like warm temperature and high temperature elements, high pH / high temperature elements use a polysulfone permeate tube and polypropylene feed spacers, as well as special high temperature adhesives. Because most high pH / high temperature elements are used in process applications, they are generally offered in a sanitary configuration using a net wrap or sanitary hard shell outerwrap.

As described above, there is not a "one element meets all" solution here. In other words, there is not a single element that can be applied to all types of high temperature applications. Instead, there is one special element intended for warm temperature operation and another option for operation at up to 80°C (176°F). Then, there is yet another distinct element built to handle operation at standard temperatures (50°C / 122°F) while allowing for periodic heat-sanitizations at up to 90°C (194°F). And finally, there is an advanced element that can handle operation at up to 60°C (140°F) while also allowing intense cleanings to take place at up to pH 13 and 70°C.

These four different element constructions are intended to handle unique and specific operating and cleaning conditions. Since these conditions vary based on the application, these elements must be built with materials of varying degrees of strength and durability.

CONCLUSION

Industry-standard RO and NF spiral-wound membrane elements have played a crucial role in a variety of desalination applications in an effort to combat increasing water scarcity around the world. Consequently, additional applications have been and are being developed, requiring special spiral-wound elements capable of handling high temperature or extreme cleaning conditions. When it comes to operation above 45°C (113°F), however, there is a common misconception that it is the membrane itself that limits the maximum operating temperature for the element. While the cellulose acetate RO membranes of the early 1960s were indeed limited to a maximum temperature of 30-32°C (86-90°F), thin-film composite membranes proved to surpass these constraints, tolerating operating temperatures up to 80°C (176°F) continuous and sanitization temperatures up to 90°C (194°F). Industry-standard elements are limited to a maximum temperature of 45°C (113°F), not because of the membrane, but due to the other plastic materials used in the element construction.

Given the temperature limitations of element materials, the Wagner Unit, developed by Jørgen Wagner, may be used to determine whether an advanced or customized element solution is needed for certain operating conditions. Once this has been calculated, there are currently four different categories of high temperature elements to choose from, including warm temperature, high temperature, heat-sanitizable, and high pH / high temperature elements. Each distinct category calls for a unique element construction using sturdier materials to allow the element to tolerate conditions above 45°C. By using these alternative, more rigid materials, these elements may be used for the growing demand of treatment of high temperature streams including boiler blowdown, pulp and paper wastewaters, produced water, laundry wastewater, annealing baths, mining wastewater, high purity waters, and many, many more.

REFERENCES

Al-Mutaz, I.S. & Al-Ghunaimi, M.A. (2001). “Performance of Reverse Osmosis Units at High Temperatures”. *The IDA World Congress On Desalination and Water Reuse, Bahrain*. Retrieved from https://www.researchgate.net/publication/264420571_Performance_of_Reverse_Osmosis_Units_at_High_Temperatures.

Andes, K., Bartels, C., Liu, E., & Sheehy, N. (2013). Methods for Enhanced Cleaning of Fouled RO Elements. *The International Desalination Association World Congress on Desalination and Water Reuse 2013*, 8. Retrieved June 11, 2019, from http://membranes.com/knowledge-center/technical-papers/.

DuPont (2015), “Cleaning and Sanitization: Sanitizing RO & NF Membrane Systems”. Retrieved June 14, 2019 from https://www.dupont.com/content/dam/Dupont2.0/Products/water/literature/609-02102.pdf.

DuPont (2017), “DOW™ Specialty Membrane XUS120308 and XUS120304 Reverse Osmosis Elements”. Retrieved June 17, 2019 from https://www.dupont.com/content/dam/Dupont2.0/Products/water/literature/609-50258.pdf

Franks, R., de la Cruz, J., Bartels, C., & Van Gils, G. (2017, March). How High-temperature RO Can Assist Industrial Wastewater Recycling And Energy Conservation. *GWI | Ultrapure*. Retrieved June 11, 2019, from https://www.ultrapurewater.com/articles/wastewater/how-high-temperature-ro-can-assist-industrial-wastewater-recycling-and-energy-conservation.

Kucera, Jane. (2015). *Reverse Osmosis: Design, Processes, and Applications for Engineers* (2nd ed.). Hoboken, NJ: Wiley-Scrivener, 57, 63-64, 243.

MICRODYN-NADIR (2019), “TRISEP® SB20 Cellulose Acetate (CA) RO Elements”. Retrieved June 14, 2019 from https://www.microdyn-nadir.com/spiral-data-sheets-1.

Microspec, “Materials – Polysulfone”. Retrieved June 14, 2019 from https://www.microspecorporation.com/materials/engineering-resins/polysulfone/.

Suez Water Technologies & Solutions, “CE series brackish water RO elements (cellulose acetate)”. Retrieved June 14, 2019 from https://my.suezwatertechnologies.com/WTS CustomerPortal/s/document-library.

Suez Water Technologies & Solutions (2015), “Duratherm* EXL series industrial high temperature elements”. Retrieved June 17, 2019 from https://my.suezwatertechnologies. com/WTSCustomerPortal/s/document-library.

TriSep Corporation (2014), “8” RO Element for Warm Temperature Operation”. Retrieved June 17, 2019.

Wagner, Jørgen. (2012). Wagner Unit & Diagram. Retrieved June 11, 2019, from http://wagnerdk.dk/DownLoads.htm.