Beyond the Mesh: 3D-Printed Feed Channels and the Future of Reverse Osmosis

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ABSTRACT

For over 60 years, reverse osmosis (RO) elements have relied on a single feed spacer design, providing sufficient performance to launch an industry but also limiting performance and innovation. This study introduces a transformative approach using 3D-printed patterns directly on RO membranes, enabling precise control over feed channel geometry. Combining simulations, lab experiments, and field data, we reveal how custom designs influence flow, fouling, and efficiency. The findings establish a foundation for next-generation spacers tailored to specific applications, unlocking new potential in RO element optimization.

BACKGROUND:

Since the introduction of spiral-wound reverse osmosis (RO) membranes, the importance of feed channel mixing in mitigating polarization at the membrane surface has been well recognized. This high-concentration boundary layer reduces permeate quality, increases osmotic pressure, and promotes scale formation. Highlighting the critical role of mixing, Bill Eykamp, an early president of Koch Membrane Systems, famously remarked, "The secret of membranes is that the membranes aren't the secret."

Despite this early recognition, the low cost and acceptable performance of extruded mesh spacers have led generations of developers to focus almost exclusively on membrane chemistry—pursuing higher rejections, lower operating pressures, and extended lifetimes. Yet, while membranes have steadily advanced, the feed spacer architecture has remained largely unchanged. As membrane performance improves, the limitations of mesh-based feed channels increasingly constrain system potential.

To overcome this, an alternate approach to creating feed channel was developed by printing features directly onto the membrane surface. These printed features precisely define feed channel geometry and introduce controlled disruptions that modulate local flow velocities throughout the element—offering a level of control previously unavailable. Eliminating the need for a separate spacer sheet reduces material within the feed channel, enabling a thinner yet more hydraulically open flow path providing lower pressure drop along with space for more membrane area in an equivalent element geometry when compared with traditional mesh designs.

These features combine to convey the following benefits in RO systems:

- Increased productivity
- Increased recovery
- Reduced energy consumption
- Reduced fouling
- Extended cleaning intervals that reduce chemical use

This paper will explore the development of printed spacer technology, its role in enhancing element performance, recent advances in feed channel design, and real-world comparisons between printed and traditional mesh spacers.

Several printing techniques have been developed to fabricate these feed spacer features directly onto the membrane surface, ensuring strong adhesion without damaging the delicate membrane. The production method used for elements discussed herein employed a modified large-format inkjet printer and a light-cured resin. The resin was deposited in successive layers to build up the desired feature height. This digitally controlled process allows for rapid pattern changes and near-limitless design flexibility.

In typical manufacturing, printing is applied to one half of the membrane leaf. When the leaf is folded during element construction, the printed features align to form the feed channel without risk of opposing features interfering. This approach also minimizes obstruction of the active membrane surface—less than 3% of the total area is covered by printed structures in a typical design. A photo of the printer can be seen in Figure 1.

Figure 1:

Modified large format printer used for printed spacer production

The printing technology has been used to print on all the major RO membrane types (LE, BW, SW), from a wide range of manufacturers along with gas separation, ion exchange, and UF/MF membranes.

BETTER FEED CHANNELS

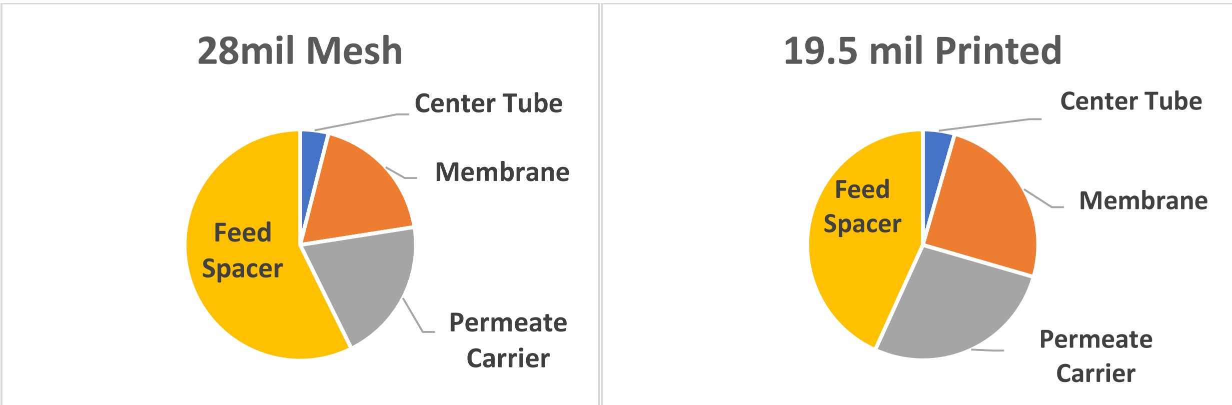
Throughout its years of use, RO element design based on mesh feed spacer has come with inherent tradeoffs. The feed channel height is twice the height of the strands making up the mesh, and the mesh mechanical structural integrity is also determined by the strand diameter. Thus, thin mesh materials require denser strand spacing, leading to higher pressure drop than even drop of thickness would suggest. Over the years, some improvements have been made to mesh spacer design including designs with alternating thick and thinner strands, tapered strand designs, different strand angles, and more recently thicker (36 mil) ultra-low pressure drop designs, but the limitations imposed by the continuous extrusion process remain. Because the strands need to span the entirety of the length and width of the extrusion, each strand continuously blocks roughly half of the flow channel as the water must flow above and below them to pass through the element.

In contrast, printed feed spacers allow decoupling of spacer thickness from the spacer geometry and design. Because of this, printed spacers can maintain a target feed channel height without filling as much feed channel volume. As a result, a considerably thinner feed channel can be created while still providing adequate flow and minimizing pressure drop.

Figure 2 shows the overall volumetric composition of an element with a 28 mil mesh feed spacer compared to a 19.5 mil printed spacer in an 8040 element. The mesh volume breakdown shows the feed channel makes up the majority of the overall volume of the mesh element. The proportion is even greater for a 34 mil mesh element. Additionally, due to the continuous nature of the extruded mesh mentioned above, the strands of the mesh constitute ~10% of that total channel volume as compared to the printed features which take up only ~2.5% of the channel.

Figure 2:

Volume composition of mesh vs printed element

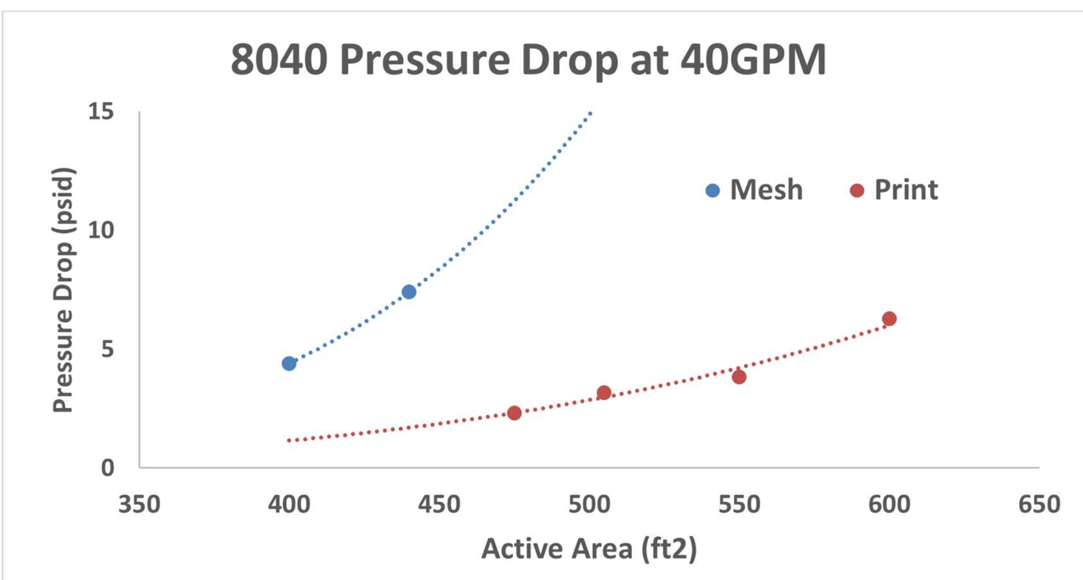


The reduced volume in the feed channel with the printed channel allows for additional membrane and permeate carrier to be incorporated into the same element geometry, providing numerous benefits.

Figure 3 illustrates the step change reduction in pressure drop at the same feed flow rate as a result of the use of printed spacer channels, even with significant reductions in channel height. In this work, elements with 505 ft^2 of membrane area utilizing a 19.5 mil spacer thickness were utilized, a selection made to provide a combination of increased area and decreased pressure drop relative to the most commonly used 28 and 34 mil mesh materials.

Figure 3:

Active area vs pressure drop for mesh & printed spacer elements



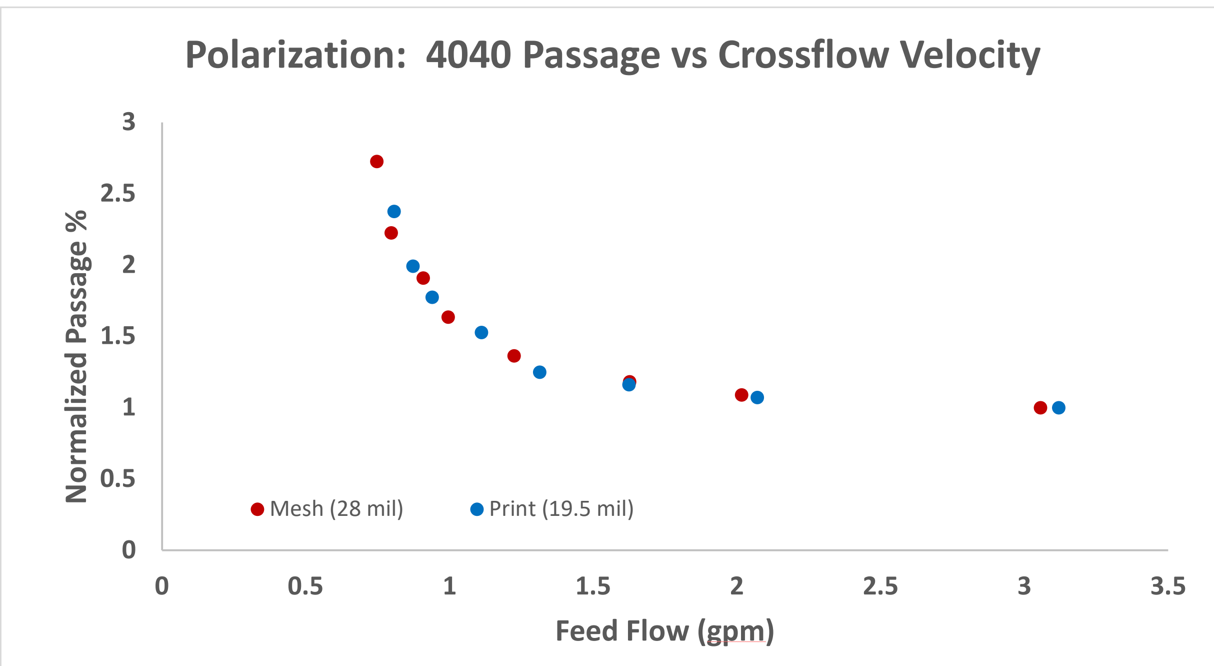
MIXING AND ELEMENT PERFORMANCE - Although the decreased channel height leads to higher crossflow velocities at a similar flow rate, the more open design of the printed feed spacer has raised concerns that the reduced pressure drop may indicate inadequate mixing and reduced membrane performance.

To experimentally measure the degree of concentration polarization in 4040 elements we conducted performance measurements at a constant flux of 10gfd for elements made with either a 28 mil mesh, or a 19.5 mil printed spacer. Feed flow rate was varied between 0.75 and 3.2 gpm by adjusting a valve on the concentrate line. Rejection after a change in feed flow rate was allowed to stabilize before measurements being made (typically 15 minutes after an adjustment to flow rate).

As the rejection of each element was slightly different, the rejection made at the highest crossflow velocity (i.e. lowest recovery) was used to normalize rejection values for that element at lower crossflow velocities. The normalized salt passage is shown in Figure 4.

Figure 4:

Salt passage vs crossflow velocity for mesh and printed spacer



Changes to rejection resulting from decreasing crossflow velocity are a result of two factors; the higher recovery resulting in an increased average feed side salinity and decreased mixing resulting in a higher concentration at the membrane surface (i.e. concentration polarization). A transport model for the element, assuming film theory, and matching that used in commercial projection software, was developed to enable the determination of a Sherwood number relationship for both the printed channel and mesh using the equations shown in Figure 5. Best fit values shown are similar to the values used when modelling mesh elements. This is consistent with the overlapping normalized rejection curves as a function of feed flow rate shown in figure 4.

Figure 5:

Equations used for concentration polarization Sherwood number correlation

$$\frac{C_m}{C_b} = (1 - R + R * exp^{-\frac{J_w}{K}})^{-1} \qquad K = \frac{Sh * D_{NaCl}}{d_h} \qquad Sh = 0.12\, Re^{0.875} Sc^{0.25}$$

These results confirm that the thinner feed channel with higher crossflow velocity of the printed spacer element exhibits essentially identical performance to a mesh spacer element under a broad range of operating conditions.

STAGNATION ZONES - While the tortuous flow paths created by mesh feed spacers do induce some localized mixing, the continuous strands also introduce a significant drawback beyond added volume and pressure drop: they create stagnant zones immediately downstream of each strand.

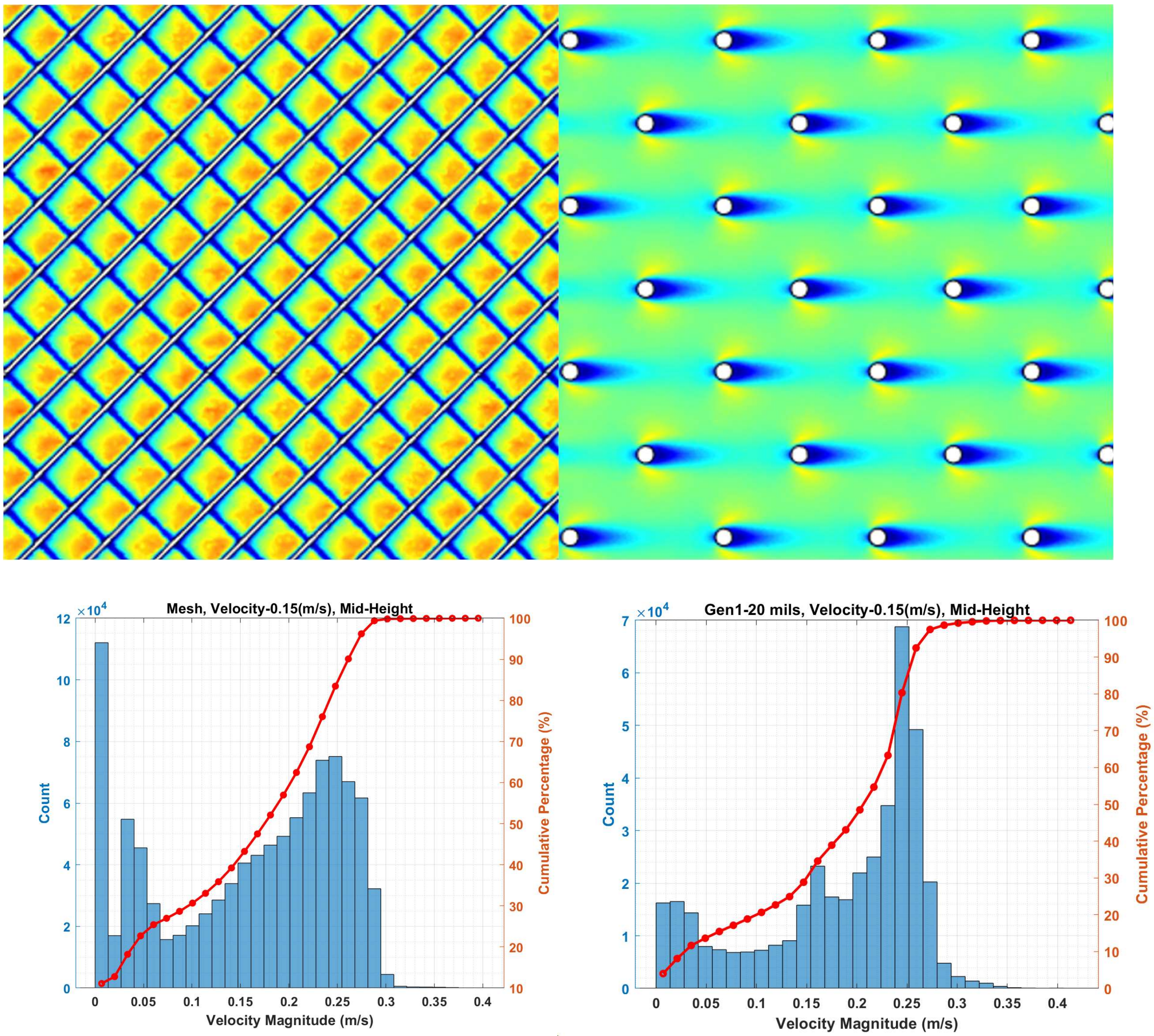
Both printed and mesh spacer designs have been evaluated using COMSOL Computational Fluid Dynamics (CFD) software to better understand how different flow channel patterns influence fluid behavior. Initial modeling has focused on small segments of the feed channel—approximately 114 mm × 114 mm (4.5” × 4.5”)—at fixed inlet velocities, with mass transfer at the membrane surface intentionally excluded. This approach isolates the impact of spacer geometry on flow distribution, mixing, and stagnation.

Although flow within the feed channel is complex, the laminar regime typical of spiral-wound membrane operation produces stable, developed flow fields that can be meaningfully analyzed. These simulations provide insight into how different spacer geometries affect fluid dynamics.

A key metric involves a move from considering primarily the average crossflow velocity, to a crossflow velocity histogram. This can be used to illustrate the amount of the membrane surface where low velocities near the surface may result in the accumulation of solids. An example visualization of velocity magnitude at the mid-height of the flow channel is shown in Figure 6.

Figure 6:

Mid-height velocity fields and vector histograms of mesh and printed spacer from CFD modeling



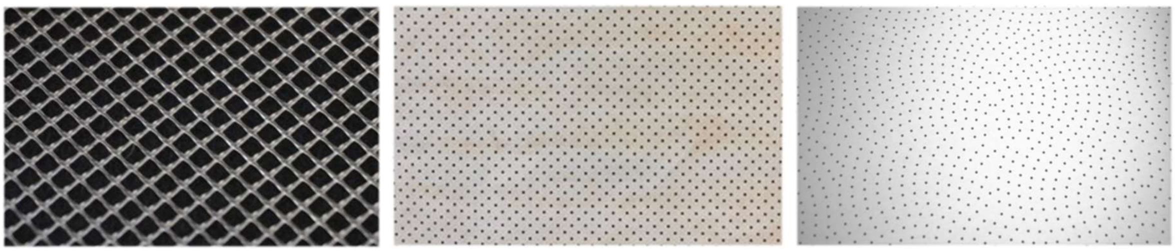
While it is challenging to directly correlate variations in flow velocity to overall performance, velocity histograms may be used to show that mesh feed spacers generate significantly more regions of zero or low flow. For example, the most common average velocity in a CFD cell for a mesh channel was actually zero. In the printed channel, the lower amount of material reduces these shadow zones and dramatically drops the low velocity regions.

DESIGN POSSIBILITIES OF PRINTED FEED SPACERS – Early printed spacer designs for the active membrane area were based on diamond-shaped patterns, resembling the nodal intersections of traditional mesh spacers. While this layout has demonstrated excellent performance, significant opportunities remain for further optimization of printed geometries.

The diamond dot array tends to align stagnation zones directly behind each feature and leaves regions between dots where flow is minimally affected. However, the design flexibility offered by printed spacers enables rapid and precise experimentation with alternative patterns. As shown in Figure 7, one such variation replaces the regular array with a mathematically generated layout that reduces periodicity. This approach minimizes shadowed stagnation zones and increases flow deflection throughout the feed channel, potentially improving mixing and reducing fouling.

Figure 7:

Feed spacer mesh and two variations of printed feed spacer

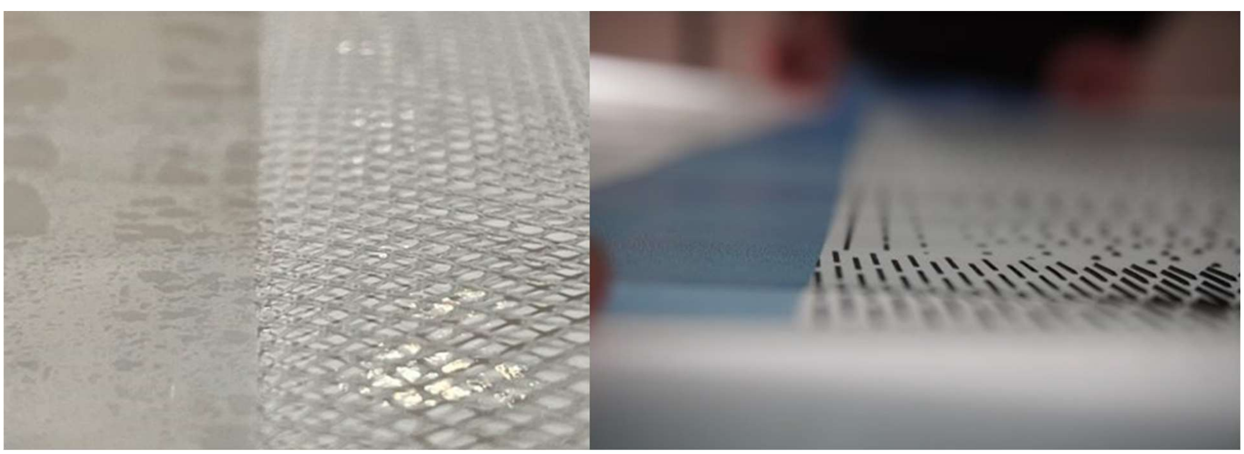


Similarly, the pattern can be made more dense or sparse to affect the mixing vs open area for specific applications if needed for better clearing of solids or increased mixing. Different shapes other than dots can be printed to direct flow within the channel.

As the printing process effectively deadens the permeability of the membrane beneath the print, even at very low print heights, printing can be used in some instances to replace tape for fold protection in the printed leaves as seen in Figure 8.

Figure 8:

Tape and printed fold protection



Print height, along with feature shape, can be precisely controlled, opening additional avenues for performance and manufacturing improvements. For example, tapering the height of printed features near the fold of the membrane leaf and adjusting the pattern in that region reduces the risk of damaging the opposing membrane surface during element rolling and creates a thinner fold. This enhances the consistency and reliability of the production process and reduces the occurrence of insert point leaks where a leaf is pushed away from the central tube during rolling.

The flexibility of the printing process utilized to produce printed feed spacers allows for freedom of design within the feed channel that has not been previously possible, creating the possibility for tailoring feed channels for specific applications.

USE CASES

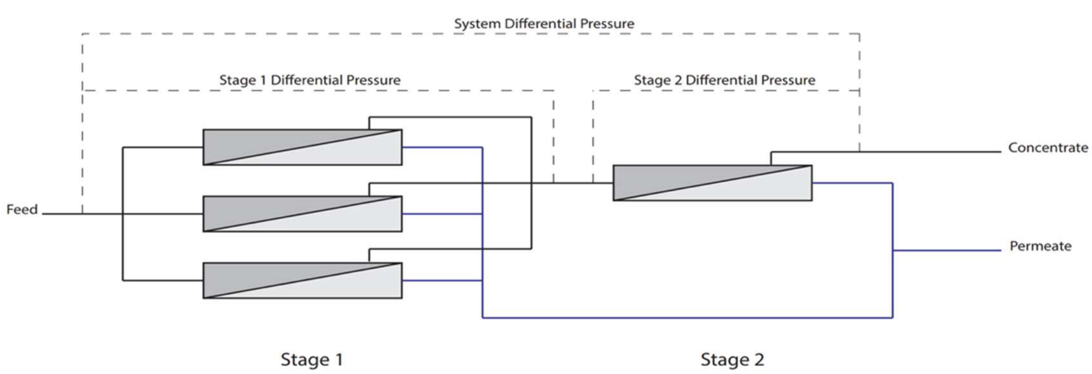
ENERGY SAVINGS – Earlier presentations have described some advantages of elements using printed spacer technology in a side-by-side test utilizing two Reject Recovery Reverse Osmosis (RRRO) systems at Micron Semiconductor's Boise fab[1]. In that facility, two identical RRRO systems are run continuously in parallel, offering a unique location to evaluate changes to system performance resulting from the use of printed spacer in a direct comparison with a system using conventional mesh spacers. A first test demonstrated energy savings created by the combination of lower pressure drop through the system and lower operating pressure due to the increased membrane surface area, as well as a significantly slower rate of DP increase through the printed spacer system over the 8-month test. This first test used the same lot of flat sheet membrane in elements assembled at the same rolling facility to focus on the effect of the change in feed channel.

A follow-up test using the same test systems was subsequently conducted using 505 ft^2 elements with printed spacers compared against a new set of the commercial elements typically used in this application utilizing 400 ft^2 elements with a 34 mil mesh feed channel.

Each system has 4 RO housings, with each housing containing 4 elements (8040) for a total of 16 elements. These housings are configured in a 3-1 array and a variable frequency drive (VFD) is used to adjust the pump's feed pressure to deliver a constant 63 gpm (US gallons per minute) of purified water from each system. A schematic of the RRRO system is shown in Figure 9 along with locations where pressure drops are measured.

Figure 9:

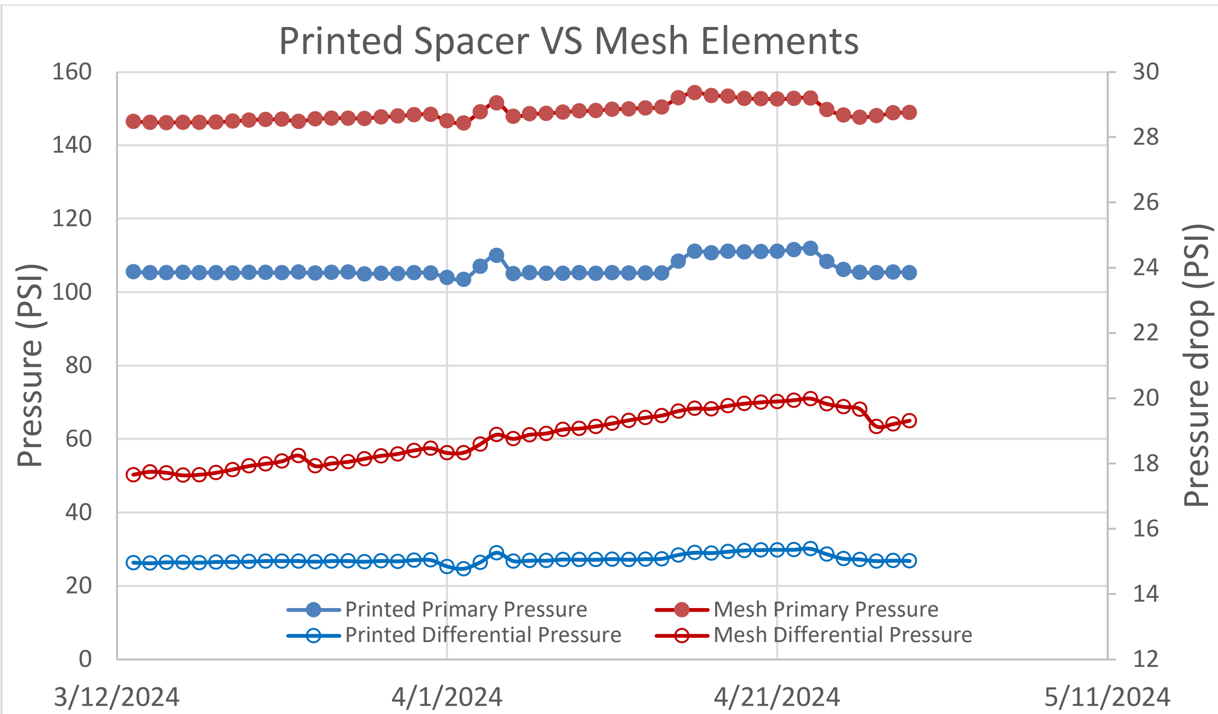
RRRO system layout



Similar trends were seen in the second test as the first, with a 35% reduction in energy use due to the combination of reduced pressure drop and lower primary pressure required due to the additional surface area of the printed spacer elements permitting operation at a lower flux rate. Permeate quality was maintained with the printed spacer skid showing 1.1% salt passage, while the mesh elements showed 1.7% passage. Additionally, the printed spacer elements showed a significantly slower rise in pressure drop than their mesh counterparts.

Figure 10:

RRRO system operating and differential pressure trends

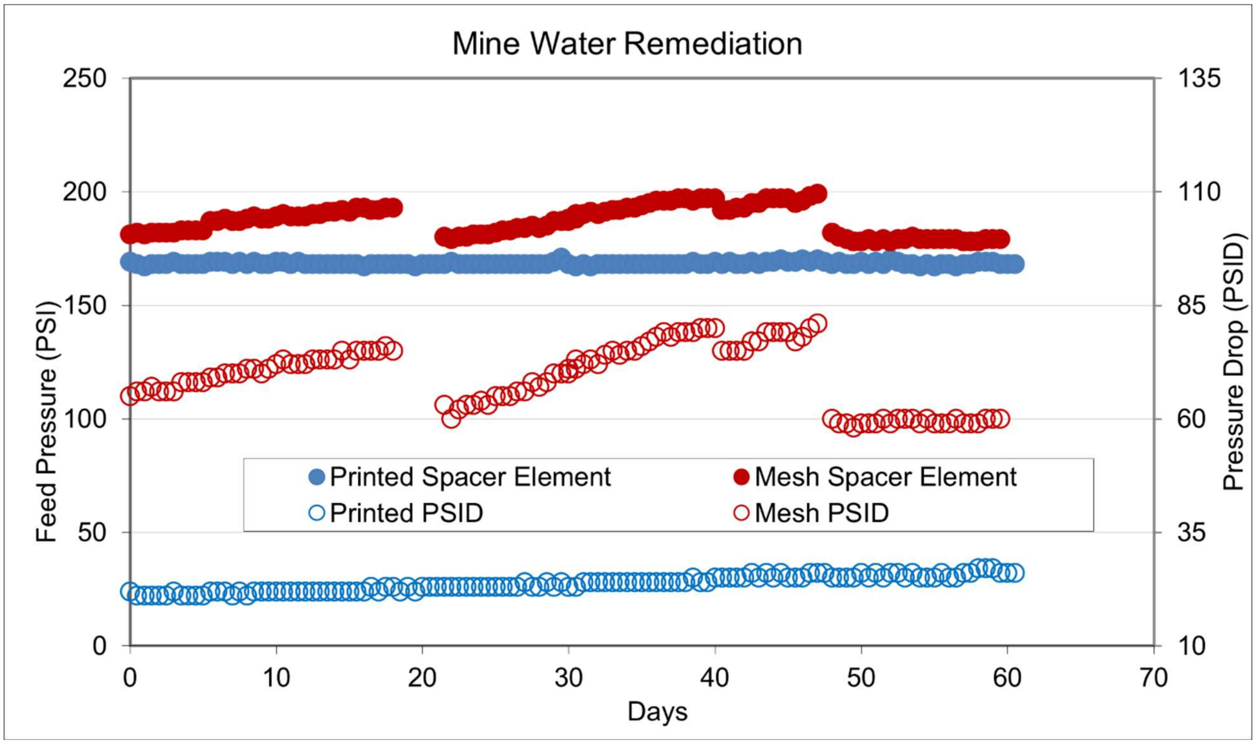


BW ELEMENTS OPERATING AT LE PRESSURES – In a groundwater remediation system from a mining facility, 312 printed spacer elements were installed in a 1.5 MGD system which had previously used 400 ft^2 low energy elements. The system used 2 stages with 36 6M vessels in stage 1 and 18 6m vessels in stage 2 operating at 78.5% recovery. The feed water had a TDS of 2200ppm with $CaSo_4$ and $BaSO_4$ above solubility limits. Prior to installation of printed spacers, the system had a 90-day cleaning frequency.

Figure 11 shows a comparison of operating pressures and pressure drop through the system before and after the installation of printed spacer membrane elements.

Figure 11:

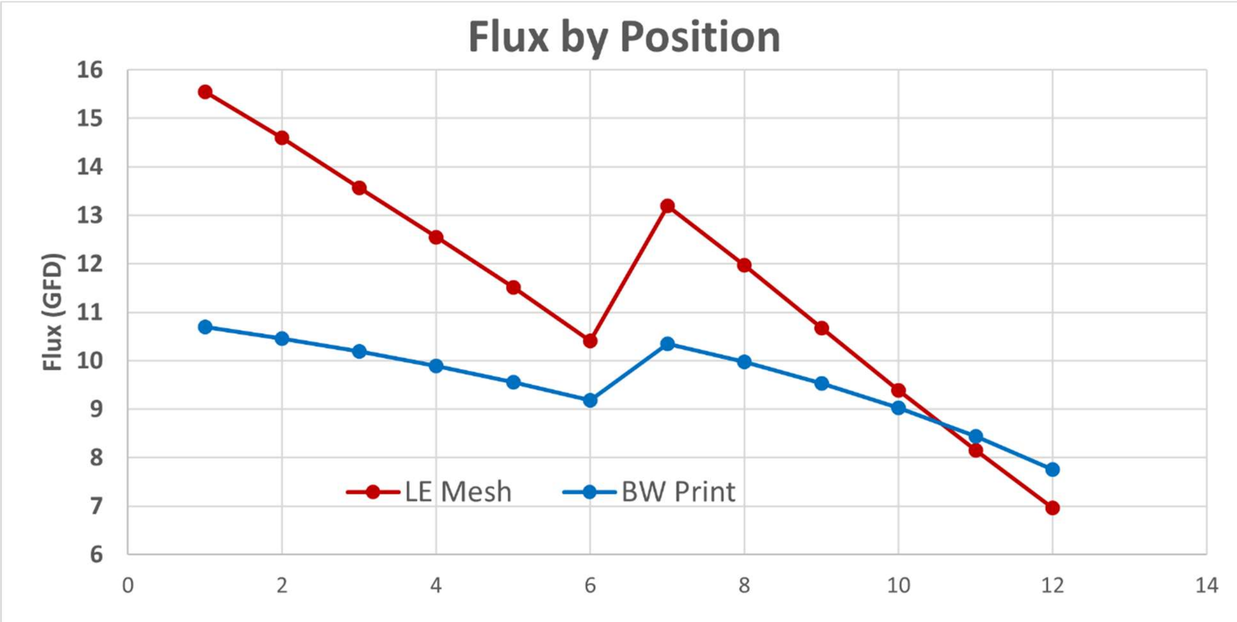
Operating pressure and pressure drop through 60 days of operation before and after installation of printed spacer elements



The added surface area and lower pressure drop of the printed spacer elements combine to allow operation comparable to the previously used low energy elements while also providing more even flux distribution of the elements throughout the system, as seen in the summary from CLIIR projection software in Figure 12.

Figure 12:

Flux comparison of LE mesh and BW printed spacer elements



REDUCED CLEANING FREQUENCY – In a semiconductor fab's wastewater recovery system, printed spacer elements were installed in a 2-stage, 15:10, 5M design configuration in one of four parallel RO trains, with the objective of reducing energy consumption and cleaning frequency on a challenging feed stream. The remaining three trains continued to operate with conventional 400 ft² brackish water elements.

While this is not a direct one-to-one comparison, since not all trains were refreshed with new elements simultaneously, approximately 75 of the worst-performing elements in the other trains were replaced within three weeks of the printed spacer replacements. The reduction in cleaning frequency by more than 2× shown in Table 1 is still notable, and aligns with observations in other systems, where printed spacer elements have benefited from lower operating fluxes due to fixed permeate flow spread over a larger membrane area.

Table 13:

Cleaning frequency in semiconductor fab

	Cleanings/wk previous 15 wks	Cleaning/wk 15 wks after install
Train 1	0.93	0.73
Train 2	1.00	0.33
Train 3	1.00	0.66
Train 4	1.53	0.80

CONCLUSION

The introduction of 3D-printed feed spacers represents a pivotal departure from the decades-long reliance on conventional extruded mesh. This paper has demonstrated through laboratory testing, computational fluid dynamics, and extensive field data that this technology successfully overcomes the inherent tradeoffs of traditional spacers. The findings confirm that printed spacers deliver substantial performance gains including significantly lower pressure drop, increased active membrane area, and a dramatic reduction in fouling-prone stagnation zones while maintaining equivalent mixing and separation efficiency. By uncoupling spacer geometry from its structural constraints, this innovation establishes a new paradigm for RO element design, unlocking the potential for highly optimized, application-specific feed channels that promise to redefine efficiency and reliability in water treatment systems.

REFERENCES

Kurth, C., et al. (2024). Comparison of Semiconductor Reverse Osmosis System Performance With Conventional and 3D Printed Feed Channels. *IEEE Transactions on Semiconductor Manufacturing*. 37, 458-463.