Evaluation of an emerging water treatment technology: ceramic membranes

S. N. Kommineni, J. Bryck, C. Stringer, C. Stevens, N. Meyers, B. Karnik, R. Hoffman and L. Sullivan

ABSTRACT

Historically, low-pressure membranes (microfiltration (MF) and ultrafiltration (UF)) used in potable water treatment are made of polymers (polysulfone (PS), polypropylene (PP), polyethersulfone (PES), polyvinylidene fluoride (PVDF) etc). Recently, membranes made of ceramic materials (aluminium oxide) have been developed by MetaWater (Japan), Kubota (Japan) and others and is being marketed in the United States (US) by Krüger, Inc. (Cary, NC). Ceramic membranes offer several potential advantages over polymeric membranes, including higher mechanical robustness and ability to handle higher loading of particulates, higher resistance to oxidants and membrane cleaning chemicals, higher membrane integrity, longer service life and compact footprint. The authors conducted collaborative evaluations of this emerging technology at two different places; (i) Elm Fork Water Treatment Plant (WTP) of Dallas Water Utilities (DWU), Dallas, Texas, USA and (ii) Graham Mesa WTP, City of Rifle, Rifle, Colorado, USA. The evaluations included pilot testing of ceramic membranes in direct filtration mode (i.e. without clarification) and with coagulant addition. The water streams that were pilot tested at Elm Fork WTP included Trinity River water, spent filter backwash wastewater and lagoon recycle water (spent filter backwash water combined with clarifier blow down water). The City of Rifle pilot testing was conducted on Colorado River water. This paper presents the key results of these two pilot studies. Results of pilot testing were used to define the potential membrane flux, backwash protocols (interval and duration), chemical enhanced backwash (CEB) and clean-in-place (CIP) protocols. Pilot test results and engineering judgment were used for developing concept-level sizing and outlining parameters for future evaluation. This paper will discuss the key technical and economic considerations of the emerging treatment technology and its potential applications for potable water treatment. This paper will be of interest to water providers that are considering alternatives to treat challenging source waters (waters with high particulates and under heavy microbial influence), build new compact water treatment plants, increase plant capacity through membrane retrofits and treat recycle streams at existing WTPs.

Key words | ceramic membranes, emerging membrane materials, emerging water treatment technologies, membrane filtration, recycle water treatment

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INTRODUCTION

Low-pressure membranes, including MF and UF are widely used for drinking water treatment. The use of low-pressure membranes for drinking water treatment is driven by the fact that the MF/UF membranes are absolute barriers to

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pathogens such as, *Giardia* and *Cryptosporidium*. The MF/UF membrane fibers are typically made of polymers such as, PS, PP, PES and PVDF. Polymeric MF/UF membranes require robust pre-treatment such as coagulation, flocculation, and clarification to remove particulates, organics, and other membrane foulants. More recently, membranes made of ceramic materials (aluminium oxide, titanium oxide etc.) have been developed and used to treat various source waters.

The first full-scale ceramic membrane system was brought online in France in 1990. Presently, over 70 ceramic membrane plants of capacities ranging from 0.01 million gallons per day (mgd) to 10 mgd are in operation globally. In the US, ceramic membranes are approved for potable water treatment in the states of Colorado and California. Potential applications of ceramic membranes in water treatment include:

- Compact new water treatment plants (for most waters, ceramic membranes can be applied in a direct filtration mode).
- Retrofitting and expansion of existing water treatment plants.
- Spent filter backwash wastewater treatment, and
- Recycle water treatment.

This paper discusses the results of two pilot studies. Pilot tests were conducted at DWU's Elm Fork WTP and City of Rifle's Graham Mesa WTP. Pilot testing at the Elm Fork WTP included source water (Trinity River water), spent filter backwash and lagoon recycle water (spent filter backwash water combined with clarifier blow down water). Pilot testing at the Graham Mesa WTP included Rifle Pond water which is a man-made pond that collected and stored Colorado River water. Key objectives of the pilot studies were to:

- Confirm ceramic membrane capabilities.
- Establish ceramic membrane design and operating criteria such as membrane flux, trans-membrane pressures (TMPs) and membrane recovery.
- Evaluate and establish pre-treatment requirements (coagulant dose).
- Obtain information for conceptual sizing and preliminary design of ceramic membrane treatment process.

Unit conversions

Parameter	US Units	SI Units
Pressure	1 psi	730 kilogram-force/square meter
Flux	1 gfd	40.7 litres/square meter-day
Flow	1 mgd	2,627 litres/minute
Flow	1 gpm	3.78 litres/minute

MATERIALS AND METHODS

Dallas Water Utilities pilot testing

The DWU pilot unit was a skid mounted portable system with two parallel trains; each train consisted of two ceramic membrane modules (Figure 1). Each train was capable of treating up to 1.2 gallons per minute (gpm) flow at fluxes of 100–150 gfd (gallons per square foot per day). Each water stream was tested for approximately two-three weeks. Bench-scale tests were conducted to define the pre-treatment conditions (e.g. coagulant type, dose). Test matrix included varying coagulant dosages, membrane fluxes, backwash protocols and CEBs. Table 1 summarizes the test conditions, membrane operations and water quality monitoring. The sample locations are illustrated in Figure 2. The field parameters were monitored twice-per-week while the laboratory parameters were monitored once-per-week.

City of Rifle pilot testing

The City of Rifle pilot testing was conducted using a larger, single element pilot system. The pilot system had a nominal flow rate of 18.7 gpm at a flux of 100 gallons per square foot

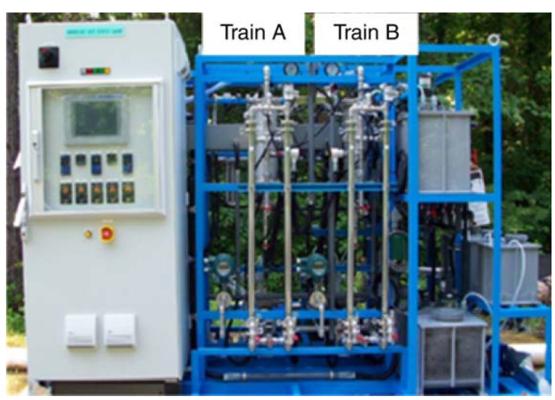

Figure 1 | DWU ceramic membrane pilot system.

Table 1 | DWU pilot test matrix

		Water quality monitoring	
Source water	**Pre-treatment and ceramic membrane performance monitoring**	**Field parameters**	**Laboratory parameters**
• Trinity River Water at Elm Fork	• Coagulant dose • Membrane flux	• pH • Alkalinity	• Total organic carbon (TOC)
• Spent filter backwash water	• TMP • Backwash effectiveness	• Turbidity • Color	• Disinfection by-products (DBPs)
• Lagoon recycle water	• CEB effectiveness • CIP effectiveness • Membrane recovery	• Dissolved oxygen • UV 254 absorbance • Conductivity • Ammonia • Iron	• Metals • Anions
		• Total suspended solids (TSS)	
		• Nitrite	

per day (gfd) and a maximum flow of 50 gpm at 268 gfd (Figure 3). The City pumped Colorado River water from the Rifle Pond (a pre-sedimentation pond) to the pilot plant. Pilot testing was conducted for approximately three months. Process flow diagram for City of Rifle pilot plant is shown in Figure 4. Table 2 provides details on the source waters and membrane performance parameters.

RESULTS AND DISCUSSION

Dallas Water Utilities pilot testing

The membrane operational results for Trinity River Water are shown in Figure 5. Ferric sulfate was evaluated at dosages of 30–50 milligrams per litre (mg/L). This ferric sulfate dosage resulted in pin floc formation. Membrane fluxes were varied between 50–100 gfd. Optimum membrane operating parameters for Trinity River water were determined to be:

- Membrane flux of 75 gfd.
- Ferric sulfate dose of 50 mg/L.
- Filtration cycle time of 60 minutes (min).
- Backwashes interval of 60 min; backwash duration of 45 seconds (sec).
- CEB interval of 24 hours. CEBs will include soaking and recirculation with citric acid or sodium hypochlorite.
- CIP interval of 4 months. CIPs will include soaking and recirculation with citric acid and sodium hypochlorite.

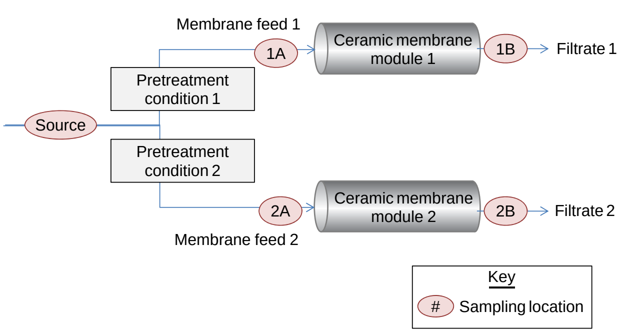

Figure 2 | DWU pilot test sample locations.

Figure 3 | City of Rifle ceramic membrane pilot system.

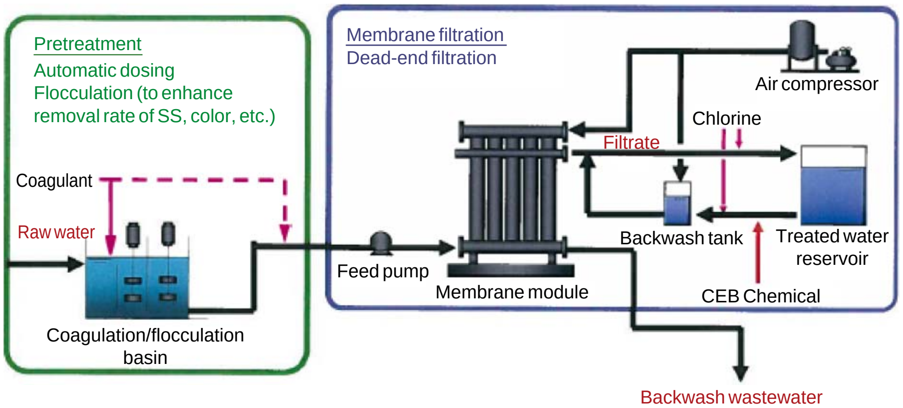

Figure 4 | City of Rifle ceramic membrane pilot system process flow diagram.

Table 2 | City of Rifle ceramic membrane pilot test matrix

Source water	Pre-treatment and ceramic membrane performance monitoring	Water quality monitoring: Field parameters	Water quality monitoring: Laboratory parameters
• Colorado River water from pre-sedimentation basin (Rifle pond)	• Coagulant dose	• pH	• TOC
	• Membrane flux	• Temperature	• MIB
	• TMP	• Alkalinity	• Geosmin
	• Backwash effectiveness	• Turbidity	• Iron
	• CEB effectiveness	• Particle size distribution	• Manganese
	• CIP effectiveness	• UV 254 absorbance	• Anions
	• Membrane recovery		• Algae

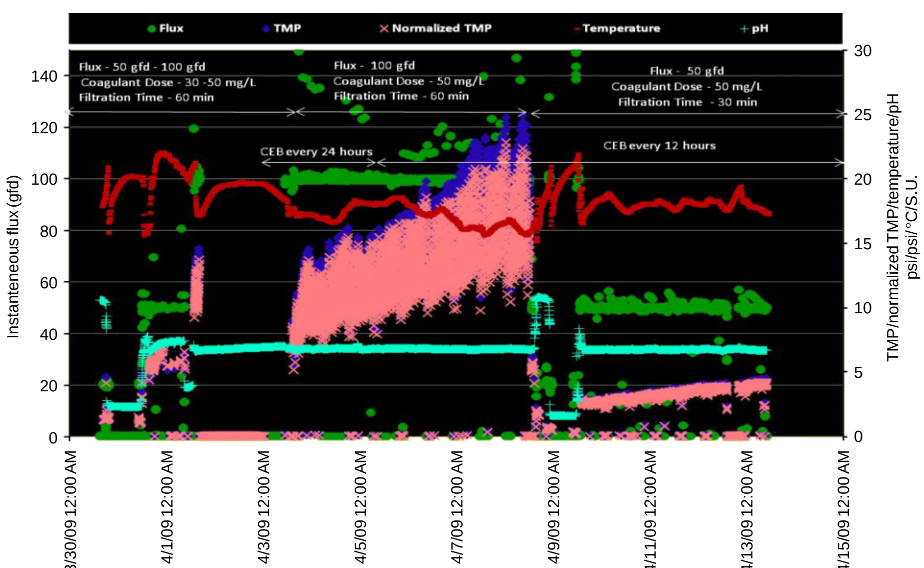

Figure 5 | DWU ceramic membrane pilot test results for trinity river water.

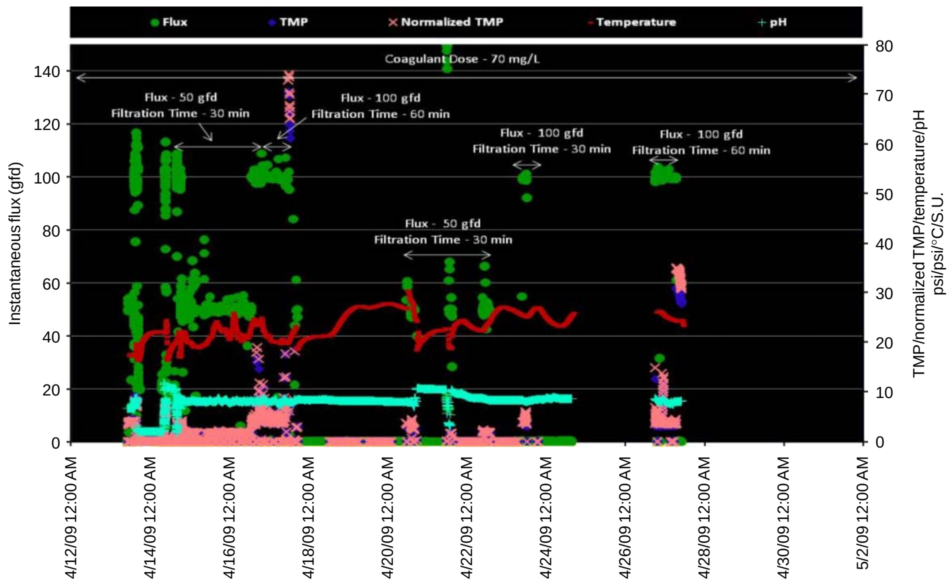

Figure 6 | DWU ceramic membrane pilot test results for spent filter backwash water.

The results for the spent filter backwash wastewater stream are shown in Figure 6. Ferric sulfate was added at a dose of 70 mg/L. Membrane fluxes were varied between 50–100 gfd. Optimum membrane operating parameters for the Elm Fork WTP spent filter backwash water were determined to be:

- Membrane flux of 100 gfd.
- Ferric sulfate dose of 70 mg/L.
- Filtration cycle time of 60 min.
- Backwashes interval of 60 min; backwash duration of 45 sec.
- CEB interval of 24 hours; CEBs will include either acid or sodium hypochlorite.
- CIP interval of 4 months. CIPs will include soaking and recirculation with citric acid and sodium hypochlorite.

Results of water quality monitoring from the DWU pilot testing are summarized in Table 3.

City of Rifle pilot testing

Results of Rifle pilot testing are shown in Figure 7. Pilot was operated at a flux of approximately 160–165 gfd. Note that the maximum flux allowed by the state of Colorado is 175 gfd at 20°C, and maximum TMP is 55 psi. The average TMP for the data shown in Figure 7 is 21 psi (Figure 6). The nutrient-rich

Table 3 | DWU ceramic membrane pilot testing water quality results

	Trinity river		Spent filter backwash		Lagoon recycle	
Parameter	Feed water	Membrane filtrate	Feed water	Mem. filtrate	Feed water	Mem. filtrate
Alkalinity, mg/L	99	63	63	45	245	38
pH, S.U.	8.0	6.9	8.5	7.6	8.5	8.3
Turbidity, NTU	154	0.022	134	1.2	>5,000	0.032
TOC, mg/L	5.8	4.1	5.3	4.2	6.4	5.1
Iron, mg/L	1.3	0.06	15	0.03	93	0.05
TTHM, μg/L	NA	10.2	NA	7.03	NA	4.8
HAA5, μg/L	NA	8.8	NA	11.8	NA	11

Note: S.U.—Standard Units; NTU—Nephlometric Turbidity Units; TTHM—Total Trihalomethanes; HAA5—Haloacetic acids; NA—Not available; μg/L—micrograms per litre.

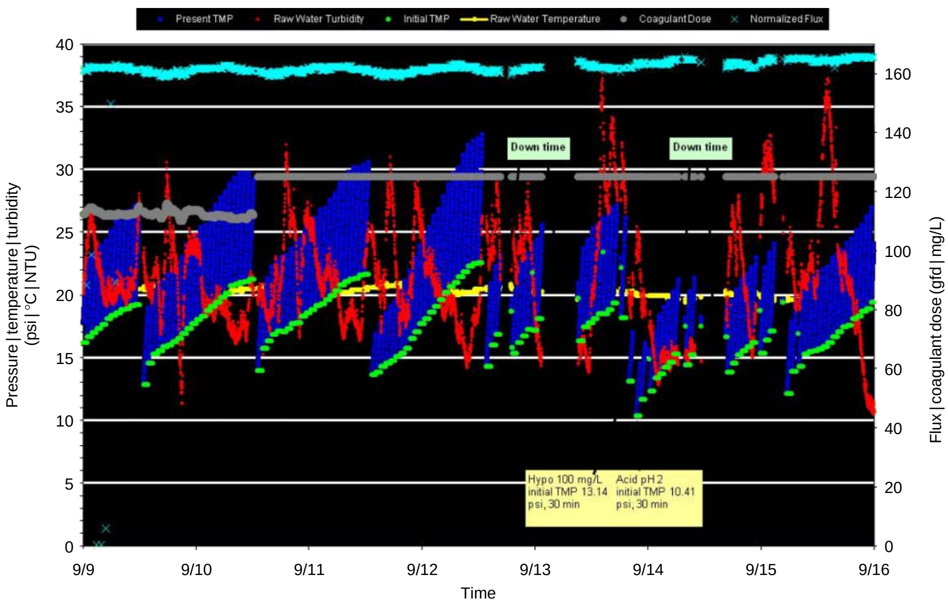

Figure 7 | Rifle ceramic membrane pilot test results.

Table 4 | City of Rifle ceramic membrane pilot testing water quality results

Parameter	Raw water	Membrane filtrate
Turbidity, NTU	23	<0.07
Alkalinity, mg/L as $CaCO_3$	154	102
pH, S.U.	8.0	6.7
UV254 absorbance, cm^{-1}	0.061	0.015
Dissolved aluminium, μg/L		3
Dissolved iron, μg/L	37	33
Dissolved manganese, μgL	90	40

Note: S.U.—Standard Units; NTU—Nephlometric Turbidity Units; UV—Ultraviolet; μg/L—micrograms per litre.

source water facilitated some growth (possibly algae) on the pilot unit strainer and flocculation tanks. Pilot had to be shutdown to periodically clean the strainer, lines and tanks.

Results of water quality monitoring from the Rifle pilot testing are summarized in Table 4.

CONCLUSIONS

The key findings of the two pilot studies are:

- Ceramic membranes are a viable technology for treating high particulate water streams.
- Ceramic membrane performance is dictated by the feed water quality, pre-treatment and membrane design/operating conditions.
- The CEBs and CIPs were able to restore the membrane fluxes and TMPs to the operational target values.
- An understanding of coagulant chemistry and pre-treatment is necessary to obtain consistent performance from ceramic membranes. Conditions for pin floc formation have to be carefully established for optimal membrane performance.

Following issues need to be considered in comparing ceramic membranes to polymeric membranes:

- Ceramic membranes can last up to 20 years. Polymeric membranes last for 7–10 years. Life-cycle cost comparison should account for the longer life span of ceramic membranes.
- Ceramic membranes have higher integrity. Polymeric membranes have occasional breaks in membrane fibers that require plugging or repair.
- For most applications, ceramic membrane can be operated in a direct filtration mode. However, for certain applications, pre-treatment with clarification may be needed to meet certain water quality goals and/or treatment objectives.