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# **A new integrated potable reuse process for a small remote community in Antarctica**

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## **Abstract**

To meet water reuse and discharge requirements in Davis Station, Antarctica, an advanced water treatment plant (AWTP) had been designed and tested for nine months. The key design factors for operating in small communities in remote areas included low maintenance requirement (low chemical inventory, minimal onsite labour), high LRVs for pathogens, robust operation, and high automation. Based on these requirements, the seven-barrier AWTP included ozonation, ceramic microfiltration, biological activated carbon, reverse osmosis, ultraviolet radiation, calcite filtration and chlorination. The nine month test demonstrated that the plant was able to provide minimum LRVs of 12.5 for virus and bacteria, and 10 for protozoa. The overall estimated chemical consumption was lower than equivalent continuous operations elsewhere due to a reduced number of Clean in Place (CIP) cycles as compared to industry. This was achieved by optimised integration of the barriers. Furthermore, there was no functional failure of major barriers and the automated online pressure decay test (PDT) validations for MF and RO were successful. Although some minor improvements, such as a reduced frequency of RO pre-filter cartridge replacement, are still needed, the new integrated plant has fulfilled the requirements of high pathogen LRVs, remote online control and validation, and relatively low chemical consumption.

**Keywords:** Water treatment; water reuse; potable reuse; advanced water treatment plant

## **1. Introduction**

Australia's Davis Station, Antarctica, a small community in a remote area, was established in January 1957 and has been constrained by water shortages for more than fifty years. The water supply is reliant on an installed reverse osmosis (RO) plant that treats water from a small nearby tarn. However, the requirement for controlling environmental discharges has resulted in the salinity of the feed water to the RO plant increasing gradually, due to it also being the receiving water for the RO concentrate (Pekin, 2012). A further significant environmental issue at Davis Station is the environmental impact of ocean sewage outfall on the sensitive marine ecosystem, with pathogens and chemicals of concern identified as impacting on the environment (Stark et al., 2011).

To achieve a sustainable water source and minimise the effects of wastewater discharge to the marine environment, a secondary wastewater plant including anaerobic and aerobic processes and membrane bioreactor, as well as an advanced water treatment plant (AWTP) for production of potable water have been proposed. The implementation of a potable water recycling plant at Davis Station needs to conform to the Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies (Natural Resource Management Ministerial Council et al., 2008), as the station is under the control of the Australian Government. Further, similar to most remote communities, the availability of trained water operators for Davis Station is limited; the population is low and varies greatly seasonally; and the chemical inventory is minimised to reduce space requirements on the limited supply ship visits. Therefore, the operation and validation of the potential water recycling plant needs to be robust, highly automated and remotely operable, with low on site operator requirements and minimal chemical consumption.

Compared to a large-scale municipal purified water recycling plant, in which pathogens shed by a few people during a disease outbreak are diluted by the bulk flow, more stringent pathogen log reduction values (LRV) defined in Equation (1), are required for small scale communities (Barker et al., 2013).

$$LRV = -\log\left(\frac{C_p}{C_f}\right) \quad (1)$$

where  $C_f$  and  $C_p$  are respectively the concentrations of pathogen in the feed and product water.

This arises from the increased proportion of the small community that is likely to become sick during a disease outbreak, and the consequence is that 3 - 6 log higher LRV as shown in

in Table 1 (Barker et al., 2013) is required to meet the Australian and World Health Organisation requirement for a DALY (disability-adjusted life year) of less than  $10^{-6}$  days per person per year (Natural Resource Management Ministerial Council et al., 2008; World Health Organisation, 2011). Since one of the major purposes of the scheme is also to minimise the environmental impacts of sewage discharge, the introduced chemicals and disinfection by-products should also be critically controlled in the discharge to the Antarctic Ocean.

The high LRV requirements for this plant and the need to remove chemical of concerns from the final ocean discharge means that a conventional water recycling plant consisting of biological wastewater treatment - ultrafiltration (or MBR) – RO – advanced oxidation is unsuitable for this application, as this process is unable to meet the pathogen LRV requirements or to extensively remove chemicals of concern from the RO brine. Under the Australian regulatory environment no single pathogen barrier is able to be credited with more than 4 LRV (Department of Health & Human Services, Victoria, 2013), and credited LRV for reverse osmosis is limited to 2 or less because of the need for on-line verification. Furthermore, the LRV ascribed to biological processes is low and variable, and requires on-site validation which is not practical for Davis Station.

Therefore, to satisfy all critical requirements, seven barriers were selected for the AWTP that included:

- a) Ozonation, which provides pathogen inactivation, boosts dissolved organic carbon (DOC) bio-degradability, degrades chemicals of concern (CoC) and lowers cleaning chemical consumption for the downstream ceramic micro-filtration (MF) by increasing backwash efficiency (Dow et al., 2015; Duke et al., 2013)
- b) Ceramic microfiltration membranes (MF), which act as a pathogen barrier, lower chemical consumption by using direct contact with ozone to reduce fouling and the need for chemical cleaning, and have much better robustness and long-term integrity than polymeric membranes
- c) Biological activated carbon (BAC) filter, which digests DOC to reduce the organic fouling potential of the reverse osmosis (RO) feed so as to reduce the replacement frequency and CIP for RO membrane array, and also removes additional trace organic compounds from the RO brine discharged to the Antarctic Ocean. However, the BAC will increase the concentration of particulates in the BAC effluent and thereby

increases the frequency of replacing the cartridge filter upstream the RO array, but the RO brine will better meet the water quality objectives for this site.

- d) RO, which is a barrier for pathogens and CoCs, and reduces the salinity of the treated water
- e) Ultraviolet radiation (UV), which is a barrier for pathogens, especial protozoa
- f) Calcite filtration, used to increase water stability
- g) Chlorination, which is a barrier for pathogens and provides a long term chlorine residual to suppress pathogen regrowth

**Table 1** Claimed LRVs for the potable reuse plant and CCPs for each barrier

Barrier	CCPs	LRV*		
		Virus	Bacteria	Protozoa
Ozonation	CT	2	2	0
Ceramic MF	PDT	1	1	4
BAC	Turbidity	0	0	0
RO	Conductivity and PDT	1.5	1.5	2
UV	Dosing	4	4	4
Calcite Filter	pH	0	0	0
Chlorination	CT	4	4	0
Total claimed LRVs		12.5	12.5	10

\* The LRVs are credited based on health regulator guidelines e.g. the USEPA Long Term 2 Enhanced Surface Water Treatment Rule, Guidelines for validating treatment processes for pathogen reduction, (Department of Health & Human Services, Victoria, 2013).

In this study, the AWTP was tested and assessed based on the key design requirements during nine months of operation. All the CT values were calculated for a temperature of 19°C, as the treatment plant will be housed in a 19°C temperature controlled room at Davis Station. The assessment provides a reference for small scale potable reuse plant design, i.e., barrier selection, requirements and critical control point (CCP) selection as shown in Table 1 (Gray et al., 2015a). Furthermore, some new technologies, such as the combination of ozonation, ceramic MF and BAC, and pressure decay tests (PDT) for online RO integrity validation, were used in this plant. This study also demonstrated the effectiveness of these technologies.

## 2. Experimental and Demonstration method

A schematic of the AWTP flowsheet is shown in Figure 1. The small AWTP that will

operate at Davis Station was constructed and trials run at Selfs Point Wastewater Treatment Plant (WWTP), Hobart, Tasmania, Australia. The secondary effluent before disinfection was used as the feed to the AWTP. During the plant operating period, the DOC range in the feed water was 7.5 to 9.4 mg/L, and TN was stable at 2.0 mg/L, except for a few spikes as high as 8- 16 mg/L due to upstream maintenance activities.

The AWTP was contained in four shipping containers. At Davis Station, it is anticipated that the plant will operate intermittently with almost continuous operation during the summer months, and operation every second day over winter. To simulate these conditions, a virtual feed tank of 3500 L was created in the plant operating software, and filled at a rate of less than 20 L/min – the flowrate from the virtual tank to the AWTP. The level of the virtual tank was calculated from the amount of feed into the virtual tank minus the amount out. The level in the virtual tank controlled plant start-up and shut-down in normal operation, with the plant put online when the virtual tank level reached 3,500 litres and offline when the level dropped to 500 litres. The recovery of the RO system was set to 70% during the test and the overall recovery of AWTP was between 65 and 67.5%, due to use of RO permeate for the ceramic MF backwash.

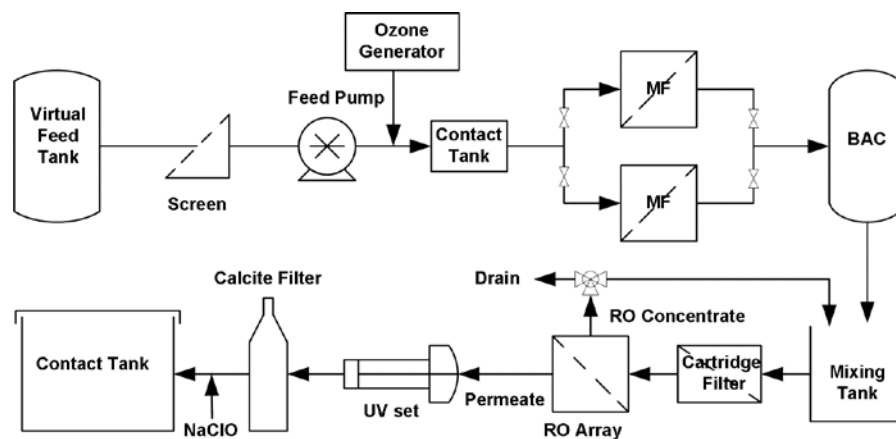


Figure 1: Schematic of the potable reuse plant

Ozone production was via a Wedeco OCS-GSO system and set at 19-20 mg per litre waste water, with approximately 11.7-14 mg/L ozone dosed into the liquid phase. The ozone system included a 480 L contact tank with an internal tank, a circulating venturi dosing system operating at a circulation flowrate of 2 m<sup>3</sup>/min, a pressure swing absorption (PSA) oxygen generator and an ozone generator. The ozone system started approximately 10 to 15 min earlier than the feed pump to build up the ozone concentration in the ozone contact tank.

The MF barrier comprised two 0.1 µm Metawater<sup>®</sup> ceramic membranes operated

alternatively (duty/standby) in dead end mode. The operating flux was approximately 50 Lm<sup>-2</sup>h<sup>-1</sup> and a PDT was used to ensure membrane integrity after each online period.

The BAC barrier used Acticarb<sup>®</sup> BAC GA1000N activated carbon with an Empty Bed Contact Time (EBCT) of 20 min, and head loss and volume of treated water was used to trigger the backwash of the BAC filter, which occurred during offline periods.

Five FILMTEC BW30-4040 RO elements were used in the RO array, and the designed transmembrane pressure and permeate flow were 9.4 bar and 14 L/min, respectively. The RO system incorporated a recycle stream to increase the overall recovery to 70%, with a single pass recovery of approximately 50%. The membrane integrity was monitored by both conductivity and PDTs. The PDT was conducted based on the method described by Zhang *et al.* (Zhang et al., 2016). The RO PDT was used to achieve the required LRV for protozoa and a LRV of 2 across the RO membranes was claimed. The LRV verification and the pressure of the PDT are related via Equation (2) (Allgeier et al., 2005).

$$LRV_{DIT} = \log \left( \frac{Q_p \cdot ALCR \cdot P_{atm}}{\Delta P_{test} \cdot V_{sys} \cdot VCF} \right) \quad (2)$$

where  $Q_p$  is the filtrate flow,  $ALCR$  is the air-liquid conversion ratio,  $P_{atm}$  is the atmosphere pressure,  $\Delta P_{test}$  is the testing pressure,  $V_{sys}$  is the tested system volume, and  $VCF$  is the volumetric concentration factor.

For this system the initial pressure used for the PDT was 85 kPa and a pressure decay rate below 3.7 kPa/min indicated a protozoa LRV of 2 could be claimed for the RO system.

Two UV units (Wedeco Spectron 6) were used in series to achieve a minimum UVC dose of 189 mJ/cm<sup>2</sup>, as required for 4 LRV of virus. Each UV unit was able to achieve an Ultraviolet C dose of > 400 mJ/cm<sup>2</sup>, and the two units were operated to ensure water quality was maintained if one failed during service.

The calcite filter (Puretec<sup>®</sup>) had an EBCT value of 5 min to achieve Ca<sup>2+</sup> concentration no less than 20 mg/L, and its need for replenishment was monitored by filtrate pH.

The designed free chlorine dose was 0.9 mg/L with a residual no less than 0.7 mg/L after 30 min of contact time. Both doses were monitored by online chlorine meters. The CCPs for all the barriers are listed in Table 1. All CCPs related instrumentation, except for the pressure

transmitters and flowrate meters, were verified weekly.

The ozone mass transfer efficiency to the feed water was estimated by measuring the difference between the gas flow rate from the ozone destroyer between operation in dry mode (ozone generator not operating) and operation mode. The 10% residence time for CT value calculation,  $T_{10}$  (10% of the feed passes through the contactor) for the ozone contact tank and UV units were measured using the step dose method (USEPA, 1991) with rhodamine WT dye.

To minimise labour requirements, clean-in-place (CIP) of the ceramic MF membranes with manual chemical addition to the CIP tank was not practiced. However, 100 mg/L NaClO solution was used for chemically enhanced backwash (CEB) instead of 50 mg/L as recommended by the manufacturer. The backwash pressure was also reduced to 1.6 bar from the manufacturer recommendation of 4 bar, which minimised hydraulic shock and vibration within the treatment system during backwash. To reduce the chemical inventory and storage capacity, only 90 L of 600 mg/L NaOH and 90 L of 550 mg/L HCl solutions were used for the RO CIP.

Two samples were taken for each barrier weekly for analysing DOC (measured by a Shimadzu, TOC\_V with TNM-1 unit), total nitrogen (TN measured by Shimadzu, TOC\_V with TNM-1 unit), total phosphate (TP, measured by Shimadzu ICP2000), calcium (measured individually by Shimadzu ICP2000) and other metals (measured by Shimadzu ICP2000) for comparison with the Australian Drinking Water Guideline (ADWG). *E.coli* and total coliforms were tested weekly by plate counting for samples of plant feed, ozone effluent, ceramic MF filtrate, BAC filtrate, RO permeate and product water. The Somatic coliphage in the plant feed, ozonation effluent, ceramic MF filtrate, BAC filtrate and product water were analysed 5 times during the operation period.

Biodegradable dissolved organic carbon (BDOC) of feed, ozonation effluent, ceramic MF filtrate and BAC filtrate were analysed three times during the trial by the Joret method, and were performed by Research Laboratory Services Pty Ltd.

The chemical consumption and plant operation time were calculated based on the data recorded by the control system (SCADA).

The data presented in this study were the combination of online and offline data, which were



aligned within a five minute time interval.

### 3. Results and Discussion

#### 3.1 Assessment of Ozonation System

##### 3.1.1 Ozone production, ozone dosing and contact time ( $T_{10}$ )

In Table 2, the ozone produced and dosed (including dissolved and consumed ozone) into the feed (20 L/min) are shown. In larger-scale plants, the ratio of dosed ozone to DOC is normally below unity (Gottschalk et al., 2009). However, as seen in Table 1, the ratio in this demonstration plant was about 1.4 - 1.9 mg  $O_3$ /mg DOC. In a large scale plant, ozone is used to remove odour, colour and UV-absorbance, and increases biodegradable organic carbon ahead of biological stages (Camel and Bermond, 1998). Here, besides the major purposes of the large scale plant, the ozone was also used as disinfectant to achieve the required LRVs shown in Table 1.

The percentage of produced ozone dosed into the ozone system (using Venturi injection) was between 60.4% to 73.3% as shown in Table 2, which is higher than that of the bubble columns (30 - 55%) with similar ozone doses (Xu et al., 2002).

Table 2 Ozone production and ozone dosed into waste water

Date	Produced ozone (mg/L)	Dosed ozone (mg/L)	Percentage (dosed/produced)	$O_3$ :DOC
27/11/14	20.7	13.5	65.0%	1.6
27/01/15	20.6	14.9	71.9%	1.8
10/02/15	19.3	11.7	60.4%	1.4
25/02/15	20.3	14.9	73.3%	1.9

Since the residence time used in the CT value calculation was based on the residence time for 10% of the feed to pass through the contact tank ( $T_{10}$ ), the  $T_{10}$  of the ozone contact tank was measured. The measured  $T_{10}$  values were 4.7 and 4.9 min (average  $T_{10}$  = 4.8 min) based on two hydraulic residence time tests using rhodamine WT fluorescent dye, as shown in Figure 2. The  $T_{10}$  value was about one fifth of the mean hydraulic residence time (24 min) calculated based on the feed flow rate and contact tank volume.

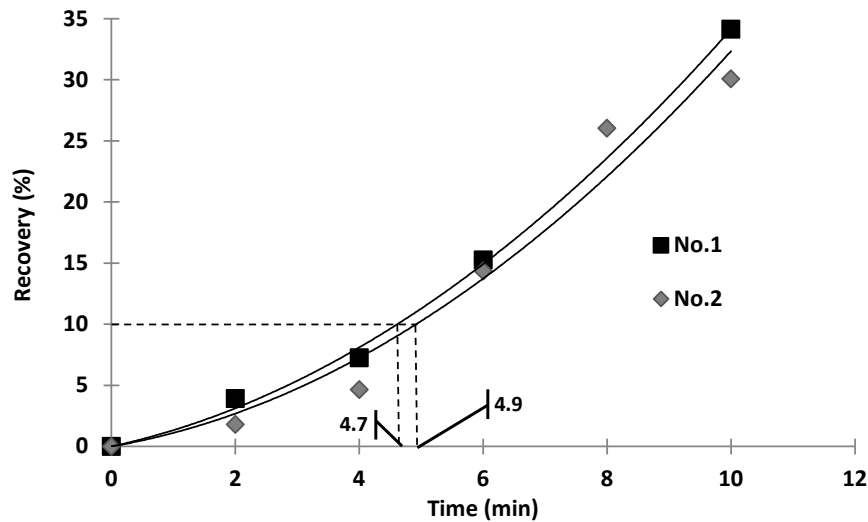


Figure 2:  $T_{10}$  measurements for the ozone contact tank (recovery from 0 to 33%)

### 3.1.2 Ozone system performance

As the first barrier, ozonation was employed to convert non-biodegradable (or slowly biodegradable carbon) to biodegradable dissolved organic carbon (BDOC), degrade CoCs and to serve as a disinfection barrier. As seen in Table 3, the BDOC content in the wastewater increased from 29-32% before ozonation to 56-59% after ozonation. Comparison with the ozone dosing in Table 2 shows more than 95% of the ozone was consumed or degraded during 24 min contact with the wastewater.

Table 3 Influence of ozonation on BDOC in the wastewater

Days	Ozone Residual (mg/L)	Feed			Post-ozonation			DOC Reduction (%)	Reduction + Conversion (%)
		DOC (mg/L)	BDOC (mg/L)	BDOC/DOC (%)	DOC (mg/L)	BDOC (mg/L)	BDOC/DOC (%)		
127	0.015	8.9	2.6	29	8.7	4.9	56	2.2	28
183	0.136	8.7	2.4	28	8.1	4.5	56	6.9	31
15	0.478	8.5	2.7	32	7.5	4.4	59	11.7	32

As the ozone residual increased from 0.015 to 0.478 mg/L, the DOC reduction increased from 2.2% to 11.7%. However, ratios of the total DOC reduction and conversion to original DOC were approximately the same at different ozone residuals. Fahmi et al. found that the DOC reduction was mainly from BDOC mineralisation by ozonation (Fahmi et al., 2003). Therefore, high ozone residual facilitates BDOC decomposition.

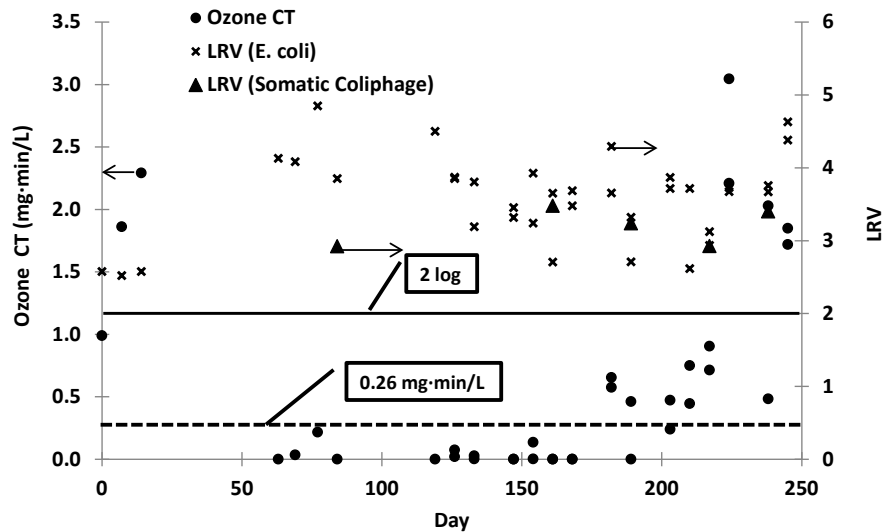
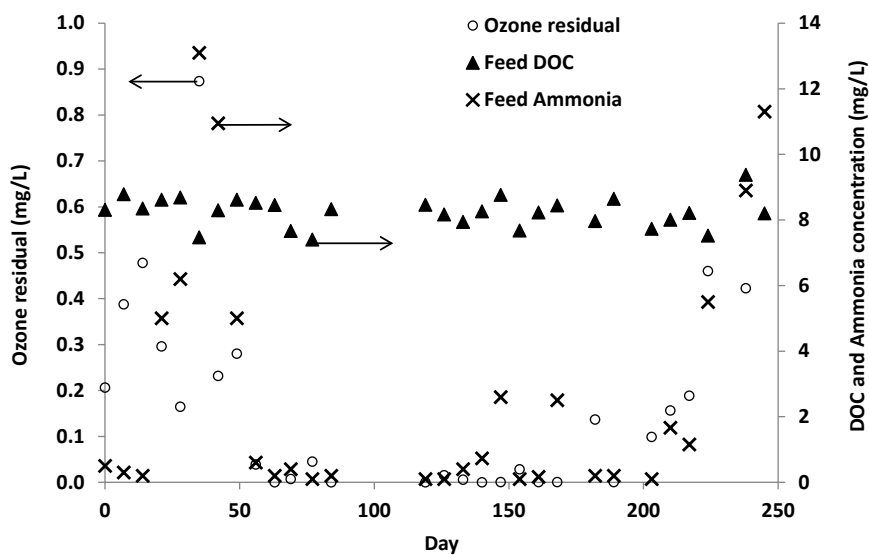
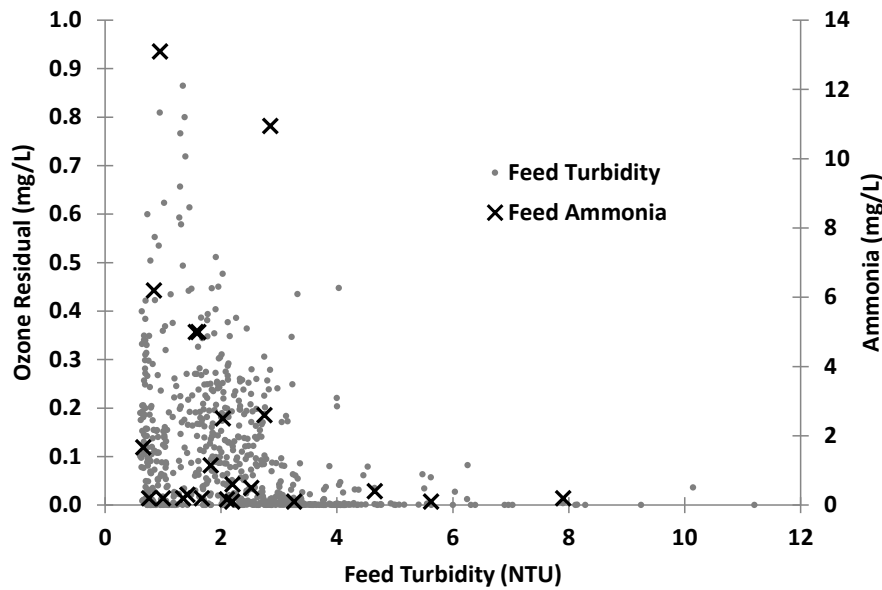


Figure 3: LRV of ozonation barrier to *E. coli* and ozone residual in the wastewater

Figure 3 shows the CT value and measured LRV based on naturally occurring *E. coli* and *Somatic Coliphage*, where 0.26 mg·min/L is the CT value required by the USEPA Long Term 2 Enhanced Surface Water Treatment Rule (LT2) to achieve 2 LRV for virus. It can be found that the measured LRVs were greater than 2.5, regardless of the ozone CT value. However, no clear relationship between the ozone CT value and pathogen LRVs was found.



a. Influence of feed ammonia and DOC on ozone residual



#### b. Feed turbidity vs ammonia concentration and ozone residual

Figure 4: Parameters affecting the ozone residual

In Figure 4, ammonia, DOC and turbidity values for the feed water are shown, as they may influence the ozone residual. Since the ammonia and DOC concentrations were not measured online, the online ozone residual data in Figure 4a were selected based on the sampling time ( $\pm 10$  min). It was established that the concentration of DOC in the feed water did not show any clear relationship with residual ozone. Interestingly, it can be found that the ozone residual showed the similar trend to the ozone residual. However, the higher ammonia concentration should theoretically lead to more ozone depletion due to the slow oxidation (von Gunten, 2003). In Figure 4b, the relationship of turbidity to ammonia concentration and ozone residual are shown. It can be found that the ammonia concentration was relatively high when the turbidity was low. Furthermore, as the feed turbidity increased, the ozone residual in the wastewater declined. Therefore, it seems that the turbidity shows a dominant influence on ozone residual in this study. Thus, pre-filtration to remove suspended solids seems important to maintain high ozone residual concentrations.

The relatively high turbidity values for feed to the ozone system may lead to the discrepancies seen between the LRV obtained for *E.coli* and *Somatic coliphage* for the range of residual ozone CT values achieved compared to those specified by the USEPA rule. The USEPA rule was developed for surface waters with low turbidity and low DOC values compared to the feed to the AWTP, and these differences in feed water quality may lead to the resultant differences in LRV obtained for low ozone residual CT value.

## 3.2 Ceramic MF barrier

### 3.3.1 Pathogen rejection and validation

During the test, the *E. Coli* and *Somatic coliphage* were respectively less than 40 and 10 MPN (most probable number)/100 mL in the ozonated water (MF feed), and were not found in the MF filtrate.

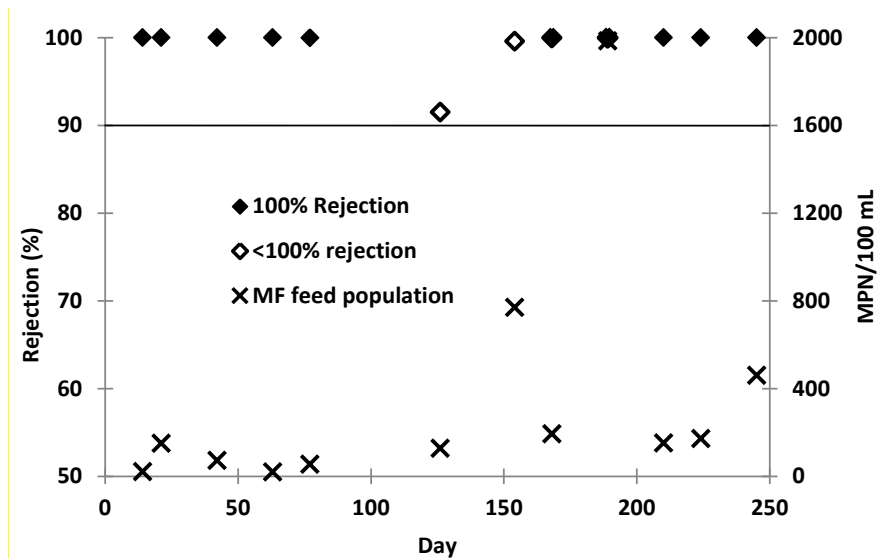


Figure 5: MF rejection of coliforms. Solid diamonds for coliform data that was  $<1$  MPN/100 ml for MF filtrate; Open diamonds for coliform data  $\geq 1$  MPN for MF filtrate.

The total coliform population rejection calculated based on the total coliform population in the MF feed and MF filtrate is shown in Figure 5. If the detected coliform population was less than 1 MPN/100 mL in the MF filtrate, the data point is shown by a solid marker in Figure 5 and 0 MPN/100 mL was used in the calculation of rejection. As shown by the open diamonds, two total coliform rejections less than 100% (91.5% and 99.6%) were detected in the first month after the pilot plant had been offline for 1 month (from December, 2014 to January, 2015), but disappeared in the second month. Therefore, it is proposed that there was coliform growth on the filtrate side of the ceramic membrane when the whole plant was put offline for about one month. However, during the total operating period, the rejection of total coliforms was not less than 90% ( $LRV > 1$ ). It was also proposed that the ozone residual in the MF feed might contribute to further inactivation of coliforms, but from November, 2014 to May, 2015, the ozone residual in the MF feed was also zero most of time. Therefore, it can be confirmed that the ceramic MF membrane was able to achieve at least 1 LRV for coliform by size exclusion only.

The Department of Health Services, California, has approved the Metawater<sup>®</sup> ceramic MF membrane for removal of 4 LRV for protozoa, 1 LRV for virus and 1 LRV for bacteria when the pressure decay rate is <1.4 kPa/min under a PDT pressure of 1.4 bar. In Figure 6, the decay rates are shown. It was found that the decay rates were all less than 1.4 kPa/min, except for three tests. This may be due to an issue caused by the valves on the filtrate side of the membrane not completely sealing during the PDT tests, as the decay rates reverted to being <1.4 kPa/min without any remediation of the ceramic MF. Therefore, the pressure decay rate of a blank test was measured with all valves closed on both sides of a pressurised membrane, and the PDT rates were corrected by subtracting the blank test decay rate. Figure 6 (on the right side of the vertical red line) shows that the PDT rates were all less than the 0.2 kPa/min with the correction, well below the required limit.

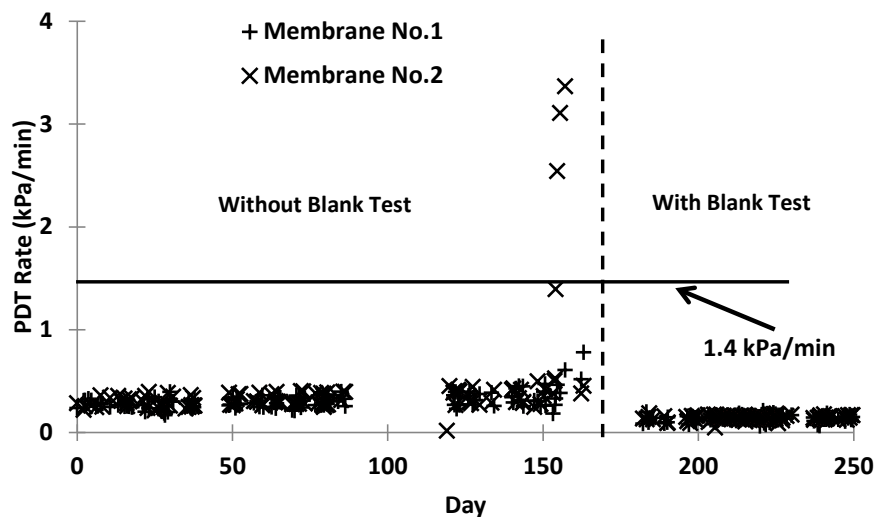


Figure 6: Ceramic MF PDT results

### 3.3.2 Interaction with ozonation for DOC reduction

It has been reported that ceramic  $\text{ZrO}_2$  membranes may act catalytically with ozone (Zhu et al., 2011) to boost the oxidation effect of ozone on organic matter. However, it was found for the Metawater<sup>®</sup> alumina membrane that if a chlorine free potable water was used as feed, there was no obvious ozone residual change observed in MF feed and filtrate as shown in Figure 7. Therefore, the catalytic effects of the ceramic membrane might be too weak to boost the decomposition of ozone (Batakliiev et al., 2014).

Although the membrane material did not improve ozone decomposition, a DOC reduction

across the ceramic membrane is indicated, except for four pairs of samples which were taken just after backwash. The associated data is shown in Figure 8. Therefore, it was proposed that enhanced oxidation still occurred on the membrane surface, induced by the organic matter absorbed on the membrane surface (Staehelin and Hoigne, 1985). In Table 4, it was also observed that the total DOC reduction of 5.7 - 9.3% was almost all from BDOC reduction. This is consistent with the findings of Fahmi, et al. (Fahmi et al., 2003), and demonstrates enhanced oxidation (bioactivity will be suppressed by ozone) by the alumina (metal oxide) in the ceramic MF to organic matter (Bataklijev et al., 2014). Thus, the combination of ozone and ceramic MF is able to reduce the organic load on the downstream RO membranes, as well as acting as a barrier for pathogens.

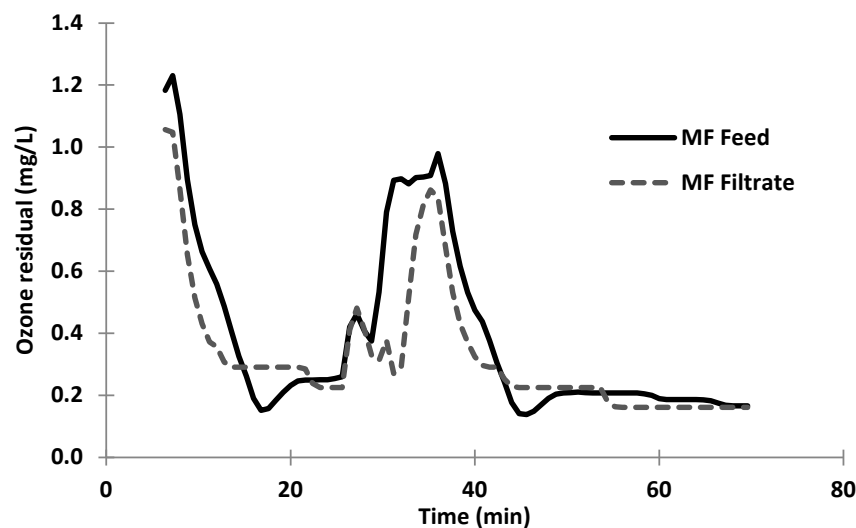


Figure 7: Ozone residual in MF feed and filtrate (dechlorinated potable water as the plant feed)

Figure 9 plots the relationship between the ozone residual in the feed and filtrate of the MF. The data indicates that for any given ozone residual in the MF feed, there was a fixed upper limit for the residual in the MF filtrate. Since it was demonstrated that the alumina MF membrane had no effect on ozone decomposition based on a potable water feed, the upper limit might have resulted from interaction of ozone and organic matter absorbed on the membrane surface. To achieve an ozone residual greater than zero in the MF filtrate, a minimum feed ozone residual greater than 0.21 mg/L was required based on the fitting equation to the data in Figure 9.

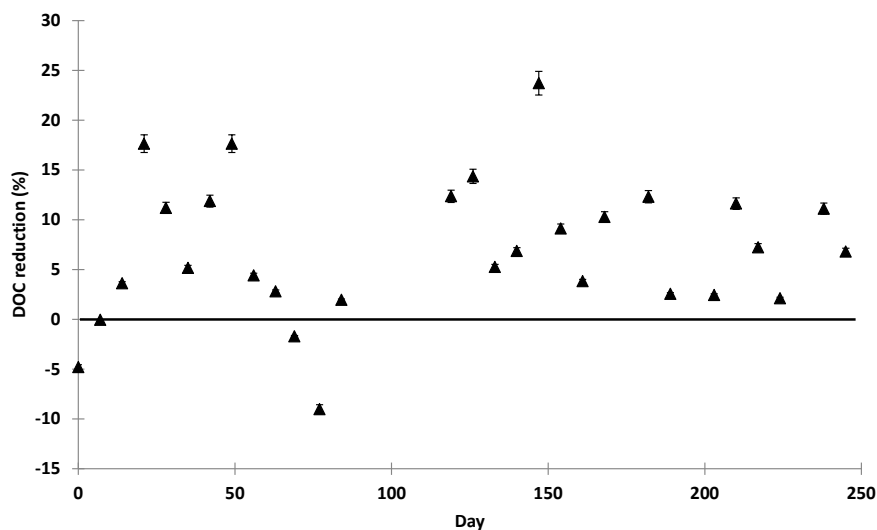


Figure 8: DOC reduction across MF

Table 4 DOC and BDOC change across ceramic MF membrane

Days	DOC		BDOC		DOC Reduction (%)
	MF Feed	MF Filtrate	MF Feed	MF Filtrate	
15	7.5	6.8	4.4	3.8	9.3
127	8.7	8.2	4.9	4.4	5.7
183	8.1	7.6	4.5	4.0	6.2

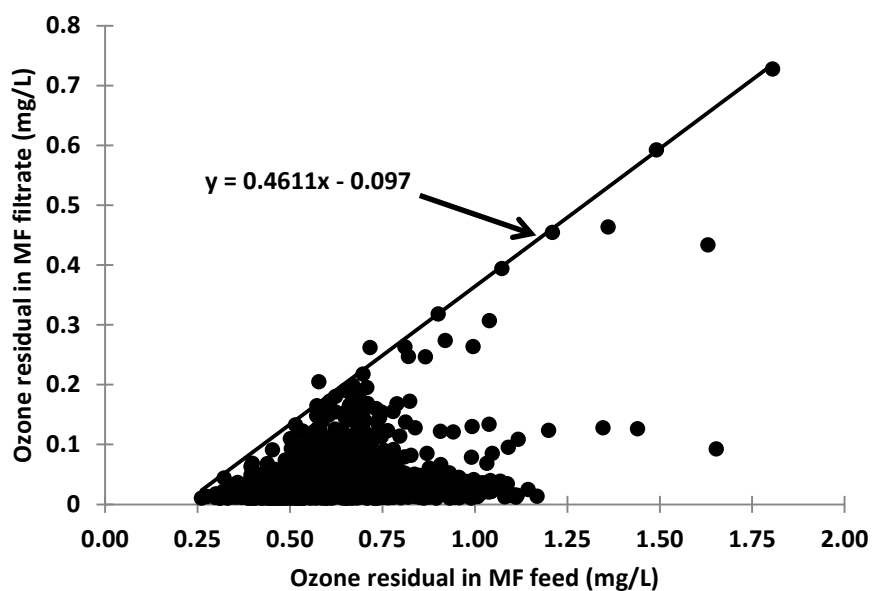


Figure 9: Ozone residual in MF feed vs ozone residual in MF filtrate (data presented only for results with measureable ozone residual in the MF filtrate)



### 3.3.2 Backwash and chemical consumption

The backwash and irreversible fouling performance of the No. 1 ceramic membrane are shown in Figure 10. The time when each CEB was performed is also indicated. From between operating days 0 and 144, 1 ML of total wastewater was treated, with 0.5 ML treated by each ceramic membrane. With the help of ozonation (Duke et al., 2013), Figure 10 indicated that the backwash and CEB were able to effectively minimise the build-up of irreversible fouling, as the feed pressure following backwash only showed minor increases of  $< 8$  kPa above the initial clean membrane feed pressure (initial feed pressure is given by the line in Figure 10) and the trend did not continuously increase. The total theoretical chemical consumption for CEB of two membranes during these 144 days was 144 g or 0.144 mg of NaClO per litre of treated water. Furthermore, if the backwash pressure could be increased to 4 bar as recommended by the supplier, the chemical consumption of the ceramic membrane could be further optimised and lower chemicals consumptions expected.

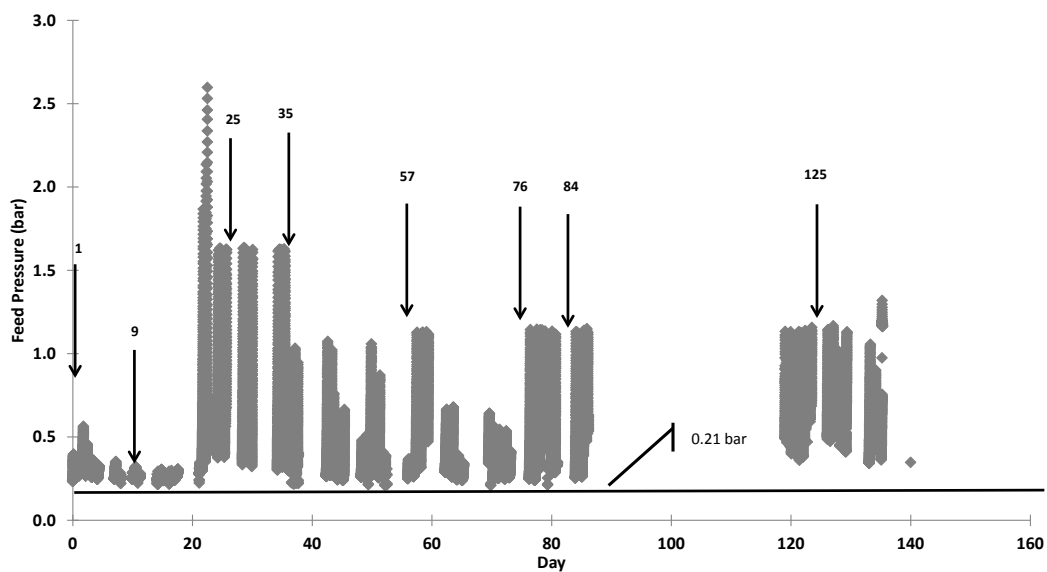


Figure 10: MF backwash and irreversible fouling

### 3.3 BAC barrier

A major purpose of the BAC barrier was to reduce trace organics, and to reduce BDOC, to subsequently reduce the organic fouling potential for the RO membranes,

In Table 5, the DOC and BDOC changes across the BAC are shown. BDOC reduction increased almost linearly with time, consistent with increasing bioactivity of the BAC with time. This compares to the consistent 30-34% reduction of the non-BDOC fraction due to

absorption. With the help of ozonation, the BDOC removed by BAC increased approximately 20% once the biological activity on the BAC stabilised, while the same BAC removal efficiency of non-BDOC was maintained. A data summary is shown in Table 5. Since the presence of biodegradable compounds at  $\mu\text{g/L}$  concentrations can lead to RO membrane bio-fouling(Vrouwenvelder and van der Kooij, 2001), the BAC effluent BDOC values  $>1 \text{ mg/L}$  are characteristic of water that will support biofouling. Therefore, an increase in the EBCT of the BAC barrier to further reduce the BDOC of the BAC effluent may be required to lower the bio-fouling potential of the RO feed.

Table 5 Non-BDOC and BDOC reduction across BAC

Days	Influent		Effluent		Non-BDOC Reduction (%)	BDOC Reduction (%)
	DOC (mg/L)	BDOC (mg/L)	DOC (mg/L)	BDOC (mg/L)		
15	6.8	3.8	3.9	1.9	33.3	50.0
127	8.2	4.4	4	1.5	34.2	65.9
183	7.6	4	3.6	1.1	30.5	72.5

### 3.4 RO barrier

The RO barrier was used for removal of pathogens and CoC. The salt rejection of the RO barrier was  $98.0 \pm 0.5\%$ , shown in Figure 11. The resultant LRV was calculated as 1.68-1.84. This LRV was sufficient for bacteria and virus rejection, but the required 2 LRV for protozoa could not be validated by salt rejection.

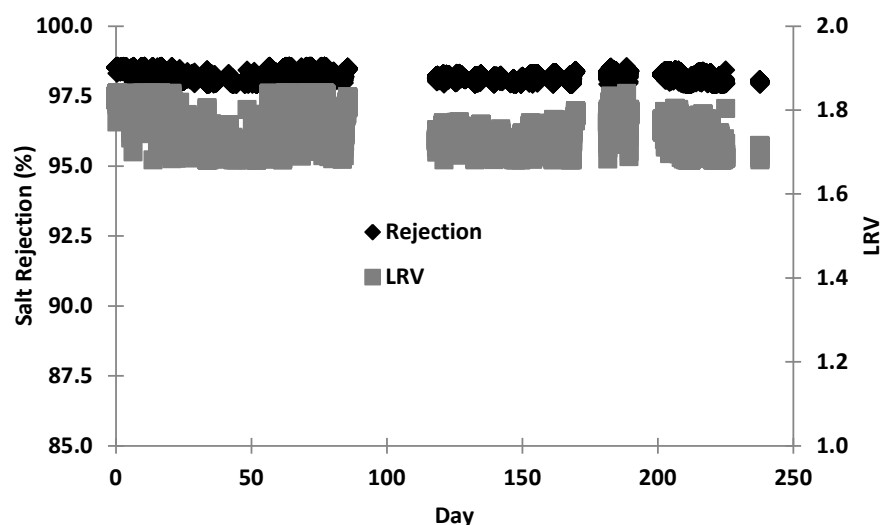


Figure 11: Salt rejection across RO barrier and LRV based on the salt rejection

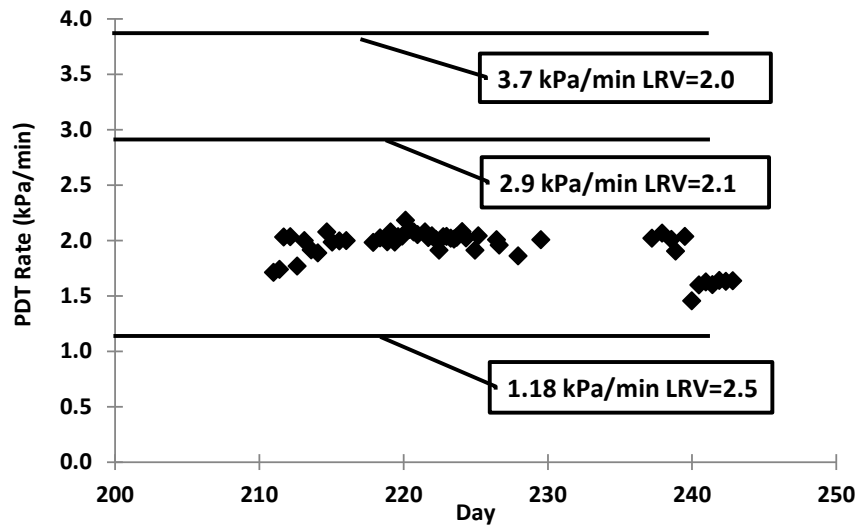


Figure 12. PDT rate for RO system

A pressure decay test with an initial pressure of 85 kPa (45 kPa transmembrane pressure + 40 kPa back pressure) was used to detect possible membrane defects larger than 3  $\mu\text{m}$  (Zhang et al., 2013). The pressure decay rates of the RO barrier are shown in Figure 12. The RO decay rates were well below the maximum value of 2.9 kPa/min.

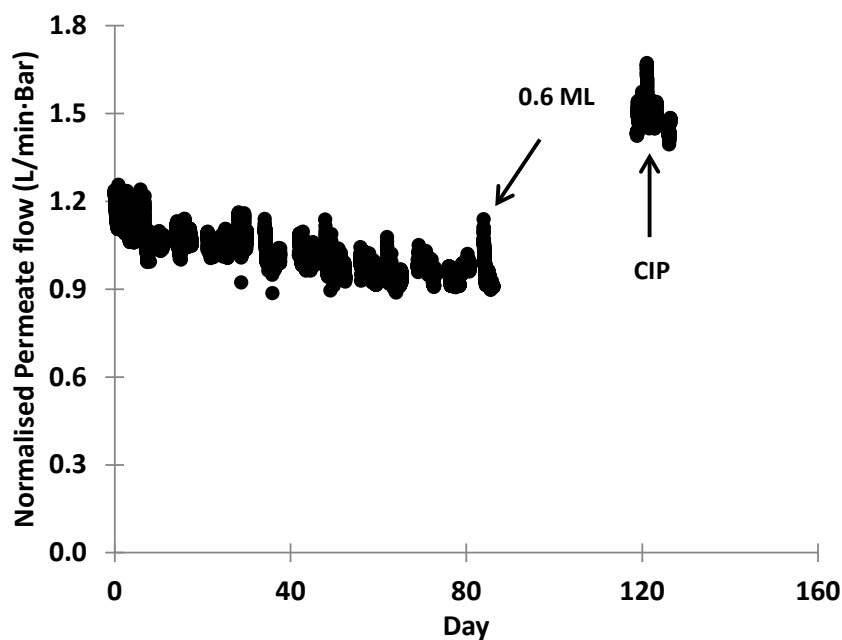


Figure 13: Effect of CIP on normalised permeate flowrate for RO membrane

A CIP was conducted for the RO elements after 0.85 ML wastewater was treated (0.6 ML produced water, 15.8  $\text{m}^3/\text{m}^2$ ). The flow data is shown in Figure 13. Compared to the initial

specific permeate flow of 1.49 L/min-bar, the specific permeate flow recovered to 96.5% of that of the new RO membranes after CIP. The chemical consumption of CIP per litre of permeate was 0.09 mg NaOH and 0.08 mg HCl, based on the CIP recipe described in the experimental section. Based on a maximum wastewater production of 4.32 ML annually at Davis Station, Antarctica, and 70% recovery from RO, it is estimated that CIP would be needed 5 times annually and consume 675 g 40 wt% NaOH solution and 762 g 32.5 wt% hydrochloric acid.

The replacement of the RO feed pre-filter cartridge (see Figure 1 for location), required the greatest manual intervention in the plant as it required replacement every 2 weeks. The study indicated that a self-cleaning filter would be a more desirable option for remote areas that lack frequent operator visits.

### **3.5 Other barriers**

The dose of the two UV units and the lamp output decay with time are shown in Figure 14. Although the UV intensity of each lamp decayed with time, each unit could still achieve the minimum required UVC dose.

The  $\text{Ca}^{2+}$  in the product water is shown in Figure 15. The calcite filter was replenished twice during testing, when the pH of the product stream was less than 6.5. In excess of 0.6 ML of permeate passed through the filter between replenishments, which required slurry of 32.5 litre calcite (density 1.5 kg/L) be loaded into the filter. Therefore, the estimated calcite consumption was 80 mg/L (or 32 mg/L  $\text{Ca}^{2+}$ ), which met the minimum 20 mg/L  $\text{Ca}^{2+}$  target value. Based on the designed production, 240 kg calcite would be consumed annually at Davis Station, Antarctica.

The dosing of chlorine barrier was set to 0.9 mg/L. Therefore, the annual consumption of 12.5 wt% NaClO will be 22 kg in the station.

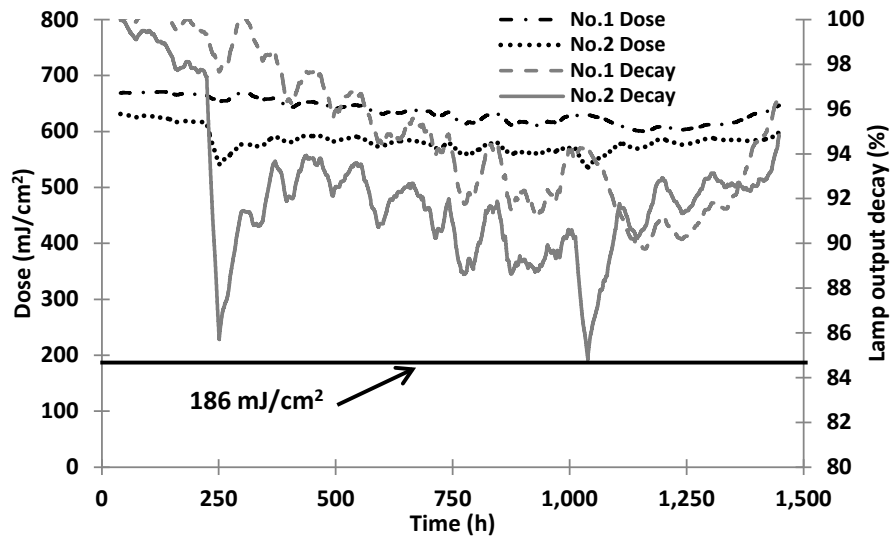


Figure 14: UV dose and output decay of UV units

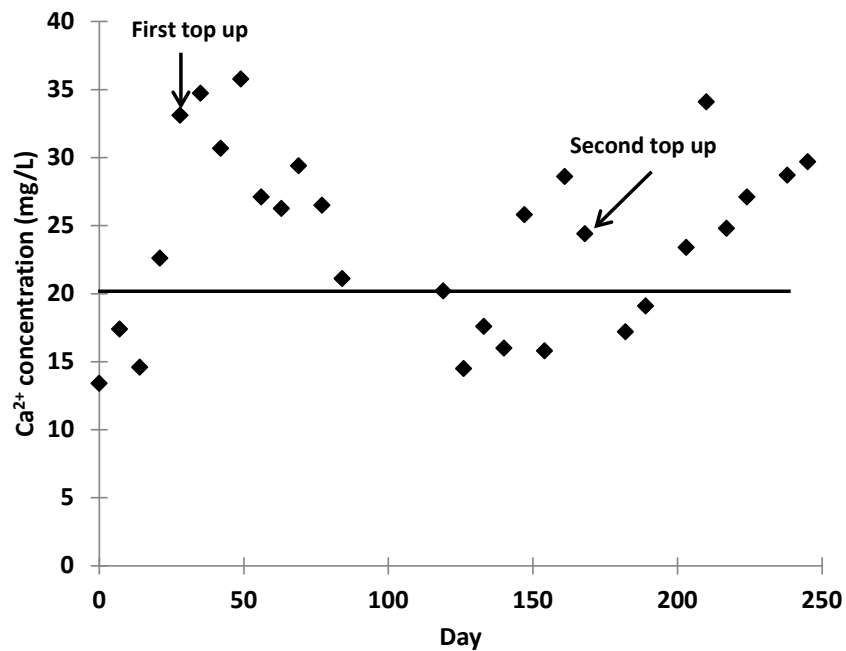


Figure 15: Calcium ion concentration in the product water

### 3.6 Overall assessment

The pilot plant was tested over 278 days and operated intermittently for a total of 1500 hours. Excluding plant standby (not due to faults) of 95 days, the average plant operation was 8.2 h/day. Based on the wastewater production in summer at Davis Station, the plant needs to operate for 18.75 hour per day. Therefore, the estimated proportion of the total operation hours to the theoretical maximum operating hours is 44:100. The plant also achieved remote start-up and shut-down between batches, although further control system testing is still

needed, as SCADA coding errors accounted for more than 90% of the unscheduled plant shut downs.

During the test period, there was no functional failure of the major barriers, and there was no *E.Coli* or *Somatic Coliphage* detected after the ceramic MF barrier. Data for CoCs and disinfection by-products are not reported here, but both were effectively and reliably removed with product water concentrations all below the threshold limits required by the ADWG (Gray et al., 2015b). The concentrations of the metals and organics of concern to health in the product water were all well below the values in ADWG. Furthermore, most of the faults that occurred during operations could be rectified remotely.

Operator involvement was still required for weekly instrument verification and cartridge filter replacement.

#### **4. Conclusion**

A direct potable reuse plant with new integrated barriers designed for a small remote community was tested for its robustness, online validation, high pathogen LRVs and COCs removal. The test duration was approximately 9 months. The total operating availability was about 44% of the maximum plant requirements, although the plant was designed to operate in batch mode. Automated online pathogen verification was achieved. There was no functional failure of major barriers. Most control system faults could be solved remotely. Therefore, the plant is considered suitable for use in remote areas.

The ozone residual in the ozonation effluent was found to be closely related to the feed turbidity, rather than DOC and ammonia levels in the feed. The data indicated that pre-filtration is needed to achieve detectable ozone residual. Nevertheless, 2 LRV for *E.coli* and virus was achieved based on a minimum ozone dose.

The combination of ozonation and ceramic MF membranes enhanced DOC reduction across the ceramic MF membrane by up to 20% and with the help of upstream ozonation, the DOC removal efficiency of BAC improved by approximately 20%.

The PDT for the RO membrane was able to validate 2 LRV for protozoa, but required a blank test to identify leaks and validate to 2.5 LRV.

Based on the test conditions, the overall estimated annual chemical consumption of the plant

to treat 4.32 ML wastewater or produce about 3.0 ML of potable water was 675 g 40 wt% NaOH, 762g 32.5 wt% HCl, 27 kg 12.5 wt% NaClO, and 240 kg calcite. These quantities are sufficiently low to be easily accommodated on the annual supply ship to Antarctica. Low chemical use will also be important for other remote sites, where transport of supplies is infrequent and expensive.

There were several operational issues identified during the test, such as rapid fouling of the RO system pre-filter. However, these issues can be relatively easily resolved by selection of appropriate equipment and perhaps redesign of the process units (i.e. longer EBCT for the BAC).

The AWTP was able to be verified online and largely realised low maintenance requirements (low chemical inventory, low onsite labour involvement), high LRVs for pathogen, high levels of robustness, and automated operation.

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