

## Indirect integrity testing on a pilot-scale UF membrane

M. E. Walsh, M. P. Chaulk and G. A. Gagnon

### ABSTRACT

As the use of membranes as the main unit operation within potable water treatment plants increases, methodologies to monitor membrane integrity has become a vital issue for the drinking water industry. This study evaluated the two most commonly used indirect integrity test procedures, namely particle counting and turbidity measurements, on permeate. A pilot-scale UF membrane module was intentionally operated under challenge conditions, defined as operation of the pilot-scale module for extended periods past the manufacturer's recommended run time. Indirect integrity test methodologies were evaluated on the intentionally compromised system to determine the capabilities of these monitoring procedures in detecting individual fibre pinholes. Both indirect test procedures failed to detect the intentional breach within the membrane operating system that occurred as a result of the challenge operating conditions. Dissolved organic carbon (DOC) and colour measurements were evaluated to determine their capability as potential alternative indirect integrity test procedures, and showed promising results in their ability to identify a significant increase in the concentration of dissolved contaminants within the permeate stream. In particular, there was a 150% increase, from  $3.2 \pm 0.4 \text{ mg l}^{-1}$  to  $7.9 \pm 1.8 \text{ mg l}^{-1}$  in DOC during the challenge trial when 1% of the membrane fibres were compromised, while turbidity measurements were constant at  $0.20 \pm 0.04 \text{ NTU}$ . This study demonstrates the need for robust on-line or rapid indirect test methodologies for monitoring membrane integrity in the drinking water industry.

**Key words** | fouling, membrane integrity, particle removal, ultrafiltration, water treatment

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### INTRODUCTION

The use of low-pressure membranes for the treatment of drinking water has become an increasingly popular treatment alternative to conventional treatment processes for many water utilities because of their capability to produce water that contains low concentrations of contaminants (Taylor *et al.* 1987; Jacangelo *et al.* 1995a,b; Madaeni *et al.* 1995; Best *et al.* 2001). The production of water that is safe for human consumption requires intensive monitoring of the processes and final product to evaluate the performance of the treatment train (AWWARF 2002). Increasing governmental regulations within Canada and the United States have forced many utilities to re-evaluate their operations, as well as their system monitoring practices. For those utilities that employ membrane technology as their main treatment

system, the ability to quickly identify breaches within the membrane process is important to ensure the consistent supply of high quality water and compliance with regulations. Accordingly, membrane integrity and monitoring long-term performance of membrane processes has become a critical issue.

With no formal federal regulations established for membrane filtration as a water treatment technology in the United States, individual states have developed a variety of policies. A regulatory survey for microfiltration (MF) and ultrafiltration (UF) systems found that 15 of the 29 states surveyed required some form of integrity monitoring beyond the typical turbidity monitoring (Allgeier 2001). With the recent promulgation of drinking water regulations

in the United States such as the Disinfectants/Disinfection By-product Rule (USEPA 1998) and the Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) (USEPA 2002), the need for methodology capable of detecting breaches within a membrane operating system is increasingly important in order to maintain compliance with such regulations. The *Membrane Filtration Guidance Manual* (USEPA 2003) was developed by the US Environmental Protection Agency to assist utilities on the use of membranes for water treatment as they apply specifically to the proposed Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) (USEPA 2001). While the membrane guidance manual was created to assist utilities operating membranes in complying with the proposed LT2ESWTR Rule, it also represents a seminal basis for membrane integrity testing practices.

In the drinking water industry, integrity test methods are classified as either direct or indirect. Direct methods are capable of providing immediate data on the presence of a compromised membrane unit (e.g. pressure decay test, bubble point test and diffusive air flow test) while indirect methods (e.g. particle counts and turbidity measurements) rely on water quality parameters to indicate potential problems. Recent work published by Farahbakhsh *et al.* (2003) provides a comprehensive summary of the current state of knowledge on integrity monitoring methods for membrane filtration systems. The *Membrane Filtration Guidance Manual* creates a multi-tiered approach to integrity monitoring, involving the performance of direct tests once every 24 hours of membrane operation. It is a requirement that indirect testing is performed continuously on each membrane unit, with turbidity classified as the default standard for indirect testing.

Conventional plants often rely on on-line analytical instruments such as turbidimeters to measure failure or breakthrough of rapid filtration or equivalent systems (Hargesheimer *et al.* 1998; Eismor *et al.* 2001). Particle counters, although currently not as widely used as turbidimeters, can also provide indirect test results on system performance. Indirect integrity test methodologies were evaluated on a pilot-scale UF membrane system to determine the capabilities of these monitoring procedures in detecting individual fibre pinholes within an intentionally compromised membrane module. However, the sensitivity

of these tests may not be optimal for membrane unit operations that are capable of producing water of a much higher quality (Adham *et al.* 1995; Johnson 1997; Hong *et al.* 2001; Carr *et al.* 2003). Particle counters are capable of measuring finished water quality of 1 to 100 particles ml<sup>-1</sup> (dia. >2 µm) and turbidity meters are sensitive to 0.02–20 NTU. Both measurements are capable of detecting acute problems in filter ripening and breakthrough within conventional filtration systems (Harrington *et al.* 2003; O'Leary *et al.* 2003). Although the use of these on-line instruments is important as a monitoring technique to provide immediate information on the performance of a membrane system with regard to pathogen removal (Mourato *et al.* 1998), their capability for detecting precursor signals to breaches in a membrane operating system may be questionable. Precursor signals in membranes are defined for this paper as chronic increases in dissolved material (e.g. NOM, metals).

The difficulty in effectively monitoring and detecting the passage of dissolved contaminants through a compromised membrane fibre with the current direct and indirect test methodologies is a genuine concern for both regulators and utility managers. As outlined by Alspach and Allgeier (2003), the most significant factor limiting the virus removal credit awarded to UF membranes is the infeasibility of using current direct integrity test methods to detect a virus-sized breach. Alspach and Allgeier (2003) argued that with the bubble point test application for the detection of viruses at a resolution of 0.01 µm, a required test pressure of 27.6 MPa (4,000 psi) would be required, a value far in excess of what any current membrane design could withstand.

The purpose of this research was to evaluate integrity testing methodologies through the use of an ultrafiltration (UF) membrane. In particular, the experiments evaluated both direct and indirect integrity testing procedures on an intact UF membrane and one that had been operated for an extended period of time under challenge conditions. Both evaluations involved the use of waste residuals from a conventional water treatment plant (WTP), specifically a combination of waste filter backwash water and clarifier blowdown. The UF membrane was submerged in the waste residual stream and operated for extended operational periods beyond the manufacturer's recommended run time to allow for an accelerated fouling rate and eventual

degradation of the module fibres to simulate the initial stages of a failure in the membrane operating system.

Previous research by Crozes *et al.* (1993) illustrated the propensity of natural organic matter (NOM) adsorption on membrane surfaces to result in irreversible fouling. However, subsequent research demonstrated that maintaining the transmembrane pressure below certain limits can minimize the rate of irreversible fouling (Crozes *et al.* 1997). Previous membrane integrity studies have evaluated the results of cutting individual fibres within a membrane test module (Mourato *et al.* 1998; Landsness 2001; Sadar & Herrington 2002; Carr *et al.* 2003; Sethi *et al.* 2003). However, the unique aspect of the present investigation is that results were obtained that are representative of an initial breach, or the preliminary stages of membrane failure. For the purpose of this paper, the initial stage is defined by the formation of pinholes within individual fibres that could result in the passage of smaller size contaminants such as NOM, microorganisms or metal-bound colloids. Kitis *et al.* (2003) evaluated reverse osmosis (RO) and nanofiltration (NF) membrane elements in a series of microbial removal and integrity tests with fibres compromised through the intentional introduction of pinholes and found reduced surrogate removals could be achieved when elements were compromised in this manner.

## METHODOLOGY

### Description of membrane system

A pilot-scale UF system (model ZW-10; ZENON Environmental Limited, Burlington, Ontario) with a 0.04 µm nominal pore size and a 0.1 µm absolute pore size was used for this study. The ZW-10 module utilizes a ZeeWeed™ 500 hollow-fibre membrane model with a nominal membrane surface area of 0.93 m<sup>2</sup> (10 ft<sup>2</sup>) and operates in an 'immersed' outside-in configuration. The membrane module was immersed into a process tank containing an equalized mixture of water treatment plant waste residuals, specifically waste filter backwash water and clarifier blowdown. The physicochemical characteristics of the equalized waste stream are presented in Table 1. Typically, UF membranes do not achieve high removal

**Table 1** | UF membrane feedstock water quality characteristics

Analyte	Average	Standard deviation
pH	6.86	± 0.41
Colour, ACU	1,133	± 321
Turbidity, NTU	70.5	± 22.4
DOC, mg l <sup>-1</sup>	64.1	± 24.9
Manganese		
Total, mg l <sup>-1</sup>	0.42	± 0.13
Colloidal and dissolved mg l <sup>-1</sup>	0.22	± 0.10
Aluminium		
Total, mg l <sup>-1</sup>	28.60	± 10.01
Colloidal and dissolved, mg l <sup>-1</sup>	0.24	± 0.36
Iron		
Total, mg l <sup>-1</sup>	5.55	± 0.43
Colloidal and dissolved, mg l <sup>-1</sup>	0.43	± 0.38

rates of colour or natural organic matter (NOM) when used alone (Laine *et al.* 1989), and it has been suggested that other conventional technologies, such as carbon adsorption or coagulant polymer addition, must be used in conjunction with membranes to achieve filtration separation of these elements (Laine *et al.* 1990; Lebeau *et al.* 1998; Mourato *et al.* 1999; Clunie *et al.* 2001). However, by using the equalized WTP waste residual streams as a feedstock for the membrane evaluations, the presence of residual alum from the main treatment train of the WTP in conjunction with cationic coagulants applied within the waste handling area of the plant provided a 'raw' feed to the membrane that closely paralleled a high NOM raw water with coagulant pretreatment, and as such, NOM removal rates achieved with UF filtration were quite high.

Permeate was produced through the introduction of a vacuum applied to the inside of the hollow fibre membrane, drawing the filtered waste residuals into the lumen of the fibre. The system was operated at a constant flux of 0.023 m h<sup>-1</sup> and a permeate flow averaging 0.0216 m<sup>3</sup> h<sup>-1</sup>.

Since the membrane module is immersed in a process tank at atmospheric pressure, the absolute value of the vacuum applied to the system equals the transmembrane pressure (TMP), and for this research project was operated within the standard operating range of 0.7–17.0 kPa (0.1–2.5 psi). All operational trials were run at a consistent mean liquid temperature of 10°C.

Cleaning procedures for the pilot-scale UF system included a 5-h soak in 1,000 mg l<sup>-1</sup> citric acid solution, followed by operations in a forward flow configuration for 30 minutes and a backward flow configuration for 30 minutes. The process tank was then drained, recharged with tap water and operated in a forward flow configuration for an hour.

### Integrity testing methodology

Integrity tests were conducted on the intact UF membrane system to simulate a control trial, and on the same UF membrane that had been operated for an extended period of time under challenge conditions. With the challenge trial, the waste residual stream was continuously fed to the membrane pilot system for an extended operational period beyond the manufacturer's recommended run cycle period before cleaning. Once the transmembrane pressure was increased by approximately 80% of the initial pressure, a direct integrity test was performed on the membrane module to determine the condition of the individual fibres.

As described in the *Membrane Filtration Guidance Manual* (USEPA 2003) direct integrity test methodologies can be employed to identify and isolate integrity breaches within a membrane module. The three major direct integrity tests that are utilized are the pressure hold test, the diffusive air flow test and the bubble point test. All of these tests are capable of detecting breaches within a membrane operating system; however, the bubble point test is perhaps the most valuable in terms of directly identifying the location of a compromised fibre(s) (Lee *et al.* 2003; Sethi *et al.* 2002 2003). Due to the ability of this direct test to locate a compromised fibre within a membrane module, the bubble point test was used in this research project to identify breaches in the UF membrane before and after the challenge trial. The bubble point is the pressure required to push liquid out of the largest pore, and, therefore, the application of a pressure

below this bubble point on the upstream of the membrane module allows for the identification of the compromised fibre(s). As described by Farahbakhsh *et al.* (2003), the bubble point pressure for the ZW-10 UF membrane employed in this research was calculated using:

$$P = \frac{4k\gamma \cos\theta}{d}$$

where,  $P$  = bubble point pressure (Pa or psi),  
 $k$  = correction factor for the shape of the largest pore,  
 $\gamma$  = surface tension of the wetting liquid (N m<sup>-1</sup> or lb<sub>f</sub>ft<sup>-1</sup>),  
 $\theta$  = contact angle between the liquid and the membrane and  $d$  = diameter of the largest pore (m or ft).

For most membranes, a contact angle of 45° and correction factor of 0.25 are most often employed (USEPA 2001). For the ZW-10 UF operating system, the bubble point pressure was calculated to be 760 kPa (110 psi). In evaluating the indirect integrity test methods, both particle counts and turbidity measurements were taken during both the control and challenge membrane trials. In addition, several water quality parameters including dissolved organic carbon (DOC), colour and inorganic metal concentrations were measured during each operational trial.

### Analytical methods

Waste residual feed stream and UF permeate samples were collected during each trial of the experiments, and analysed for water quality parameters according to *Standard Methods* (1995). The parameters that were monitored were turbidity, colour and DOC. In addition, aluminium, manganese and iron metal analyses were characterized in two different size fractions, namely total, and colloidal and dissolved. For each membrane run trial, turbidity and colour measurements were sampled five times ( $n = 5$ ), while metal analysis encompassed three samples ( $n = 3$ ). DOC data represent four samples taken for the control and isolation and cleaning membrane trials ( $n = 4$ ) and nine samples taken during the compromised fibre trial ( $n = 9$ ).

Turbidity was measured using a HACH 4100 turbidimeter (USEPA Method #180.1). Apparent colour was measured using a spectrophotometer (HACH DR/4000, HACH Co., Loveland, Colorado) with the American Dye

Manufacturers Institute (ADMI) weighted ordinate method. Samples for dissolved organic carbon (DOC) analysis were filtered through a 0.45  $\mu\text{m}$  pore-size membrane filter (Cole-Parmer<sup>®</sup> Nylon Membranes) and rinsed with deionized water as described in *Standard Methods*. These samples were then collected headspace-free in 40-ml glass vials and preserved with concentrated phosphoric acid. Measurements were performed with a TOC-V CHP analyser (Shimadzu Corporation, Kyoto, Japan).

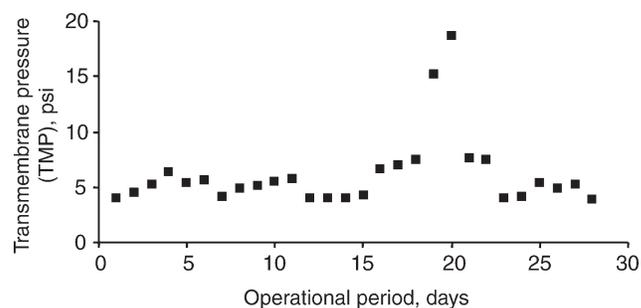
Total aluminium, manganese and iron concentrations were measured using a HACH DR/4000 spectrophotometer according to method #3500-Al, 3111B and 3500-Fe D, respectively (*Standard Methods 1995*). Colloidal and dissolved fractions of these metals were analysed with the same methodology after filtering through a 0.2  $\mu\text{m}$  filter (Carlson *et al.* 1997).

Particle counts were analysed using an on-line HACH 2200 PCX particle counter (HACH Co., Loveland, Colorado). The bin size selection was based on values recommended by the USEPA, specifically, 2–3  $\mu\text{m}$ , 3–5  $\mu\text{m}$ , 5–7  $\mu\text{m}$  and 7–10  $\mu\text{m}$ .

## RESULTS AND DISCUSSION

### Creation of challenge conditions and direct integrity test evaluation

Prior to the control trial, no bubbles were detected below the bubble point pressure of 750 kPa (110 psi), allowing for a control operational period where no fibres were compromised. At the completion of the control trial, an extended operational run was applied for 35 days to achieve an increase of 80% in the transmembrane pressure from the initial pressure of 4 kPa (0.58 psi) to 19 kPa (2.8 psi) (Figure 1). At the completion of the extended operational run, three pinholes were identified on three separate fibres within the UF module at an applied pressure of 35 kPa (5 psi). Visual inspection of the membrane fibres during the control and challenge trials showed a dramatic discoloration of the individual fibres in the absence of the routine cleaning procedures. Figure 2 presents scanning electron microscope (SEM) microphotographs taken of the membrane fibres during the control and challenge trials, and

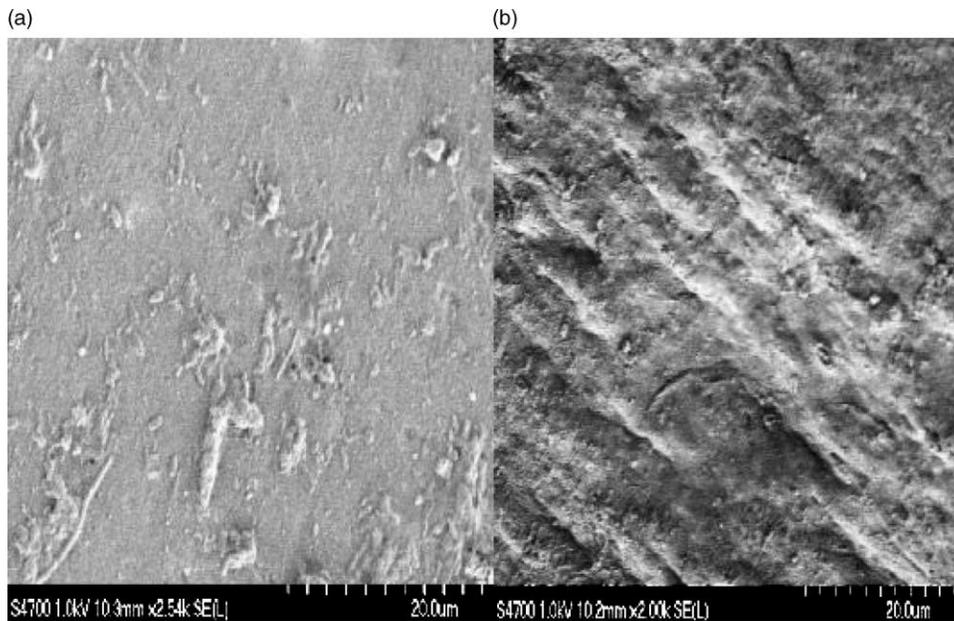


**Figure 1** | Transmembrane pressure of UF membrane operating system during challenge trial.

illustrates the fouling of the membrane surface during the extended operational run. The SEMs show the microscopic deposition and fouling which was experienced by the membrane module under stress conditions, in terms of increased scale formation and surface deposition. Similarly, visual inspection of the UF permeate showed a brownish discoloration of the treated water which was not present during the control trial.

### Indirect integrity test evaluations

At the completion of the intentional extended operational run, the application of the bubble point test at an applied upstream air pressure of 35 kPa detected the presence of three pinholes on three individual fibres within the membrane module at an estimated size of 2  $\mu\text{m}$ . The number of fibres impacted was estimated to represent only 1% of the total fibres contained within the pilot-scale module. Once the compromised fibres were identified within the membrane module through this direct integrity test, particle counts and turbidity measurements were taken on the UF permeate to evaluate the effectiveness of these tests in determining the presence of these formed pinholes within the membrane module. Particle counts were taken over a 24-hour period on the UF permeate during the period of membrane operation when compromised fibres had been identified, and data representing particles in the size ranges between 2 and 10  $\mu\text{m}$  are presented in Figure 3. The initial recordings of particle counts for all size distributions measured during the first several hours of operation represent the presence of air bubbles within the sampling line, and are not indicative of actual particles recorded in the membrane permeate. After adjustment of the particle

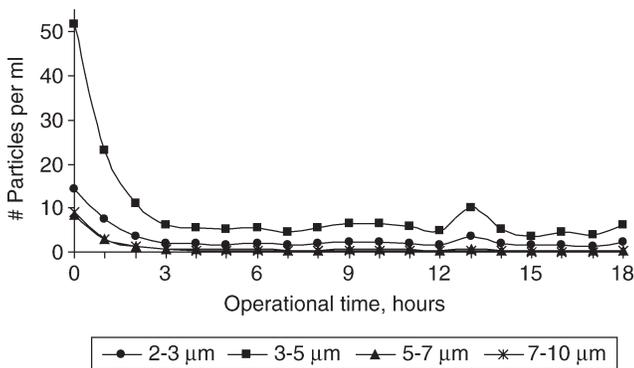


**Figure 2** | SEM micrographs of (a) integrated membrane during control trial and (b) fouled membrane during challenge trial.

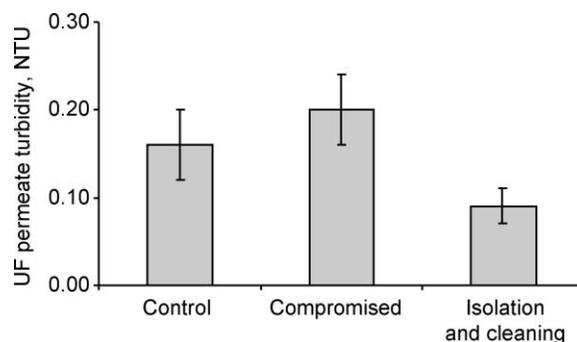
counters to remove entrained air bubbles in the sampling line, permeate particle counts in the size ranges greater than  $10\ \mu\text{m}$  averaged less than  $1\ \text{ml}^{-1}$  through the challenge trial period. Although the UF membrane was operating with several  $2\ \mu\text{m}$  holes located within the module, total particle counts after the 24-hour run averaged less than 10 counts  $\text{ml}^{-1}$ .

Turbidity measurements were also taken throughout the control and challenge trials, as well as after the compromised membrane fibres were isolated and the module had been cleaned. As presented in Figure 4, the turbidity increased from an average of  $0.16 \pm 0.04$  NTU to  $0.20 \pm 0.04$  NTU between the period of integrated

membrane operation and after the pinholes were formed within several of the membrane fibres. Although there was an increase in the turbidity measurements from the control to the challenge trials, the difference between the turbidity data of these two trials was not statistically significant at the 95% confidence interval ( $\alpha = 0.05$ ). At the completion of the challenge trial, the compromised membrane fibres were isolated and the module was cleaned according to the manufacturer's specifications. Subsequent analysis of the permeate water did show the reduction of the turbidity readings to  $0.09 \pm 0.02$  NTU. Although changes in the turbidity were observed through the control trial with the integrated membrane module and the subsequent challenge



**Figure 3** | UF permeate particle count data with compromised membrane fibres.



**Figure 4** | UF permeate turbidity data from integrity test trials.

trial and isolation of compromised fibres, the statistical analysis of the data sets demonstrates that these differences are not significant.

As surmised by other researchers (Johnson 1997; Carr *et al.* 2003), the two most widely used indirect test methodologies of particle counting and turbidity monitoring may not be the most effective in identifying precursor signals to breaches in a membrane operating system. Although the permeate water from the UF module was visually discoloured and 2  $\mu\text{m}$  pinholes were identified within several of the module fibres through direct test methodology, both particle count technology and turbidity measurements failed to recognize a significant change in the permeate water quality. Particle counting technology has proved to be an effective monitoring tool for the indication of larger scale contaminants such as pathogenic organisms within treated water streams; however, these instruments are unable to recognize particles less than 2  $\mu\text{m}$ . Similarly, the results of the turbidity tests as an indirect integrity test for membranes shows that this technology may not have the sensitivity required for identifying initial breaches within a membrane operating system. Although both particle counting and turbidity testing are recommended as valid indirect integrity test methodologies, the passage of dissolved material through a compromised membrane module cannot be detected with the current sensitivity limits of these technologies.

#### Alternative indirect test methodology evaluations

With the limitations of both the particle counters and turbidity measurements as indirect integrity tests for the identification of the compromised membrane module determined in the first phase of this research, other water quality parameters were evaluated as a means to identify different indirect test methodologies which may provide a way to identify the intentional breach experienced by the membrane fibres. Dissolved organic carbon (DOC), apparent colour and metal analysis were evaluated as potential surrogate indirect integrity test procedures on the UF permeate.

As presented in Figure 5, UF permeate DOC concentrations increased significantly between the control and challenge trials. The initial DOC during the control trial averaged  $3.2 \pm 0.4 \text{ mg l}^{-1}$ , and then was increased more

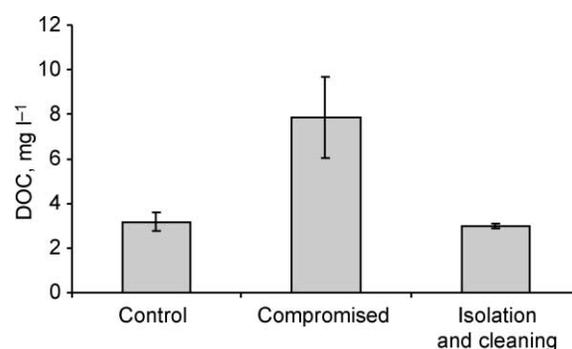


Figure 5 | UF permeate DOC data from integrity test trials.

than twofold to  $7.9 \pm 1.8 \text{ mg l}^{-1}$  during the challenge trial when compromised fibres had been identified. Similarly, colour measurements of the UF permeate increased from a control average reading of  $3 \pm 1$  ACU to  $14 \pm 1$  ACU during the compromised fibre trial (Figure 6). Both the DOC and colour measurements taken during the control and compromised trials showed a statistically significant difference between data sets at the 95% confidence intervals. After the completion of the challenge trial, the isolation of the compromised fibres and cleaning of the membrane module resulted in both of these test parameters returning to levels equal to or lower than the original control trial results ( $2.97 \pm 0.11 \text{ mg l}^{-1}$  DOC and  $2 \pm 1$  ACU for DOC and colour measurements, respectively). Although not monitored through each of the membrane operational trials, UV-254 monitoring of the membrane permeate could offer additional information on the integrity of a membrane system through its use as a surrogate measurement parameter for natural organic matter (NOM) and DOC (Edzwald *et al.* 1985).

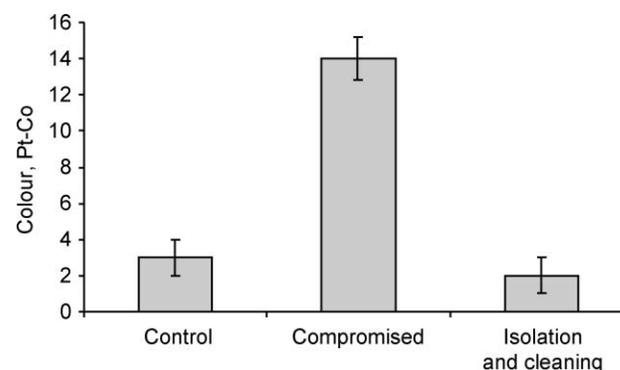


Figure 6 | UF permeate colour data from integrity test trials.

As an alternative monitoring tool, the potential for using standard metal testing procedures for the detection of an initial breach within a membrane system was evaluated. Results of metal testing conducted during both the control and the compromised membrane trials show that total manganese concentrations were statistically significantly different at 0.064 and 0.119 mg l<sup>-1</sup> concentrations, respectively (Table 2). Although the colloidal and dissolved manganese concentrations did not show a similar significant difference between the control and compromised trials, this can be attributed to the fact that, during the control trial, 22% of the manganese concentration was in the particulate fraction, while during the compromised membrane trial, 47% of the total manganese concentration was in the particulate fraction, greater than 0.2 µm. With the higher particulate concentrations experienced during the compromised membrane trials, the propensity for colloidal and dissolved manganese to pass through the membrane pinholes was reduced due to the lower concentrations of the manganese in this metal fraction.

Aluminium and iron concentrations in the UF permeate were also evaluated as a potential indirect integrity monitoring tool. Measurements of both total aluminium and iron concentrations failed to show a significant difference between the data sets of the integrated and compromised membrane trials (Table 2). Conversely, colloidal and dissolved iron concentrations were significantly different between these two membrane operational trials. Again, in evaluating the different fractions of the metal concentrations during each trial, the colloidal and dissolved aluminium concentrations during the control and challenged membrane trials were 70% and 81%, respectively. However, with the iron measurements, the colloidal and dissolved fraction increased significantly from 39% to 69% from the control to the compromised membrane runs.

## CONCLUSIONS

In evaluating indirect integrity methodologies on a UF membrane, the two most commonly used test procedures failed to detect the presence of pinholes within several fibres of the intentionally compromised membrane module. Both particle counts and turbidity measurements showed similar data sets for both a control trial during which an integrated membrane module was operated, and a challenge trial during which the membrane module was intentionally compromised through continuous operation with a high turbidity waste residual stream. Extended operation of the UF module resulted in increased transmembrane pressure and eventual fouling of the membrane. Although visual inspection of the UF permeate showed a discoloration of the treated water after the extended operational period, and the application of the direct integrity test (bubble point test) identified the presence of 2 µm pinholes on several fibres within the membrane module, the subsequent application of indirect test procedures of particle counting and turbidity measurements failed to identify the breach in the membrane operating system.

Alternative indirect test procedures were evaluated as potential surrogates for membrane monitoring, and included the water quality test parameters DOC, colour and metal concentration analysis. Both the DOC and colour tests showed a significant difference between the control and compromised trial runs; both tests exhibited a statistically significant increase in concentrations at the 95% confidence interval. After the compromised fibres were isolated from the membrane module and the unit was cleaned, both the DOC and the colour test parameters returned to levels equal to or lower than the original control trial results.

In terms of using metal concentration monitoring as an indirect integrity tool, manganese concentrations showed

**Table 2** | Metal concentrations with control and compromised membrane trials

	Manganese (mg l <sup>-1</sup> )		Aluminium (mg l <sup>-1</sup> )		Iron (mg l <sup>-1</sup> )	
	Total	Colloidal and dissolved	Total	Colloidal and dissolved	Total	Colloidal and dissolved
Control membrane	0.064	0.050	0.040	0.028	0.041	0.016
Compromised membrane	0.119	0.063	0.067	0.054	0.051	0.035

a significant increase from the control to the challenge trial, within both the particulate and colloidal and dissolved metal fractions. Measurements of both total aluminium and iron concentrations failed to show a significant difference between the data sets of the integrated and compromised membrane trials. However, in evaluating metal concentrations as a potential indirect integrity monitoring tool, consideration should be given to the source water being treated, and the expectant fractional metal concentrations within the feed stream to a membrane system.

Although indirect test procedures involving DOC, colour and metal analysis may not provide immediate results compared with the use of on-line devices such as particle counters and turbidimeters, their capability as an indirect monitoring tool for membrane systems with feed-water high in colloidal and dissolved constituents may provide a viable analytical tool in determining the chronic changes in integrity of the operational system.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical support and equipment provided to this project by ZENON Environmental Ltd and the Halifax Regional Water Commission. In addition, the authors acknowledge the funding support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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First received 2 March 2004; accepted in revised form 28 August 2004