IMMERSED ULTRAFILTRATION MEMBRANES FOR TREATMENT OF ORGANICALLY LADEN SURFACE WATER

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ABSTRACT

Ultrafiltration membranes are becoming increasingly prevalent in potable water treatment applications. This trend can be attributed to the improved cost effectiveness of membrane systems as compared to conventional treatment technologies and to progressively more stringent water quality regulations. In particular, increased awareness related to the formation of disinfection by-products (DBPs) such as trihalomethanes (THMs) and halo-acetic acids (HAAs) has required utilities to improve the removal of their organic precursors.

Excellent removal rates of as high as 75% for TOC and 95% for colour have been achieved for at drinking water plants using ZeeWeed® immersed ultrafiltration membranes in combination with a coagulant, pH control, and/or powdered activated carbon (PAC). As compared to a conventional plant using coagulation-flocculation-clarification-filtration, a membrane system incorporating coagulant addition can be designed with a reduced flocculation hydraulic retention time and with the elimination of the clarification step. The process then uses coagulation-flocculation-ultrafiltration. Coagulant is added prior to a flocculation tank that flows directly into the membrane tank where suspended particles are filtered by the membranes. With the elimination of clarification, the floc need only be larger than the membrane pores to be removed, eliminating settleability concerns. This leads to a decrease in plant footprint due to lower flocculation retention time, as well as to decreased chemical consumption and residuals disposal costs. The addition of PAC can also be incorporated upstream of the membrane tanks to increase organics removal.

A large proportion of drinking water treatment plants in Alberta, Canada are designed for the treatment of surface water sources. With many of these water sources having highly variable organics, reaching seasonal peaks as high as 25 mg/L TOC, effective organics removal is essential prior to chlorine disinfection. For conventional water treatment plants, this can be particularly challenging during periods where turbidity peaks can exceed 1,000 NTU.

This paper will describe the use of enhanced coagulation with immersed ultrafiltration membranes, its advantages as compared to conventional treatment plants, and will discuss details of coagulation, PAC dosing, pH adjustment, and treated water quality for several full scale plants in Alberta including: 1) Mountain View Regional Water Services Commission, Anthony Henday WTP – 6 MGD, polyaluminum chloride; 2) Municipal District of Lesser Slave River, Canyon Creek WTP – 0.25-0.33 MGD, aluminum sulphate addition; and 3) Municipal District of Lesser Slave River, Hamlet of Smith WTP – 0.16-0.19 MGD, aluminum sulphate and polyaluminum chloride addition. Data will also be presented for several pilot scale evaluations performed in Alberta.

Keywords: Ultrafiltration, Water, Water Treatment, Organic, Pathogen, Turbidity

INTRODUCTION

As the health risks associated with trihalomethanes (THMs) and haloacetic acids (HAAs) have become more widely recognized, regulatory agencies have reacted by placing tighter limits on the levels of these by-products of chlorine disinfection in drinking water supplies. In Canada, an interim maximum contaminant level (IMCL) has been set to 100 µg/L for total THMs. In the US, the USEPA has introduced the Disinfectants-Disinfection Byproduct Rule (D/DBPR). With the first stage of this rule, finalized in 1998, the MCLs have been set to 80 µg/L for total THMs and 60 µg/L for five haloacetic acids (HAA5).

In order to minimize the formation of disinfection by-products produced by the reaction of chlorine with natural organic matter (NOM), colour or TOC, the USEPA has identified enhanced coagulation as the best available technology in the Stage 1 Disinfectants/Disinfection Byproducts Rule (D/DBPR). Enhanced coagulation is defined as the addition of coagulant for TOC removal in more elevated doses than those typically required for turbidity or colour removal. It may also include pH adjustment as a means of optimization. When combined with immersed membrane ultrafiltration, this type of coagulation is not only the ideal solution for NOM, colour and TOC removal, but is also an effective means of removing turbidity and microbiological parameters such as *Giardia* or *Cryptosporidium*.

Until lately, the conventional method for removing NOM, colour and TOC for drinking water treatment consisted of rapid mix coagulation, flocculation, clarification and filtration. In recent years, several drinking water plants have implemented immersed ultrafiltration membranes in combination with enhanced coagulation in lieu of conventional coagulation-flocculation-clarification-filtration to treat surface waters with high levels of organics.

The immersed membrane described in this paper is commercially known as ZeeWeed®. This membrane has been implemented at several drinking water plants in western Canada and globally. This paper describes the application of this type of immersed membrane with enhanced coagulation for TOC and disinfection byproduct precursor removal, and presents operating data from pilot and full-scale projects.

REGULATIONS

As outlined above, an interim maximum contaminant level (IMCL) has been set to 100 µg/L for total THMs in Canada while the USEPA has introduced a Disinfectants-Disinfection Byproduct Rule (D/DBPR) which sets MCLs to 80 µg/L for total THMs and 60 µg/L for five haloacetic acids (HAA5). In addition to these MCLs, the D/DBPR sets requirements for TOC removal based on feed water TOC levels. These TOC removals, outlined in Table 1, help to ensure that disinfection byproduct formation is minimized during post chlorination for disinfection.

Table 1: USEPA TOC Removal Requirements (% TOC removals)

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L)		
	0-60	**60-120**	**>120**
2.0 – 4.0	35%	25%	15%
4.0 – 8.0	45%	35%	25%
>8.0	50%	40%	30%

The Canadian Guidelines for Drinking Water Quality also include an aesthetic objective for true colour of < 15 colour units (PCU). Similarly, the USEPA has a non-enforceable secondary standard for true colour of < 15 colour units (PCU).

IMMERSED ULTRAFILTRATION MEMBRANES

The flow sheet for an immersed ultrafiltration membrane plant with enhanced coagulation consists of pre-screening, rapid mix coagulation, flocculation and ultrafiltration with no requirement for clarification, as shown in Figure 1. The flocculation tank may be a separate tank, or a separate compartment within the process tank. The flocculation tank flows directly to the process tank compartment where shell-less hollow-fibre ultrafiltration membranes are immersed directly in the flocculated water. Permeate pumps are used to draw clean water (permeate) from the inside of the membrane fibres under a slight vacuum. The outer surface of the membrane fibres is intermittently scoured using air provided by blowers to minimize fouling.

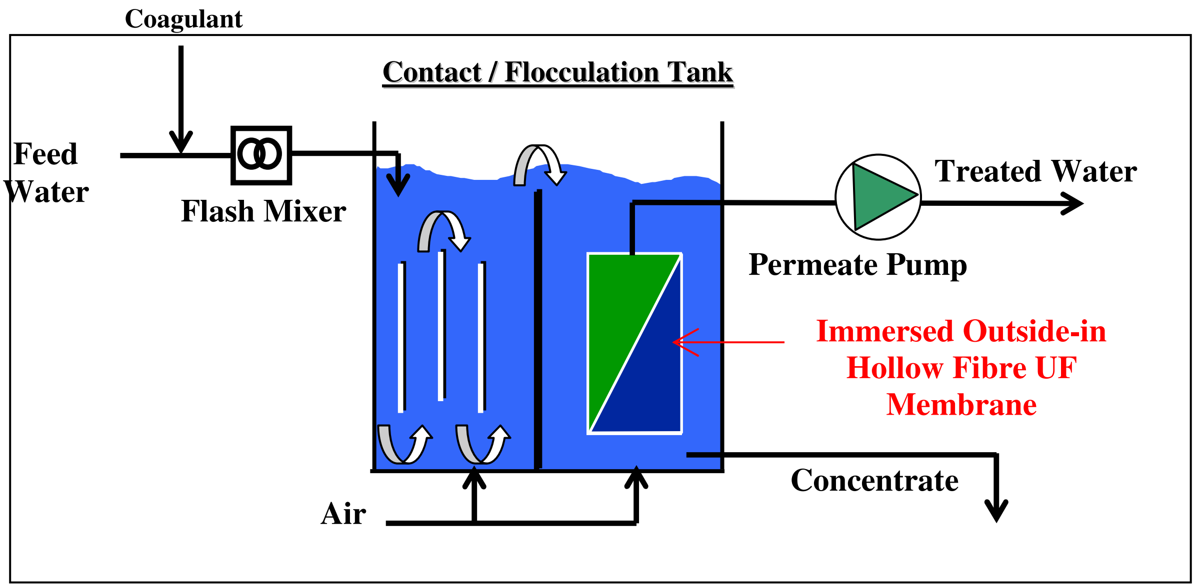


Figure 1: Immersed Ultrafiltration with Coagulation – Process Flow Diagram (adapted from Best et al, 1999)

Wood based powdered activated carbon can also be injected prior to the flocculation zone to further improve organics removal. The air scour used to clean the membranes maintains the carbon in suspension.

The membranes have a nominal pore size of 0.04 µm and an absolute pore size of 0.1 µm. As such, they act as a barrier to turbidity, bacteria and viruses, including Giardia cysts (6-16 µm) and Cryptosporidium oocysts (4-7 µm). Without coagulation, dissolved NOM and organics would pass through the membrane pores; but with proper coagulant dosing, colour removals approaching 95% and TOC removals up to 75% can be achieved depending on the feed water characteristics, coagulant dosing and pH adjustment.

Pin-sized flocs are sufficient to be rejected by the membrane's small sized pores and require less coagulant than would be required for the formation of settleable floc. This represents a benefit for the use of immersed membranes to separate clean water from coagulated solids since the lower coagulant dose translates to lower operating costs associated with coagulant consumption and sludge production.

The membrane's physical barrier also eliminates the problems experienced in conventional plants when clarifier upsets cause overloading of the filters which in turn experience breakthrough causing high turbidity in the treated water.

The outside-in operating mode of the immersed membranes, with clean water being drawn to the insides of the membrane fibres (lumen), ensures that the small diameter fibre cannot become plugged with solids. This reduces the fouling potential of the membranes, which is particularly relevant in enhanced coagulation applications as the coagulated organics add to the feed water solids loading.

The ZeeWeed® 500 series immersed ultrafiltration membranes are particularly well suited for use in enhanced coagulation applications. The membrane fibres are supported with an inner braid which provides fibre durability. The relatively large outside diameter of 1.9 mm of the fibers (see Figure 2) affords them a high resistance to breakage. These factors ensure a long membrane life, even with high solids concentrations in the raw water. In addition, the membranes are resistant to oxidants and to a wide pH range, allowing them to be easily cleaned with acids, bases or oxidants.

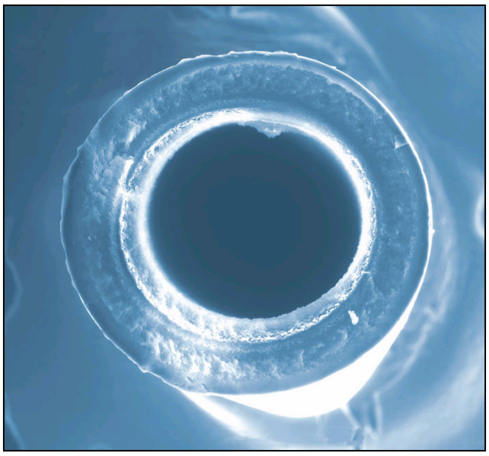


Figure 2: ZeeWeed® Fibre Cross-Section

The individual membrane fibres are assembled into building blocks known as "modules" or "elements". The spatial arrangement of the fibres within the potting material of an element is specifically designed to provide the membranes with a tolerance to high solids levels. The distribution ensures the efficiency of the intermittent aeration in scouring the membrane surface. The fibre slack and spacing minimize the accumulation of solids within the membrane elements, reducing cleaning requirements and maintenance.

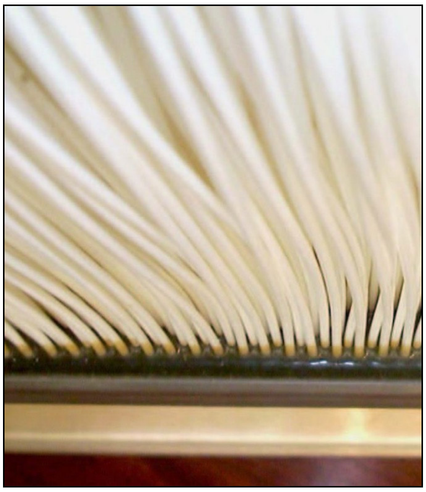


Figure 3: Defined Spatial Distribution of Fibres

The membrane elements are assembled into larger units known as cassettes. Several cassettes may be installed together in parallel into a single process train (refer to Figure 4), and several process trains may be used to meet a particular plant's production capacity. The modular nature of the cassettes allows them to be used to retrofit existing tankage in conventional drinking water treatment plants. Membranes have been installed in both clarifiers and filter basins for plant retrofits.

By retrofitting the filter basins with membranes, a utility could increase the capacity of the filters while maintaining the existing rapid mix-flocculation-clarification-filtration flowsheet. This is possible due to the higher loading rate on the membranes as compared to the filters. However, since the ZeeWeed® 500 series membranes do not require clarification prior to the filtration stage, the utility could consider fitting the clarifier with ultrafiltration membranes as well, further increasing the capacity of the plant. By reducing the number of process operations down to three with rapid mix, flocculation and ultrafiltration, the complexity of the plant is reduced. The automated design of the membrane plant further simplifies the operation of the water treatment plant.

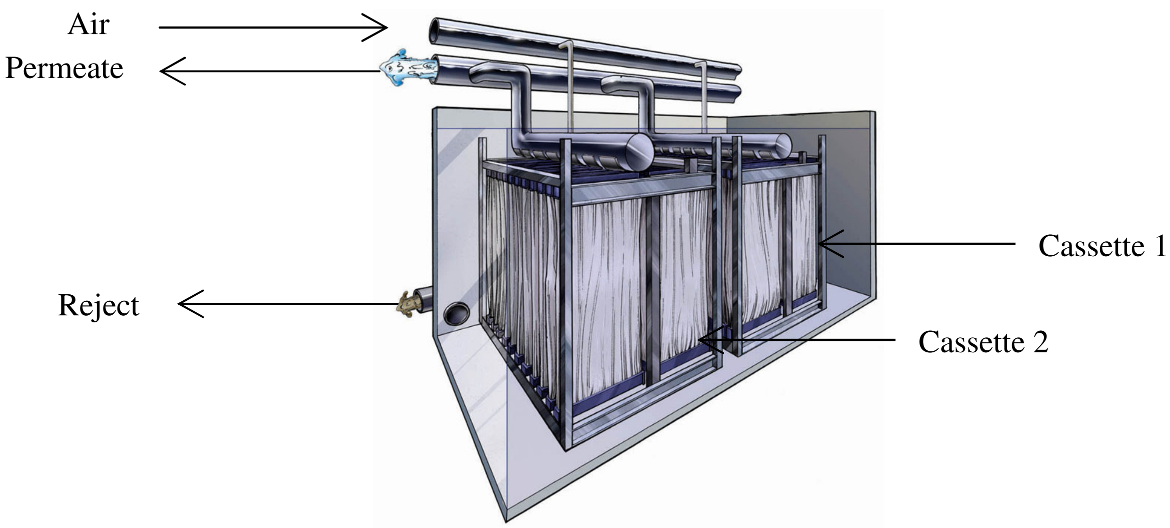


Figure 4: ZeeWeed® Ultrafiltration Process Train (2 cassettes)

With fewer process operations, an immersed ultrafiltration membrane plant with enhanced coagulation has a smaller overall footprint than a conventional plant. The footprint is further reduced by the fact that a shorter retention time is required for the formation of pin-sized floc, allowing for a smaller flocculation tank. This reduces the capital cost of the plant.

In summary, the advantages of using enhanced coagulation with immersed ultrafiltration membranes for TOC removal are:

- High colour removal, approaching 95% depending on feed water characteristics, coagulant dose and pH
- High TOC removal, approaching 75% depending on feed water characteristics, coagulant dose and pH
- Reduced coagulant consumption
- Reduced sludge production associated with lower coagulant dose
- Physical barrier prevents breakthrough
- Low fouling potential due to inside out flow configuration and optimized fibre placement
- Strong, chemically resistant fibres
- Potential for retrofit
- Reduced facility complexity
- Small footprint

OPERATING DATA

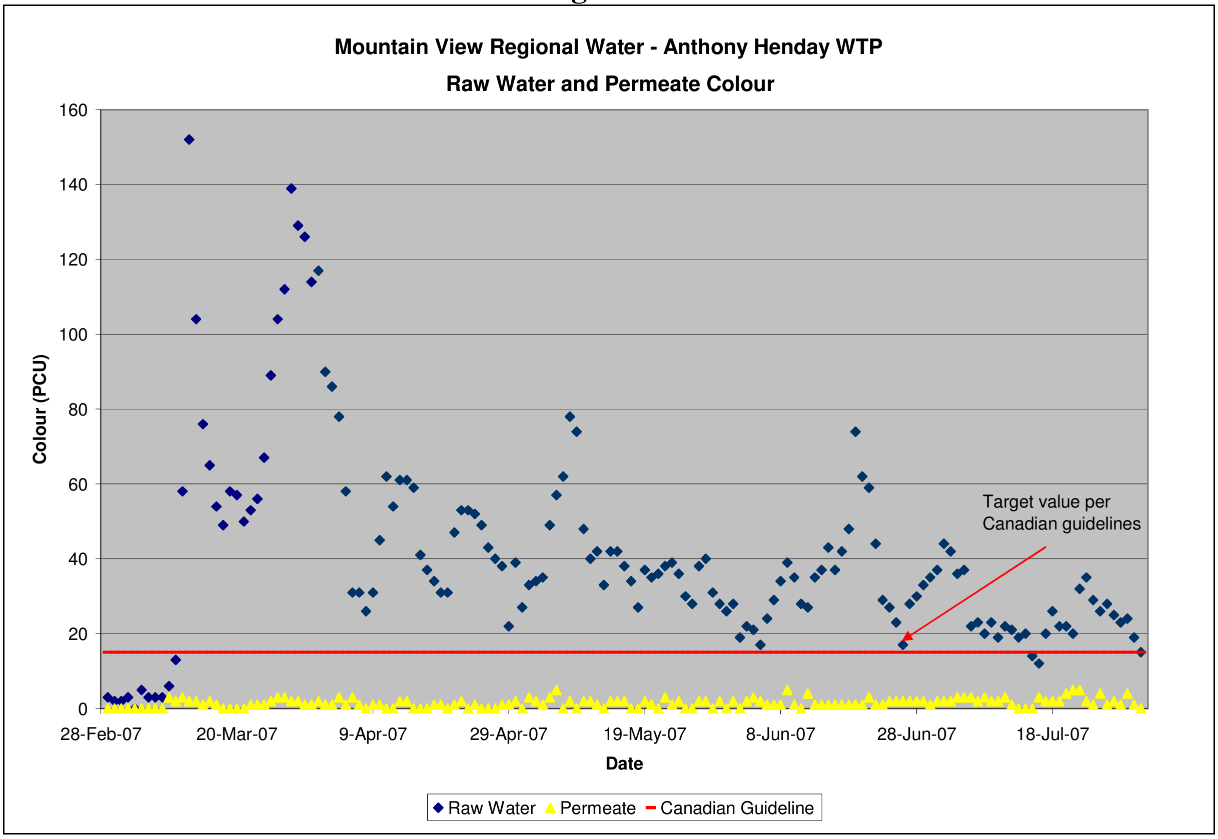
Full Scale Plants

Mountain View Regional Water Services Commission – Anthony Henday WTP
The Anthony Henday membrane ultrafiltration plant is located in Innisfail near Red Deer Alberta. It provides water to the communities of Bowden, Crossfield, Innisfail, Carstairs, and Didsbury, as well as to the Bowden Institute and PrimeWest Energy. The project was a retrofit in which membranes were installed into existing clarifiers and dual media filters in order to increase water quantity and quality from the plant. The retrofit was performed in two stages. In the first stage, which was completed in April 2001, the clarifier was taken off line in order to install two (2) trains of ultrafiltration membranes into the circular basin. During this time, the existing filters handled unclarified coagulated raw water. In phase two, two filters were retrofitted with membranes while the first phase membrane trains and an additional temporary membrane train provided treated water to meet demand. This was completed in May 2001. The combined capacity of the four trains of immersed ultrafiltration membranes is 22.67 MLD (6 MGD). The raw water to the plant is from the Red Deer River.

The flowsheet for the plant includes a traveling screen remaining from the conventional plant, a strainer, rapid mixing for the addition of polyaluminum chloride (PACL) coagulant, possible addition of PAC, flocculation and ultrafiltration. There is also an injection point for potassium permanganate at the front end of the plant for periods of high taste and odour, which typically last about six weeks in the Spring.

True colour data for the Anthony Henday WTP for 2007 is shown in Figure 5a below. The colour can get very high in the raw water to this plant, particularly in the Spring. Regardless of feed water colour, which ranged from 0 to 152 PCU, appropriate adjustments to the coagulant dosage ensured that the permeate colour remained less than 6 PCU with an average of 1.5 PCU. This is well below the Canadian guideline of 15 PCU. The removal rates ranged from 0% (when there was no feed water colour) to 99% using coagulant dosages of 0 to 260 mg/L of IsoPAC PACL.

Figure 5a



Turbidity data for the Anthony Henday WTP for 2007 is shown in Figures 5b and 5c below. The turbidity can get very high in the raw water to this plant, particularly in the Spring. Regardless of feed water turbidity, which ranged from 0 to 1021 NTU, the physical barrier of the membrane ensured that the turbidity remained less than 0.09 NTU with an average of 0.04 NTU. This is well below the Alberta membrane regulations of 0.1 NTU. The removal rates ranged from 96% to 99.996%.

Figure 5b

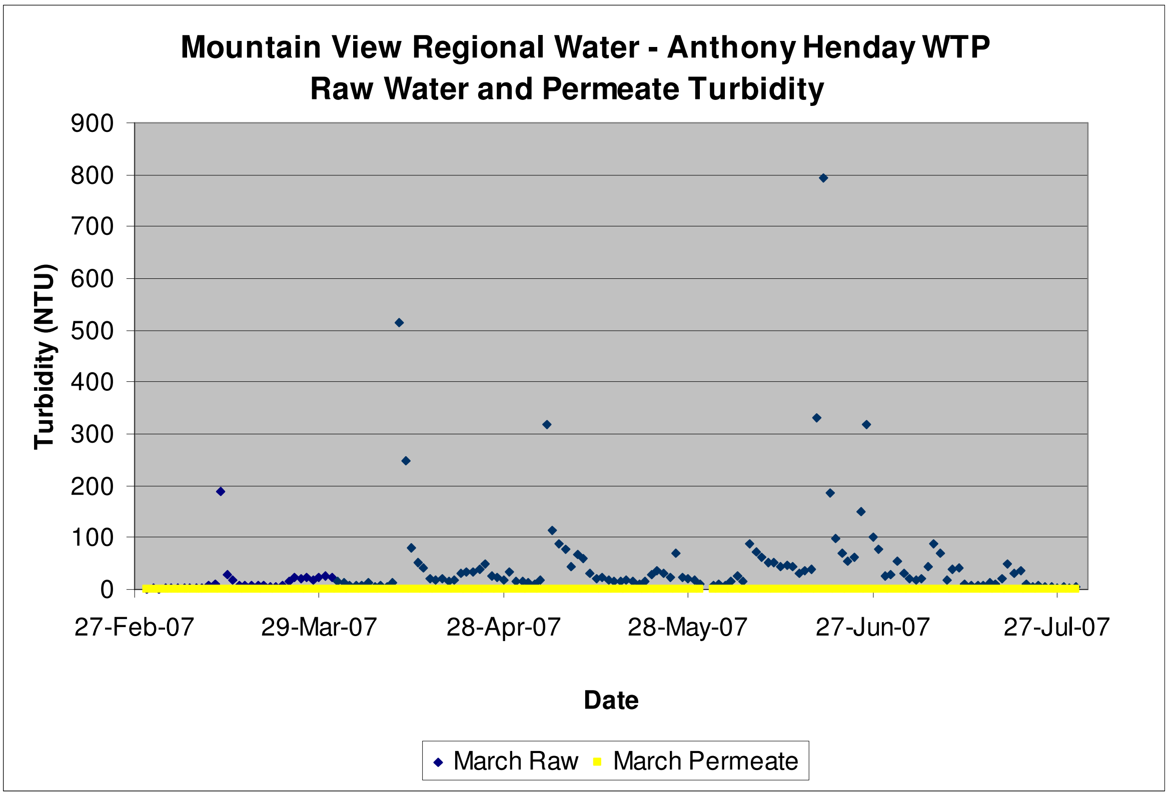
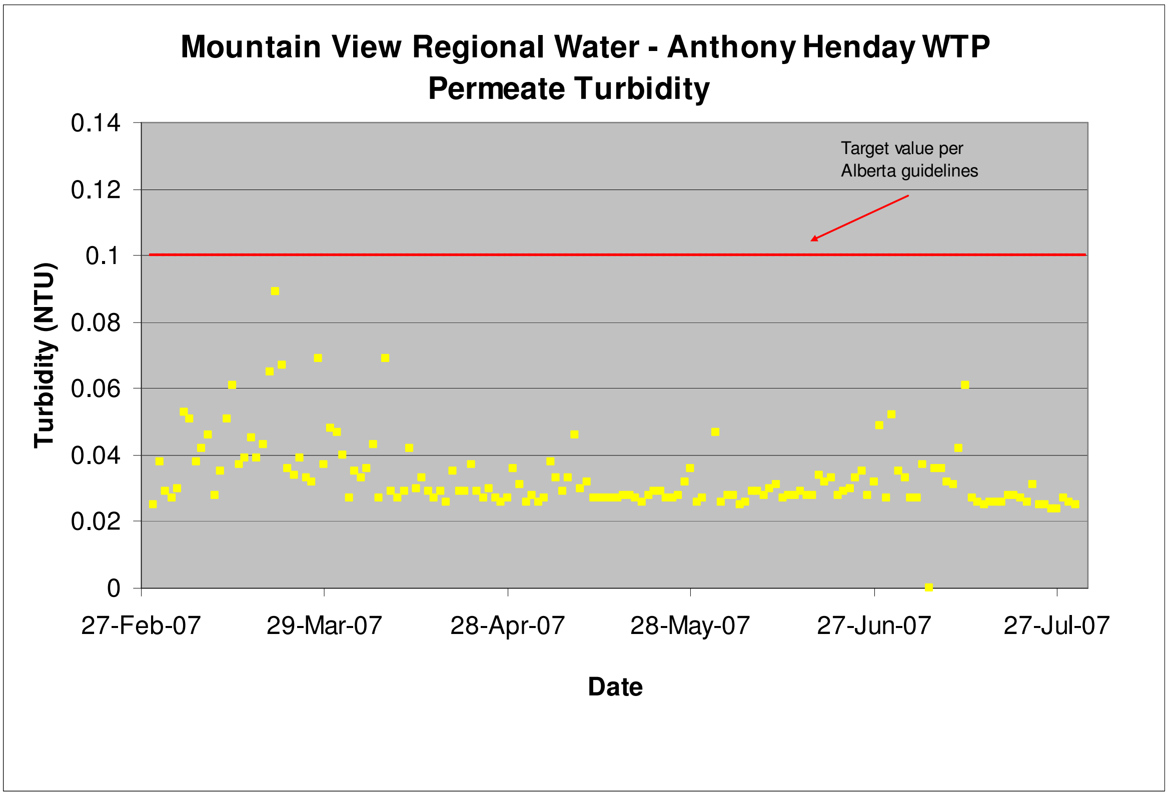


Figure 5c



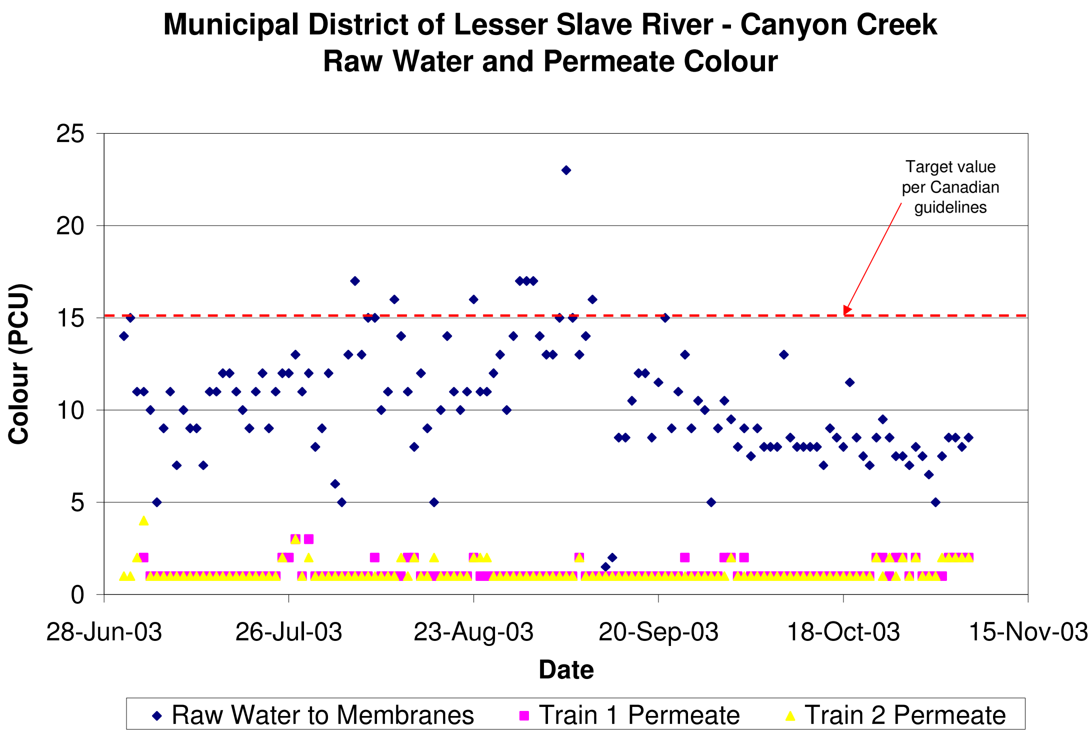
Municipal District of Lesser Slave River – Canyon Creek WTP
The Canyon Creek drinking water treatment plant provides water to the residents of Canyon Creek as well as to the residents of the neighboring communities of Widewater and Wagner near Slave Lake, Alberta. The plant capacity is 11 L/s (0.25 MGD) in Winter and 14.5 L/s (0.33 MGD) in Summer, although the skid mounted equipment is sized to allow expansion of the plant to 19.7 L/s (0.45 MGD) in Winter and 23.7 L/s (0.54 MGD) in Summer by adding only membranes. Prior to the installation of the immersed ultrafiltration membrane plant, drinking water was being treated by a conventional packaged system comprising rapid mixing, flocculation, clarification and filtration. The membrane plant was added to the existing system in order to increase capacity, as well as to improve the treated water quality. Raw water to the plant is from Lesser Slave Lake.

With both the conventional and the membrane plants in service, it is possible to operate either plant individually, both in parallel, or both in series with the conventional plant being used as pre-treatment to the membrane plant as demand allows. Chemicals that may be added to the feed water to the membrane plant include coagulant, PAC, potassium permanganate and pH adjustment chemicals. To date, the use of potassium permanganate directly in the membrane plant feed water has not been required, nor has PAC addition.

Colour levels in the raw water to the membrane plant and permeate are shown in Figure 6 for a period where the membrane system received raw water from Lesser Slave Lake. The raw water apparent colour varied between 5 and 23 PCU. Using alum coagulant at dosage rates of 50 to 110 mg/L and pH adjustment to 6.8, the permeate colour was reduced to < 4 PCU which is equivalent to removal rates of 60 to 95%.

There is no TOC data available for this plant for the time period studied.

Figure 6



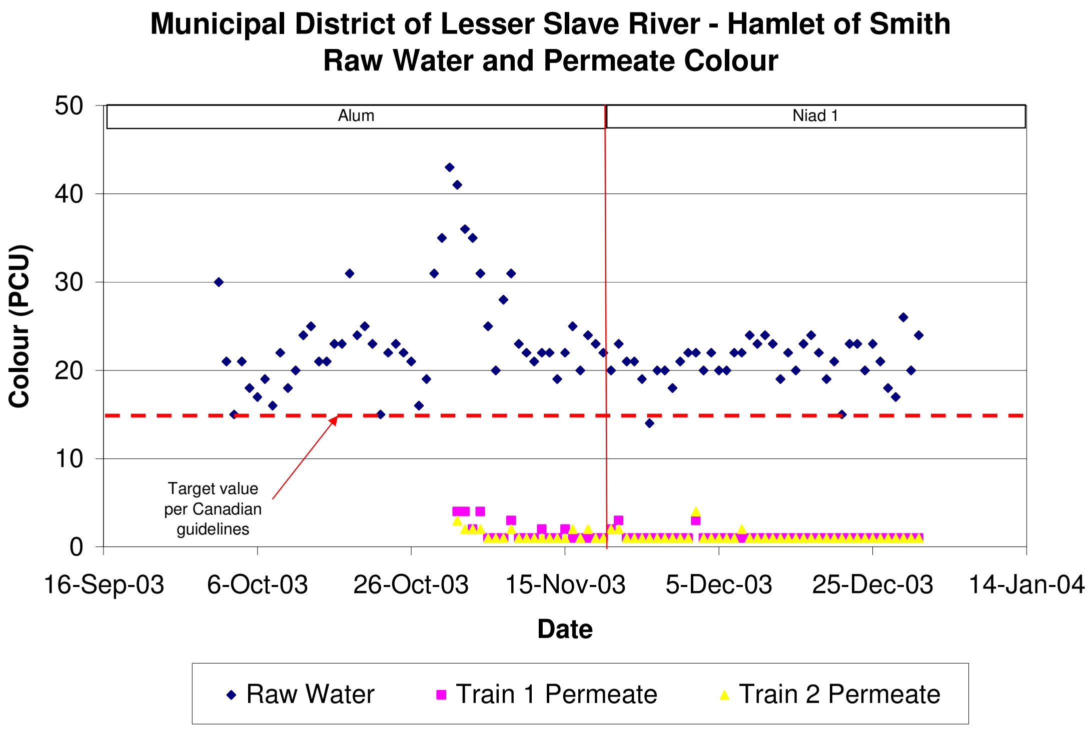
Municipal District of Lesser Slave River - Hamlet of Smith WTP

The Hamlet of Smith is a small town located near Slave Lake, Alberta. The drinking water treatment plant provides water to the few hundred residents of the hamlet and has a capacity of 7.1 L/s (0.16 MGD) in Winter and 8.5 L/s (0.19 MGD) in Summer. The skid mounted equipment is sized such that the plant can be expanded for future demand by simply adding membrane elements. The immersed ultrafiltration membrane plant was installed during the Summer of 2003 to improve upon an existing plant that used coagulation with pressure filters. The goal was to increase capacity, and improve treated water quality. Raw water to the plant is from the Athabasca River.

The old pressure filters are still in use as rough pre-treatment to the membrane system, but coagulant addition is being done downstream of these filters. The plant is also equipped to dose potassium permanganate for high raw water manganese events and PAC for high taste and odour events, although neither of these chemicals have been required to date.

Figure 7 shows five months of raw water and permeate colour data. Colour is tested by the platinum cobalt method on unfiltered samples, and is therefore a measure of apparent colour. However, since the permeate has passed through a 0.04 µm filter, the permeate true and apparent colour are equal. For feed colour levels varying from 14 to 43 PCU, permeate colour has been consistently reduced to less than 5 PCU, well below the Canadian aesthetic objective of 15 PCU. The colour removals have been excellent, ranging from 81 to 96%. Both alum in dosages up to 40 mg/L and Niad 1, a polyhydroxy aluminum chloride product, dosed at 11 to 93 mg/L have been effective. The switch was made to Niad 1 before Winter in anticipation that alum would be less effective at the colder temperatures.

Figure 6



Only a few TOC data points are available for this plant as TOC monitoring is infrequent. These are summarized in Table 2 below for the Niad 1 coagulant. With a target coagulation pH of 6.8, only 23.3% TOC removal was achieved. The removal rate more than doubled to 58.1% when the pH was decreased to 6.2 using sulfuric acid and the coagulant dose was doubled. This indicates that with optimization of the dose and coagulation pH, high TOC removal is achievable.

Table 2: Hamlet of Smith TOC Data

	Raw Water TOC (mg/L)	Permeate TOC (mg/L)	pH Set Point	Coagulant Dose (mg/L)	TOC Removal (%)
December 4, 2003	3	2.3	6.8	30	23.3
December 17, 2003	3.7	1.55	6.2	60	58.1
January 7, 2004	3.4	1.7	6.2	60	50.0

Pilot Plants

Most full scale plants are not equipped to perform TOC testing on a regular basis as the equipment required does not form a part of most on site laboratories. During pilot scale evaluations however, demonstrating TOC removal capabilities is frequently a requirement.

Town of Slave Lake Pilot

The TOC data from a pilot study performed for the Town of Slave Lake is presented in Table 3 below. Raw water was from Lesser Slave Lake. Different operating scenarios were used without coagulant, with alum, with alum and pH adjustment, and finally, with the addition of PAC.

Table 3: Town of Slave Lake Pilot TOC Data

	Coagulant (Alum) Dose (mg/L)	pH Set Point	PAC Dose (mg/L)	Raw Water TOC (mg/L)	Perm. TOC (mg/L)	TOC Removal (%)
Oct 4, 2000	-	-	-	10.9	9.5	13
Oct 17, 2000	100	-	-	10.8	6.8	37
Oct 19, 2000	100	-	-	10.8	7.7	29
Oct 20, 2000	100	6.2	-	10.8	5.4	50
Nov 6, 2000	100	6.2	10-20	10.2	2.9	72

The TOC removal obtained by direct filtration was quite low, indicating that most of the organics in Lesser Slave Lake were in a dissolved form that passed through the membrane pores. With the addition of coagulant, the TOC removal was increased to an average of 33%. Optimization by adjustment of the pH down to the optimum pH for alum coagulation improved the TOC removal by 17%. PAC addition also improved TOC removal, bringing it up to 72% for PAC dosages of 10 to 20 mg/L. The data suggests that with pH adjustment, the TOC removal requirements of the USEPA D/DBPR can be met for any raw water alkalinity and that PAC addition can help to exceed the TOC removal requirements.

For the same time period, the true colour data is shown in Figure 8. For raw water colour ranging from 2 to 39 PCU, the colour removal achieved was 27 to 97%, averaging 75%.

The trends in colour removal and TOC removal follow a similar pattern, as shown in Figure 9.

Figure 8

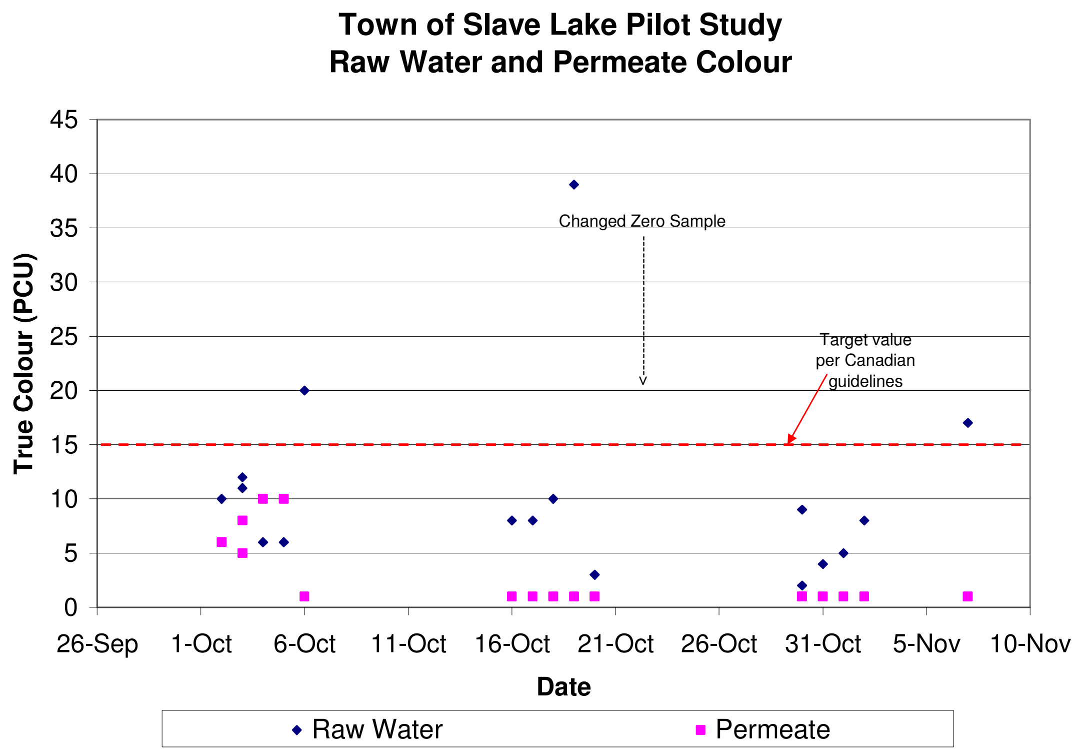
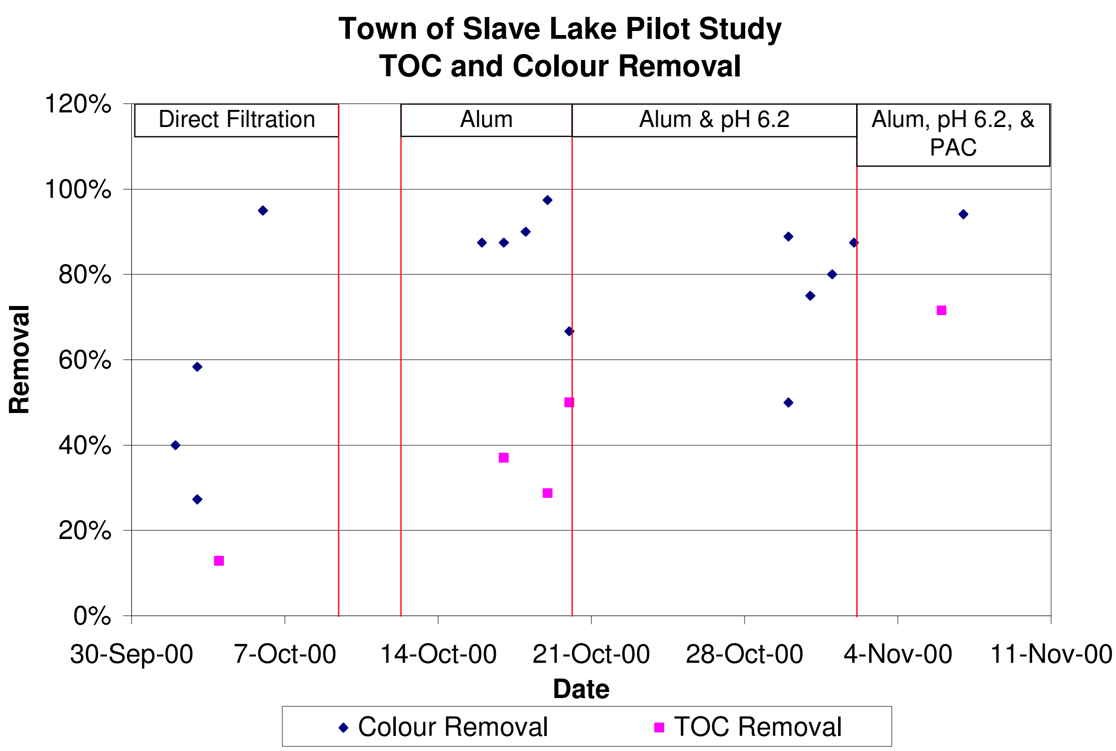


Figure 9

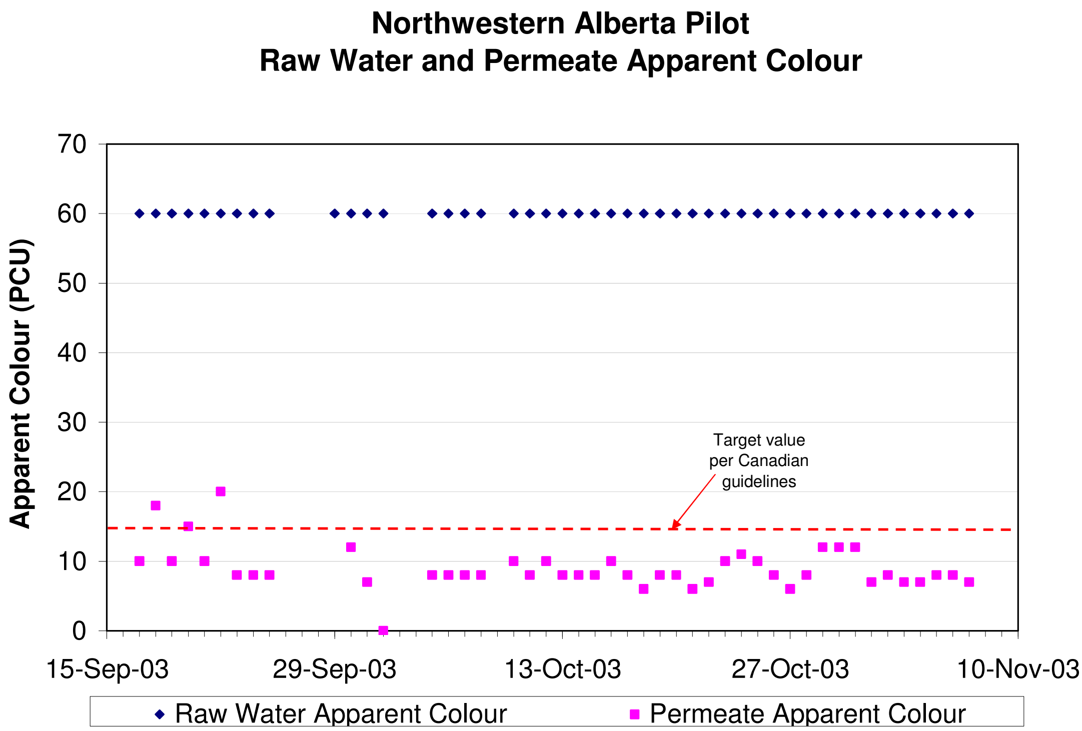


Northwestern Alberta Pilot

Pilot testing treating creek water for a town in northwestern Alberta took place from September to November of 2003. Alum coagulant was tested at doses of 100 to 200 mg/L. Adjustment of the pH using hydrochloric acid was not found to have any impact on the raw water due to its alkalinity at the alum dosages being used. A trial was also performed with PAC addition at doses of 10 to 75 mg/L to determine its effect on TOC removal. The results of the pilot study are shown below.

Figure 10 shows raw water and permeate apparent colour for the study. The colourimeter used for the study had a maximum detection limit of 60 PCU. The raw water colour was consistently measured at 60 PCU, indicating that the raw water colour was actually higher than 60 PCU. Even with that high colour, the permeate colour was reduced to less than 15 PCU on all samples but two.

Figure 10



The TOC data for this pilot is summarized in the table below and demonstrates a TOC removal of greater than 50%. The addition of PAC in this case does not seem to have increased the TOC removal, however it may have contributed to taste and odour removal and did not have a negative impact on the membrane performance.

Table 4: Northwestern Alberta Pilot TOC Data

	Coagulant (Alum) Dose (mg/L)	PAC Dose (mg/L)	Raw Water TOC (mg/L)	Perm. TOC (mg/L)	TOC Removal (%)
Sept 23, 2003	150	-	19	6.4	66.3
Oct 1, 2003	200	-	17.7	7.1	59.9
Oct 23, 2003	150	-	25	11.2	55.2
Oct 30, 2003	150	10	21.9	9.2	58.0

While the operating data presented in this paper has focused on colour and TOC data in the raw water and treated water, additional data is available to demonstrate the reliability with which turbidity is removed irrespective of the feed water turbidity level. In addition, third party studies have demonstrated removal rates exceeding 6 log for *Giardia* and *Cryptosporidium*.

CONCLUSIONS

As regulations on total trihalomethanes (TTHMs) and haloacetic acids (HAA5) become more stringent to protect public health, utilities are being required to practice enhanced coagulation. Immersed ultrafiltration membranes combined with enhanced coagulation are an ideal pre-treatment strategy for maintaining high treated water quality in terms of *Giardia* and *Cryptosporidium* removal, turbidity reduction, and NOM, TOC and colour removal to minimize the formation of disinfection byproducts.

The advantages of ZeeWeed® immersed ultrafiltration membranes combined with enhanced coagulation as compared to a conventional rapid mix-flocculation-clarification-filtration plant include:

- High colour removal, approaching 95% depending on feed water characteristics, coagulant dose and pH
- High TOC removal, approaching 75% depending on feed water characteristics, coagulant dose and pH
- Reduced coagulant consumption
- Reduced sludge production associated with lower coagulant dose
- Physical barrier prevents breakthrough of contaminants
- Low fouling potential due to outside in flow configuration and optimized fibre placement
- Strong, chemically resistant fibres
- Potential for retrofit
- Reduced facility complexity
- Small footprint

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