Introduction and applications of advanced water treatment with membrane filtration in Europe, Australia and NZ

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Abstract
Low pressure membranes are now well established world-wide as a reliable process in the treatment of surface waters for potable use. Although the Europe & Australia/New Zealand each have a significant installed base of large scale operating plants, the application for membranes in each region have been quite different. The UK's installed membrane base has, to date, been predominantly focussed on integrating membranes with conventional unit processes and polishing of media filtered and high quality waters. By comparison, Australia/NZ installations have had a wider range of applications. In many of these treatment plants membranes have been applied in direct filtration applications and form the main unit process.

This paper reviews the complimentary findings of Australian/NZ operational experiences and membrane investigative work in the UK derived from the treatment of complex water sources.

Design considerations applicable to preconditioning of variable and complex feed waters prior to direct membrane filtration differ significantly from conditions typically adopted for conventional treatment processes. These are discussed along with implications for engineers and water authorities considering the use of membrane filtration for the production of potable water.

Keywords
Algae; colour; coagulant; manganese; membrane; potable; surface

INTRODUCTION

Membrane Filtration (MF) has established a proven track record of achieving the treated water standards required for potable water on a wide range of feed waters. Membranes present a complete barrier against micro-organisms and particles and hence produce consistent filtrate quality independent of a number of parameters. They are also valuable in reducing harmful disinfection by-products (Lerch et al 2005, La Trobe-Bateman & Barrott 2005). These factors, combined with the ability to automate the process, it's compact size and flexibility for future system changes/upgrades have resulted in a growing number of MF installations. The role of MF in these installations varies from acting as either the main unit process, or as part of a multiple step process. Table 1 summarises the current status of MF installations in the UK and Australia.

Table 1 Drinking water treatment (approx) by Membrane Filtration in the UK and Australia

Water Source	United Kingdom		Australia	
	Rated Output ML/day	No. of plants	Rated Output ML/day	No. of plants
Ground water	944	54	7	5
Surface & mixed	383	9	459	71
Total all sources	1,327	63	466	76

The installation data shows a significant difference in the application of membranes in the two countries:

- Installations in the UK have predominantly been "polishing" applications. MF feed has been either clean ground water, high quality surface water or treated water from conventional systems (eg ex media filters). MF has been used as a polishing step with the main aim of membrane treatment being to remove cryptosporidium, while colour removal has been handled by upstream conventional processes.
- Installations in Australia and New Zealand have largely used MF as the main unit process in the treatment train with membranes usually operating in "direct filtration". Waters

across the region suffer various levels and types of contaminants including blue-green algae, high levels of colloidal materials, iron, manganese, colour, taste and odour. In some cases all of these can occur simultaneously.

As a result, Australia and NZ have the greater operating history of treating difficult and complex feed waters. However, the quality of many feed streams in the UK is degrading. Water discolouration has increased due to disturbances in weather patterns in recent years. Aerobic conditions produced in soil during drought have lead to increased microbial action, releasing peat acids which are subsequently flushed into water sources during storm events resulting in periods of highly coloured water (Drage et al, 2005). Higher summer temperatures have fostered algal growth with the possibility of subsequent iron and manganese release associated with build up of anaerobic sludge layers in water storages. As a result an increasing number of projects are looking to MF as much more than a polisher. Considerable research and testing is ongoing to verify and optimise the performance of membrane filters operating as the main unit process in a treatment train, and large scale projects are proceeding.

MF systems have different characteristics to conventional technologies. As a result, those implementing MF projects have the dual task of selecting the optimum process design for membrane treatment and the more fundamental question of the design basis upon which plant sizing and operation is based. These issues, and the experiences of practitioners in Europe, Australia and NZ are discussed below.

CONTAMINANTS AND PROCESS RELATED ISSUES

Turbidity

Turbidity is probably the first parameter considered in the design of any treatment system, and is a key treated water parameter. As mentioned above, Membrane filtration's ability to maintain consistent treated water turbidity irrespective of feed water quality (illustrated in Figure 1 in the case of a surface feed subject to dramatic disturbance during rain) is one of the main factors that has driven the growth of installations in the potable water market.

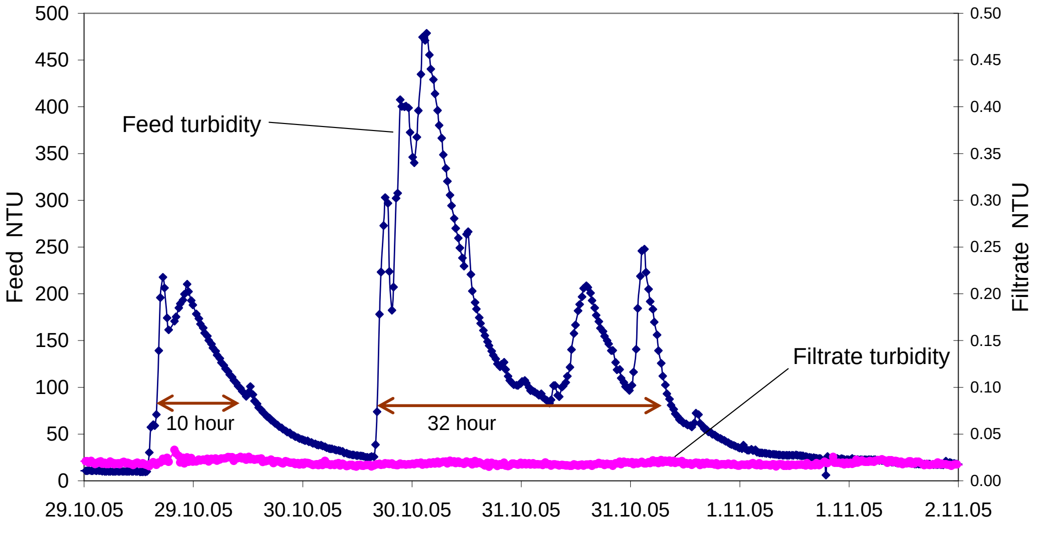

Figure 1 Typical performance of a Membrane Filter system during turbidity events

The mechanism by which MF removes suspended solids is very different to those at work in traditional treatment systems:

Membrane Filters remove solids at their surface to form a filter cake, irrespective of the nature of the solids removed. The MF membrane is a positive barrier to contaminants.

Media filters remove solids throughout the filter bed and rely on attractive forces far more than "seiving" effects

Clarification devices rely on chemical addition to form large flocs that can be readily separated by gravity.

The performance shown in Figure 1 shows the benefit of the positive barrier removal mechanism employed by MF. This allows designers to reassess one of the fundamental design decisions applied to treatment facilities – the question of how to design for "spikes" in feed turbidity and suspended solids.

Feed "spikes" are the dominant feed water characteristic of many treatment facilities. At these installations, contaminants are at low levels during normal conditions, but increase by 1 or more orders of magnitude for short periods (usually 1 – 5 days). These events are typically the result of river first flush after rainfall and have short term effects on backwashing and cleaning.

Although MF systems produce consistent water quality during a spike in feed conditions, they exhibit a significant increase in fouling rate, resulting in a drop in recovery and/or cleaning/backwash interval. This poses two key questions for end-users and MF suppliers:

How long does a spike have to be before it is considered a base condition?

What reduction in plant performance can be accepted during a spike?

There is no simple answer, but a good knowledge of spike frequency, duration and extent is essential to achieve the correct balance between membrane inventory and plant flexibility. Some end-users have optimised membrane inventory and operating cost by recognising different "modes" of feed conditions. A 33ML/day MF plant installed at Tauranga in NZ took this approach by identifying 4 modes of operation:

Feed Water Mode	1	2	3	4
Maximum Duration	No limit	No limit	3days	3 days
Turbidity (NTU)	<15	15 – 50	>50 – 100	>100 – 500
True Colour (HCU)	< 10	10 – 30	>30 – 50	>50-200
Plant downrate factor	0%	18%	27%	39%
Cleaning chemical guarantees	Yes	Yes	No	No

Table 2 Definition of operational modes at Oropi WRP.

The changeover between operating modes was handled automatically by the plant's control system eliminating the need for plant operators to change plant settings during peak events. The design took advantage of the distribution systems lower demand during wet weather to minimise both capital and operating costs.

Coagulation

As in the case of particulate removal, the role and manner of use of coagulation in membrane plants differs from conventional practice. MF systems do not require a settleable floc, but rather one which minimises interference with the membranes while carrying out its primary function effectively. Optimum conditions for clarification and/or direct media filtration are not usually the same as those for conventional treatment (Choi and Dempsey, 2005). Coagulant dosage for MF systems is normally lower than required for clarification.

Coagulant dosing can also have a beneficial effect on MF performance by improving filterability by the membrane. This generally observed effect, where a low dose of coagulant (typically 1 mg/l as metal or lower) improves membrane performance is usually ascribed to improved permeability of the accumulated filter cake and/or the removal of organics which are causing fouling. The latter effect was shown clearly at test work carried out at the Invercannie WTW in Scotland.

Invercannie is a 70ML/day treatment plant using ozone and slow sand filtration prior to MF for cryptosporidium removal. Despite the fact that the MF feed is very low in suspended solids, membrane fouling was observed. This was found to be the result of soluble organic content of up to 7 mg/L escaping the sand filters (refer to Table 3 over).

Sample Point		Raw Water		MF Feed	
Parameter	Unit	Mean	Range	Mean	Range
Temperature	°C	12	2 - 23	12	2 - 23
Turbidity	NTU	0.4	0.1 – 2.5	0.16	0.1 – 0.3
Colour	HCU	16	3 - 46	6	2 – 18
Iron	ug/L	55	17 - 154	23	17 – 83
Manganese	ug/L	4	1 - 13	1.2	1 – 13
pH	-	7.2	6 – 8	7	6.3 – 7.8
TOC	mg/L	5	1 – 29	2	0.75 - 7

Table 3 Invercannie water characteristics

Investigation of the phenomenon involved replacing the Ozone/Sand filters with a system dosing Poly-aluminium chloride (PACl) with 15 minutes contact time prior to the membranes. Figure 2 shows the membrane TMP response is shown for two separate colour events which took the usual 20 – 40 Hazen value to over 100 and for which the PACl dosing was automatically controlled by a link with an on-line colour instrument.

As the filtrate colour failed to remain below 10 Hazen during the first event and also the TMP increased strongly the coagulant level was increased by 35%, retaining the link to colour. At the same time the daily maintenance wash was switched from sodium hypochlorite to sulphuric acid as a precaution against higher levels of aluminium floc. Both measures were successful as shown in the second set of curves. It would appear that insufficient coagulant allowed organics to cause fouling of the membrane in the first colour event. Fouling was kept to a minimum in the second event, even though the extent of the feed colour event was greater than the first event.

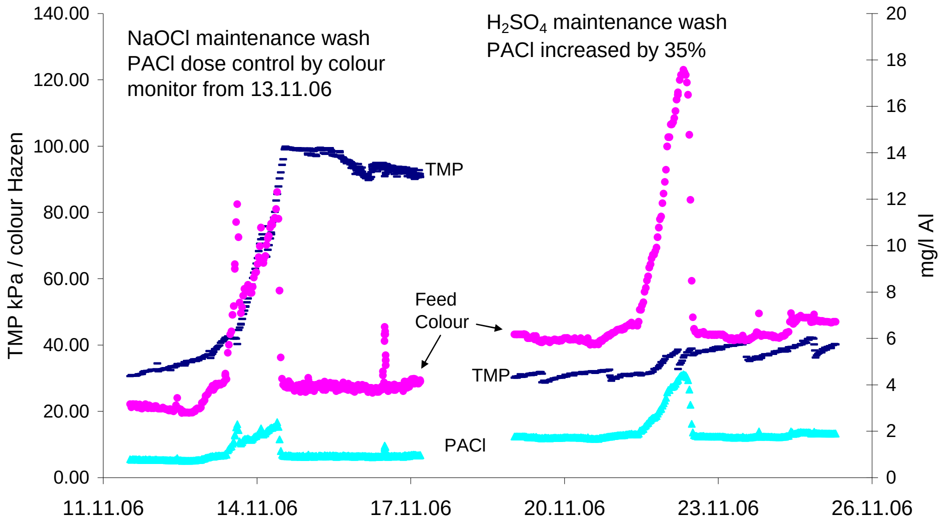

Figure 2 Coagulant dosing impact on fouling

In addition to the presence/absence of coagulant, the type of coagulant can have a significant impact on membrane performance. Some coagulants, despite being marketed by their manufacturers as equivalent products, can have a marked difference in performance.   Figure 3 demonstrates this effect on a cold, coloured water filtered by PP membrane. Characteristics of the water are given in Table 4.

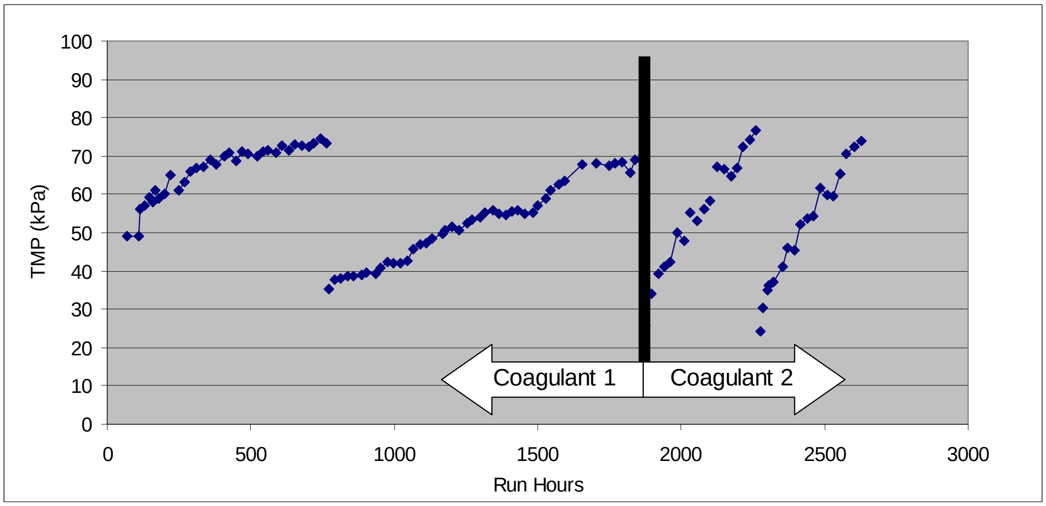

Figure 3 Impact of Coagulant type on membrane performance

The data, taken from an extended trial carried out as pre-work for a 40ML/day drinking water plant, examines the effect of two ACH (aluminium chlorohydrate) coagulants. One was sulphate based, the other chloride based. As can be seen in the data, the rate of fouling observed for the two coagulants was markedly different with the sulphate based coagulant showing a much higher fouling rate.

Parameter	Unit	Mean	Range
Temperature	°C	11	3 - 20
Turbidity	NTU	1.1	0.4 – 13
Colour	HCU	17.1	9 – 29
pH	-	7	6.1 – 8.2
TOC	mg/L	3.5	1.1 – 7.4

Table 4 Dunedin raw water characteristics

Similarly, coagulant's impact on membrane performance can also be influenced by pH. This is demonstrated in Figure 4 which shows the rise of membrane resistance on a ferric salt coagulated upland surface water in the north of England. Characteristics of the water are given in Table 5.

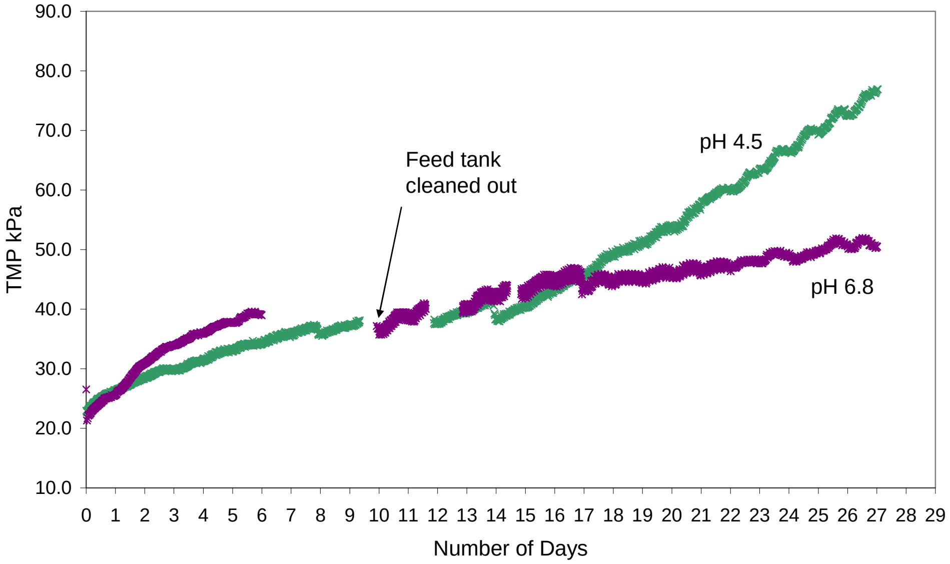

Figure 4 pH effect on rate of Trans Membrane Pressure (TMP) change

The application used PVDF membranes and 15 mins contact time between the coagulant dose point and the MF system.

Parameter	Unit	Range
Temperature	°C	8 – 12
Turbidity	NTU	0.2 – 0.6
Colour	HCU	10 – 20
pH	-	4.0 – 4.3
Fe	mg/L	0.35 – 0.45

Table 5 Arnfield raw water characteristics

A pH of 4.5 is often chosen as the optimum performance of Iron coagulants. Initial operation at this pH resulted in a steady rise in TMP over a 4 week period. The pH of the coagulated water was then adjusted to 6.8 just before the membrane. After resolving a buildup of solids in the feed tank, the rate of TMP rise was much lower than operation at the lower pH.

The difference in performance is likely to be caused by a tendency for the flocs to adhere to each other more strongly near the membrane surface at low pH resulting in a higher specific cake resistance. A similar pH effect can be seen with other coagulants. Research using tap water with added humic acids has shown a similar result using coagulation with poly-aluminium chloride. Coagulation at a pH of 6.75 gave a lower fouling rate than at pH 5.5 prior to a PES UF membrane (Gitis et al., 2005). The research also found the removal of organics (mainly humic acids) was not affected by the pH change, which points to different specific cake resistances rather than different levels of organics fouling on the membrane surface.

Algae

Membrane filters are very effective in removing algae. Many membrane plants operate with a seasonal challenge which is fully rejected and gives a manageable level of fouling. However, the impact of algae on a membrane filter is significant. Algae forms a relatively impervious filter cake on the surface of the membrane surface which results in higher operating pressures and higher backwash frequency. This is shown clearly by the operation of the 59ML/day MF plant at Ennerdale in the UK.

The feed to the Ennerdale plant is a good quality surface feed subject to summer algae blooms. The summer blooms result in an increase in operating TMP as shown in Figure 5. This higher rate of fouling can be fully recovered by a chemical clean. (Hillis et al., 2003).

Parameter	Unit	Mean	Range
Temperature	°C	10.6	3 – 18
Turbidity	NTU	0.32	0.1 – 0.8
Colour	HCU	3.5	1 – 6.3
pH	-	6.9	6.2 – 8.1
Plate counts	No./mL	273	37 - 1320

Table 6 Ennerdale raw water characteristics

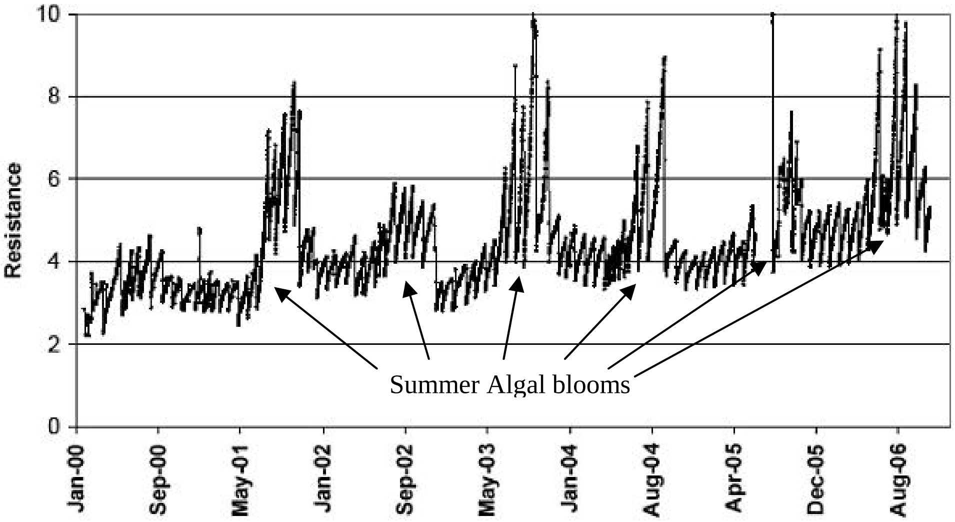

Figure 5 Ennerdale long term operating data

Although algae is a design issue for treatment facilities in the UK and Europe, the extent of algal contamination of feed waters in Australia is several orders of magnitude worse. This is a consequence of regular droughts, still water conditions and high nutrient levels caused by run-off from farming land and sewage treatment plant discharges to the environment. The result can be large algal outbreaks sometimes stretching hundreds of kilometres along rivers and lakes. The impact of these blooms is made all the worse by the common occurrence of toxic blue-green algae. This renders the water unusable for either human or animal consumption. The problems created by algae continue after the cells die. The breakdown of algal cells releases high levels of taste & odour compounds along with toxins.

To address the problems created by the higher levels of algae seen in Australian waters, MF is one of several unit processes employed in advanced potable water facilities. The Aqua2000 project in Bendigo is a good example of this approach. This 126ML/day facility uses a low level of coagulant at a controlled pH prior to a contact tank and subsequent membrane filter system. Filtered water is treated by Ozone and BAC for destruction of organic compounds before distribution. Other installations aim to reduce capital cost by relying on powdered activated carbon (PAC) dosing during periods of feed contamination. Again, membranes are a useful unit process that allows the PAC to be dosed into the feed water thereby simplifying the process train.

Parameter	Unit	Mean	Range
Temperature	°C	15.6	8 - 24
Turbidity	NTU	2.1	1 – 11
Colour	HCU	13.7	7.5 - 30
pH	-	7.9	7.2 – 8.2
DOC	mg/L	7.4	6.3 – 8.9

Table 7 Aqua2000 raw water characteristics

Iron and Manganese

MF removes insoluble contaminants in feed water (soluble species are not removed). Hence, membrane filtration is successful in removal of Iron and Manganese only if the species are in the insoluble state.

Iron is the easier of the two metals to remove. Pretreatment consisting of aeration, pH adjustment and possibly an oxidant such as sodium hypochlorite will ensure iron is precipitated prior to filtration, and hence can be removed. Mineral acid or citric acid cleaning is usually very effective. Most problems seem to arise when the presence of iron in the feed comes as a surprise and reveals itself through fouling deposits which have built up over a period. This can be avoided using periodic preventative cleans.

Manganese chemistry is not as straightforward as that for iron, particularly when predicting rates of reaction rather than thermodynamic instability. The reaction of manganese with oxygen is slow even at high pH, and sodium hypochlorite does not help much. As a result, a stronger oxidant can be used, such as ozone, chlorine dioxide, or potassium permanganate. Ozone oxidises manganese quickly, but may take the process beyond Mn(IV) to a higher soluble oxidation state. It is sometimes used when there is already an ozone plant on site and where it is performing another useful function. For lower levels of manganese, up to 0.4mg/l, chlorine dioxide may be a good choice (its use at higher levels is limited in Europe because no more than 0.5 mg/l of chlorine dioxide can be used in drinking water). Potassium permanganate remains the most likely choice for high levels of manganese, even though its own decomposition produces manganese solids (an additional 67% of hydrated manganese oxides) which must be filtered by the membrane, and overdosing can result in “pink water”.

A key factor for the membrane process is to avoid oxidation or precipitation steps occurring on or within the membrane itself. For example, a reaction time for potassium permanganate may be as low as 5 minutes, but up to 20 minutes may be necessary when it is organically complexed. This effect seems more pronounced at initial levels below 200µg/L as Mn (Gregory and Carlson, 2003). Occasionally it may be unsuccessful in the presence of high levels of organics (Gallagher et al, 2005) and a different oxidant must be used. There is a further possible interference between the oxidant and a coagulant (US EPA, 1999) in the case where coagulant suppresses pH and hence slows manganese oxidation. While this may not be a problem for free manganese, which will usually react within 5 minutes, when it is complexed it may be preferable to complete the oxidation as far as possible before a coagulant is added.

These effects are illustrated in the design of the 30 ML/day treatment plant at Banwell in south west UK. The plant combines MF with permanganate dosing, coagulant dosing, pH control and 2 stage retention to address feed water colour, high levels of Manganese and algae.

Parameter	Unit	Mean	Maximum
Temperature	°C	15	25
Turbidity	NTU	4	39
Colour	HCU	10	25
Manganese	mg/L	0.1	1.2
pH	-	8.3	9.1
Algae	No./mL	2,400	40,000

Table 8 Banwell raw water characteristics

Chlorine Dioxide was found to be unsuccessful for the removal of Manganese as the dose required exceeded the UK limit of 0.5 mg/L and there were doubts over the rates of reaction in this process. The use of $KMnO_4$ consistently removes Mn down to <20 ug/L. 10 mins of retention at the natural pH of 8.0 is included before the coagulant dosing point. A further 10 mins retention is included after the coagulant dosing point with pH controlled to the range of 6.5 - 7.0. The coagulant used is PACl dosed at 1 mg/L as Al. Treated water colour is always reduced to <5 Hazen

THE ROLE OF PILOT TESTING

The discussion above details a number of aspects of MF plant design and operational settings that are highly dependant on the nature and variability of the feed source. The optimum solution for complex waters is not always clear. This is a common issue in many parts of the world. As a result, pilot tests (trials) have become a common step in examining the application of MF for complex waters. Pilot trials have many benefits in confirming the correct design philosophy and reducing project cost and risk. Unfortunately, some trials in recent years have been carried out in a manner that has failed to achieve the expected outcomes. Inadequate pilot trialing (in some cases) has led to treatment systems that failed to operate as expected.

It is useful to differentiate between two levels of trialing:

Demonstrations	are a short on-site test that demonstrates the technology and indicates the quality of treated water that can be achieved. They should not be used as a basis of final plant equipment sizing or overall process design
Pilot Trials	are a well planned program designed to investigate the expected operating conditions of a full scale plant.

Characteristics of each are tabulated below:

Type	Demonstration	Pilot Trial
Duration	1 day to 2-3 weeks	1-12 months
No. of clean cycles	<2	2 or more
Feed analyses	Scant (eg Turb & colour)	Regular detailed feed water analysis
End user involvement	Little or none	Good – ideally the end user runs the trial with assistance from the equipment vendor.
Event logging	Little or none	Logging of events/upsets and explanation of causes
Planning and reporting	Little or none	Detailed trial protocol written before the trial commences. Detailed final trial report written
Other	N/A	May include repeated runs to investigate impact of variables eg alternative coagulants, different feeds etc.

Table 9 Characteristics of site test options

Perhaps the most important measure of a successful pilot trial is the demonstration of repeatable performance through 2 or more chemical cleaning cycles. Figure 6 below is an excerpt of the data taken from an 8 month cold water surface water trial.

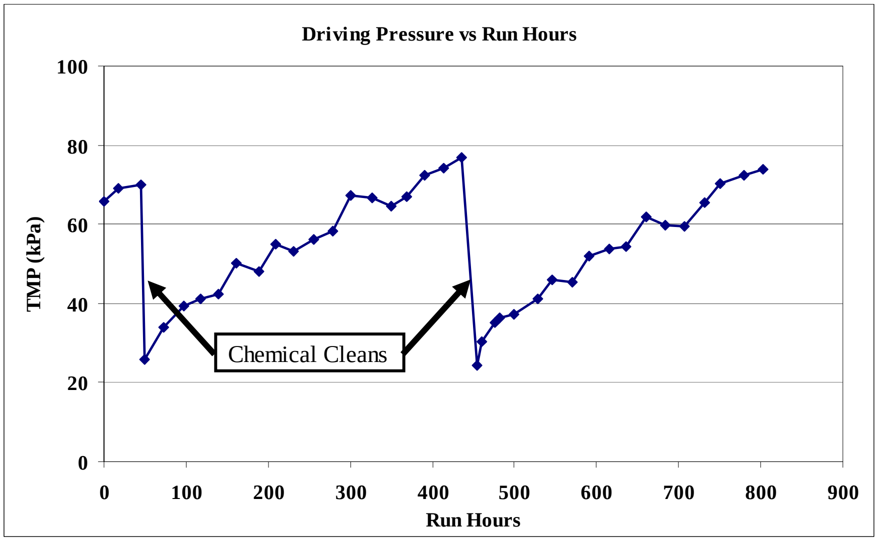

Figure 6 Ideal trial performance

There are three key features to note:

1. The repeatable slope of the curve in each cycle.
2. The repeatable baseline condition after CIP
3. The long period of time needed to achieve 2 cleaning cycle (approx 2 months)

A trial carried out so that it is able to demonstrate these feature will significantly reduce the risk that a full scale plant will not achieve performance.

CONCLUSIONS

Membrane Filtration has established a proven track record of achieving the treated water standards required for potable water on a wide range of feed waters. Membranes present a complete barrier against micro-organisms and particles and hence produce consistent filtrate quality independent of a number of parameters.

The application of Membranes in the UK has been largely limited to polishing applications, whereas membrane plants in Australia and New Zealand have relied on membranes to operate as direct filters to treat a wide range of feed streams. This experience provides valuable information on the design and application of future membrane projects.

The type of contaminants in a given feed water must be carefully considered in the design of a MF system. MF's ability to maintain filtrate quality despite sudden "spikes" in feed turbidity open up the opportunity to review the sizing criteria for treatment plants. Significant capital and operating cost savings can be made by sizing membrane plants to maintain low chemical consumption and high recovery during normal periods, and allowing a relaxation in throughput and operating cost related parameters during the <5% of time that feed conditions are at their extreme.

The use of coagulants in MF systems can be beneficial to the operation of the membranes, particularly at low dosage levels. The choice of coagulant must be made with care as different coagulants can exhibit marked changes in membrane performance. Similarly, the conditions at which coagulant is dosed, in particular pH, can strongly influence fouling rate and membrane efficiency. Membranes successfully remove algae, but must be used in conjunction with processes capable of removal/destruction of dissolved organic materials to maintain potable water quality in the event of heavy algal outbreaks.

Membranes are also capable of removing iron and manganese provided they are in the insoluble form. Care must be taken in the design of pre-treatment systems to ensure metals have precipitated prior to being fed to membranes.

Thorough pilot testing is strongly recommended for complex feed waters, particularly in the light of the factors detailed above.

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