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Bruce DURHAM[1], Marie Marguerite BOURBIGOT[2], Tom PANKRATZ[3]

MEMBRANES AS PRETREATMENT TO DESALINATION IN WASTEWATER REUSE. OPERATING EXPERIENCE IN THE MUNICIPAL & INDUSTRIAL SECTORS

Summary. This paper reviews the benefits of the wastewater reuse for industrial and municipal applications. It demonstrates how continuous microfiltration (CMF) pretreatment to RO can reduce capital and operating costs of RO systems, improve their efficiency and enable reliable operation on a wider variety of water sources. This information is supported by operational data from a number of CMF – RO installations worldwide on difficult to treat feed waters.

MEMBRANY JAKO OCZYSZCZANIE WSTĘPNE PROCESU ODSALANIA ŚCIEKÓW. DOŚWIADCZENIA PRAKTYCZNE Z SEKTORA PRZEMYSŁOWEGO ORAZ MIEJSKIEGO

Streszczenie. Referat omawia korzyści płynące z ponownego wykorzystania ścieków oraz możliwości zastosowań opisanych rozwiązań w sektorze komunalnym i przemysłowym. Dowodzi on, jak daleko zastosowanie ciągłej mikrofiltracji (CMF) przed RO może zredukować koszty inwestycyjne i eksploatacyjne systemów RO, podnieść ich skuteczność i umożliwić niezawodne działanie w zastosowaniu do wód różnorodnego podchodzenia. Prezentowane informacje poparte są licznymi danymi eksploatacyjnymi uzyskanymi w skali światowej z instalacji CMF-RO stosowanych dla trudnych do oczyszczania wód różnego pochodzenia.

[1] Memcor Ltd, Vivendi Water, Wirksworth, Derbyshire DE4 4BG Tel. +44 1629 821167 Fax.+44 1629 825169, email: bdurham@memcor.co.uk

[2] Vivendi Water 52, rue d'Anjou 75384 Paris Cedex 08, Tel. +33 149 24 60 86, Fax +33 149 24 63 58, email: maggie.bourbigot@generale-des-eaux.net

[3] OTV, Vivendi Water Systems L'Aquarene 1, place Montgolfier 94417 Saint- Maurice Cedex France, Tel. +33 145 11 58 37, Fax.+33 145 11 58 10, email: tpankratz@otv.fr

1. Introduction

Once limited to sites with extreme water deficits or unusual effluent disposal constraints, reuse of reclaimed water has become an increasingly strategic water management option for growing communities worldwide. Because of increasing public acceptance, health protections, and comprehensible regulatory guidance, non-potable water reuse applications have been widely practiced. Communities considering a non-potable reuse program are nevertheless still faced with institutional, legal, and liability issues inherent in reclaimed water services. Furthermore, because of these unique jurisdictional and market constraints, it is important to optimize the economic benefits and financial performance of non-potable reuse projects.

The economic analysis provides the basis for justifying a water reuse project in monetary terms. It makes a comparison of the total costs and benefits associated with the project against those of alternatives developed to provide additional water supply and/or additional wastewater disposal. In the case studies presented below, the economic analysis has demonstrated the benefit of the reuse projects.

The total cost, including capital construction, operation and maintenance costs, has been largely optimized during the last five years. Innovative approaches are proposed both in term of the reduction of energy consumption and optimization of pretreatment prior to reverse osmosis (RO) or nanofiltration (NF). This is important when there is a need for advanced treatment due to regulation or because of specific applications (presence of too high salt content for use in irrigation, need for high quality industrial water or aquifer recharge application). This paper will focus more specifically on these Integrated Membrane System applications.

2. Water quality comparison and effectiveness: MF/ UF to conventional pretreatment prior to reverse osmosis

The current total capital cost for the pretreatment can be greater than 50% of the overall cost of a reuse plant using RO. In addition to this significant cost factor, water quality factors are also critical issues. A major problem with RO and NF facilities is their susceptibility to fouling with suspended solids, colloidal material, organics, bacteria or scale from dissolved ions in the raw water. The implications of fouling are; irreversible membrane damage, reduced flux rates and increased operating costs from frequent chemical cleaning. Cellulose acetate RO membranes have historically been used in reuse applications due to their lower fouling tendency over thin film composite (TFC) membrane, and their ability to withstand higher chlorine dosages. Unfortunately, cellulose acetate (CA) membranes require significantly higher feed pressures to achieve the same production rate, thereby resulting in higher operating costs (24 bar for CA versus 9 to 13 bar for TFC)[1]. By reducing the fouling potential on variable quality feed water, the use of thin film composites has been reliably proven to reduce the power cost for the RO portion of the plant by up to 60%[1]. Microfiltration (MF) or ultrafiltration (UF) pretreatment prior to RO can significantly reduce this fouling potential over the conventional pretreatment processes.

A large number of full-scale water reclamation and reuse installations, pilot and demonstration plants have been undertaken in recent years to compare the conventional pretreatment system with either MF or UF, followed by RO. The Advanced Water Treatment process based on microporous membranes such as microfiltration and ultrafiltration followed by reverse osmosis has become the industry standard for the treatment of municipal wastewater in indirect potable reuse projects [2].

The effectiveness of MF/UF systems compared to conventional systems can be evaluated in terms of:

The quality and variability of the feed water
The capacity of the system and the space available
The quality of the MF/UF product water which is largely independent of the feed quality
The amount of cleaning or maintenance required for the pretreatment system
The reliability, capital and operating costs of the NF or RO system.

In reuse plants, the feed water to the pretreatment system is often secondary sewage (biologically treated municipal wastewater). This can have a variable and at times high suspended solids load with a high proportion of colloidal material, organics and bacteria. These constituents can cause irreversible failure to the downstream RO system if not successfully removed during pretreatment.

Numerous studies have been undertaken to evaluate the effectiveness of MF/UF pretreatment. Significant in these has been the long-term study (> 53,000 hrs) and demonstration undertaken at the world renowned **Water Factory 21** (WF21), at the Orange County California Water District so that they can design their 336,000 m^3/d system.

WF21 has over 25 years operating experience with RO to produce potable quality reclaimed water for potable use following aquifer injection. This is to prevent the intrusion of seawater into the groundwater basin and to recharge the reservoir capacity. The reinjected water is stored for a period of approximately two years in the ground water basin before use. The ground water supplies 75% of the water used by nearly two million residents. The facility has used conventional pretreatment, and cellulose acetate RO membrane for treating secondary sewage, and has continually met or surpassed all drinking water quality standards during that time. Increased coastal pumping from the groundwater basin has increased the demand for water imported from Northern California. Reclaiming secondary sewage consumes only 50% of the energy to import water from Northern California and 66% of the energy costs from the Colorado River. The reclamation of wastewater will also delay by 10 years a $150 Million investment in a new ocean outfall. The uncertainty over the price and availability of imported water adds to the many strong incentives to maximize the recovered water at WF21. Orange County is now undertaking the design phase of a major expansion at WF21 so that they can reclaim 336,000 m^3/d by 2020.

The result of earlier piloting work has led to operation of a 2,712 m3/d CMF/RO demonstration project which has been running since 1994 to generate water quality data, develop detailed costs, and refine design criteria for the full-scale system [1].

The water produced from the Memcor CMF plant (continuous microfiltration) contains exceptionally low numbers of bacteria, suspended solids and significantly reduced turbidity.

Table 1

Comparison of conventional and CMF quality and operating cost for RO pretreatment

Water quality	Influent	Conventional	CMF treated
Turbidity NTU	2-5	1	<0.1 [3]
Suspended solids mg/l	5-10	2-3	<1 [3]
Total Organic Carbon mg/l	10-12	8-10	8-10 [3]
Silt Density Index	>6	5-6	1-2 [3]
Bacteria CFU/100ml	$10^5 - 10^6$	3-4 log reduction	5-6 log reduction [3]
Organics removal (1997)		50% GAC, 50% RO	100% RO [1]
Process performance (TOC) (1999)	-	2 mg/l (blended 50% GAC + 50% RO)	0.3 mg/l [1] (100% MF/RO)
Process performance (TOC)	-	2 mg/l	0.3 mg/l [1]
Space required		21 m^3 / d / m^2	106 m^3/ d / m^2 [1]
RO cleaning interval	-	4-6 weeks	8-12 months [1]
Operating and maintenance costs (Chemicals, power, gas, membranes, UV)	-	$0.26 per m^3	$0.15 per m^3 [1]

Note that MF pretreatment provided an approximate 60 to 70% improvement in reduction of turbidity of the pretreated water compared to conventional pretreatment; and a 70 to 80% improvement in SDI measurements. The CMF pretreated water always produced SDI results significantly below the minimum cut-off value of 3 as recommended by the RO manufacturers, while the conventional system could only produce pretreated water with measured SDI's 5 to 7.

A number of key design statements have been made during the pilot studies that started in the early 1990's.

- Outside to inside flow through hollow fiber membranes appears to be less sensitive to high influent turbidities than inside to outside membranes [4]. (No lumen blockage risk). This has also been supported by other long-term pilot studies comparing MF v UF when pretreating TFC RO [5]. 60 of the 74 membrane water and wastewater applications in the USA use outside to inside hollow fiber designs (81%) [12]
- High porosity membranes to maximise productivity [6]
- Symmetrical membrane for strength and filtration efficiency [6]
- Centrifugal potting of fibers or the use of soft resins to prevent the problem of fiber breakage at the resin interface due to resin wicking [6]
- Direct filtration rather than cross flow to maximise efficiency [6]
- Proven and efficient backwash [6].

The successful results from WF21 encouraged the **City of Scottsdale,** [17] East of Phoenix, Arizona in 1994 to start the pilot work to develop their innovative Water Campus to ensure sustainable water supplies in this desert community. The over-abstraction of ground water as well as the absence of local surface water justified the project. The City of Scottsdale has a rapidly increasing population resulting in a fast growth in water demand and wastewater production. This was combined with increasing cost of water import and wastewater export. This outstanding project takes advantage of aquifer storage to offset the need to increase the size of the WTP capacity. This helps with the efficient resource management during the seasonal changes in the water demand. Memcor CMF technology enables the Water Campus to reliably treat a combined flow 57,000 m^3/d of surface water for aquifer injection as well as the "droughtproof " secondary sewage source prior to RO. The RO systems are then used for the production of 38,000 m^3/d of potable water for ground water recharge and subsequent potable abstraction.

The 141 acre Water Campus site now includes:

- 190,000 m^3/d Conventional water treatment plant (WTP) to treat surface water from the Central Arizona Project Canal. (10-22°C) (CAP)
- 45,600 m^3/d Water reclamation plant (WRP) (screens, primary clarifiers, secondary biological treatment, tertiary mono media filters, 20-32°C, 0.5-1.5NTU)
- 38,000 m^3/d Advanced water treatment plant (AWT) (57,000 m^3/d CMF & 38,000 m^3/d TFC RO to treat both CAP and WRP for aquifer recharge)
- Feeds 27 aquifer recharge wells for indirect potable reuse
- Supplies 17 golf course irrigation schemes in the desert with tertiary sewage from the WRP.

Another excellent example are the four separate CMF RO Integrated membrane systems (IMS) installations as part of the **West Basin Water Recycling Plants** in LA, California [7]

These wastewater reuse projects were started with a water injection project to control saline ingress into the fresh water aquifer. Secondary sewage from the Hyperion Wastewater plant is now used in a variety of ways. The initial construction of the reuse plant was completed in June 1995 and consisted of conventional pretreatment. Microfiltration was pilot tested for nine months prior to its implementation under a phase 2 expansion. In 1997 a 11,280 m^3/h Memcor CMF plant started protecting an RO system producing water used for injection in a barrier scheme to control saline ingress. Four CMF/RO systems have now been installed by West Basin Municipal Water District [12] at 50% less than a comparable conventional pretreatment cost. They are used to supply nearby Mobil (17,000 m^3/d), Arco (19,000 m^3/d) and Chevron (19,000 m^3/d) refineries with feed for their high-pressure boilers and cooling water.

A very real issue particularly for applications in the reuse market is the integrity of the membrane systems. MF/UF technologies must be capable of maintaining integrity over the life of the membrane element. Membrane integrity refers to leakage of the reject stream into the product through breaks or inadequate sealing in a membrane system. For example, these leakage areas can result from defects during manufacturing and through damaged inter-connector O rings. If the MF/UF membrane is to be considered a barrier for bacteria, then the users must be able to depend on the integrity of the membrane system.

The oldest CMF system at West Basin has 5 skid mounted units each with 90 modules containing approximately 20,000 hollow fibers per module. The 9 million membrane fibers are regularly checked using the automatic membrane integrity test as part of the operating procedure since April 1997.

The integrity test is a standard system, which holds air pressure across the membrane to identify any broken fibers. One damaged fiber can be detected out of the 9 million installed. The integrity test has been qualified to 4.5 log sensitivity. Modules with broken fibers can be easily identified acoustically and then individual modules can be isolated so that the unit can be returned to service without maintenance shutdown. Damaged modules can be easily and quickly removed (15-30 minutes) from the unit when convenient and are then pin repaired onsite and returned to stock.

Two sub-modules have been repaired in the last two years of operation. This represents the pin repair of 2 out of 450 submodules and represents probable 10 individual fibers repaired out of a total of 9 million fibers. This is supported by similar reliability results from **Eraring Power Station** in Australia. Eraring Energy has a CMF/RO system that has been treating secondary sewage for super critical boiler feed since 1995. This has enabled the 2640 MW coal fired plant to be operated as a zero liquid discharge station. They have not replaced any membranes to date (Aug 2000) and pin repairs have been minor. The 3840 m^3/d CMF system protects the CA -RO membranes that have not been cleaned in the last 12 months [9].

In evaluating the effectiveness of MF/UF compared to conventional pretreatment it is important to consider the level of cleaning, backwashing, and maintenance required by the MF/UF system.

The MF/UF systems clearly provides pretreated water of a higher quality than conventional systems when protecting RO or NF, but can require more extensive cleaning, backwashing or maintenance compared to conventional systems unless designed correctly. Water Factory 21 strongly believe from their operating experience that membrane systems are easier to maintain and operate than their conventional system [2].

The membrane systems process risk is different than conventional depth filtration technology. Membranes reliably produce the treated water quality, as they do not unload suspended solids into the filtrate. They are more sensitive however to the efficiency of backwash and periodic chemical cleaning, as the production will stop if these stages do not operate correctly.

Pilot studies are critical to the success of a project. They can save up to 30% in capital cost by understanding the variability and nature of the feed water, optimising the design and minimising chemical cost. Recent pilot studies for very large reuse systems required chemical cleaning of the MF system on highly fouling estuary and canal water every 5 to 10 days and on good quality secondary sewage every 6 to 8 weeks. Secondary sewage is often more consistent and is less fouling than a polluted and variable surface water as demonstrated at Scottsdale [17]

3. Cost Comparison: MF/UF to conventional pretreatment

For Water Factory 21, the MF system has been found to [1]:

- Occupy 1/5 less space than the conventional system, for the same effluent capacity
- Does not require chemical pretreatment other than prechlorination
- Is easily automated and less maintenance intensive
- Improves the performance of the downstream RO process, allowing for the change to thin film composite RO membranes over cellulose acetate membranes, resulting in a reduction of the power cost by 60%
- Overall cost benefit of 41% savings in operation and maintenance cost, from $0.26/$m^3$ to 0.15/m^3 resulting from changing from conventional pretreatment with cellulose acetate membrane, to MF with thin film composite RO membranes

The same trend is found in the **West Basin** Water Recycling Plant, California [10]. Cost considered in the study included capital, O&M labor, chemical cost, sludge handling and disposal, power cost, and replacement parts and supplies. The plant utilizes cellulose acetate RO membranes. The following table compares the cost for the conventional pretreatment versus the MF pretreatment, based on the actual historic capital cost data, and operating cost over the period July, 1997 to October, 1998:

Table 2

West Basin. Comparison of Conventional and CMF capital and operating cost for RO pretreatment

Cost Description	**Conventional Pretreatment $/m^3$**	**MF Pretreatment $/m^3$**
Fixed costs		
Capital costs	0.22	0.13
O&M Labor	0.04	0.02
Replacement Parts & supplies	0.01	0.02
Subtotal Fixed Costs	0.27	0.17
Variable Costs		
Chemical Costs	0.09	0.03
Sludge Production & Handling	0.06	0.003
Power	0.02	0.02
Subtotal Variable Costs	0.17	0.05
Total Fixed & Variable Costs	0.43	0.22

This data indicates that MF pretreatment for the reuse application is approximately 45% less expensive than the conventional pretreatment trains.

4. Benefits associated with the reuse projects

The WF21 reclaiming secondary sewage consumes only 50% of the energy to import water from Northern California and 66% of the energy costs from the Colorado River. Furthermore the reclamation of wastewater will delay by 10 years a $150 Million investment in a new ocean outfall. At the Eraring Power Station in Australia, the 2640 MW coal fired plant was able to operate as a zero liquid discharge station by reusing sewage and delay over $5 Million investment in sewage outfall and potable distribution infrastructure. This ability to close the water cycle into a zero liquid discharge or near zero liquid discharge loop has been repeatedly used to recover wastewater from municipal potable waterworks. CMF system are being used to recover washwater to produce potable water so that the actual liquid sludge discharge is limited to 0.1 to 0.5% on 60,000 m^3/d applications. These are being operated on sites where there are no drains or sewer to dispose of the wastewater. This is of key importance in maximising the output from existing works and the efficient use of scarce water sources.

Another example is one of the largest and most innovative projects utilising a public-private partnership project in Hawaii. The City of **Honolulu** is faced with improving their wastewater discharge level to the Bay and at the same time they had to deal with water conservation. Through the use of recycled wastewater the pollutant load to the Bay is reduced and the potable water supply is preserved for domestic use. The 20 year design, build operate project, undertaken by VIVENDI Water, started operation in August 2000, is recycling 45,360 m^3/d of the Honoliuli secondary sewage for reuse for both the municipal and local industry. The municipal use is for irrigation of golf courses managed by the City. The CMF & RO treated wastewater is reused for boiler feed at the Power station and petrochemical complex. The RO permeate needs minimal additional treatment to polish the quality before its use in the boiler. (Currently the industrial user must pump groundwater or purchase potable water and treat it to remove silica and other dissolved salts in order to be acceptable for use in the boiler).

The usage of water is summarised as follows:

- 129,000 m^3/d total primary sewage available
- 49,000 m^3/d biologically treated, pulsed bed Hydroclean filtered & UV for irrigation at \$0.30/m3.(City golf courses)
- 7,600 m^3/d further treated through CMF RO to supply the Campbell industrial park (power station and petrochemical complex) with high purity water for boiler feed at \$1.32/m^3

5. Submerged Membranes – the way forward?

Submerged MF membrane systems are being operated and large systems are currently being built to take advantage of the latest developments in membrane technology for lower cost. Over twenty systems are now installed globally (excluding small industrial plants) and have the following benefits on small as well as very high flowrate systems [12] for RO protection.

- Proven membrane filtration in a simpler and lower cost configuration
- Identical treated water reliability for RO pretreatment
- Ability to treat difficult, variable feed waters
- Similar membrane integrity test
- 50% reduction in membrane system footprint
- Ability to increase output 6 fold from existing footprint by retrofitting existing plant

- Supply of temporary containerised plant for rapid installation or emergency applications

Submerged membrane systems such as CMF-S have been developed from the experience of CMF on wastewater applications and have been operated in parallel to CMF on the majority of wastewater sources to compare backwash and chemical cleaning efficiency.

These submerged membranes increase the opportunity to implement projects far larger than Scottsdale at a lower whole life cost while taking advantage of existing infrastructure. The integrated membrane process uses electricity rather than chemicals to treat wastewater. The power costs can represent the largest segment of the operating costs at over 30%. This can be reduced by installing wastewater reclamation plants on or next to power stations that provide lower cost electricity and improve the system efficiency by reusing waste heat. This has led to the development of dual-purpose power and water plants that together improve the efficiency of the combined system. They also provide a flexible engineering platform to achieve a continued reduction in whole life cost and demonstrate the economic and environmental justification for more sustainable water resource solutions.

6. Conclusions

The future will be dominated by unrelenting demands for increasing quantity and quality of reuse water produced at decreasing costs. The largest application has been to provide water for irrigation where pathogen risk minimisation is the primary consideration. However, the need for membrane filtration to produce a high quality water source for either industrial use or aquifer recharge has emerged as a major application over the last ten years. Underlying the development of non-potable water reuse is the economic value of treated water, the quality of which is driven by regulations and technology. The trend towards public–private partnerships and long-term design build operate contracts are some of the key commercial methods to achieve the challenge. Reclaimed water, as shown in this paper, can be a competitive water resource to satisfy growing, and predominantly non-potable, urban and industrial water demands.

Besides generating a new water resource, and limiting effluent discharges to the environment, water reclamation and reuse conserves freshwater resources for the highest quality need, i.e. drinking water.

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Streszczenie

Problemy związane z ograniczonymi zasobami wody stają się coraz bardziej powszechne. Zmuszają one użytkowników do oczyszczania wód zanieczyszczonych do parametrów umożliwiających ich ponowne wykorzystanie.

Procesy membranowe, takie jak odwrócona osmoza (RO), znajdują zastosowanie do oczyszczania zarówno takich zanieczyszczonych wód, jak również wód morskich. Zakres stosowania procesów membranowych, zwłaszcza do oczyszczania ścieków, był ograniczony z powodu wrażliwości membran RO na zanieczyszczenia oraz ze względu na niską skuteczność stosowanych powszechnie konwencjonalnych procesów technologicznych wstępnego oczyszczania ścieków.

Referat ten omawia korzyści płynące z ponownego wykorzystania ścieków oraz możliwości zastosowań opisanych rozwiązań w sektorze komunalnym i przemysłowym. Dowodzi on, jak daleko zastosowanie ciągłej mikrofiltracji (CMF) przed RO może zredukować koszty inwestycyjne i eksploatacyjne systemów RO, podnieść ich skuteczność i umożliwić niezawodne działanie w zastosowaniu do wód różnorodnego podchodzenia.

Prezentowane informacje poparte są licznymi danymi eksploatacyjnymi uzyskanymi w skali światowej z instalacji CMF-RO stosowanych dla trudnych do oczyszczania wód różnego pochodzenia.