# EVALUATION OF ADVANCED WATER TREATMENT FOR INDIRECT POTABLE REUSE

James DeCarolis*, Samer Adham*, Zakir Hirani*, Joan Oppenheimer*, Shane Snyder** Bill Pearce***

*MWH, 9444 Farnham Street, Suite 300, San Diego, California 92123 USA;
**Southern Nevada Water Authority Research and Development Department; ***City of San Diego, CA

## ABSTRACT

The City of San Diego (City) and MWH recently completed a 18-month pilot testing program to determine the effectiveness of a three-step Advanced Water Treatment (AWT) process to produce water suitable for indirect potable reuse from tertiary water produced at the North City Water Reclamation Plant (NCWRP). This testing program was conducted as part of the City's Water Reuse Study, which was initiated in 2004 to explore all options for utilizing recycled water which can be produced by the City's existing water reclamation facilities. The option of using AWT for indirect potable reuse is only one of several options the City has identified to meet water recycling goals. The AWT process consisted of three steps: ultrafiltration (UF); reverse osmosis (RO); and ultraviolet (UV) light + hydrogen peroxide. The main objectives of this testing program were to assess the water quality performance of the AWT process and evaluate the long term operational performance of new generation RO membranes currently offered for water reuse applications. In addition, the study aimed to assess the ability of UV + hydrogen peroxide to remove a diverse group of endocrine disrupting compounds (EDC) and pharmaceuticals and personal care products (PPCP). Results from the study showed the product water from the AWT pilot system met all federal and State of California drinking water standards. In addition, 21 contaminants of concern measured in the RO permeate and UV peroxide effluent including NDMA, 1,4 dioxane and perchlorate were all below current notification levels established by California Department of Health Services (CDHS). RO performance testing showed no decrease in specific flux occurred for a runtime of 1,250 hours at flux of 12 gfd and feedwater 75% recovery. Lastly, UV applied at an equivalent dose to achieve 1-log destruction of NDMA with 5 ppm hydrogen peroxide achieved greater than 98% removal of all EDC/PPCP, with the exception of TCEP, spiked upstream of the UV process.

## KEYWORDS

Advanced Water Treatment, Water Reuse, Water Reclamation, Ultrafiltration, Reverse Osmosis, Advanced Oxidation, UV

## INTRODUCTION

Due to decreasing water supplies worldwide, many municipalities and other water treatment providers are turning to advanced water treatment (AWT) to reclaim wastewater for non-potable and indirect potable reuse applications. Typical AWT systems such as the NEWater Reclamation plants in Singapore use an integrated process train consisting of low-pressure membranes (i.e. microfiltration or ultrafiltration) followed by reverse osmosis membranes. Other AWT facilities such as that currently being constructed by the Orange County Water

District (Orange County, CA) as part of the Ground Water Replenishment Program incorporate an advanced oxidation process (AOP) downstream of RO to destroy contaminants of concern such as NDMA. As more and more AWT facilities are being built or planned it is important to understand the removal efficiencies and operational performance of new generation RO membranes offered for such applications. In addition, information is needed regarding the effectiveness of AOP processes, such as UV + peroxide, to destroy endocrine disrupting compounds (EDCs) and pharmaceutical and personal care products (PPCPs) commonly found in reclaimed water.

The City of San Diego (City) Water Department and MWH recently completed an 18-month pilot testing program to evaluate an AWT process consisting of (UF > RO > UV + peroxide) during operation on tertiary treated wastewater from the City's North City Water Reclamation Plant (NCWRP). This testing program was conducted as part of the City's Water Reuse Study, which was initiated in 2004 to explore all options for utilizing recycled water which can be produced by the City's existing water reclamation facilities. The option of using AWT for indirect potable reuse is only one of several options the City has identified to meet water recycling goals. Funding for the testing program discussed in this paper was provided in part by grants received through the California Department of Water Resources and the San Diego County Water Authority. The objectives of this testing program follow:

- Evaluate the water quality performance of an AWT consisting of UF→ RO →UV + Peroxide during operation on tertiary treated wastewater from the NCWRP;

- Assess the long term operational performance of new generation RO membranes currently offered for water reuse;

- Determine the impact of an advanced oxidation process consisting of UV + Peroxide on a target list of endocrine disrupting compounds (EDC) and pharmaceuticals and personal care products (PPCP).

## MATERIALS AND METHODS

### Description of AWT Pilot Treatment Train

A schematic of the AWT pilot treatment train evaluated during this study is provided in **Figure 1.** As shown, the pilot train contained the following unit processes UF membrane system (provided by Zenon Environmental and GE/Ionics), dual-stage RO system (containing 18 Saehan 4040 BLR, 4" by 40" membranes) and a low pressure high output (LPHO) UV system (provided by Trojan Technologies). Due to availability of the pilot equipment the Zenon UF system was only utilized for the first 9-months of testing and later replaced by the GE/Ionics UF system. As shown, the Ionics UF utilized ferric chloride in the feed to destabilize colloidal particles and aid in organic removal. Free chlorine and ammonium chloride were added upstream of both UF processes to provide 1-2 mg/L chloramine in the permeate to prevent biological fouling of the downstream RO system. Lastly, hydrogen peroxide was added upstream of the UV process which when exposed to UV resulted in the formation of free hydroxyl radicals.

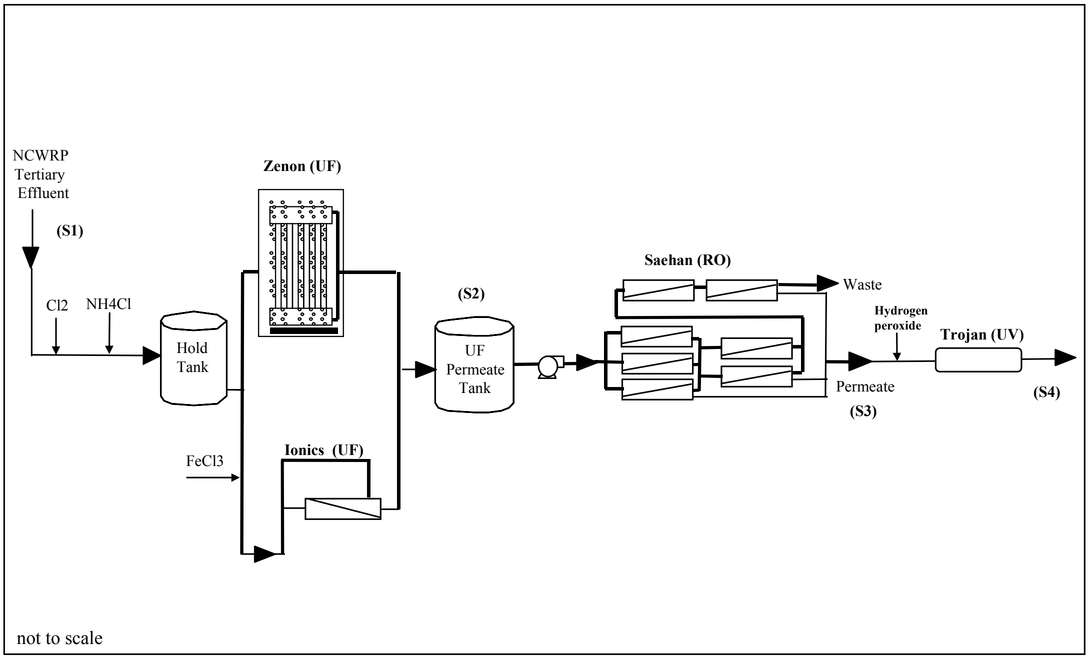


**Figure 1: Schematic Diagram of the AWT Pilot Treatment Train**

## AWT Water Quality Performance Evaluation

The primary objective of this study was to assess the ability of the AWT system to remove key contaminants present in the NCWRP tertiary effluent. This was accomplished by implementing a comprehensive water quality monitoring program on the major unit processes of the pilot scale AWT. As identified in **Figure 1**, sampling locations, designated by S#, were selected throughout the train to assess removal abilities of each unit process. Specific sampling locations include tertiary effluent (UF Feed), RO Feed (UF permeate), RO Permeate (UV Feed) and UV + peroxide product water. Sampling events were performed several times during the course of the project under set operating conditions.

The specific operating conditions for each unit process in the AWT are presented in **Table 1**. The operating conditions of the membrane processes were selected based on findings from past membrane studies conducted by the project team and recent testing performed at Orange County and West Basin, California and Scottsdale, Arizona. Lastly, the operating conditions of the UV pilot were determined by adding RO permeate water with nitrosodimethylamine (NDMA) and determining the flow and power set points which resulted in a 1-log destruction.

**Table 1 Operating Conditions of Various Unit Processes of the AWT Pilot Train**

| Process | Operating Parameters |
|---|---|
| **Ultrafiltration** | Target Flux = 30 - 40 gfd |
| | Transmembrane pressure = 1 -10 psi |
| | Backwash frequency = 15 - 30 min |
| | Backwash pressure = 90 psi (Air) |
| | Flow mode = direct flow (no recirculation) |
| | Ferric chloride feed dose = 2.5 mg/L |
| | Free chlorine dose during backwash = 0 - 10 mg/L |
| | Chemical cleaning: when $P_{tm}$ = 7 psi |
| | |
| **Reverse Osmosis** | Target Flux = 10 - 12 gfd |
| | Recovery = 75-85% |
| | Feed pH = 7 - 8 |
| | Antiscalant dose = 2 mg/L |
| | Combined chlorine feed dose = 1-2 mg/L |
| | Chemical cleaning (per mfg recommendation) |
| | |
| **UV** | Target Flow = 100 gpm |
| | Lamp Power ~ 1200 W |
| | Lamp Power Setting = 60% |
| | Hydrogen Peroxide Dose = 5 mg/L |

In order to assess the performance of AWT, an extensive water quality sampling plan was initiated during this study. Accordingly, on multiple occasions throughout the testing period, samples were collected from the water entering and exiting each step of the AWT process. Samples were analyzed by several certified laboratories for a full spectrum of contaminants including:

- Contaminants regulated under federal and California Department of Health Services (CDHS) primary and secondary drinking water standards;
- Twenty one (21) contaminants of concern with current notification levels per CDHS and,
- Twenty-nine (29) endocrine disrupting compounds (EDC) and pharmaceuticals and personal care products (PPCP)

The specific EDC/PPCP compounds measured during this study is provided in **Table 2**. This list contains compounds commonly found in secondary wastewater such as caffeine and ibuprofen along with compounds identified in literature as being commonly found in the environment (Kolpin 2002). In addition, these compounds are characterized by a wide variety of physical/chemical properties. Though the selected compounds are not currently regulated, a number of them do appear in the CDHS Groundwater Recharge Reuse Draft regulations dated December 2004 (). All EDC/PPCP analyses were conducted at the SNWA research laboratory using LC/MS/MS (liquid chromatograph/mass spectrometer) and GC/MS/MS (gas chromatograph). Details on the specific methods can be found elsewhere

(Vanderford, 2003). As specified in **Table 2**, the MDL for these methods are extremely low (i.e. 1 – 10 ng/L)

**Table 2 EDC/PPCP Target List**

| Compound | Use | MDL[1] (ng/L) |
|---|---|---|
| Hydrocodone | pain relieve | 1 |
| Trimethoprim | anti-biotic | 1 |
| Acetaminophen | analgesic | 1 |
| Caffeine | stimulant | 10 |
| Erythromycin-$H_2O$ | anti-biotic | 1 |
| Sulfamethoxazole | anti-biotic | 1 |
| Fluoxetine | anti-depressant | 1 |
| Pentoxifylline | resude blood viscosity | 1 |
| Meprobamate | anti-anxiety | 1 |
| Dilantin | anti-convulsant | 1 |
| TCEP | fire retardent | 10 |
| Carbamazepine | anti-seizure/analgesic | 1 |
| DEET | mosquito repllant | 1 |
| Atrazine | herbicide | 1 |
| Diazepam | muscle relaxant/anti-anxiety | 1 |
| Oxybenzone | sunscreen | 1 |
| Estriol | steriod | 5 |
| Ethynylestradiol | synthetic birth control | 1 |
| Estrone | steriod | 1 |
| Estradiol | steriod | 1 |
| Testosterone | steriod | 1 |
| Progesterone | steriod | 1 |
| Androstenedione | steriod | 1 |
| Iopromide | x-ray contrast reagent | 1 |
| Naproxen | analgesic | 1 |
| Ibuprofen | pain relieve | 1 |
| Diclofenac | treatment of arthritis | 1 |
| Triclosan | anti-biotic | 1 |
| Gemfibrozil | anti-cholesterol | 1 |

[1] method detection limit.

**Evaluation of Long Term Reverse Osmosis Membrane Operational Performance**

A key objective of this study was to assess the long operational performance of the RO membrane system while operating on tertiary treated water from the NCWRP. The specific RO membranes tested at the pilot scale was based on results from bench scale testing conducted on four new generation RO membranes. The specifications of the membranes evaluated at the bench scale are provided in **Table 3**. These membranes represent the latest RO membranes currently available for water reuse applications. Bench scale evaluations were performed using a modification of the Rapid Bench-Scale Membrane Test (RBSMT) known as the Batch Internal Recycle Membrane Test (BAIReMT), as proposed by DiGiano *et. al*. 1999. The BAIReMT configuration requires permeate and concentrate to be returned to the feed tank. In addition, a fraction of concentrate will be recycled to the RO system, in order to increase overall system recovery. A schematic of the experimental setup is shown in

**Figure 2**.

## Table 3 RO Membrane Specifications

| | KOCH | SAEHAN | TORAY | HYDRANAUTICS |
|---|---|---|---|---|
| Commercial designation | TFC 4820-HR 4 | RE 4040-BLR | TM710 | ESPA2-4040 |
| Membrane material | Polyamide (thin-film composite) | Polyamide (thin-film composite) | Polyamide (thin-film composite) | Polyamide (thin-film composite) |
| Operating pH range | 4-11 | 3-10 | 2-11 | 3-10 |
| Maximum feedwater turbidity | 1 NTU | < 1 NTU | 1 NTU | 1 NTU |
| Maximum feedwater SDI (15 min) | 5.0 | < 5.0 | 5.0 | 5.0 |
| Maximum operating temperature | 113 F ( C) | 113 F (45 C) | 113 F ( C) | 113 F (45 C) |
| Maximum Feed Water Chlorine Concentation | <0.1 ppm | <0.1 ppm | none | <0.1 ppm |
| Maximum operating pressure | 600 psig | 600 psig | 600 psig | 600 psig |
| Nominal membrane surface area | 85 $ft^2$ | 85 $ft^2$ | 87 $ft^2$ | 85 $ft^2$ |
| Spiral Wound configuration | | | | |
| Element length | 40.0 inches | 40.0 inches | 40.0 inches | 40.0 inches |
| Element diameter | 4.0 inches | 4.0 inches | 4.0 inches | 3.95 inches |
| Permeate channel diameter (outer) | 0.75 inches | 0.75 inches | 0.75 inches | 0.75 inches |

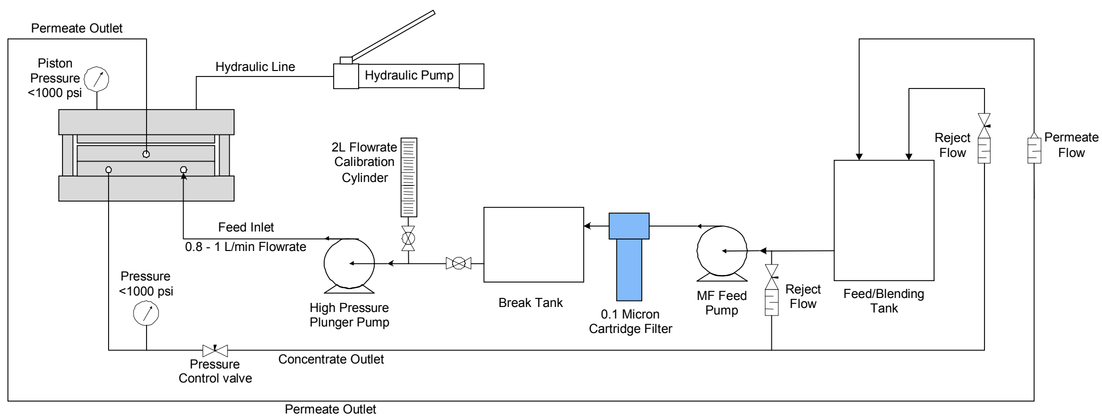


**Figure 2 BAIReMT System – Experimental Setup**

Bench scale analysis was conducted by operating membrane coupons obtained from elements provided by each supplier under set operating conditions and assessing the decline in specific flux and conductivity rejection over a 10 hour period. The best performing membrane from bench scale testing was then operated at the pilot scale. Factors considered in assessing performance included specific flux, decline in specific flux and conductivity rejection.

Pilot testing was conducted using a multi-stage RO pilot system provided by the City of San Diego Water Department. A schematic of the unit is provided in **Figure 3**. As shown, the UF effluent was dosed with antiscalant to inhibit the precipitation of limiting salts present in the feed water. Next, the RO feed water was filtered through 5-micron cartridge filters. The effluent of the cartridge filters was then pressurized and introduced to the RO pilot units. Lastly, the concentrate of all the RO membranes was directed to waste. Long term performance of the RO membrane system was assessed by monitoring the rate of increase in net operating pressure during operation at a constant flux rate of 12 gfd. The impact of feedwater temperature on the net operating pressure was accounted for by monitoring the temperature corrected specific flux rate (i.e. flux per unit pressure) with respect to operating time. Specific methods for calculating these parameters can be found elsewhere (Adham & DeCarolis 2004). During the initial period of testing, the system was operated at various feed water recovery rates to assess the maximum recovery the system could achieve without severe membrane fouling. Once the recovery was determined the system was operated under steady conditions to assess long term fouling resulting from the presence of biological and organic constituents present in the wastewater.

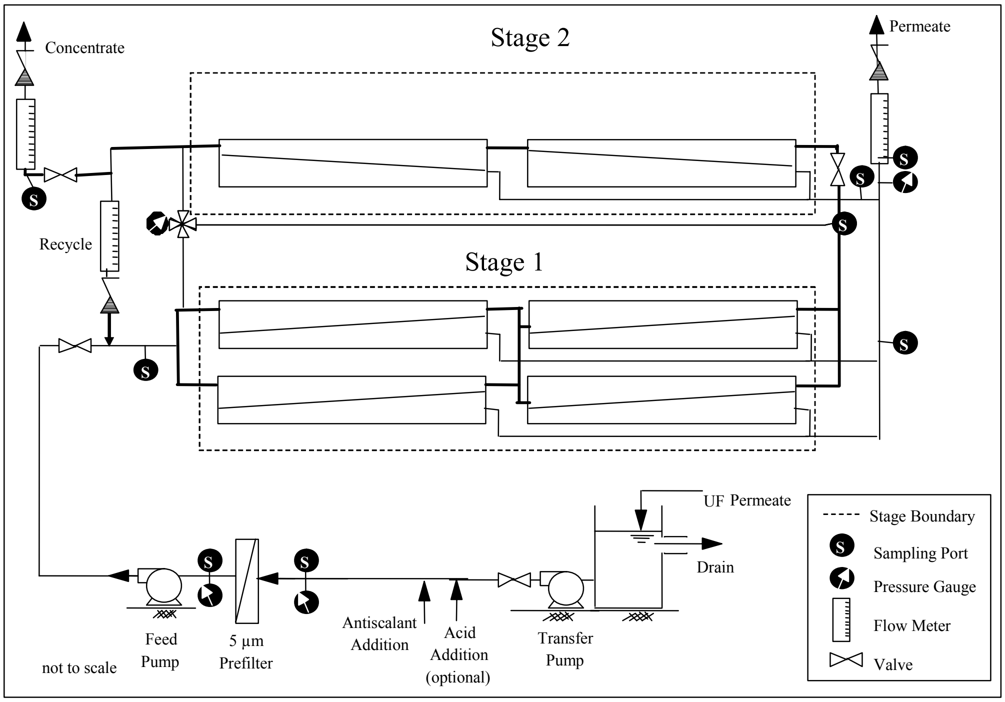


**Figure 3 Process flow schematic of Two stage RO pilot system**

## Evaluation of UV on Select EDC/PPCP

The effect of UV on the destruction of EDCs and PPCPs at an operational dose to achieve 1 log NDMA destruction was assessed at the pilot scale by conducting a series of spiking experiments. This was accomplished by first adding NDMA into the RO permeate upstream of the UV process in order to determine the flow and lamp power settings necessary to achieve 1 Log removal of NDMA. At the same time, samples were collected and analyzed using a collimated beam (CB) apparatus. Data from the CB experiment were then used to establish a dose response curve and determine the applied dose required to achieve a 1 Log destruction of NDMA for this water source.

During the second experiment, a cocktail solution containing eight (8) EDCs/PPCPs, selected from the target list described above, along with NDMA was spiked upstream of the UV reactor during operation at the lamp power and flow settings established from the first seeding experiment. Spiking was required due to the trace level of these compounds in the

RO permeate. In addition, inputting known concentrations of these select compounds allowed the efficacy of the UV + peroxide process to be readily determined. The eight (8) compounds, shown in **Table 4**, were selected because they represent a wide variety of chemical structures. All compounds were spiked at a nominal dose of 500 ng/L. This dose was based on previous removals seen during studies conducted by SNWA at Trojan Technology Facilities.

**Table 4: Target EDC and PPCP**

| Chemical | Usage Category | Mass available (purchased) | Supplier | Form | Concentration |
|---|---|---|---|---|---|
| TCEP | Fire Retardant | 25 g | Sigma Aldrich | Liquid | 97.0% |
| Oxybenzone | Sunscreen | 5 g | Sigma Aldrich | Powder | 98.0% |
| Caffeine | Stimulant | 25 g | Fluka | Powder | 99.0% |
| Triclosan (Irgasan) | Germicide | 5 g | Fluka | Powder | 97.0% |
| DEET | Insecticide | 250 mg | Sigma Aldrich | Liquid | 97.3% |
| Ibuprofen | Analgesic | 1 g | Sigma Aldrich | Powder | 98.0% |
| Estrone | Hormone | 1 g | Sigma Aldrich | Powder | 99.0% |
| Iopromide | Contrast media | 400 mg | USP | Powder | 97.9% |

## RESULTS AND DISCUSSION

### AWT Water Quality Performance

Results from this study showed that the AWT process effectively removed nearly all inorganic and organic compounds measured in the feed wastewater to levels near or below detection limit. In addition, all parameters measured in the RO permeate and UV+ peroxide product water were below the maximum contaminant levels (MCL) established by federal and California State primary and secondary drinking water standards. Twenty-one (21) contaminants of concern measured in the RO permeate and UV + peroxide product water including NDMA, 1,4 dioxane and perchlorate were below current notification levels established by CDHS. As presented in **Table 5**, EDC/PPCP analysis results indicate that RO was effective at reducing all measured compounds present in the influent to levels near or below their method detection limit. Lastly, compounds which did pass the RO process in trace amounts were completely removed by UV + Hydrogen peroxide process.

**Table 5: EDC/PPCP Results (SNWA Research Laboratory)**

| Parameter | Units | Method Detection Limit | AWT Process Location | | |
|---|---|---|---|---|---|
| | | | RO In (n=2) | RO Out (n=2) | UV + Peroxide (n=2) |
| Hydrocodone | ng/L | 1 | 80 | <1.0 | <1.0 |
| Trimethoprim | ng/L | 1 | 384 | 2.95 | <1.0 |
| Acetaminophen | ng/L | 10 | <10 | <10 | <10 |
| Caffeine | ng/L | 10 | <10 | <10 | <10 |
| Erythromycin-H2O | ng/L | 1 | 298 | <1.0 | <1.0 |
| Sulfamethoxazole | ng/L | 1 | 892 | 2.9 | <1.0 |
| Fluoxetine | ng/L | 1 | 33 | <1.0 | <1.0 |
| Pentoxifylline | ng/L | 1 | 12 | <1.0 | <1.0 |
| Meprobamate | ng/L | 1 | 292 | 1.5 | <1.0 |
| Dilantin | ng/L | 1 | 144 | <1.0 | <1.0 |
| TCEP | ng/L | 10 | 272 | <10 | <10 |
| Carbamazepine | ng/L | 1 | 279 | 2.4 | <1.0 |
| DEET | ng/L | 5 | 293 | <5.0 | <5.0 |
| Atrazine | ng/L | 1 | 1 | <1.0 | <1.0 |
| Diazepam | ng/L | 1 | 1 | <1.0 | <1.0 |
| Oxybenzone | ng/L | 5 | 21 | <5.0 | <5.0 |
| Estriol | ng/L | 5 | 14 | <5.0 | <5.0 |
| Ethynylestradiol | ng/L | 1 | <1.0 | <1.0 | <1.0 |
| Estrone | ng/L | 1 | 101 | <1.0 | <1.0 |
| Estradiol | ng/L | 1 | 18 | <1.0 | <1.0 |
| Testosterone | ng/L | 1 | <1.0 | <1.0 | <1.0 |
| Progesterone | ng/L | 1 | <1.0 | <1.0 | <1.0 |
| Androstenedione | ng/L | 1 | 5 | <1.0 | <1.0 |
| Iopromide | ng/L | 1 | 632 | 1.4 | <1.0 |
| Naproxen | ng/L | 1 | 255 | 1.2 | <1.0 |
| Ibuprofen | ng/L | 1 | 79 | <1.0 | <1.0 |
| Diclofenac | ng/L | 1 | 89 | <1.0 | <1.0 |
| Triclosan | ng/L | 1 | [1] 324 | [1] 3.4 | [1] <1.0 |
| Gemfibrozil | ng/L | 1 | 1022 | 1.3 | <1.0 |

< Indicates measured values were below the method detection limit; [1] n=1

## Reverse Osmosis Operational Performance

Bench scale testing was conducted on four new generation RO membranes currently offered for water reuse to select the best performing membrane for evaluation at pilot scale. A summary of the overall results from the bench scale testing is provided in **Table 6**. This data was generated by operating membrane coupons at a constant flux of 20 gfd using tertiary wastewater obtained from the NCWRP. As shown, the decline in specific flux of the membranes varied from 11.9% - 29.6% after 10 hours of runtime and conductivity rejection ranged from 94.8%-99.3%. Based on these results, the project team selected RO 1 for further testing at pilot scale. The premise for this decision was that RO 1 demonstrated the lowest decline in specific flux, achieved high salt rejection and had the highest specific flux of the membranes tested.

**Table 6 Bench Scale Testing Results**

| Membrane ID | Conductivty Rejection (%) | Initial specific flux at 25 Deg C, gfd/psi | % Decline in specific flux | | |
|---|---|---|---|---|---|
| | | | After 1 hour | After 5 hours | After 10 hours (end of the run) |
| RO 1 | 98.7 | 0.168 | 6.19 | 8.80 | 11.90 |
| RO 2 | 98.7 | 0.161 | 11.43 | 15.53 | 24.22 |
| RO 4 | 99.3 | 0.142 | 15.77 | 22.54 | 29.58 |
| RO 3 | 94.8 | 0.151 | 8.61 | 13.91 | 19.21 |

After completing bench scale testing RO 1 membranes were operated in a dual stage pilot system over a target period of 5,000 hours. During the first 1,200 hours of operation, the system was operated under a range of feed water recoveries (75%-85%). The purpose of this operation was to determine the upper recovery limit the membranes could successfully operate without causing precipitation of limiting salts present in the NCWRP tertiary effluent. In addition, because the rejection capabilities RO systems decrease as recovery increases, water quality sampling was conducted at 85% recovery to assess removal efficiencies under these conditions.

During the initial operating period, the RO membranes exhibited fouling, as determined by the increase in net operating pressure, while operating at 85% recovery. However, data collected during this period was limited because of an upset in the NCWRP, which resulted in interrupted feed flow to the AWT pilot system. Shortly after, high levels of free chlorine were detected in the RO feed and the conductivity rejection of membranes decreased sharply (i.e. 95% to 88%). Such data indicates the membranes were irreversibly damaged from exposure to chlorine. As a result, it was necessary to replace the membranes. This occurrence was due to the location of the intake of the pilot feed water pump in the NCWRP treatment train and would not be possible during full-scale AWT application. After this event, the project team installed an on-line free chlorine analyzer upstream of the pilot system to shutoff the pilot feed pump should chlorine be detected.

After installing the new membranes, the RO pilot was restarted at target flux of 12 gfd and recovery of 85%. As shown in **Figure 4**, during the ensuing 718 hours of operation the membranes fouled, as indicated by sharp decrease in specific flux (i.e. 0.20 to 0.13 gfd/psi). This data confirmed pervious results described above which suggested operation at 85% recovery caused precipitation of salts on the membrane surface. In order to assess the long-term operational performance of the RO membranes, the membranes were cleaned and restarted under conservative recovery conditions of 75%. This operation allowed the project team to evaluate membrane fouling caused by presence of biological and or organic matter present in the RO feed. Typically this type of fouling is much slower than that associated with salt precipitation. As shown in **Figure 4**, the system operated for 1,250 hours under these conditions with no observed membrane fouling as indicated by a decrease in specific flux.

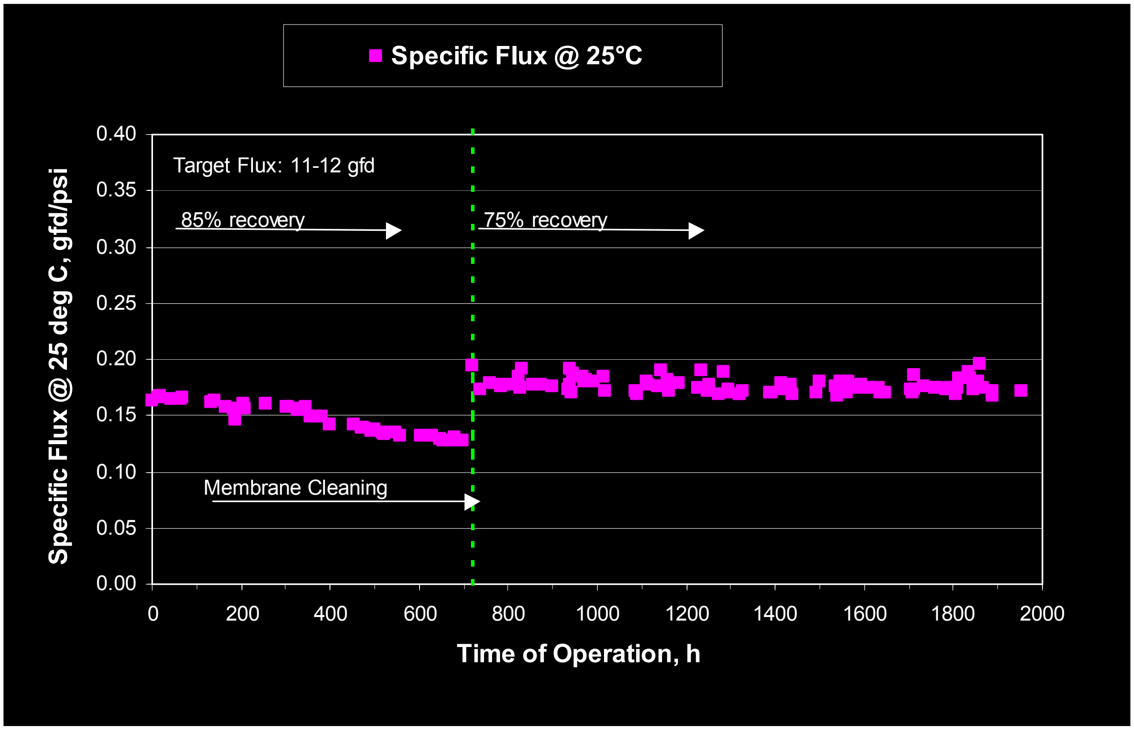


**Figure 4 RO 1 Membrane Operational Performance**

## Impact of UV on EDC/PPCP

NDMA was spiked downstream of the RO process to determine the UV pilot settings (flow and power) required to achieve 1-log destruction of NDMA. Results from this experiment showed the electrical energy order (EEO) of the pilot system to be approximately 0.17 kWh/1000 gal/order. During the pilot testing experiment samples were also collected for analysis using a collimated beam (CB) apparatus. The dose response curve generated from CB testing is provided in **Figure 5**. From this plot the applied dose required to achieve 1-LRV of NDMA for the given feed water was 1,104 $mJ/cm^2$.

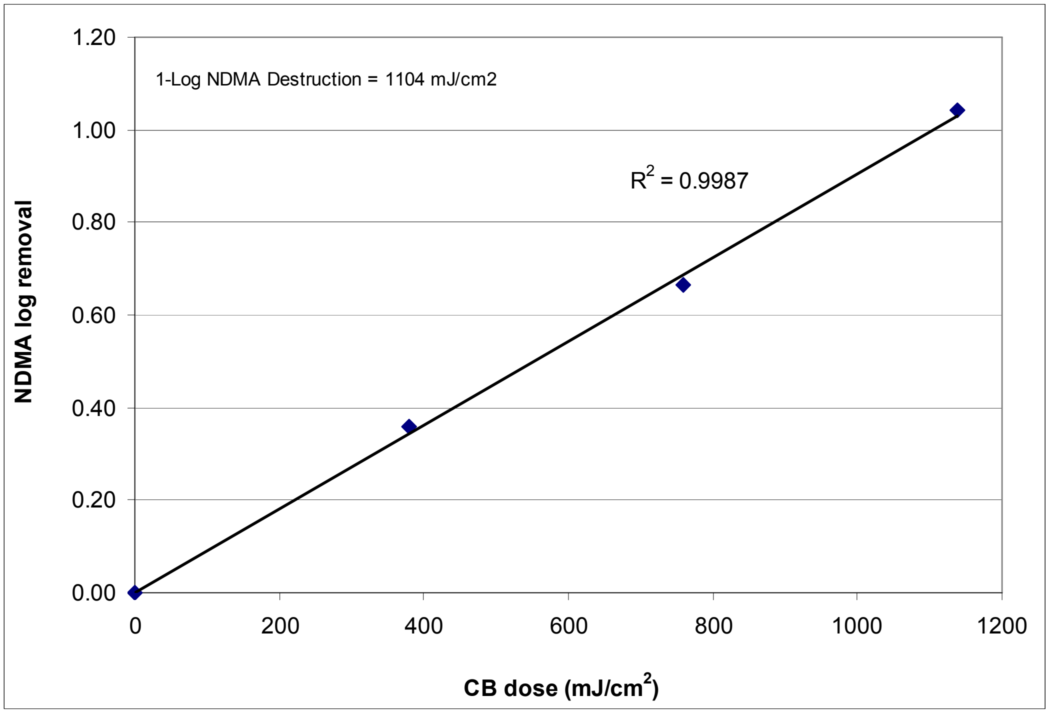


**Figure 5: Results from UV Collimated Beam Testing for NDMA Destruction**

Following the establishment of operating conditions to achieve 1-log NDMA, an additional spiking experiment was conducted using the eight select EDC and PPCP compounds listed in Table 4. This experiment included the addition of 5-mg/L hydrogen peroxide upstream of the UV process. Influent and effluent concentrations of the EDC and PPCP compounds measured during this experiment are shown in **Table 7.** These results show the UV peroxide process achieved more than 98% destruction of most of the tested EDC and PPCP compounds with the exception of TCEP. Though TCEP was resistant to UV peroxide it was well removed by the RO process, as shown in **Table 5**. The average EEO values of the spiked EDC/PPCP compounds and NDMA are presented in **Figure 6**. As shown, all the EEO values of EDC and PPCP compounds except TCEP were lower than the NDMA EEO value (0.17).

**Table 7 UV Testing EDC/PPCP Removal Results**

| [1]Spiked Compound | Units | UV+peroxide IN AVE (n=3) | UV+peroxide OUT AVE (n=3) | Removal % |
|---|---|---|---|---|
| Caffeine | ng/L | 720 | <10 | >98.6% |
| DEET | ng/L | 681 | 3.6 | 99.5% |
| Estrone | ng/L | 89 | <1.0 | >98.8% |
| Ibuprofen | ng/L | 726 | 2.1 | 99.7% |
| Iopromide | ng/L | 646 | 5.3 | 99.2% |
| Oxybenzone | ng/L | 328 | <1.0 | >99.7% |
| TCEP | ng/L | 781 | 503 | 35.6% |
| Triclosan | ng/L | 359 | 1.5 | 99.6% |

[1] compounds added to the UV influent

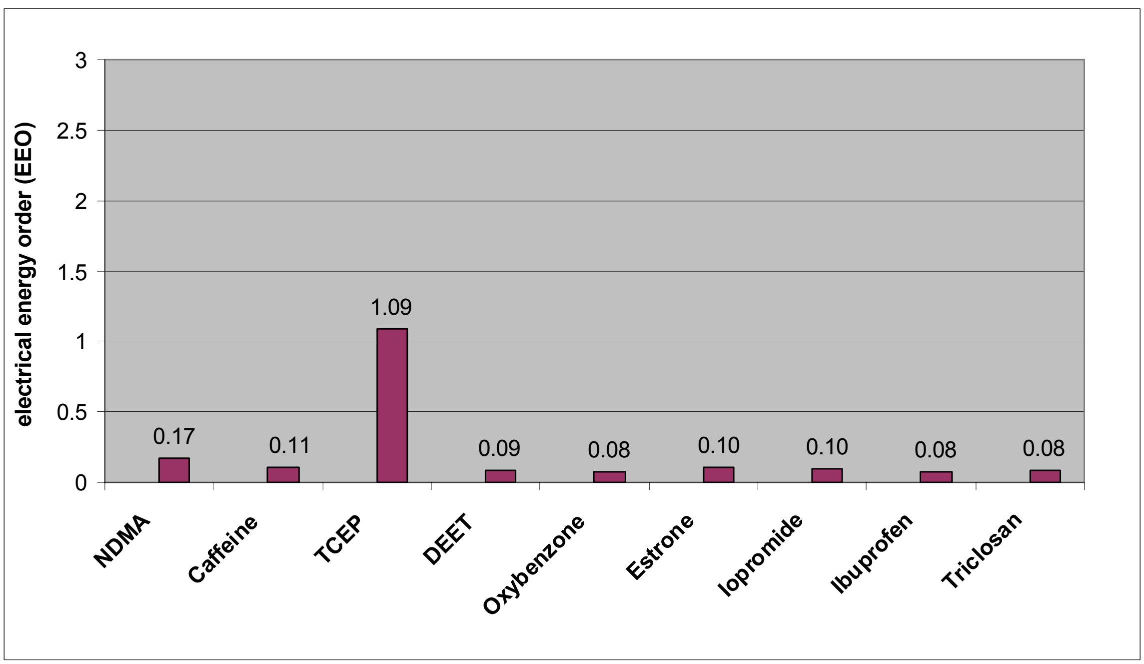


**Figure 6: EEO values of the spiked NDMA, EDC and PPCPs Treated with UV/Peroxide**

## CONCLUSIONS

- AWT product water met all federal and State of California drinking water standards;
- Twenty one contaminants of concern measured in the RO permeate and UV + peroxide product water including NDMA, 1,4 dioxane and perchlorate were below current notification levels established by CDHS;
- RO was effective at removing a target list of EDC/PPCP detected in tertiary water from the NCWRP to levels near or below their MDL;
- Bench scale tests conducted on new generation RO membranes offered for water reclamation showed varying performance in terms of membrane fouling, conductivity rejection and efficiency (i.e. specific flux);
- Long term operation of the RO pilot system on tertiary water from NCWRP showed no fouling for greater than 1200 hours with recovery of 75% and flux of 12 gfd;
- The average EEO value for removal of NDMA spiked to the NCWRP tertiary effluent after UF and RO treatment was 0.17 Kwh/1000 gal/order
- Collimated beam testing showed the equivalent UV dose required to achieve 1 log NDMA destruction was 1,104 $mJ/cm^2$;
- The UV dose for 1 log NDMA destruction with 5-ppm hydrogen peroxide achieved more than 98% removal of all spiked EDC/PPCP with the exception of TCEP which removal was 36%; however, water quality analyses conducted during this study showed RO removed TCEP below its MDL;
- The UV EEO values of the target EDC and PPCP compounds with hydrogen peroxide addition ranged from 0.08 – 1.09 kWh/1000gal./log removal.

## ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the following individuals and organizations for their contributions to the successful completion of the project.

- The California Department of Water Resources and San Diego County Water Authority for providing grant funding to the project
- Larry Wassserman, Steve Lagos and Neil Tran of the Metropolitan Wastewater Department of San Diego for providing assistance in data analysis and reviewing project test plans
- Dana Chapin and Reginald Williams of the City of San Diego Water Quality Lab for assistance in the transportation and coordination of water quality sampling throughout the project
- Andrew Eaton and Linda Geddes of MWH laboratory for providing analysis of water quality data generated during the project
- Janie Zeiliger and the entire staff of the Southern Nevada Water Authority Research Lab for sample coordination and performing EDC/PPCP analysis
- The following membrane suppliers: Zenon Environmental and GE/Ionics (UF), Saehan Industries, Toray, Koch Membrane Systems and Hydranautics (RO).

## REFERENCES

Adham S., DeCarolis, J., Application of Membrane Bioreactors followed by Desalting Reverse Osmosis Membranes for the Treatment of Primary Wastewater for Reuse, Desalination Research and Innovation Partnership Report, (2004).

DiGiano et al., Alternative Tests for Evaluating NF Fouling, JAWWA 92:2:103-115 (1999).

Kolpin, D. W., Furlong, E. T., Meyer, M. T., Thurman, E. M, Zaugg, S. D., Barber, L. B., and Buxton, H. T., "Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999-2000: A National Reconnaissance", Environmental Science and Technology, 36(6), 1202-1211.

Vanderford, Brett, J., Pearson, Rebecca A., Rexing, David J., and Snyder, Shane A. "Analysis of Endocrine Disruptors, Pharmaceuticals, and Personal Care Products in Water Using Liquid Chromatography/Tandem Mass Spectrometry" (2003) Anal.Chem. (75):6265-6274.