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Boiler Makeup Water Dechlorination Using Advanced Ultraviolet Technology at Plant Bowen Water Research Center

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Boiler Makeup Water Dechlorination Using Advanced Ultraviolet Technology at Plant Bowen Water Research Center

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EPRI Project Manager
R. Breckenridge

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Southern Research Institute
2000 Ninth Ave. South
Birmingham, AL 35205

Principal Investigators
B. Pakzadeh
J. Wos
J. Renew

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Mike Caravaggio
George Offen
Stephen J. Shulder

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ABSTRACT

Reverse osmosis (RO) technology is commonly used in power plant applications to provide high-purity feed water for the boiler and steam cycle. However, many plants are faced with frequent membrane and micron-filter maintenance and replacement as a result of biofouling and fouling by solids. It is important to make sure that the membrane elements in the RO are protected from biofouling and oxidation from chlorine. The operational impacts of biofouling on RO technology include more frequent membrane element replacement costs, production losses, and increased energy costs.

In an effort to protect the RO membranes and address fouling concerns, this project evaluated an alternative dechlorination treatment system to replace sodium metabisulfite (SMBS), reduce the usage of chlorination, and achieve a chemical-free dechlorination process.

During a three-month period from March 4 through May 30, 2014, EPRI evaluated the performance of the Hydro-Optic™ (HOD) ultraviolet (UV) water treatment technology, manufactured by Atlantium Technologies, Inc., for use as a chemical-free dechlorination approach to improve the overall quality of RO feed water. The technology evaluation was undertaken at the Water Research Center at Georgia Power's Plant Bowen near Cartersville, Georgia. The technology was installed after the media filters and before the cartridge micron filter and the RO train. Operational parameters as well as dechlorination and bacteria removal efficiencies of the HOD UV technology were evaluated at a flowrate of 680 gpm (154 m^3/hr.)

Results were promising and showed that the HOD UV system met the treatment objectives. The HOD UV technology effectively removed free and total chlorine from boiler feed water to undetectable levels from levels above 0.7 mg/L at the inlet (upstream of HOD UV system). Bacteria levels were also reduced to an average of 3.8 organisms per mL. Overall, the results indicated that the HOD UV system dechlorinated and disinfected the RO feed water to purity levels that were within typical specifications for boiler feedwater.

Power plants looking to replace the use of sodium bisulfite (SBS) or SMBS and achieve a chemical-free dechlorination process may benefit from a physical process such as the HOD UV technology. The HOD system decomposes the free chlorine oxidant in process water to protect RO membranes. Additionally, the HOD technology provides disinfection to reduce the membrane biofouling potential by eliminating anaerobic and aerobic bacterial growth. UV treatment allows for a dechlorination treatment approach with the potential to eliminate the handling, storage, and operational requirements of chemical disinfection solutions. Thus, the HOD UV process may be a viable dechlorination technology.

Keywords

Boiler makeup water
Disinfection
Membrane fouling
Dechlorination
Hydro-Optic ultraviolet system
Reverse osmosis

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1 INTRODUCTION

The Hydro-Optic (HOD) UV system from Atlantium Technologies, Inc. offers a chemical-free dechlorination treatment approach for boiler makeup water. Through photodecomposition by ultraviolet (UV) light, the HOD system decomposes the free chlorine oxidant in process water to protect reverse osmosis (RO) membranes. Additionally, the HOD technology provides disinfection to reduce the membrane biofouling potential by eliminating anaerobic and aerobic bacterial growth. By reducing the operational impact of biofouling, the HOD UV technology may extend time between membrane element replacements and reduce associated costs including cleaning in place (CIP), and it may mitigate production losses and reduce energy costs.

As an oxidizer in aqueous solutions, free chlorine generating solutions such as sodium hypochlorite are commonly injected into the feed lines of the water treatment process at power plants to reduce the microbial load. RO membrane elements are easily damaged by strong oxidants. As a result, free chlorine compounds must be removed from the feed water in order for the RO system to operate properly. The dechlorination process reduces free available chlorine or chloramines in feed water to protect RO membranes and other chlorine-sensitive equipment.

Dechlorination is typically achieved by passing feed water through granular activated carbon (GAC) filters or by injecting a sodium bisulfite (SBS) or sodium metabisulfite (SMBS) solution into the feed water. GAC filtration is not frequently used in power plants, while SBS or SMBS chemical neutralization is common practice.

While the above-mentioned chemical treatment approaches are effective, they may be subject to operational difficulties such as inconsistent dosage and microbe proliferation of anaerobic bacteria on the membrane. The formation of biofouling layers may also result from bacteria surviving the chlorination stage and reaching the membranes post-dechlorination. The difficulty of GAC filtration is the large footprint required, while SBS/SMBS neutralization is chemically based and has additional handling, storage, and operational requirements. Chemical feed systems require an injection pump and piping and a storage system, and they typically have automated control based on oxidation-reduction potential or an oxidant analyzer.

Through a collaborative effort between Southern Research Institute, the Electric Power Research Institute, Atlantium Technologies, Inc., Georgia Power, and Southern Company Services, a full-scale trial demonstrating the ability of the HOD UV system to provide microbe- and chlorine-free water to RO membranes was completed in May 2014.

The project evaluated the effectiveness of an HOD UV system to dechlorinate boiler makeup water, providing acceptable feed quality for RO membranes. The objectives of the project included the following:

1. Provide HOD UV performance data on removal efficiencies of free and total chlorine as well as bacteria
2. Evaluate functionality of the HOD UV system under typical power plant operational conditions including high flowrates, variable feed water conditions, and pretreatment stability
3. Provide a basis for system design

2
BACKGROUND

The Hydro-Optic™ (HOD) UV System

Through advanced engineering, the Hydro-Optic UV technology is based on fiber optics and hydraulics. The HOD system uses a proprietary medium-pressure high-intensity polychromatic lamp providing two times more UV than that of conventional medium-pressure lamps and sixteen times more UV than that of conventional low-pressure lamps. The technology has the ability to effectively “recycle” a required dose throughout the reaction chamber using a patented internal reflection technology similar to fiber optic science. Proprietary software, logic, sensors, and controls enable automatic dose adjustment according to changing water quality conditions in real time in order to maintain the required dose at all times.

Total internal reflection (TIR) is an optical phenomenon applied in the field of fiber optics whereby quartz or glass is used to guide/extend the paths taken by UV light photons. The core of the HOD UV system is its water disinfection chamber made of high-quality quartz surrounded by an air block instead of traditional stainless steel. This configuration uses fiber optic principles to trap the UV light photons and recycle their light energy. The photons repeatedly bounce through the quartz surface back into the chamber, effectively lengthening their paths and their opportunities to inactivate microbes.

Unlike chemical treatment approaches, UV systems employ a physical process for disinfection. When bacteria, viruses, and protozoa are exposed to the germicidal wavelengths (nanometers (nm)) of UV light, they are rendered incapable of reproducing. In addition, UV light can also destroy chemical contaminants through a process called UV oxidation. UV light is most commonly produced through medium-pressure (MP) or low-pressure (LP) lamp technologies.

Medium-pressure UV lamps provide polychromatic UV light (200–415 nm), while low-pressure lamps provide monochromatic light (254 nm). MP lamps produce a high-density broad-spectrum UV light inclusive of wavelengths responsible for disinfecting certain resistant viruses. Since different microorganisms are sensitive to different UV wavelengths, MP lamps can easily inactivate more microorganisms, such as algae and adenoviruses, through their broad UV germicidal spectrum. When a microorganism has been inactivated by an LP UV system, it can still repair itself by using its own cell-repair mechanism or by summoning host repair mechanisms. In an MP UV system, the various wavelengths work together to disable cell repair mechanisms. MP lamps disable the proteins and enzymes needed to trigger repair, achieving permanent microbial inactivation at a lower dose than LP systems.

Figure 2-1 presents a schematic drawing of a medium-pressure HOD UV lamp and chamber.

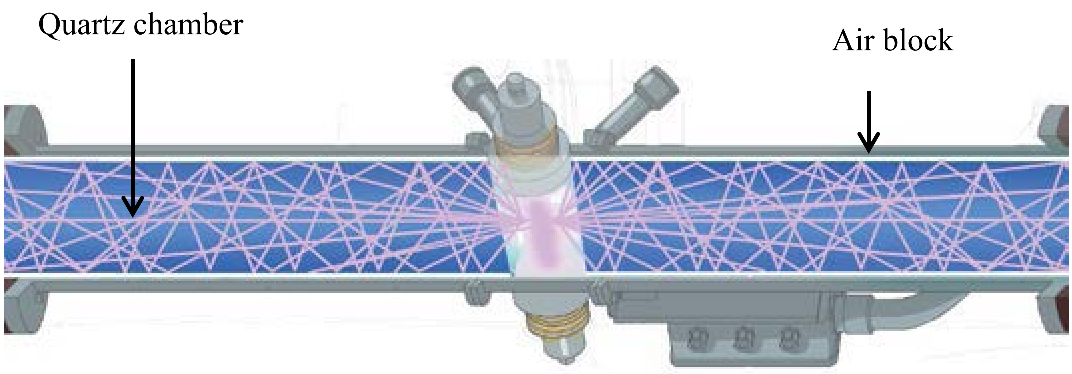

Figure 2-1
Medium-pressure HOD UV lamp and chamber

Maintaining a correct UV dose with any UV system is dependent on three parameters: UV intensity, water UV transmittance, and water flowrate. Since these parameters are dynamic and fluctuate, continuous measurement is required. The HOD UV system measures these critical data points in real time and inputs the data into its operating algorithms. The proprietary software enables the reactor to self-adjust and manage a "safety zone" so the unit continuously provides the minimum dose or registers and reports off-spec status when any of the critical parameters affecting UV dose fluctuate outside of the "safety zone." The HOD UV system is in compliance with USEPA regulations for water treatment—regulations such as the USEPA Long Term 2 Enhanced Surface Water Treatment Rule (requiring the treatment of *Cryptosporidium*) or the Ground Water Rule (requiring 4-log virus treatment) (Atlantium Technologies, Inc.).

Chlorination–Dechlorination Processes in RO Systems

Strong oxidants such as chlorine, and other chlorine-based disinfectants such as sodium hypochlorite or chloramines, can easily damage most RO membrane elements. As a result, free chlorine compounds must be removed from the feed water in order for the RO system to operate properly. The dechlorination process reduces free available chlorine or chloramines in feed water to protect RO membranes and other chlorine-sensitive equipment.

Passing feed water through activated carbon filters is a typical non-chemical dechlorination approach; however, it is not a practice commonly used in power plant applications. Chemical neutralization, through the injection of an SBS or SMBS solution into the feed water, is common practice in power applications. The difficulty of GAC filtration is the large footprint required, while SBS/SMBS neutralization is chemically based and has additional handling, storage, and operational requirements. GAC filters also suffer from operational difficulties and microbe proliferation on the membrane. The formation of biofouling layers results from bacteria surviving the chlorination stage and reaching the membranes post-dechlorination.

Polyamide membranes are sensitive to the presence of free chlorine because it affects their salt rejection properties. As a result, membrane performance warranty terms usually include specification for the allowable level of free chlorine not to exceed a concentration of 0.1 mg/L or ppm in feed water to the membrane unit [1]. In a typical power plant dechlorination application, the water treatment facility aims to produce water with undetectable levels of free chlorine [1]. Free chlorine, in the context of water, refers to two oxidizing chlorine compounds: 1) hypochlorous acid (HOCl) and 2) hypochlorite ion (ClO^- or OCl^-). In the aqueous phase, these two components are in the following equilibrium:

$$HOCl \leftrightarrow ClO^- + H^+ \text{ (pKa = 7.5 at 25°C)}$$

The relative mass-concentrations of these two chlorine compounds strongly depend on pH. HOCl is the dominant ion at pH values below 7.5. HOCl transforms to OCl^- at pH above 7.5, and OCl^- becomes the dominant ion in the pH range of 7.5–12 [2].

Reduction of free chlorine or chloramines to the chloride ion is the main mechanism for all major chemical (SBS/SMBS) and non-chemical (GAC filters and HOD UV) dechlorination processes.

Dechlorination Using Granular Activated Carbon (GAC) Filters

Dechlorination using GAC filters is an effective method of free chlorine reduction. The end products of this dechlorination process are chloride ion and CO_2 according to the following reaction:

$$C + 2Cl_2 + 2H_2O = 4\,H^+ + 4\,Cl^- + CO_2$$

$$C + 2NH_2Cl + 2H_2O = 2NH_4^+ + 2Cl^- + CO_2$$

The dechlorination equipment used in this process consists of activated carbon filters. The flow velocity through the filters is in the range of 16.4–32.8 ft/hr (5–10 m/hr), and empty bed contact time (EBCT) is in the range of 10–15 minutes. The activated carbon bed depth is in the range of 3.3–4.9 ft (1–1.5 m) [1].

While dechlorination using GAC filters has been extensively applied in the past to treat RO feed water, the process can result in fouling of RO membranes. Membrane fouling is caused by one of two scenarios:

1. Release of carbon fines from the carbon bed and subsequent blockage of feed channels of membrane elements, mainly in the lead position in the RO membrane unit.
2. Growth of biofilm in the carbon filter and sloughing of biological fragments into the RO feed stream, causing biofouling and excessive pressure drop in the membrane unit.

Dechlorination Using Sulfite Compounds

Dechlorination using sulfite compounds relies on reduction-oxidation reaction between a sulfur-containing compound, at the +4 oxidation state, and chlorine. In this process, sulfur is oxidized to the +6 oxidation state, and chlorine is reduced to chloride ion (at the -1 oxidation state). Sulfur-containing compounds that are suitable for the dechlorination process may include:

- Sulfur dioxide (SO_2)
- Sodium sulfite (Na_2SO_3)
- Sodium bisulfite ($NaHSO_3$)
- Sodium metabisulfite ($Na_2S_2O_5$)
- Sodium thiosulfite ($Na_2S_2O_3$)

The dechlorination process consists of reaction of S^{+4} species, such as sulfite ion (SO_3^{-2}) with free or combined chlorine:

$$SO_3^{-2} + HOCl = SO_4^{-2} + Cl^- + H^+$$

$$SO_3^{-2} + NH_2Cl + H_2O = SO_4^{-2} + Cl^- + NH_4^+$$

The above reactions are rapid and result in complete conversion of chlorine compounds to the chloride ion. After the addition of a sulfite compound to the RO feed stream, a contact time below one minute for free chlorine and below five minutes for chloramines is usually sufficient for complete dechlorination. Based on the stoichiometry of the dechlorination reactions, the quantity of sulfite compound required per 1 ppm of residual chlorine ranges from 0.9 ppm of sulfur dioxide (SO_2) to 1.8 ppm of sodium sulfite (Na_2SO_3). In RO applications, the excess of sulfite compound is used, and the ratio is approximately 3:1.

The dechlorination equipment required for sulfite-based dechlorination usually consists of one or more chemical solution storage tanks and a feed pump. The rate of the sulfite compound solution addition is based on the projected residual concentration of free or combined chlorine in the feed water to the RO unit.

The dechlorination process using sulfur (+4)-containing compounds involves the supply and management of chemical inventory and periodic replacement of the dosing solution to maintain a designed concentration of the active ingredient. The application of this method of free chlorine reduction frequently suffers from the formation of biofouling layers in the membrane unit [1]. In boiler makeup applications, free chlorine is removed from the feed, prior to the RO membrane unit, during the dechlorination step. Free chlorine breaks down organic matter present in the feed water into biodegradable fragments. After the dechlorination step, any bacteria surviving chlorination and reaching the membrane unit will benefit from an increased quantity of nutrients to support their growth.

Dechlorination Using Ultraviolet (UV) Light

HOD UV can be used as a dechlorination technology to overcome the drawbacks of conventional chemical and non-chemical methods. The HOD UV treatment system offers a chemical-free dechlorination treatment approach for boiler makeup water. The HOD system decomposes the free chlorine oxidant in process water to protect RO membranes. Additionally, the HOD technology provides disinfection to reduce the membrane biofouling potential by eliminating anaerobic and aerobic bacterial growth.

Photodecomposition is the main mechanism of the dechlorination in the HOD UV system. The photodecomposition process consists of absorption of UV photons followed by decomposition of the photon-absorbing molecules:

$$2(HOCl) + 2h\nu \rightarrow 2H^+ + 2Cl^- + O_2$$

$$2(OCl^-) + 2h\nu \rightarrow 2Cl^- + O_2 \text{ [2, 3]}$$

The rate of photodecomposition of aqueous chlorine molecules follows first-order kinetics [2]. Therefore, the concentration of aqueous chlorine molecules versus applied effective UV dose follows an exponential decay curve [1].

UV light is commonly generated by two main types of lamps:

- Low-pressure (LP) lamps or low-pressure high-output (LPHO) lamps are monochromatic lamps emitting light at a wavelength of 254 nm.
- Medium-pressure (MP) lamps produce UV light in broad spectrum wavelengths ranging between 200 and 415 nm.

MP-based UV technology is the preferred choice for applications, including dechlorination, due to its broad UV germicidal spectrum. The absorption spectrum of free chlorine compounds requires the wide-ranging wavelength of an MP lamp that is 200 nm to 360 nm [2]. Photons below a 250-nm wavelength are effective for decomposition of the HOCl compound. Photons with wavelengths above 260 nm and to a maximum of 300 nm are effective for decomposition of the OCl^- compound. Both OCl^- and HOCl compounds contribute the oxidation potential [4]. When OCl^- is photo-decomposed, the HOCl compound is transformed into OCl^- to maintain the necessary equilibrium.

Figure 2-2 depicts the spectral match of LP lamps and MP lamps to the free chlorine absorption spectrum. The spectral match translates into photodecomposition efficiency. MP lamps emit a broad wavelength covering the full free chlorine absorption spectral match, while LP lamps produce a static wavelength that only addresses one point of the spectral match. As a result, MP lamps are more efficient and effective at photodecomposition.

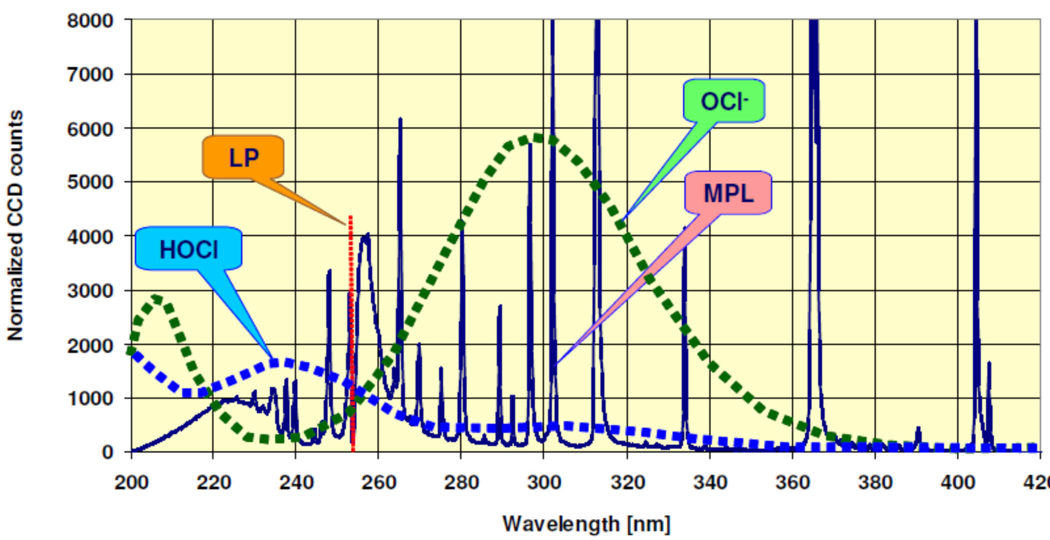

Figure 2-2
The "single-line" spectral emission of LP lamps (vertical red line) and the broad spectral emission of MP lamps (dark blue curve) overlaid on the absorption spectrum of the two free chlorine compounds (courtesy of Atlantium Technologies, Inc.)

In potable and wastewater treatment applications, a UV dose rate of approximately 10 to 200 millijoules per square centimeter (mJ/cm^2) is used to achieve disinfection of bacteria, viruses, and organisms. For example, *Pseudomonas aeruginosa* or *Pseudomonas putida* require a UV dose of 10–20 mJ/cm^2 to achieve a 4 log reduction, iron bacteria require <20 mJ/cm^2 for a 4 log reduction, *Bacillus* spp. in their spore form require <80 mJ/cm^2 for a 4 log reduction, *Enterobacter* spp. require <50 mJ/cm^2 for a 4 log reduction, and viruses require 100-200mJ/cm^2 for a 4 log reduction [1].

Research has shown that the UV dose required for effective dechlorination by oxidizing free chlorine is significantly higher than UV dose rates commonly used in potable and wastewater disinfection treatment applications [1]. Dechlorination applications typically require a UV dose above 1,000 mJ/cm^2. The elevated UV dose level used in dechlorination applications is well above the required level to achieve microbial inactivation. Therefore, the delivered UV dose will ensure disinfection and additional inactivation of chlorine-resistant microorganisms, thus reducing the risk of the membrane biofouling potential by eliminating anaerobic and aerobic bacterial growth.

The unique operating principles of the HOD UV technology enable the system to meet dechlorination requirements at lower dose rates that vary based on application-specific requirements.

Third-Party Dechlorination Studies of HOD UV Technology Performed by Atlantium Technologies[1]

Prior to promoting the HOD UV technology for industrial applications requiring the removal of chlorine or chlorine-equivalent disinfectants, Atlantium Technologies, Inc. entered into third-party laboratory and field studies to validate the long-term effects of their UV system in dechlorination applications.

Laboratory Study

Under the guidance of Dr. Mark Wilf, Atlantium Technologies, Inc. undertook a bench study of commercially available and proven dechlorination methods. Dr. Uri Levy, lead scientist for Atlantium Technologies, Inc., directed the six-month laboratory study that tested three dechlorination methods and their ability to protect RO membrane elements (Figure 2-3). Using three parallel water lines, the bench study evaluated the following dechlorination methods:

- SBS chemical neutralization
- GAC filtration chemical reaction
- Photodecomposition HOD UV

[1] This subsection was provided by Atlantium Technologies Inc., and EPRI was not involved in those studies and therefore cannot substantiate the findings.

Leading RO membrane manufacturers helped define the test protocols to ensure that all membrane functionality parameters, as well as chlorine and ORP levels, were properly monitored during the study. At the conclusion of the study, the HOD UV technology was deemed to be a safe and effective dechlorination method for use in conjunction with RO membranes by Atlantium Technologies, Inc.

Figure 2-3
Bench-scale evaluations of HOD UV technology for dechlorination

Field Study

Following the successful conclusion of laboratory analysis, the HOD UV technology was evaluated in a dechlorination field study over a four-month period. An HOD UV system was installed to treat an average flowrate of 90 gpm (20 m^3/hr). The recorded water conductivity values over the four-month period indicated constant salt rejection by the bank of RO membranes protected by the HOD UV system. Theoretical and experimental data showed the HOD UV technology to be an effective process for dechlorination of RO feed water.

Figure 2-4, taken from the last month of testing, shows the efficacy of the HOD UV technology in protecting RO membrane elements from chlorine disinfectants. The average pre-UV chlorine concentration was 1.0 mg/L (ppm), while the post-UV chlorine concentration in the membrane feed water was below a detectable level (< 0.05 mg/L/ppm).

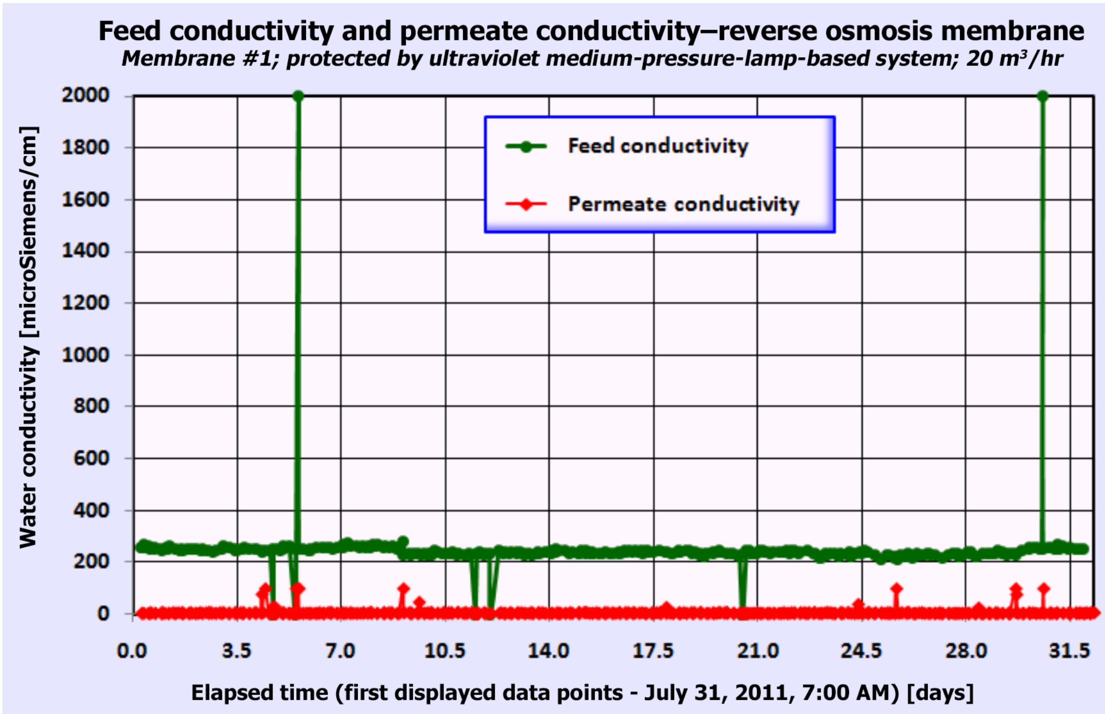

Figure 2-4
Feed conductivity and permeate conductivity using HOD UV dechlorination

Biofouling Prevention Study of HOD UV Technology[2]

A field study of the HOD UV technology for biofouling prevention was also conducted. The use of biocides, particularly chlorine, in RO desalination is widely practiced despite documented evidence showing that although biocides may be advantageous in controlling microbial counts in the water, in some cases they can actually exacerbate biofouling of RO membranes. Adverse effects of biocides have spurred the need for finding alternative RO pretreatment disinfection methods. UV disinfection is considered a viable alternative; however, limited research has been conducted to understand the effects of using UV as pretreatment for RO membrane biofouling.

During a four-month field study conducted at a brackish water reverse osmosis (BWRO) desalination plant treating groundwater, in northern Israel, an HOD UV system was applied as pretreatment disinfection prior to RO desalination. The plant contained two double-stage desalination trains operating in parallel. One train served as a reference, while the HOD UV system was installed in the other train. For the duration of the study, all normalized performance parameters were collected, and microbial counts were monitored. At the end of the study, sacrificial membranes situated at the front of the first stages were autopsied and various biofilm analyses were conducted to elucidate cell/extracellular polymeric substances (EPS) content and microbial speciation. Results showed that the presence of the HOD UV system prolonged the train performance, which manifested itself in a lower relative normalized permeate flux decline as compared to the reference train that operated without a UV pretreatment system (11% vs. 17%, respectively). Lower levels of EPS content and microbial speciation were found on the RO

[2] This subsection was provided by Atlantium Technologies, Inc., and EPRI was not involved in this study and therefore cannot substantiate the findings

membrane receiving UV-pretreated water. The differences in biofilm thickness and cell density counts (cells/cm^2) between the two membranes were notable and in favor of UV pretreatment. The HOD UV pretreatment had a substantial effect on biofilm community composition. The RO membrane receiving UV-pretreated water exhibited a biofilm in which the diversity was reduced by more than 30%. Also, the RO membrane receiving UV-pretreated water did not contain certain phylogenetic groups that were detected on the RO membrane from the reference train. At the conclusion of the four-month study, the HOD UV technology proved to be a viable and promising disinfection method to combat biofouling of RO membranes, prolonging operation of the trains between cleaning regimes.

Boiler Makeup Water Treatment Schematic Diagram and Issues

Plant Bowen, a 3,160-megawatt coal-fired power station, is faced with frequent membrane and micron-filter maintenance and replacement as a result of bio- and solids-fouling. The plant sought to protect its RO membranes and address its fouling concerns, while evaluating dechlorination treatment alternatives that would enable it to replace the use of sodium metabisulfite, reduce the usage of chlorination, and achieve a chemical-free dechlorination process.

In March 2014, the Water Research Center began a three-month evaluation of the HOD UV water treatment technology for use as a chemical-free dechlorination approach to improve the overall quality of RO feed water at Plant Bowen. Figure 2-5 shows the location of the HOD UV technology in the RO feed water treatment train. Three RZ300-19 HOD UV systems were installed on 8-inch (20.3-cm), 316 stainless steel piping to accommodate a flowrate of 680 gpm (154 m^3/hr).

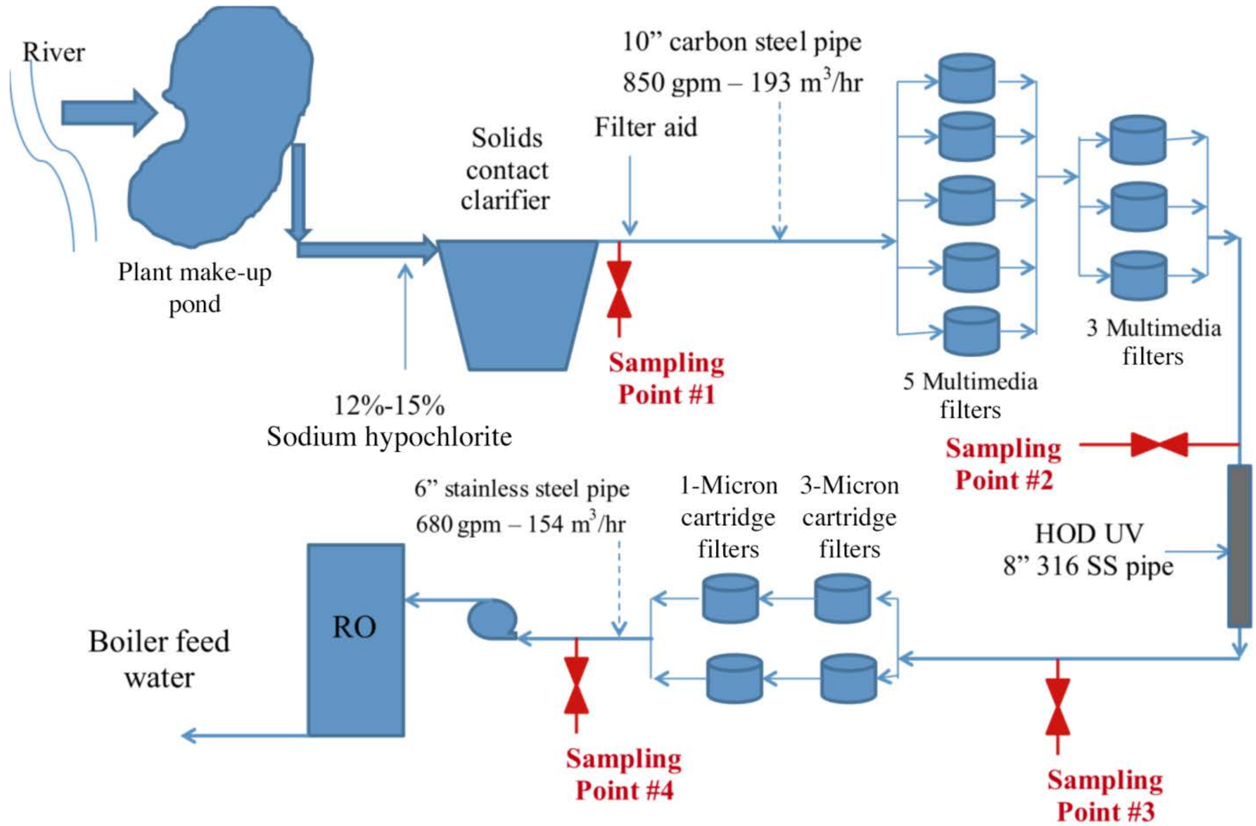

Figure 2-5
Schematic showing location of HOD UV technology in RO feed water treatment train

3 EXPERIMENTAL PLAN

In order to evaluate the dechlorination effectiveness of the HOD UV technology when applied to power plant boiler makeup water, three RZ300-19 HOD UV systems were installed and tested over a three-month period (March–May 2014), accommodating a flowrate of 680 gpm (154 m^3/hr) with 95% UV transmittance.

Equipment and Setup

To process a flowrate of 680 gpm (154 m^3/hr) and achieve dechlorination of feed water with a free chlorine concentration of 0.5 ppm, Atlantium Technologies, Inc. provided three RZ300-19 HOD UV systems. The UV units were installed in series on 8-inch (20.3-cm) stainless steel piping. The head loss, at a flowrate of 680 gpm (154 m^3/hr), was calculated as 1.18 inches (3.0 cm) per HOD UV unit. Combined, the three HOD UV units resulted in a 3.54-inch (9.0-cm) head loss in the system.

The existing pretreatment system at the research site was effective at iron removal (< 0.05 ppm). UV light is absorbed by iron, and thus UV systems are sensitive to total iron concentrations. Since the inlet water contained low concentrations of iron, the potential reduction in UV output from the HOD UV systems was low in this application.

Water quality was monitored using four sampling points (SP#1–SP#4) within the RO feed water treatment train. The sampling ports are shown in Figure 2-5.

The schematic configuration is presented in Figure 3-1. The ballasts are the power supplies that drive the lamp. The voltage clipping device (VCD) is an electrical protection device against electrical spikes, constituted from line filter and developed by the ballast's manufacturer. Figure 3-2 contains photographs of the HOD UV technology tested at the WRC.

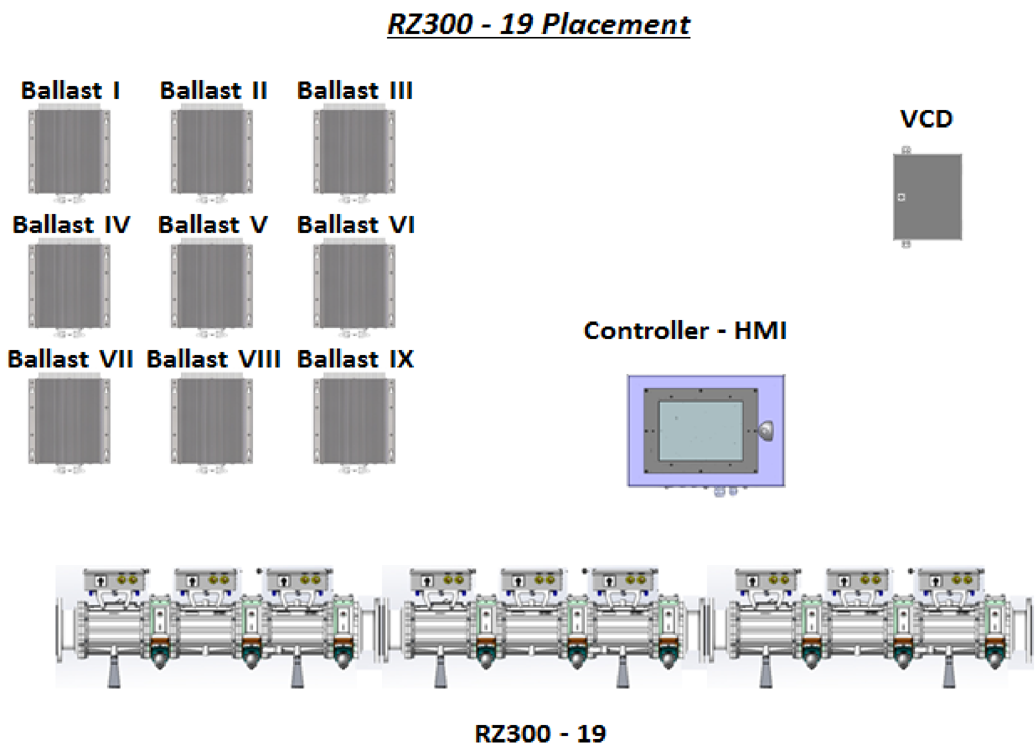

Figure 3-1
Schematic of HOD UV configuration at Plant Bowen

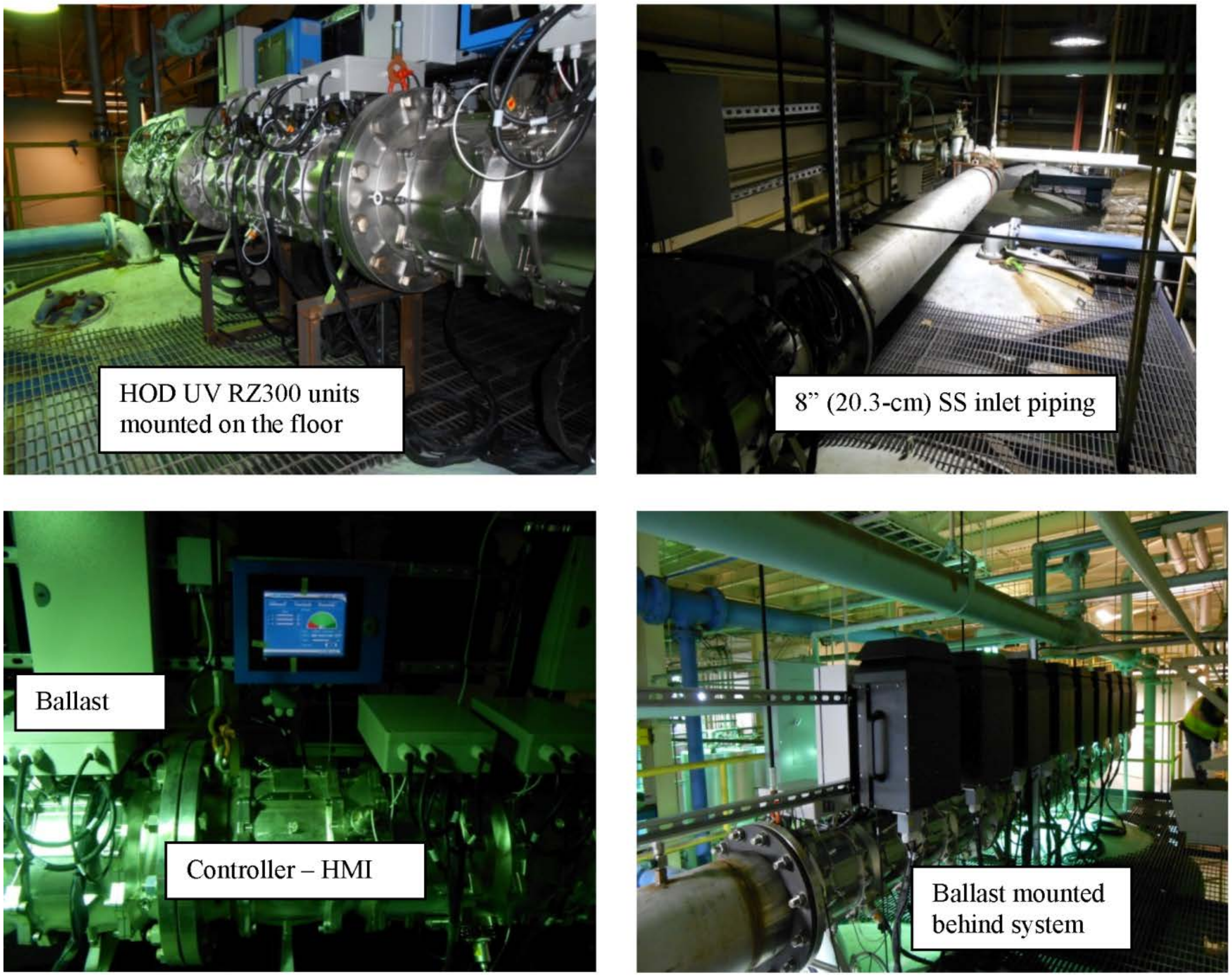

Figure 3-2
HOD UV configuration at Plant Bowen

Dechlorination Study

To evaluate the effectiveness of the HOD UV technology at removing chlorine, free and total chlorine levels were monitored at the four sampling points shown in Figure 2-5. The sampling details and equipment used are shown in Table 3-1.

Table 3-1
Free and total chlorine monitoring details

Sampling Point	Parameter(s)	Frequency	Equipment	Detection Limit (mg/L or ppm)
#1	Free and total chlorine	Daily	Colorimeter	0.05
#2, #3	Free and total chlorine	Daily	Colorimeter and titrator	0.05
#4	Free and total chlorine	On-Line	Colorimeter and on-line probe	0.01

Free and total chlorine can be measured through a colorimeter (HACH Method 8021 and 8167), titrator (SM 4500), or on-line analyzer (EPA Method 334.0) to monitor dechlorination. The HydroAct 1200 multi-sensor analyzer and data logger by Chemtrac, Inc., was used for on-line sampling of free and total chlorine at Sampling Point #4. Chemtrac, Inc. provided free and total chlorine analyzer probes for use with the multi-sensor HydroAct1200 analyzer. The membrane-covered amperometric three-electrode probes have a 0.01 mg/L or ppm resolution and detection level.

Monitoring for dechlorination can also be performed by measuring the oxidation-reduction potential (ORP) value of the water. Generally, positive ORP values indicate oxidizing conditions, while negative ORP values indicate reducing conditions. ORP values of the RO feed water were continuously monitored during the trial using an on-line ORP probe provided by Chemtrac Inc. The feed water to the RO was continuously monitored for the presence of oxidant. The ORP meter reading should always be below 300 mV. If it exceeds 300 mV, the plant operator should receive a warning that a dangerous level of oxidant is getting to the membranes and should take action, such as adding or increasing the dose of SBS to reduce the oxidant concentration. If the ORP value reaches 350 mV, an adjustment should be made until the oxidant concentration can be reduced to a safe value (ORP <300 mV). Table 3-2 shows the frequency and equipment used for ORP measurements.

Table 3-2
Oxidation-reduction potential monitoring details

Sampling Point	Parameter	Frequency	Equipment
#3, #4	ORP	Daily	Handheld probe; Ag/AgCl with saturated KCl electrolyte
#4	ORP	On-Line	On-line probe; Ag/AgCl with saturated KCl electrolyte

Monitoring of Bacteria Growth

Heterotrophic plate count tests were performed to monitor the efficacy of the HOD UV system at reducing bacterial growth in the RO feed lines and system. The monitoring equipment and frequency of bacterial growth tests are presented in Table 3-3.

Table 3-3
Bacteria growth and biofilm monitoring details

Sampling Point	Parameter(s)	Frequency	Equipment
#2 and #3	Heterotrophic plate count	Twice per week	Third-party lab

Heterotrophic plate count (HPC) measures a range of bacteria naturally present in water. Heterotrophs are broadly defined as microorganisms that require organic carbon for growth. They include bacteria, yeasts, and molds. HPC is a simple culture-based test that is intended to recover a wide range of microorganisms from water [5]. The lower the concentration of bacteria in RO feed water, the better maintained the water treatment system.

Analytical Methods

The analytical methods and procedural details are shown in Table 3-4.

Table 3-4
Analytical methods and procedure details

Parameter	Method	Container	Preservation	Holding Time
Free chlorine	SM 4500 Cl D	50 mL glass	None	Immediate
Total chlorine	SM 4500 Cl D	50 mL glass	None	Immediate
ORP	ASTM D 1498	1 L HDPE	None	Immediate
Total plate count	SM9215B-2000	50 mL poly – sterilized	Cool 4ºC	24 hours
pH	EPA 150.2	1 L HDPE	None	Immediate
Conductivity	EPA 120.1	1 L HDPE	Cool 4ºC	28 days

System Functionality

During the study, the HOD UV operational parameters were continuously monitored at constant intervals using an interconnected software output. Information was recorded by a dedicated database software application. The operational parameters monitored included the following:

- The water flow in the pipe in gpm (m^3/h) through a signal received from a flow meter
- The actual UV output of each lamp as measured by the UV unit's sensor, one per lamp
- The UV transmittance (UVT; %) of the water as measured by the UV unit's embedded UVT sensor (two per unit)
- The UV unit's delivered dose (mJ/cm^2) as calculated by the unit's controller (colored display touch screen) based on water flowrate, the actual output of each lamp, and the UVT of the water
- The water temperature (°F or °C) as measured from the UV dedicated temperature sensor

Figure 3-3 illustrates the unique sensor configuration of the HOD UV technology for assuring process functionality. Two discrete sensors are used, UV output and UVT. These parameters are critical for determining the efficacy of the HOD UV technology in the dechlorination process. To accurately measure UV output, each lamp uses its own dedicated UV sensor. The UV sensor delivers a 4–20 mA signal to the UV controller. The signal is proportional to the lamp UV output power. Each HOD UV unit uses two UVT sensors to measure the amount of UV light able to pass through the water. Combined, the two measurements reflect the actual UV power produced by each of the UV lamps and the amount of UV light available for dechlorination.

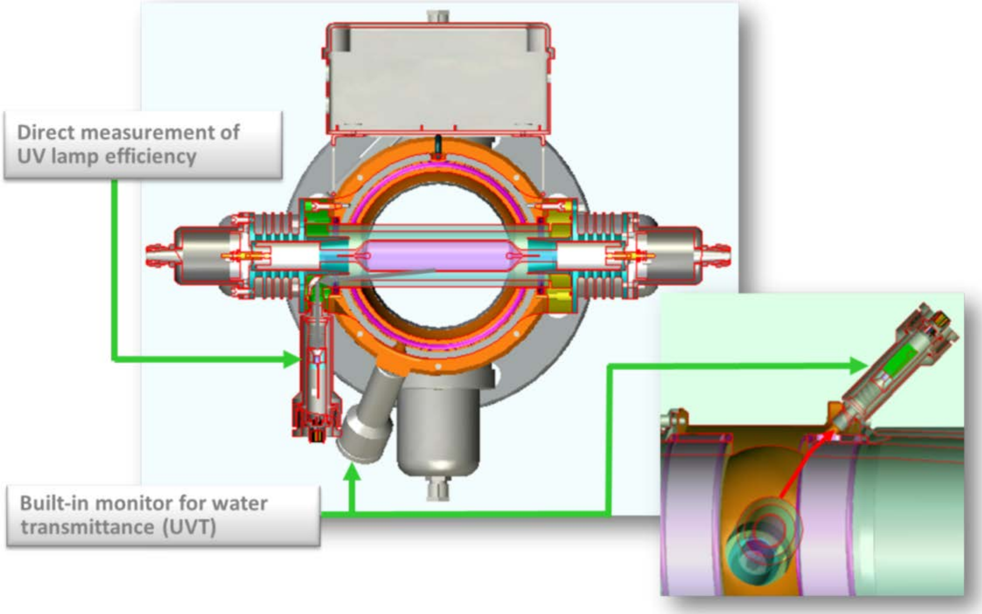

Figure 3-3
HOD UV sensor configuration

The unit was connected to remote access, enabling the plant or Atlantium team to monitor the unit remotely. Figure 3-4 presents a representative display of the remote monitoring.

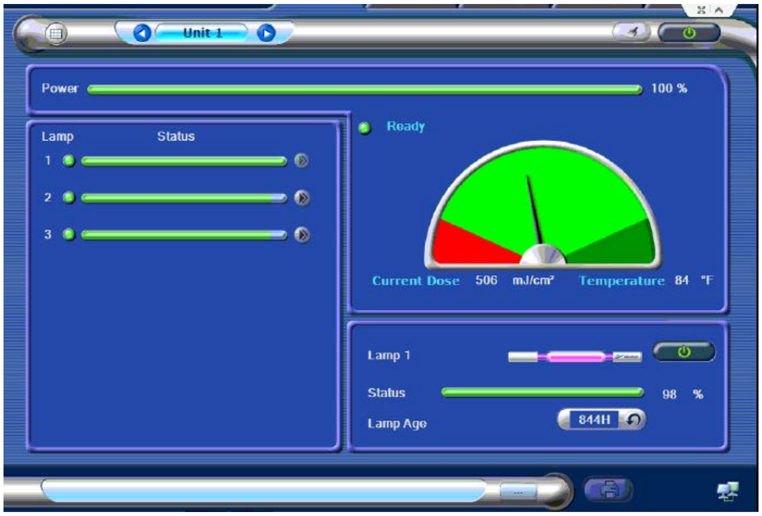

Figure 3-4
HOD UV remote access display

4
RESULTS AND DISCUSSIONS

Dechlorination Study

Processing boiler makeup water with an average inlet value of 0.3 mg/L (ppm) total chlorine and 0.2 mg/L (ppm) free chlorine, the HOD UV systems yielded a post-UV total chlorine value ranging between non-detectable and 0.11 mg/L (ppm), and free chlorine was non-detectable (<0.05 mg/L) mg/L. These values indicate that the HOD UV technology effectively removed chlorine. The post-UV ORP values fluctuated between 277 mV and 368 mV with an average value of 316 mV. The pre-RO ORP values varied between 197 mV and 444 mV with an average value of 326 mV. Moreover, pre-RO ORP levels were stable at approximately 300 mV, deemed an acceptable limit needed to coincide with plant operations and procedures.

Figures 4-1 and 4-2 present the total chlorine and free chlorine in RO boiler makeup water pre- and post-HOD UV technology versus date. As mentioned, the post-UV total chlorine ranged between non-detectable and 0.11 mg/L (ppm), and free chlorine was non-detectable (<0.05 mg/L) mg/L. The equipment startup occurred on March 4, 2014. The SMBS feed was reduced from 5 GPD (19 liters per day) on March 4, 2014, to 0 GPD (0 liters per day) on March 20, 2014. After reduction of the SMBS feed rate to zero (or near zero), the water was strictly dechlorinated by the HOD UV and the results were comparable to, or in certain instances better than, chemical dechlorination.

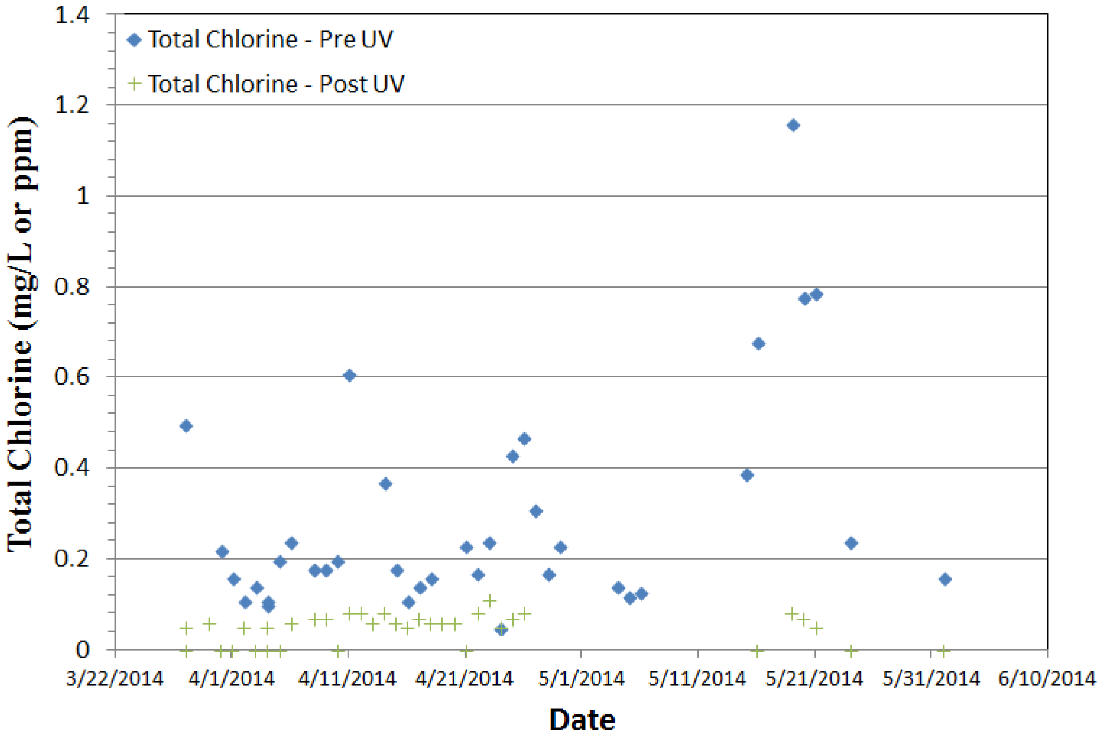

Figure 4-1
Total chlorine in RO feed water pre- and post-HOD UV (SP#2 and SP#3), with non-detectable values shown as 0.0

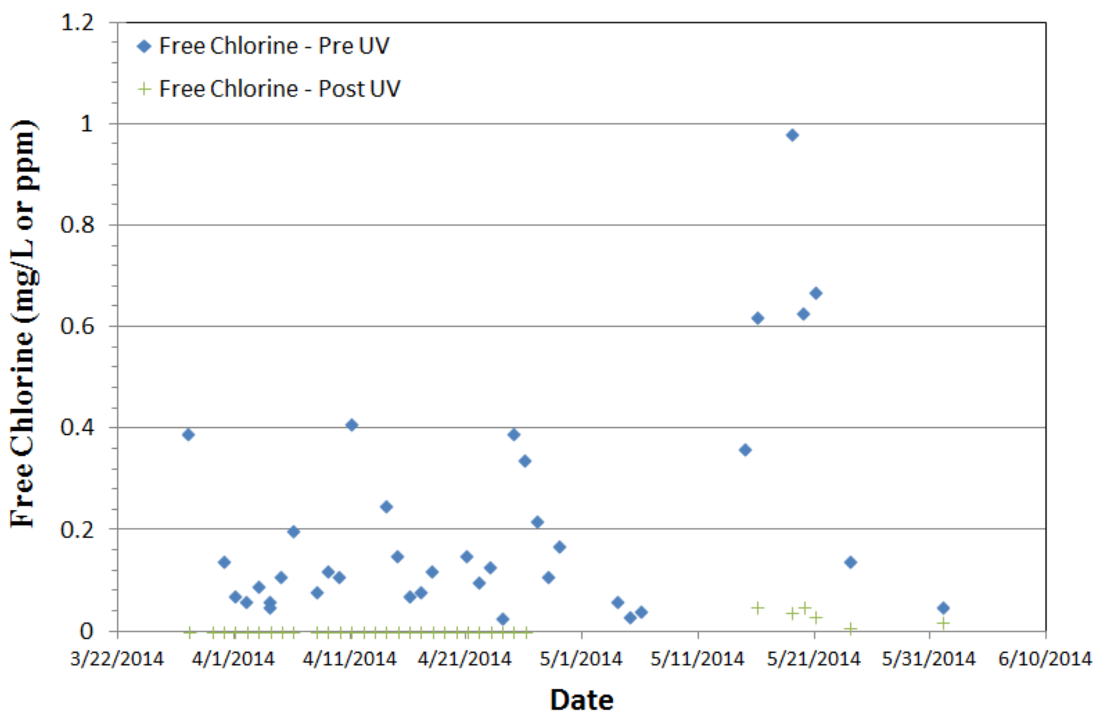

Figure 4-2
Free chlorine in RO feed water pre- and post-HOD UV (SP#2 and SP#3), with non-detectable values shown as 0.0

Figure 4-3 shows the free chlorine level versus the date. Free chlorine levels were typically non-detectable, ensuring adequate protection of the RO membranes. The free chlorine was monitored after the cartridge filters and prior to RO membranes at Sampling Point #4 using the Chemtrac equipment.

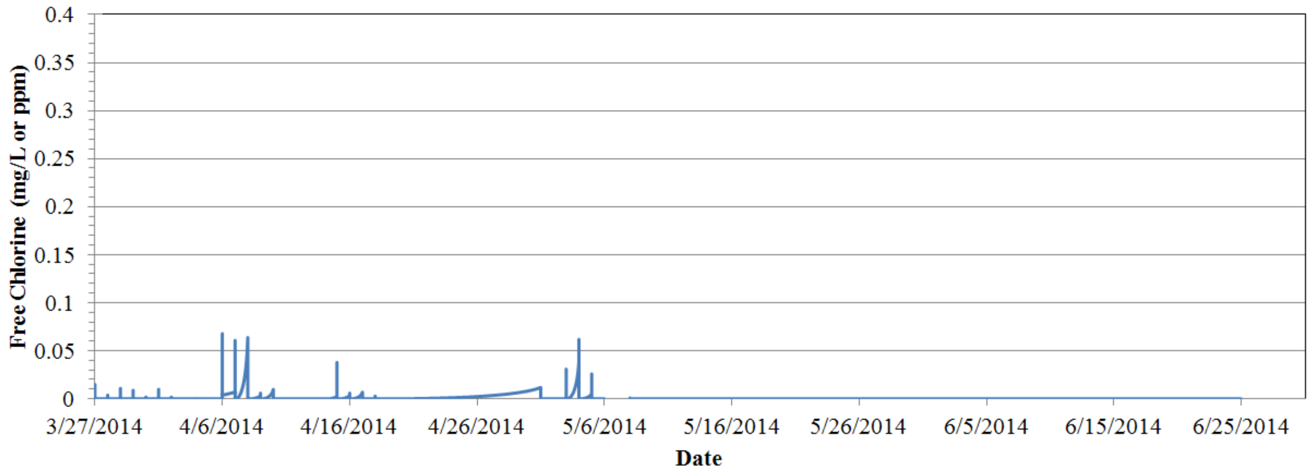

Figure 4-3
Free chlorine in RO feed water pre-RO membrane (SP#4)

The ORP values measured during the study are illustrated in Figures 4-4 and 4-5. The post-UV ORP values fluctuated between 277 mV and 368 mV with an average value of 316 mV. The pre-RO ORP values varied between 197 mV and 444 mV with an average value of 326 mV. These values indicate that the HOD UV technology effectively removed chlorine. Moreover, pre-RO ORP levels were stable at approximately 300 mV, which was deemed an acceptable limit to coincide with plant operations and procedures.

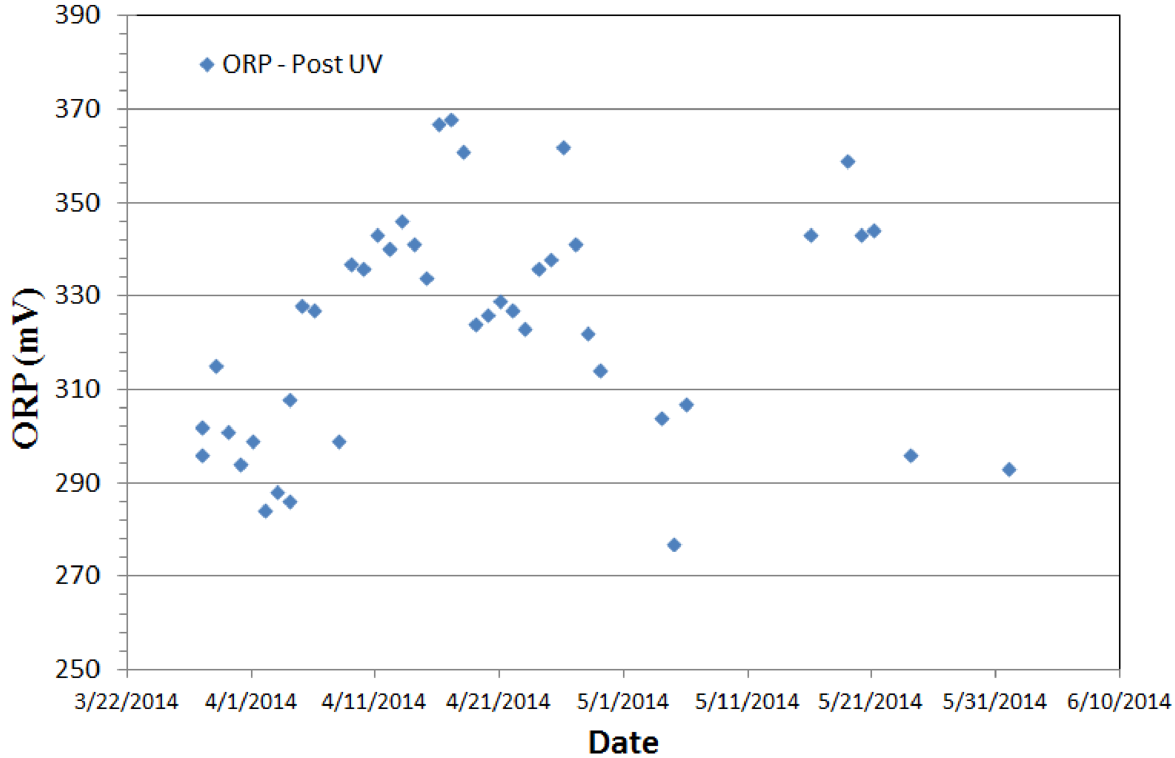

Figure 4-4
ORP in RO feed water post-UV HOD (SP#3)

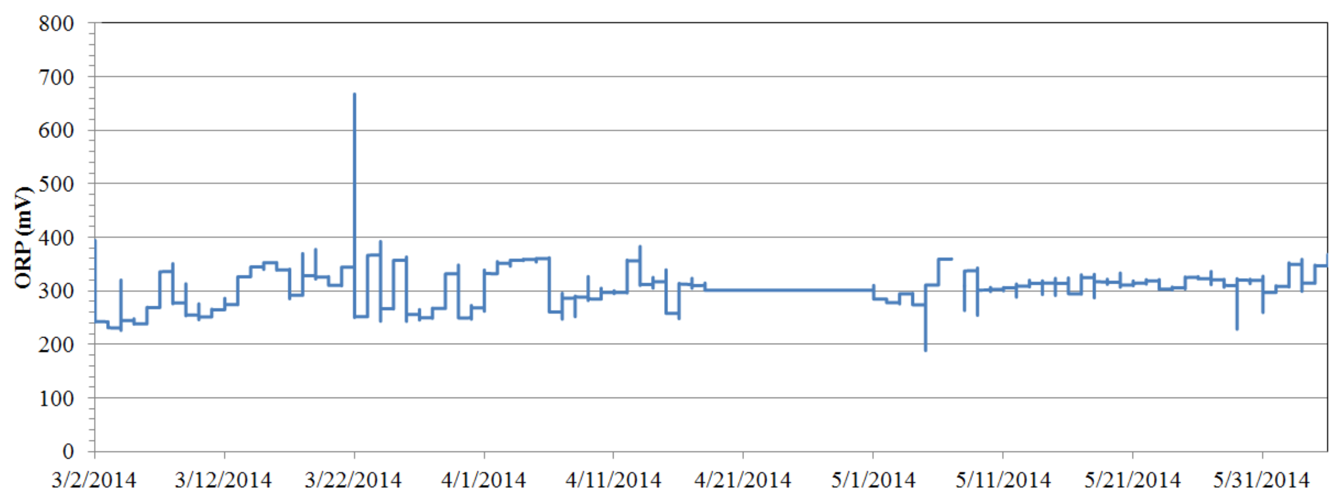

Figure 4-5
ORP in RO feed water pre-RO membrane (SP#4)

Monitoring of Microorganisms

Heterotrophic Plate Count (HPC)

The post-UV heterotrophic plate counts were comparable to those found in pre-UV samples, despite the pre-UV water being chlorinated while the post-UV water was not. The pre-UV water contained between 0.1 and 0.7 mg/L or ppm of total chlorine with an average value of 0.26 mg/L or ppm, while the post-UV water contained 0.05 mg/L or ppm total chlorine on average. In addition to successfully dechlorinating the water, the HOD UV technology simultaneously disinfected and thus controlled bacteria growth. Average heterotrophic plate counts of 3.2 and 3.8 organisms per mL were found in pre-and post-UV waters, respectively.

Table 4-1
Heterotrophic plate count results

Date	Pre UV SP#2	Post UV SP#3	RO Feed SP#4	RO Permeate	RO Concentrate
	Organisms per mL				
April 9, 2014	5.30	4.30	-	-	-
April 14, 2014	< 0.2	7.10	-	-	-
April 16, 2014	< 0.2	2.10	590		6230
April 21, 2014	6.20	5.30	-	-	-
April 23, 2014	-	2.10	23.1	-	-
April 28, 2014	1.20	1.70	-	-	-
April 30, 2014	-	1.20	6.50	-	195
May 7, 2014	-	1.70	55.5	-	-
May 12, 2014	-	0.4	195	23.1	620
May 14, 2014	-	< 0.2	26.6	6.20	80.0
May 19, 2014	-	< 0.2	16.6	-	-
May 27, 2014	-	9.30	35.5	4.80	311
June 18, 2014	-	14.1	50.7	2.60	100
June 25, 2014	-	0.4	9.00	7.10	372

The HPC counts were increased from an average of 3.8 organisms per mL to an average of 101 organisms per mL in the RO feed water. The RO feed water heterotrophic plate counts were acceptable. This shows that UV controlled the bacteria growth in post-UV waters for the plant. The likely reason for this increase was the cartridge filters, shown in Figure 2-5, that were possibly old and contained bacteria buildup prior to the startup of the HOD UV systems. The bacteria removed in the RO membrane and RO permeate had an average of 8.8 organisms per mL. The removed bacteria were discharged in the RO concentrate.

UV System Functionality During the Study

Figure 4-6 presents the system operation by detailing system's lamps power over the study period. During this period several operational modes were tested, including 100% power for all three systems, 90% power for all three systems, and 90% power for two systems with no power to the third unit. The shut-off events in Figure 4-6 reflect maintenance activity conducted on the water line.

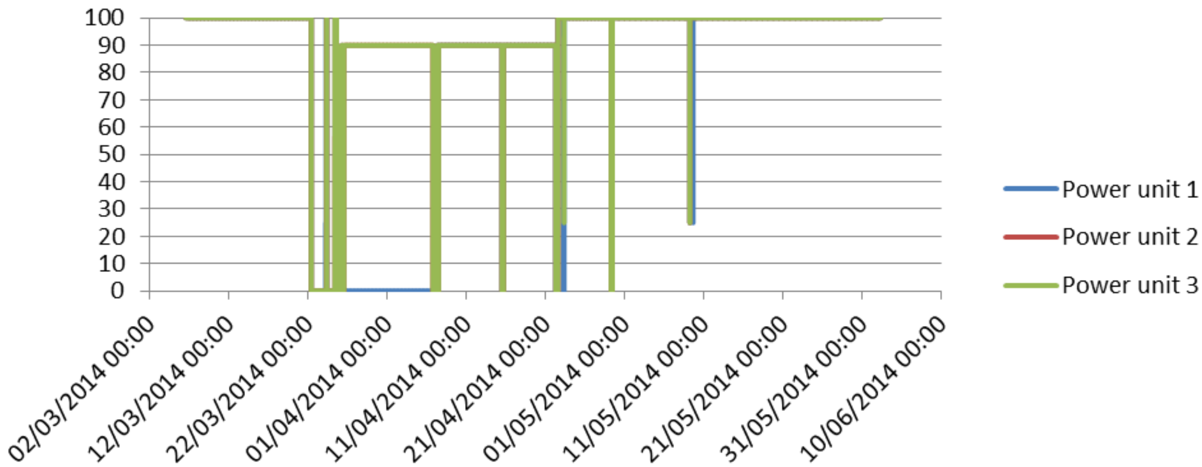

Figure 4-6
UV system operation power during the testing

Figure 4-7 presents the flowrates in gpm (m^3/h) as measured by a flow meter connected to the UV controller and recorded by the unit's data logger. The flowrates were dependent upon the number of the active RO trains. Flowrates varied between 0 gpm (0 m^3/h), or 340 gpm (77 m^3/h), or 640 gpm (154 m^3/h). During the study, the HOD UV units were operating in power mode, meaning the delivered power was not varied as a function to the flowrate. For optimizing power consumption, the HOD UV units varied power based on all water conditions, including flowrate.

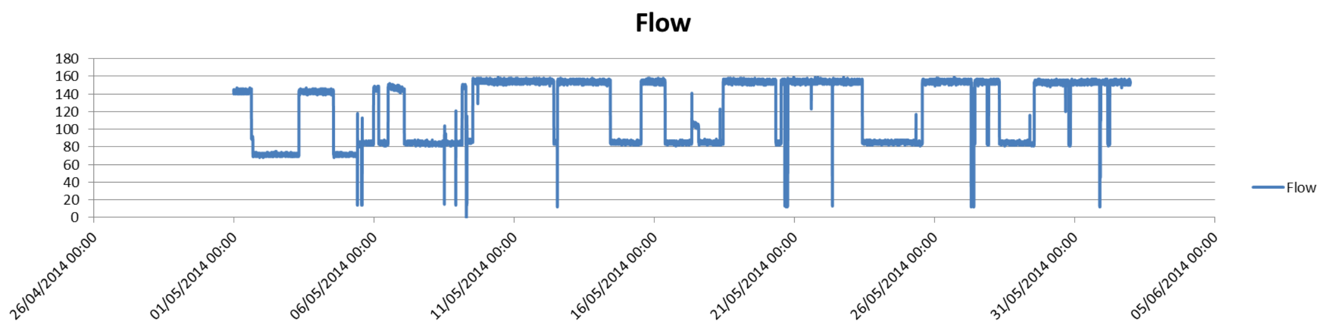

Figure 4-7
Flowrates in m^3/h versus date

The first stage of the evaluation process was based on the following protocol: operate the unit at the 640 gpm (154 m^3/h) and 340 gpm (77 m^3/h) flowrates; operate the units with one, two, three, four, or five active MP lamps. The levels of the free chlorine (mg/L or ppm) as Cl_2 at the inlet of the HOD UV units varied between 0.1 and 0.68 mg/L (ppm) with an average of 0.29 mg/L (ppm).

Test results showed that for the 640 gpm (154 m^3/h) flowrate, four lamps were suitable to meet dechlorination requirements and reduce the inlet level of 0.5 mg/L or ppm of free chlorine (Cl_2) to undetectable levels. For the inlet value of 0.64 mg/L or ppm of Cl_2, five lamps were needed to achieve dechlorination, although the lamps did not require operation at full power. The maximum driving power of each lamp was 4.2 kW.

The HOD UV systems offered redundancy that would enable the plant to treat higher levels of free chlorine that might occur during an activation period. By having this redundancy, the plant would have greater flexibility maintaining operational conditions.

Cost of HOD UV Technology[3]

During the three-month evaluation period of the HOD UV technology for dechlorination of boiler makeup water, capital expenditures and estimated annual operational expenditures were calculated by Atlantium Technologies to compare the net present value analysis of chemical versus non-chemical dechlorination approaches. The operational expenses (OPEX) associated with the operation of the HOD unit are made up the following:

- Electrical power
- Lamp replacement
- Routine maintenance as specified in the user manual:
  - Cleaning in place (CIP): cleaning solution is recirculated through the system for approximately one hour. Atlantium Technologies estimates two hours for setup and one hour for tear-down. Total estimated time, pending water quality, is estimated as four hours every other year.
  - O-rings: drain the unit and replace sleeve O-rings once a year; approximately one hour required.

The HOD UV technology provides operational flexibilities for maximum redundancy and for reducing operational costs. The systems are pre-engineered and designed to fit into existing piping schemes of boiler makeup applications. Plant decisions on redundancy would dictate the actual size of the HOD UV system suitable to meet application-specific requirements.

Table 4-2 from Atlantium Technologies elaborates annual operational expenses. Operational conditions are based on the following two modes of operation:

- Operating the unit at full redundancy; all lamps at 100%
- Operating the unit in “save” mode or dose mode; takes into account the actual flowrate, the lamp condition and the UVT of the water

[3] This subsection was provided by Atlantium Technologies Inc., and EPRI cannot substantiate the findings due to the short length of the study.

Table 4-2
HOD UV annual OPEX (costs in USD)

Operation Mode	Lamps			Electricity[1]	Parts	Labor			Total[1]
	Number of duty lamps	Number of replaced lamps per year[2]	Cost of lamps per year[3]	Total kW/h	Yearly kit – $20 per lamp	Manpower yearly hours	Hourly cost	Cost of yearly man-power	Lamps plus parts and labor
Full Redundancy	9	16	$9,600	38.7	$180	4	$75	$300	$10,080
Save Mode[4]	4 and 3	7	$4,200	15.9	$80	3	$75	$225	$4,505

Notes:
1. Electricity costs will vary and are not included in the calculation of the total costs.
2. Assumes 1.752 replacements per duty lamp per year, based on average operating life of 5000 h per lamp.
3. Assumes $600 per lamp.
4. The following was assumed for Save Mode: 70% of the time the flowrate is for two RO trains (for this, four lamps will be sufficient), and 30% of the time the plant is operating one RO train (for this, three lamps will be sufficient).

5 CONCLUSIONS

A pilot study of the HOD UV technology for dechlorination of boiler makeup water with a flowrate of 680 gpm (154 m^3/hr) was conducted at the Water Research Center at Georgia Power's Plant Bowen in Cartersville, Georgia. The evaluation commenced on March 4, 2014, and concluded on May 30, 2014. The HOD UV technology operational parameters, including functionality and power requirements, as well as chlorine and bacteria removal efficiencies, were evaluated during the three-month test program.

At the conclusion of the evaluation period, results showed the HOD UV system to consistently meet or exceed treatment objectives. The HOD UV technology removed free and total chlorine from boiler makeup water to undetectable levels from inlet free and total chlorine levels above 1 mg/L. Bacteria levels were also reduced to an average of 3.8 organisms per mL—low/acceptable levels.

Processing boiler makeup water with an average inlet value of 0.3 mg/L (ppm) total chlorine and 0.2 mg/L (ppm) free chlorine, the HOD UV systems and MP lamp technology yielded an effluent with an average total chlorine of 0.05 mg/L or ppm and average free chlorine of 0.02 mg/L or ppm. The dechlorinated water quality was comparable to, or in some cases, better than the water quality achieved with chemical treatment.

The HOD UV technology was also effective at controlling bacteria growth. The pre-UV water was chlorinated, but the post-UV water did not contain chlorine because the chlorine was decomposed by HOD UV. The RO feed water heterotrophic plate counts were acceptable. This shows that UV controlled the bacteria growth in post-UV waters.

During the evaluation process of the HOD UV technology, a varied protocol was followed: operation of the units at the 640 gpm (154 m^3/h) and 340 gpm (77 m^3/h), and operation of the units with one, two, three, four, or five active MP lamps. The levels of the free chlorine (mg/L or ppm) as Cl_2 at the inlet of the HOD UV units varied between 0.1 and 0.68 mg/L (ppm). Test results showed that for the 640 gpm (154 m^3/h) flowrate, four lamps were suitable to meet dechlorination requirements and reduce the inlet level of 0.5 mg/L (ppm) of free chlorine (Cl_2) to undetectable levels. For the inlet value of 0.68 mg/L or ppm of Cl_2, five lamps were needed to achieve dechlorination, although the lamps did not require operation at full power. The maximum driving power of each lamp was 4.2kW. The HOD UV systems offered redundancy that would enable the plant to treat higher levels of free chlorine that might occur during an activation period. By having this redundancy the plant would have greater flexibility maintaining operational conditions.

The results obtained in this short-term (four-month) evaluation suggest that power plants may be able to replace the use of sodium bisulfite (SBS) or sodium metabisulfite (SMBS) in boiler makeup water treatment and achieve a chemical-free dechlorination process by implementing the HOD UV technology. The HOD system decomposes the free chlorine oxidant in process water to protect RO membranes. Additionally, the HOD technology provides disinfection to reduce the membrane biofouling potential by eliminating anaerobic and aerobic bacterial growth. UV treatment allows for a dechlorination treatment approach with the potential to eliminate the handling, storage, and operational requirements of chemical disinfection solutions.

6
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