UV Treatment of RO Permeate for Potable Reuse at the Scottsdale Water Factory

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The city of Scottsdale water campus
The Scottsdale Water Campus, near Phoenix, Arizona, was built in the 1990s as a 20 MGD water reclamation plant and 10 MGD advanced water treatment (AWT) plant utilizing microfiltration (MF) and reverse osmosis (RO). In 2011 and 2012, the AWT plant was upgraded to 24 MGD, including a 20 MGD Sentinel™ Chevron UV reactor to treat NDMA and other potential contaminants. The primary purpose was to increase the capacity for aquifer replenishment for potable reuse. A flow schematic of the upgraded facility is shown in Figure 1, while Figure 2 shows the filtration and RO units.

UV system design
Selection of the UV supplier and equipment was based on a rigorous specification and evaluation of both capital costs and the net present value of operating costs over the life of the system. Calgon Carbon was awarded the contract with its Sentinel™ Chevron 48 AOP UV. This system offered the lowest total cost of ownership and operation by using medium-pressure UV technology combined with highly efficient turndown capability.

The UV system is designed to destroy 1-log of NDMA at 20 MGD and a minimum UV transmittance of 95%. The Sentinel™ Chevron 48 AOP reactor has 18 x 20 kW medium pressure UV lamps arranged in a compact vessel four feet (1.2 m) in diameter and six feet (1.8 m) long.

The Sentinel™ 48 AOP system uses the highest power medium pressure UV lamps in the industry resulting in fewer lamps, less maintenance and a smaller footprint. The ability to turn off banks of lamps and to turn down lamps to 40% enables the system to efficiently tailor the UV power to the plant needs, thereby reducing operating costs.

Modeling to predict full-scale performance
Full-scale performance is dependent on the flow rate, the UV lamp output, the UV transmittance of the water, the path length in the UV reactor, the UV dose response of the contaminant and the reactor hydraulics (UV dose distribution).

Computational Fluid Dynamic modeling (CFD) coupled with UV Intensity Field modeling is used to predict full-scale performance.

UV sensitivity (D_L)
In UV Disinfection the UV sensitivity (Dose per log or D_L) (Bircher, 2007) of an organism is needed in CFD modeling to predict performance. It is also needed if multiple organisms

Figure 1. Flow schematic of the Scottsdale Advanced Water Treatment plant

Figure 2. Filtration and RO units
are used in bioassay testing to arrive at a single dose equation that combines all organisms. Figure 4 shows a typical UV dose response for MS2 Phage where the $D_L$ at any point in this curve is defined as the UV dose at that point divided by the log inactivation.

NDMA UV dose per log ($D_L$)
NDMA is unique in AOP treatment as its destruction by UV AOP is predominantly by direct photolysis and not via the hydroxyl radical. Therefore, hydrogen peroxide is not necessary and is sometimes not used if NDMA is the only target compound. In this manner NDMA behaves much like a microbial organism in that the $D_L$ is independent of water quality. Figure 5 shows the UV dose response of water from the Scottsdale facility with a $D_L$ of 714 that is typical of NDMA.

NDMA absorbs at the low UV wavelengths with a peak around 228 nm as shown in Figure 6.

**Figure 4.** Typical dose response of MS2 Phage used in bioassay

**Figure 5.** Fluence (UV dose) response of NDMA

**Figure 6.** NDMA spectral molar absorption coefficient

**Full-scale fluence rate calculations**
The UV fluence rate at every point in the reactor is calculated as follows:
The spectral lamp output between 200 and 300 nm is divided into 5 nm bands, and the lamp fluence rate, $E_0(\lambda)$, at each wavelength is determined using the UVCalc fluence rate model (Bolton Photosciences Inc.). The fluence rate is multiplied by the NDMA molar absorption coefficient for that wavelength band divided by the absorption coefficient at 254 nm to give a NDMA-weighted fluence rate at each wavelength normalized to 254 nm. Since the number of photons per unit energy is proportional to the wavelength this is multiplied by the wavelength ratio to determine the equivalent photons absorbed at 254 nm. Summing this from 200 to 300 nm gives the total NDMA-weighted fluence rate at each point in the reactor (see equation 1).

$$E_0(254) = \sum_{\lambda=200 \text{ nm}}^{300 \text{ nm}} E_0(\lambda) \cdot \frac{\varepsilon_c(\lambda)}{\varepsilon_c(254)} \cdot \frac{\lambda}{254}$$  \hspace{1cm} (1)

where

- $E_0(254)$ is the NDMA-weighted 254 nm equivalent fluence rate (mW/cm$^2$)
- $E_0(\lambda)$ is the fluence rate (mW/cm$^2$) at wavelength band $\lambda$
- $\varepsilon_c(\lambda)$ is the molar absorption coefficient (M$^{-1}$ cm$^{-1}$) of NDMA at wavelength $\lambda$
- $\varepsilon_c(254)$ is the molar absorption coefficient (M$^{-1}$ cm$^{-1}$) of NDMA at 254 nm.

The ratio $\lambda/254$ converts the number of photons per unit energy at wavelength $\lambda$ to that at 254 nm. This is the same as the accepted technique used to calculate the germicidal fluence rate for the destruction of microorganisms using broad spectrum UV, except that if the action spectrum is measured in energy (Joules) multiplying by the wavelength ratio is not necessary.

This process is illustrated in Figure 7 where the NDMA-weighted fluence rate is the integral or sum under the NDMA-weighted fluence rate curve.

**CFD program**

The CFD analysis was performed using CFX software (ANSYS Inc., Canonsburg, PA). The reactor geometry was divided into a mesh of approximately 3 million volume elements and the fluid-dynamics and photo-statics are calculated in each cell with the CFD program reading the fluence rate at the mesh points.

The program calculates the destruction of the target compound in each mesh cell as the water flows through the reactor using:

$$DC = -\frac{E_0(254) \times C}{D_L \times \log e}$$  \hspace{1cm} (2)

where:

- $C$ is the concentration of NDMA in the volume element
- $E_0(254)$ is the NDMA weighted fluence rate (Equation 1) in that volume element (mW/cm$^2$)
- $D_L$ is the dose required for 1-log reduction (mJ/cm$^2$/log) for NDMA.

or for finite volume elements in CFD where the water passing through it in time $t$ with change in concentration $\Delta C$:

$$\Delta C = -\frac{E_0 C}{D_L \times \log e} t$$ \hspace{1cm} (3)

**Illustration of CFD results**

Figure 8 is a plot of the NDMA-weighted fluence rate in the reactor, while figure 9 shows the NDMA destruction through the reactor.

**Operational control equation**

The Sentinel reactor can operate with 18, nine or five lamps, and each lamp can be turned from 100% power (20 kW) to 40% power (8 kW). It has very efficient turn down from 18 x 20 kW or 360 kW to 5 x 8 kW or 40 kW to tailor the power consumption to the operating conditions (flow, UV transmittance and target NDMA log reduction). The CFD modeling is used to determine the log reduction of NDMA under a variety of operating conditions of UV absorbance, relative lamp output and flow.
Regression analysis then can be used to find the best fit of the log reduction to these parameters using Equation 4:

\[
\log t = 10^4 \times UV_A \times \left( \frac{S}{S_0} \right) \times \left( \frac{Q \times D_L}{C \times D_{UV}} \right)
\]  

(4)

where:
- \(UV_A\) is the UV absorbance = \(-\log_{10}(UVT/100)\)
- \(S/S_0\) is the relative lamp output
- \(Q\) is the flow rate, MGD
- \(D_L\) is the UV sensitivity = 714 mJ/cm\(^2\)/log

A, B, C, D and E are constants derived from fitting this equation to the results of CFD modeling for each lamp condition.

This equation is programmed into the PLC controls of the reactor enabling the NDMA log reduction to be calculated and the lamp power and number of operating lamps to be adjusted to meet the target log reduction set at the operator interface.

**Operational experience**

In a 10-day performance trial in February 2012, the system consistently achieved the target 1-log (90%) NDMA removal while continuously adjusting the number of operating lamps and lamp power to match varying plant operating conditions. This is illustrated in Figure 10.

**Conclusion**

The Sentinel AOP system is treating NDMA for the city of Scottsdale. The compact size and efficient turndown make this medium-pressure UV system ideal for potable reuse. NDMA-weighted UV dose per log \((D_L)\) can be used in CFD modeling to accurately predict the performance of the full-scale UV AOP reactor allowing UV dose pacing to continuously optimize power consumption.

This same technique can be used for UV/hydrogen peroxide or UV/chlorine AOP where the hydrogen peroxide or chlorine weighted UV dose is used instead of NDMA. However, in this instance the UV dose per log \((D_L)\) is dependent on the scavenging of background water and the oxidant. It is possible, however, to determine the effect of water quality parameters such as UV absorbance (as a proxy for TOC), pH, nitrate and alkalinity and thereby calculate the \(D_L\) of any contaminant. In this way the destruction of any contaminant can be determined and tracked.

**References**

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