A Water Environment & Research Foundation study demonstrates how improvements in treatment and monitoring technologies can be used to create a direct potable reuse system that reliably protects public health. Authors **Sarah Triolo**, **Brian Pecson**, and **Shane Trussell** of Trussell Technologies highlight the key findings of the study.

Path to DPR – Benefits of enhanced treatment and monitoring

Growing pressures on traditional water sources are forcing a shift in the way water is managed around the world. Given the stresses on groundwater and surface waters, the use of recycled municipal wastewater to supplement existing potable water systems is growing in popularity. For potable reuse to be successful, it should provide the same level of public health protection as is provided by conventional drinking water sources. To date, most planned potable reuse projects depend on a combination of treatment, monitoring, and an environmental buffer to achieve this protection. A conservatively designed buffer can provide storage and retention time, further attenuation of contaminants, and dilution. The passage of water through the buffer also provides significant time to respond to excursions or failures in upstream treatment. Access to environmental buffers, however, is not available in many communities. Accordingly, there is increasing interest in potable reuse projects that do not include an environmental buffer, i.e., direct potable reuse (DPR).

Research suggests that improvements in treatment and monitoring technologies can replace the need for retention time in environmental buffers while still providing equivalent public health protection. The goal of the WE&RF study "Demonstrating Redundancy and Monitoring to Achieve Reliable Potable Reuse" (Reuse-14-12) was to demonstrate how such improvements can be used to create a DPR system that reliably protects public health. A model DPR treatment train consisting of ozone, biological activated carbon (BAC), parallel units of microfiltration (MF) and ultrafiltration (UF), reverse osmosis, ultraviolet light (UV) with an advanced oxidation process (AOP), and free chlorine disinfection (FC) was tested at the North City Water Reclamation Plant (NCWRP) in San Diego, California, United States (US). The demonstration facility also included enhanced process monitoring for the continuous demonstration of pathogen reduction performance.

Data collection during the yearlong testing period included both extensive online monitoring and challenge testing. To accomplish the central goal of demonstrating treatment reliability, the study drew on the database of more than one million online data points collected for each unit process to quantify the degree of pathogen reduction provided. These performance data were used in a quantitative microbial risk assessment (QMRA) to compare the protection provided by the DPR train to conventional drinking water sources. Additionally, this study evaluated performance through a number of complementary projects, including (1) exploring the benefit of ozone/BAC pretreatment for the control of chemical contaminants, (2) examining new surrogates for reverse osmosis (RO) monitoring to increase pathogen removal credit, (3) quantifying the system's mechanical reliability, and (4) investigating improved ozone monitoring strategies for recycled water.

Treatment reliability analysis and QMRA

The overarching goal of this project was to assess the public health reliability of a model DPR treatment train and compare it to the risk-based targets used for drinking water and indirect potable reuse systems. The complete methods and results of this analysis can be found in Pecson et al. (2017). Since the 1989 Surface Water Treatment Rule, the target of 1 in 10,000 (i.e., 10^{-4}) infections of enteric disease per person per year due to drinking water consumption has served as a common benchmark for an acceptable level of risk, according to the US Environmental Protection Agency. The California groundwater replenishment regulations and proposed surface water augmentation regulations also use this risk target to set removal requirements for three pathogen types: enteroviruses, *Cryptosporidium*, and *Giardia*. The same risk-based targets were used in the DPR analysis.

The most widely used method to estimate pathogen risk in drinking water is quantitative microbial risk assessment (QMRA). One limitation of previous DPR QMRA efforts was a lack of data from full-scale treatment trains designed and operated specifically as DPR. The performance data generated over the yearlong testing provided an extensive, 300-gigabyte dataset for the QMRA. Unit process performance was quantified using online measurements of surrogate parameters, in accordance with existing process crediting frameworks (Table 1). The performance data were used to develop probability distribution functions

Unit Process	Surrogate Monitoring Strategy
Ozone	Three O_3 residual monitors along the length of the contactor used to calculate ozone CT
MF/UF	Continuous indirect integrity monitoring with effluent turbidity; daily pressure decay test
RO	Total organic carbon monitoring on influent and effluent; backup monitoring with electrical conductivity
UV/AOP	All UV process parameters measured to verify UV dose

Table 1. Surrogate monitoring strategies for each unit process.

Surrogate Type	Parameters
Spiked	Rhodamine WT dye, 3D TRASAR, sugar, sucralose
Naturally occurring	Calcium, magnesium, potassium, sodium, strontium, chloride, sulfate, total organic carbon, electrical conductivity

Table 2. Surrogate parameters testing for RO pathogen removal crediting

Figure 1

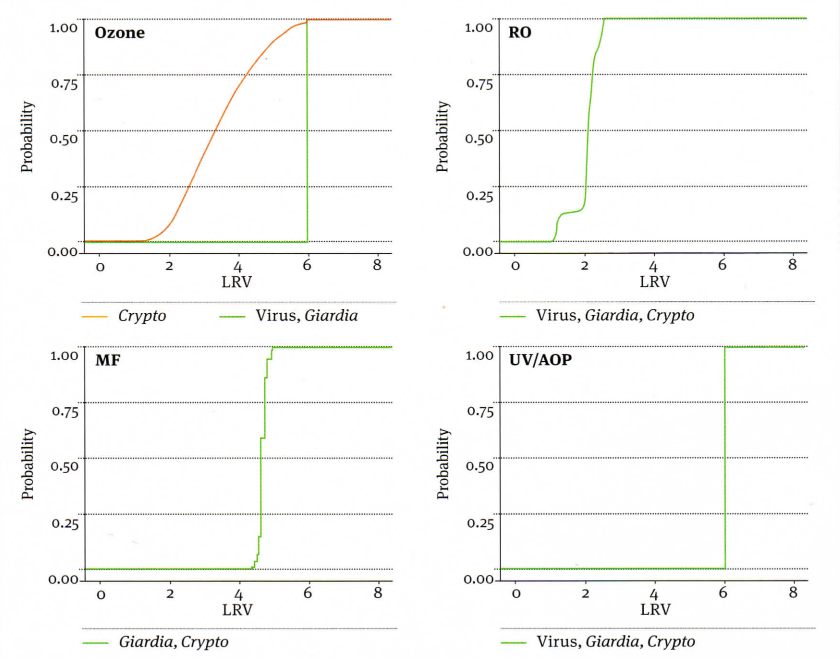

Figure 1. Probability distribution functions for unit process pathogen reduction performance, as described in Pecson et al. (2017). LRV: log reduction value.

(PDFs) that capture the inherent variability of each of the unit processes (Figure 1). The overall treatment train performance was obtained by integrating the PDFs of each unit process (Pecson et al. 2017).

Over the course of testing, no failures occurred that caused the pathogen removal performance of the treatment train to drop. Rare failure events can, however, have an important impact on a system's risk profile, so additional analysis evaluated the potential impact of such failures. Failures of varying length were incorporated into the analysis, assuming that each unit process failed completely (i.e., LRV of 0) once per year for a duration ranging from 15 minutes to 1 day.

Risk curves were developed to model the annual risk of infection from enterovirus and *Cryptosporidium* with the inclusion of failures (Figure 2). This evaluation demonstrated that even a single 15-minute failure per process per year significantly increased the annual risk of infection by more than 100-fold. Longer durations increased risk by several orders of magnitude. Nevertheless, the redundancy of the treatment train consistently maintained public health protection from pathogens even in the event of failures.

These results confirm the viability of DPR as an approach to supplementing existing water supplies and were used by the California State Expert Panel to support their conclusion that it is feasible to move forward with uniform regulations for DPR in California. The Expert Panel concluded that DPR should consist of multiple, independent barriers that provide pathogen control beyond the minimum requirements. Treatment redundancy is an effective strategy for providing operational flexibility and protecting public health in the event of a variety of failures.

Benefits of enhanced treatment robustness

A key component of potable reuse reliability is robustness, meaning the ability to address a broad variety of contaminants (both known and unknown) while also preventing the occurrence of catastrophic failures. The inclusion of ozone/BAC pretreatment increases system robustness by offering two additional barriers that provide complementary mechanisms of contaminant removal. To quantify the benefits of enhanced robustness, a series of system-wide chemical challenge tests were performed, both with and without ozone/BAC, to simulate the introduction of unexpected chemical spikes in the feedwater. Challenge tests were performed with low-molecular weight, uncharged compounds (1,4-dioxane, NDMA, acetone, and formaldehyde), which are the class of compounds known to be most challenging for removal through advanced treatment.

Concentrations of the specific compounds were monitored during chemical spiking tests throughout the treatment train. The reductions of all four spiked chemicals were greater with the inclusion of ozone/BAC pretreatment (Figure 3). Ozone/BAC enhanced the cumulative removal of all of the spiked organics and provided an additional barrier, particularly against those that are poorly removed through FAT treatment alone, such as acetone and formaldehyde. These results reinforce the importance of a robust treatment train that is able to control a broad variety of chemicals, both known and unknown.

Enhancing RO crediting

Given its proven ability to remove dissolved constituents and pathogens, RO is the workhorse of many potable reuse treatment trains. Although laboratory studies have demonstrated its ability to reject as much as 99.999 percent (5 logs) of virus, existing surrogate monitoring techniques generally provide no more than 2 logs of treatment credit for RO. This project aimed to address the potential under-crediting of RO. Challenge tests were used to (1) establish the degree of virus removal under both normal and compromised operating conditions, and (2) assess the ability of standard and novel surrogates to conservatively track virus removal.

Both spiked and naturally occurring compounds were tested as surrogates that could provide higher degrees of pathogen removal crediting (Table 2). MS2 bacteriophage removal served as the benchmark for virus removal across a range of system integrities that was varied by removing O-rings from different locations within the RO pressure vessel. Many of the naturally occurring surrogates could not provide increased sensitivity due to detection limits; others did not demonstrate an appreciable increase in the log removal relative to current methods. The most promising naturally occurring surrogate was strontium, which was able to demonstrate removals as high as 3.5 logs. Of the spiked surrogates, the fluorescent dye 3D TRASAR® demonstrated the highest removal (approximately 3.5 logs). While providing higher demonstrable removals through RO, these surrogates were also consistently conservative compared to the MS2 phage (4.6 to 7.3 logs) even during integrity compromises. Moving forward, these results can inform the selection of appropriate RO surrogates and enable utilities to balance the benefits of higher pathogen credits with the costs of increased monitoring.

DPR mechanical reliability

In addition to knowing how the system performs when it is up and running (inherent reliability), it is also important to quantify the degree to which the system is operational and functioning as designed (mechanical reliability). The goal of the analysis was to document the dependability of the mechanical systems and to identify the deficiencies whose correction would improve system reliability. The approach was to document issues that occurred during testing, evaluate the impact of these events on water quality, and summarize lessons learned that can help inform the scale-up of this type of treatment train from demonstration-scale to full-scale.

Failure, maintenance, and malfunction events were catalogued and cross-referenced with performance data to determine their impact on water quality. Through this evaluation, it was shown that no critical failures occurred during the course of the testing, demonstrating the high mechanical reliability of the treatment train. Critical malfunctions did occur in the form of communication errors between the unit processes and the central programmable logic controller. These malfunctions

Figure 2

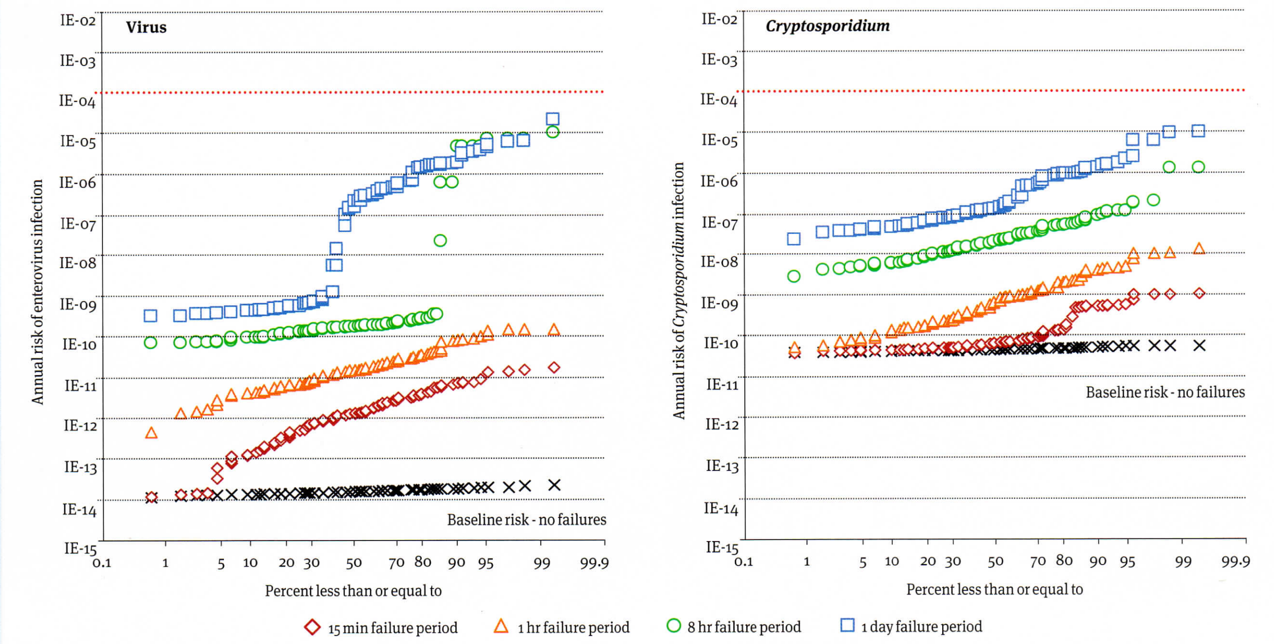

Figure 3

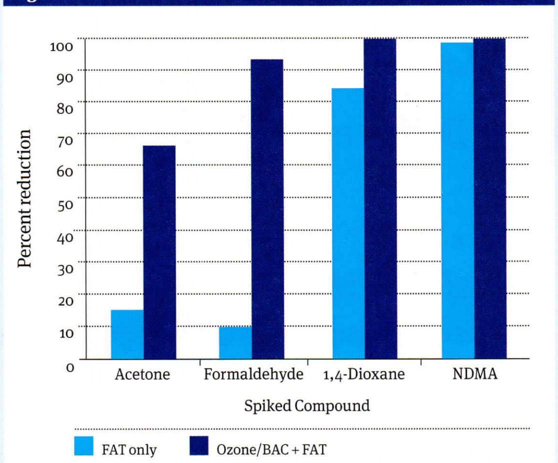

Figure 2. Estimated annual risks of infection from enterovirus and *Cryptosporidium* for baseline (i.e., no failures) and failure conditions. Dotted red line represents risk threshold of 10^{-4} infections per person per year. Enterovirus risk curve reflects the inclusion of free chlorine disinfection, which achieves 6 logs of virus inactivation credit.

Figure 3. Average percent reductions for four spiked challenge compounds through full advanced treatment (FAT) only and through FAT with ozone/ biologically activated carbon (BAC) pretreatment.

resulted in immediate shutdowns, so they posed no threat to public health.

Several strategies were identified to mitigate both critical and non-critical issues. Ensuring a robust communication system is essential for DPR systems, particularly given the need to detect and respond quickly to any excursions in water quality. These findings highlight the need for a rigorous commissioning process to validate and confirm the reliable function of the communication systems. For mechanical components such as UV bulbs, UV ballasts, and pumps that are likely to experience failure, stocking key replacement parts onsite helped to limit downtime and reduce impacts on system-wide availability. Overall, the results of this analysis showed that treatment systems can be designed with a high degree of mechanical reliability.

Enhancing ozone monitoring

The reliable control of ozonation in recycled water can be challenging due to variations in water quality, high ozone demand, and rapid ozone decay. These factors can pose significant challenges for process control and introduce greater treatment variability. One strategy for improved control is the use of multiple dissolved ozone meters, which provide real-time monitoring of residuals throughout the contactor and continuous demonstration of pathogen control.

Four ozone meters were evaluated for their ability to provide consistent and reliable measurement of ozone residual in a wastewater application. Metrics of interest included accuracy and precision of measurements as well as maintenance needs. Online meter performance was compared on a daily basis to "grab" samples using the indigo method, a standard method for measuring ozone residual concentrations. In general, foulants and overall deterioration of meter components caused the largest magnitude and frequency of measurement errors. The challenging quality of the treated wastewater accelerated meter fouling and resulted in higher than normal preventive and corrective maintenance (as compared to manufacturer specifications). Despite efforts to mitigate these impacts, unanticipated meter failure is likely to occur when using these meters for wastewater applications. Meter redundancy can limit monitoring downtime and provide additional assurance of meter accuracy.

Conclusions

DPR will rely to an unprecedented extent on treatment and monitoring to protect public health. The suite of studies undertaken in Reuse-14-12 demonstrated the ability of a DPR treatment train consisting of ozone, BAC, MF/UF, RO, and UV/AOP to provide consistent protection against both pathogens and chemicals. The studies also identified important lessons related to the mechanical reliability of DPR systems, including strategies to ensure the proper functioning of monitoring, communications, and treatment systems. Ultimately, advanced treatment will be situated within the broader context of DPR reliability features – e.g., source control, wastewater treatment, and effective operations – further ensuring the viability of these schemes as alternatives to conventional water supplies.

Authors' Note

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