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Achieving Reliability in Potable Reuse: The Four Rs

THE FOUR Rs—RELIABILITY, REDUNDANCY, ROBUSTNESS, AND RESILIENCE—PROVIDE A FRAMEWORK FOR DEVELOPING POTABLE REUSE SYSTEMS TO ADDRESS INCREASING NEEDS FOR SUSTAINABLE WATER RESOURCES AND TO MAINTAIN CONSISTENT PROTECTION OF PUBLIC HEALTH.

The need for sustainable water resources is growing all the more urgent as pressures on historical sources mount. The global effects of water shortages are worsening in the face of climate change and population migration, which further strain the delicate politics of water rights within and among countries. The time to identify new sustainable sources is now. The logic of potable reuse (i.e., the use of recycled wastewater for potable applications) is growing increasingly clear. Not only does it offer renewable, drought-proof supplies, but it also bolsters independence and provides greater dependability (Leverenz et al, 2011). The local nature of reuse reduces energy and conveyance costs, lowering carbon footprints and providing greater protection against natural disasters. As countries grapple with aging infrastructure, regional water solutions that reduce new infrastructure demands will be critical (Sedlak, 2014; Hering et al, 2013).

Although de facto potable reuse has existed throughout history, the new paradigm of planned reuse offers a way to significantly expand the scope of reuse of the national water supply while providing greater control of public health (NRC, 2012). Its significance is reflected in the global distribution of existing projects, from Europe to Africa, Asia, Australia, and to the Americas (Gerrity et al, 2013; Lahnsteiner & Lempert, 2007; Bixio et al, 2006). Given the global effect of water shortages, however, flexibility in treatment must take the place of the one-solution-fits-all mindset. Diversity in potable reuse treatment options is needed to meet the constraints of different locales. Although diversity should be sought, one element must tie all potable reuse systems together: this unifying sine qua non is public health protection. Attention to this principle is critical because the entire concept of potable reuse challenges the basic principle of separating sewage disposal from water supply, which is a public health protection fabric that is woven throughout the actions that created one of the most important public health miracles of the 20th century (CDC, 1999). Thus, developing basic principles to ensure safe design and operation is critical to steering potable reuse down sustainable paths. This article offers a framework for developing potable reuse systems that provide consistent protection of public health.

POTABLE REUSE

To date, nearly all potable reuse projects have engaged in indirect potable reuse that relies on the environment (e.g., aquifers, reservoirs) to further treat, monitor, and store recycled water before consumption. Comparatively, direct potable reuse eliminates the environmental barrier, instead piping recycled water directly into a drinking water treatment plant (i.e., raw water augmentation) or a treated water distribution system (i.e., flange-to-flange reuse) (Leverenz et al, 2011). Decreasing the time and distance between treatment and consumption is a main strength of direct potable reuse; however, it is also its main weakness because the time to detect and respond to failures that might threaten public health is shortened, placing higher demands on the system's ability to prevent and rapidly respond to such failures.

The framework proposed here places consistent public health protection as its main goal (reliability) and is supported by concepts that both prevent failures (redundancy and robustness) and respond to those that occur (resilience). These "four Rs" are intended to provide the industry with a helpful way to understand and easily recall the issues of safety in potable reuse. Special emphasis has been placed on defining terms (see the sidebar on this page), given the widespread and intermingled use of the applicable terminology. Our discussion focuses on a single definition for each "R" term that is appropriate for the potable reuse context, beginning with the cornerstone concept of reliability. Traditional discussions of public health protection in drinking water emphasize using multiple barriers in treatment (Velz, 1970). The four Rs do not replace the multiple-barrier concept; rather, they provide a framework that builds on this concept to promote safety. Throughout this discussion, examples will be given to illustrate the connection between the concepts.

RELIABILITY

Given the primary importance of public health protection, the main goal of the framework must be to deliver safe water to the consumer. This goal is identical to the one we have sought to achieve for the past century in conventional drinking water systems. As we engage new reuse paradigms, it is logical that potable reuse systems should match the level of public health protection provided by conventional sources. The industry is undertaking an intensive effort to understand how to develop potable reuse concepts that ensure equal protection for all drinking water applications (CDPH, 2014; Crook et al, 2013; Trussell et al, 2013;

Potable Reuse Primer

Acute versus chronic contaminants—Probability distribution functions can be developed for the two main contaminants of public health concern: pathogens and chemicals. The consequence of performance variability, however, is not equivalent for all types of contaminants. For contaminants that pose chronic health concerns (i.e., those that manifest health effects over long periods of exposure), short-term fluctuations in concentration are less important than average lifetime exposure levels because brief periods of higher exposure can be buffered by periods of lower exposure. This holds for the vast majority of chemical contaminants, including most chemicals of emerging concern. For pathogens, however, public health effects can result from as little as a single exposure (Haas & Trussell, 1998). Given the constant threat of such contaminants, potable reuse systems must provide continuous protection against pathogens and acute public health threats. The primary public health concern in potable reuse, therefore, is pathogens.

Reliability—The ability of a potable reuse system to provide water that consistently meets or exceeds the public health protection provided by existing drinking water supplies.

Redundancy—The use of measures beyond minimum requirements to ensure that treatment goals are more reliably met or that performance can be more reliably demonstrated.

Robustness—The ability of a potable reuse system to address a broad variety of contaminants and resist catastrophic failures.

Resilience—The ability of a treatment train to successfully adapt to failure.

NRC, 2012; NRMMC et al, 2008; NRMMC, 2006).

For conventional drinking water processes, demonstrating process performance generally has been commensurate with the level of threat in traditional source waters. With potable reuse, were a failure to occur, the higher pathogen loading in the wastewater source poses a larger potential threat to the population. To respond to this threat, potable reuse may require not only greater removal but also greater consistency of treatment if an equivalent level of protection, as in conventional processes, is to be provided.

For potable reuse, reliability can be defined as the ability of a system to provide water that consistently meets or exceeds the public health protection provided by existing drinking water supplies. The more consistently a system distributes water that meets these requirements, the more reliable it is. This definition directs the current potable reuse discussion while echoing previous potable reuse discussions (NRC, 2012; Crook et al, 1999; NRC, 1998, 1984, 1982; Robeck et al, 1987; USEPA, 1980). Other fields, such as the power-generating industry, have identified availability—or constant provision—as their key goal (Keogh & Cody, 2013). Although availability is an important goal, the water industry also has unique challenges because of its role in public health protection; therefore, constant protection (reliability) has always taken precedence over constant provision (availability).

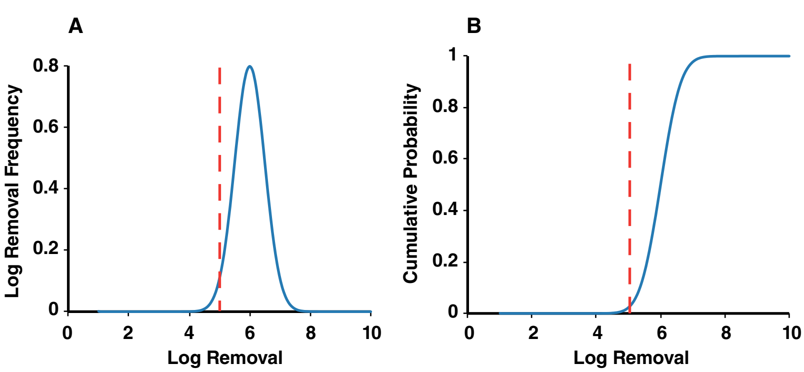
> As we engage new reuse paradigms, it is logical that potable reuse systems should match the level of public health protection provided by conventional sources.

Quantifying reliability: The probability distribution function. For the concept of reliability to be useful, it must be quantifiable in measuring potable reuse performance and the safety it provides. One way to gain insight into performance is through the use of probability distribution functions (PDFs), which describe how frequently a treatment process achieves different levels of performance (Haas & Trussell, 1998). The blue curve in Figure 1, part A, shows a sample PDF that assumes performance fits a simple, normal distribution. Several key characteristics emerge: process performance is not static but varies to different degrees, often with a tendency toward some central value. Although the process in Figure 1, part A, achieves a 6-log removal on average, it is as likely to achieve less than 6 logs as it is to achieve more than 6 logs. The system might be said to "safely" achieve 4-log removal because it removes more than 4 logs nearly all of the time; it also rarely achieves greater than 8 logs.

PDFs can be used to put a number to the abstract concept of reliability. We can quantify reliability by comparing unit performance against a given treatment goal. For example, a 5-log removal goal is overlaid as a dashed red line on both distributions in Figure 1. The PDF in Figure 1, part B, expresses the same data as Figure 1, part A, as a cumulative distribution, with each point showing the probability of the system achieving less than a given level of performance. By focusing on the intersection of the cumulative distribution and the treatment goal, we can measure the probability of the process achieving less than its stated goal. In the particular case illustration, the system fails to achieve the 5-log goal 2.3% of the time, or 8.4 days per year. Stated conversely, the process meets its goal 97.7% of the time.

PDFs can be developed by taking repeated measures of process performance and modeling the resultant data (Soller et al, 2002; Gagliardo et al, 2001; Olivieri et al, 1999). Because the levels of pathogens in drinking water are difficult to measure directly, surrogates of performance are often monitored; these measurements are then transformed to estimates of pathogen reduction using generally accepted standards. For example, to quantify the reliability of ozone in the control of *Giardia* cysts, a three-step process could be used. Ozone dose, or residual concentration × contact time

FIGURE 1 Sample probability distribution function of an ozone system designed to achieve 5-log removal of *Giardia* cysts: (A) continuous and (B) cumulative distributions



(CT), is calculated using measured values of residual ozone concentration and contact time. Ozone treatment is then transformed to a log inactivation value using US Environmental Protection Agency (USEPA)–approved CT tables based on dose and temperature. The use of online instrumentation and controls would allow the system to constantly track ozone performance and compare it against treatment goals. To understand the true reliability of the system, performance should be monitored over an extended period; in this way, all factors that might affect performance will be included in the performance dataset, including variations in source water quality, process efficiency, and operations.

Given the constraints of our existing monitoring technologies, it is not possible to detect microbiological contaminants at the low levels we seek to achieve in finished drinking water (Olivieri et al, 1999). Consequently, it is impractical to directly measure the removal of pathogens through an entire treatment train. The reliability of a potable reuse treatment train can, however, be modeled as the cumulative performance of multiple unit processes that each achieve some degree of attenuation. Multiple methods are used to model the performance of multiple processes, including Monte Carlo analysis (Olivieri et al, 1999; Haas & Trussell, 1998). Briefly, the performance of each process in the train is determined as described previously. Monte Carlo simulation is then used to construct a single PDF of the entire treatment train based on the individual PDFs. One simulation consists of randomly sampling performance from each of the unit process PDFs and calculating overall removal through the train (e.g., $\text{removal}_{\text{unit 1}} + \text{removal}_{\text{unit 2}} + \ldots = \text{removal}_{\text{treatment train}}$). Because a single iteration yields one estimate of treatment train performance, the process is repeated multiple times to develop a PDF of the entire system (Olivieri et al, 1999). This same approach was used by the USEPA in the cost–benefit analysis for the Long Term 2 Enhanced Surface Water Treatment Rule (USEPA, 2005).

As with the unit process PDF, the treatment train PDF provides a breadth of information, including both the central tendency of process performance and variability. This information allows a determination for how frequently the system will fail to meet its requirements for public health protection. Ultimately, the water industry must show that potable reuse can be performed safely; we believe its performance is best understood by quantifying the likelihood and degree of failure—and the risk associated with it.

Achieving reliability: The four Rs. Given the focus on controlling failures, two main strategies can be used to achieve reliability in potable reuse: failure prevention and failure response. The remaining three Rs are used to support these two strategies, with redundancy and robustness contributing to failure prevention and resilience addressing failure response (see a representation of this concept on this page).

Representation of a reliability framework for direct potable reuse. The two strategies for achieving reliability are failure prevention (through redundancy and robustness) and failure response (through resilience).

REDUNDANCY

In general, our use of *redundancy* refers to the treatment train's design with equipment added beyond the minimum required to achieve treatment goals. In water treatment practice, this redundancy generally takes one of two forms: (1) the addition of standby units added in parallel with other units in the process train (e.g., pumps, filters, ultraviolet [UV] reactors, microfiltration [MF] trains) or (2) the use of more conservative treatment (e.g., addition of extra process capacity or extra treatment processes). The installation of standby equipment for certain critical monitoring tasks (e.g., disinfectant residual) is another form of redundancy that is receiving increased attention. Although all these forms of redundancy are important, they do not all serve the same purpose. Specifically, the addition of parallel or standby units is primarily designed to ensure that the system can more reliably operate at its design capacity, whereas the other forms of redundancy, such as the provision of extra treatment and standby monitors, are designed to ensure that the system can both more reliably meet its treatment goals and demonstrate that it has done so. These latter forms of reliability are the focus of this discussion.

As the term is used here, redundancy's role is to serve the main goal—reliability—by preventing the distribution of water that fails to meet requirements. To this end, *redundancy* is defined as the use of measures beyond the minimum

The four Rs do not replace the multiple-barrier concept; rather, they provide a framework that builds on this concept to promote safety.

requirements that ensure treatment goals are more reliably met or that performance is more reliably demonstrated. In systems designed for potable reuse, continuous and verifiable performance has an especially high priority. As time in the environmental or engineered buffer decreases, the system must compensate by providing higher levels of treatment and monitoring. Redundancy can be included to bolster both of these concepts.

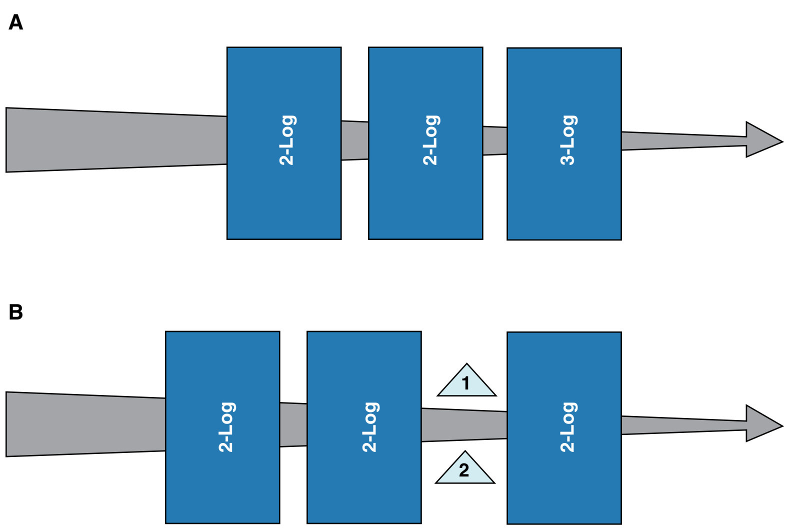
The example in Figure 2, part A, shows treatment redundancy using a multiple-barrier system with extra treatment. The system achieves redundancy by providing a 7-log removal capability when the minimum requirement is 6 logs. The benefit of additional treatment is that failures can be endured without jeopardizing the system's ability to meet its goal. For example, the system could withstand a failure that dropped performance by 1 log without affecting reliability because it would still meet its 6-log goal. In this way, treatment redundancy contributes to the creation of "fault-tolerant" potable reuse systems that can suffer failures while still minimizing the compromise to the entire system. An added benefit of treatment redundancy is that it is indiscriminate in the type of failure against which it provides protection, so compromises in monitoring, treatment, operations, or response can all be addressed through increased treatment.

As potable reuse systems are designed to rely increasingly more on treatment than on an environmental buffer, continuous verification of process performance also becomes more important. Thus, redundancy in monitoring may also improve reliability by increasing the probability that treatment performance will be accurately demonstrated (Figure 2, part B). An important benefit of redundancy as a reliability strategy is that the technology needed to build redundancy into our systems is available today. This is true for both treatment redundancy (Figure 2, part A) and monitoring redundancy (Figure 2, part B).

The benefit of treatment redundancy can be quantified by measuring its impact on reliability. Starting with the PDF averaging a 6-log removal, adding treatment redundancy (to 7- and 8-log average removal) shifts the PDF further to the right toward higher degrees of removal performance (Figure 3). As before, reliability can be measured by looking at the intersection of the stated removal goal (5-log removal) and the PDF. As removal redundancy is added to the system, the probability of failure decreases with each additional log of treatment, leading to increasingly higher degrees of reliability.

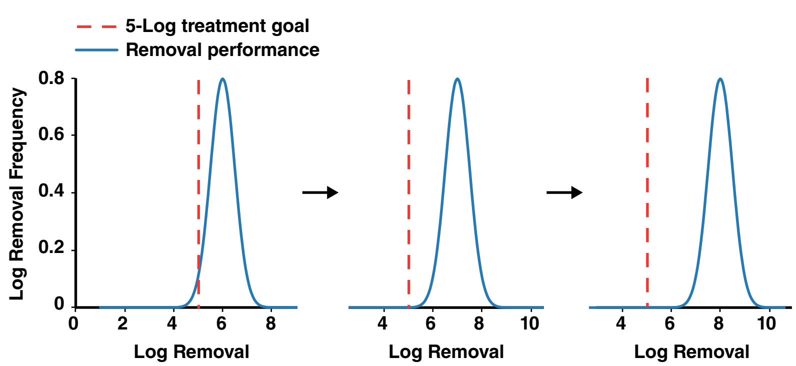
Because additional treatment comes at a cost, redundancy in removal should be added judiciously.

FIGURE 2 Types of redundancy, including (A) treatment* and (B) monitoring† redundancies



*Removal exceeds the 6-log goal
†Removal meets the 6-log goal

FIGURE 3 Benefit of treatment redundancy in achieving reliability



	6-Log average—%	7-Log average—%	8-Log average—%
Probability < 5 Log	2.3	0.003	0.0000001
Probability > 5 Log	97.7	99.997	99.9999999

One important question is, "How much treatment redundancy is enough?" In answering this question, we can look to conventional drinking water regulations. Many regulations are developed with the goal of reducing contaminants to achieve given levels of risk (NRMMC et al, 2008; NRMMC, 2006; USEPA, 2006, 1989; Regli et al, 1991). One option, therefore, is to specify that potable reuse treatment trains include sufficient removal redundancy to meet the same risk levels as drinking water.

For example, an annual risk of *Giardia* infection of 1 in 10,000 for each person each year may be selected, as is implicit in the Surface Water Treatment Rule. To accomplish this, *Giardia* concentrations must be reduced to 6.75×10^{-6} cysts per liter in the product water (Regli et al, 1991; USEPA, 1989). As concentrations are reduced below this level, lower levels of risk result. Therefore, removal redundancy could be added to ensure that the treatment process meets (or provides better protection at) a specified level of risk with a given level of consistency. Recall that a treatment that achieves the risk-based level on average will fail to reach these levels roughly half of the time. Additional removal redundancy increases the probability that the treatment will meet or exceed the risk-based goals.

Although redundancy offers a way to increase potable reuse reliability, several other elements affect performance, including design, operations, maintenance, source control, and failure response (NRC, 2012; Tchobanoglous et al, 2011; NRC, 1998; Moubray, 1997; Pescod, 1992). The inclusion of these elements into potable reuse systems increases system reliability, and, as with redundancy, shifts the PDFs to the right toward higher levels of performance.

ROBUSTNESS

Redundancy promotes reliability by preventing failures from occurring. The second component in the failure-prevention strategy is robustness. Robustness describes the ability of a potable reuse system to address a broad variety of contaminants and resist large-scale, catastrophic failures.

Where addressing a broad variety of contaminants is concerned, robustness is the use of a diversity of barriers to control a diversity of contaminants (NRC, 2012). The chemical universe is a large, varied, and ever-growing collection of compounds with a variety of physical-chemical properties. Chemicals run the spectrum from large to small (high to low molecular weight), charged to uncharged, biodegradable to refractory, man-made and "nature"-made, hydrophilic and hydrophobic, polar and nonpolar, strongly sorbent and weakly sorbent, and aliphatic and aromatic, among others. Because of this range of chemical characteristics, no single process is effective against all of this diversity. Williams and coauthors (2014) illustrated this diversity in treatment response in a convenient overview table addressing a variety of chemicals and treatment processes.

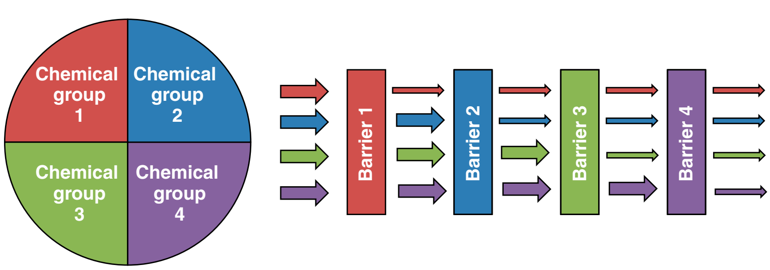
One answer is to use a diversity of barriers in a multiple-barrier system, each targeting a different class of chemicals. Supplying diverse barriers abates the threat of any single group of chemicals (Figure 4).

The fate of four chemicals through the treatment process will be discussed briefly in an example: 17β-estradiol, carbamazepine, *N*-nitrosodimethylamine (NDMA), and 1,4-dioxane. Important chemical differences between these compounds affect their removal from a given process, including differences in size (i.e., molecular weight), biodegradability, and susceptibility to photolysis or oxidation (Figure 5, part A) (Williams et al, 2014). No single process is capable of removing all of these compounds, although many processes provide at least partial protection against many of them. By providing treatment that incorporates diverse unit processes, robustness can protect against diverse chemical threats (Figure 5, part B).

This kind of robustness is also important for controlling pathogens. As with chemicals, pathogens have a

> For potable reuse, reliability can be defined as the ability of a system to provide water that consistently meets or exceeds the public health protection provided by existing drinking water supplies.

FIGURE 4 Robustness and the use of diverse barriers to protect against diverse contaminants

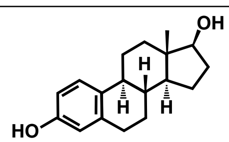
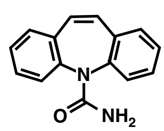
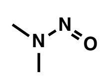
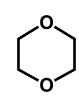


wide range of sizes and susceptibilities to treatment. Robustness has been included in treatment schemes and regulations, dating back to the Surface Water Treatment Rule (USEPA, 1989), which required both filtration and disinfection to control viruses and *Giardia* cysts. This same robustness concept should also be used to control pathogens in potable reuse schemes.

The benefits of this type of robustness in potable reuse can be illustrated by evaluating the control of chemicals and pathogens through a robust "full advanced treatment" train consisting of secondary treatment followed by MF, reverse osmosis (RO), and UV/advanced oxidation process (AOP) (CDPH, 2014). The removal of the various contaminants through this treatment train is schematically shown in Figure 6, with the size of the arrows corresponding to the relative reduction. The picture that emerges is clear—no single process can adequately address all concerns. The diversity of contaminants can only be properly addressed with a robust treatment train that uses multiple mechanisms. Without biological degradation, physical removal, and both physical and chemical destruction, the full, advanced treatment train would not achieve its goals. Even with this degree of robustness, certain contaminant groups, such as viruses, may not be fully addressed by the treatment train (this assumes 12-log virus removal per the groundwater recharge reuse regulations of the California Division of Drinking Water, with typical removal credits through the treatment process: 2-log reduction through secondary treatment, 0 logs through MF, 2 logs through RO, and 6 logs

FIGURE 5 (A) Four diverse chemical contaminants and (B) the effectiveness of treatment processes in removing chemical and microbial contaminants

A

	17β-estradiol	Carbamazepine	NDMA	1,4-dioxane
Description	Synthetic sex hormone for birth control	Anticonvulsant/ mood stabilizer	Disinfection by-product	Stabilizer
Structure				
Characteristics	Large MW Uncharged Biodegradable Low photolysis Sensitive to OH˙	Large MW Uncharged Low biodegradation Low photolysis Sensitive to OH˙	Small MW Uncharged Low biodegradation High photolysis Low reaction to OH˙	Small MW Uncharged Low biodegradation Low photolysis Sensitive to OH˙

B

Compound	Cl_2	Biological	MF	GAC	O_3	UV/AOP	UV	RO
Chemical contaminants								
17β-estradiol	Excellent	Excellent	Poor	Excellent	Excellent	Excellent	Poor	Excellent
Carbamazepine	Poor	Poor	Poor	Good	Excellent	Excellent	Poor	Excellent
NDMA	Poor	Fair	Poor	Poor	Poor	Poor	Good	Fair
1,4-dioxane	Poor	Poor	Poor	Poor	Fair	Good	Poor	Fair
Microbial contaminants								
Giardia	Fair	Unknown	Excellent	Poor	Good	Unknown	Excellent	Excellent
Cryptosporidium	Poor	Unknown	Excellent	Poor	Fair	Unknown	Excellent	Excellent
Virus	Excellent	Unknown	Poor	Poor	Good	Unknown	Good	Excellent
Bacteria	Good	Unknown	Good	Poor	Good	Unknown	Excellent	Excellent

AOP—advanced oxidation process, Cl_2—chlorine, GAC—granular activated carbon, MF—microfiltration, MW—molecular weight, NDMA—*N*-nitrosodimethylamine, O_3—ozone, OH˙—hydroxide, RO—reverse osmosis, UV—ultraviolet irradiation

*UV doses applied in AOP settings (typically 500–1,000 mJ/cm²), which often are in great excess of the doses needed for pathogen inactivation (50–100 mJ/cm²).

through UV/AOP). An additional layer of robustness—such as free chlorine disinfection—may be required to fully address viruses and meet the treatment goals.

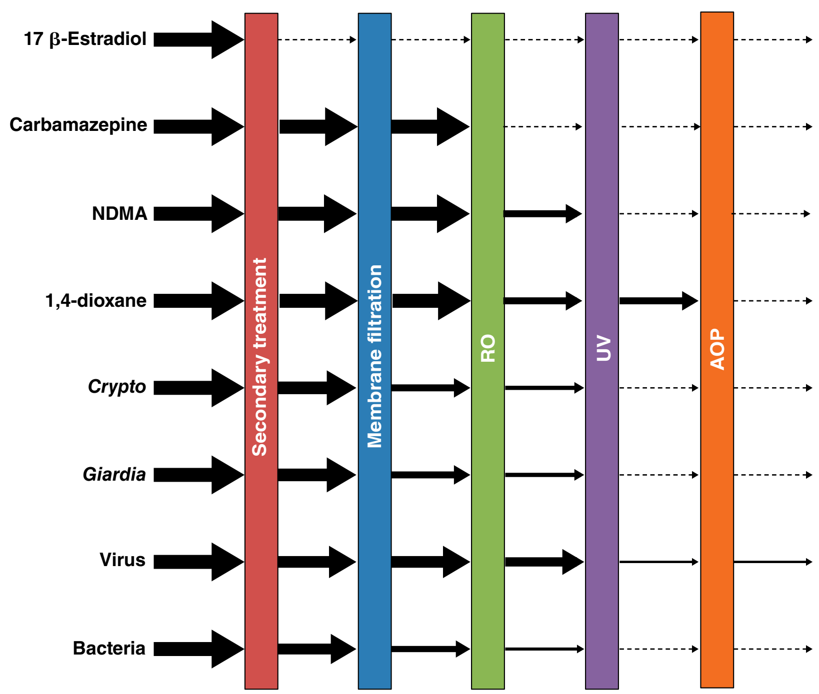
Protection against unknowns. Engineering is largely an empirical endeavor; thus, progress in water treatment design and regulation has mainly been gained by experience. As we have tested new technologies, discovered "emerging" contaminants, and come to better understand the consequences of treatments, regulations have adapted to protect public health. Examples of this occur throughout the history of water treatment, including the recognition that drinking water requires disinfection to control infectious diseases (McGuire, 2013; Crittenden et al, 2012a), to findings related to the health consequences of disinfection by-products (Bellar & Lichtenberg, 1974; Rook, 1974) and emerging pathogens such as *Cryptosporidium* (McGuire, 2006; USEPA, 2006). The consequence of these discoveries was the creation of new standards of practice and regulations such as the Disinfectants and Disinfection By-Product Rules and the various iterations of the Surface Water Treatment Rule. This empirical approach, by its nature, admits that there may be additional concerns we have not yet addressed. These unknowns pose multiple challenges, from treatment to regulation to public perception.

That there are unknown contaminants is not new; they exist in our drinking water as well as our recycled water. This threat is not unique to potable reuse systems, but it should be addressed. Even over the relatively short history of potable reuse, treatment modifications have already been adopted in response to the discovery of "new" threats. Initially, because RO was considered an absolute barrier to all contaminants, treatment trains ended with the RO process. With time, the industry recognized that some contaminants could pass through RO membranes at concentrations of health concern. The discovery of NDMA in RO permeate led to the addition of high-dose UV systems after RO—secondary, MF, RO, and UV—because UV was one of the few processes capable of further reducing NDMA concentrations. Later, 1,4-dioxane was also observed in UV-treated RO permeates, leading to the inclusion of advanced oxidation processes (McGuire et al, 2001). From this experience, the full advanced treatment train used in California typically applies five robust barriers: secondary, MF, RO, UV, and AOP. Recently, additional chemicals (including acetone) have been detected in the same effluents.

The empirical nature of the endeavor raises important questions. Will we always be relegated to responding to newly discovered

Redundancy is defined as the use of measures beyond the minimum requirements that ensure treatment goals are more reliably met or that performance is more reliably demonstrated.

FIGURE 6 Effectiveness of a robust advanced treatment train (MF/RO/UV/AOP) in the control of chemical contaminants and pathogens*



AOP—advanced oxidation process, *Crypto*—*Cryptosporidium*, NDMA—*N*-nitrosodimethylamine, RO—reverse osmosis, UV—ultraviolet irradiation

*Dotted lines show concentrations below public health thresholds.

unknowns? Can we ensure public health protection if we are not aware of all the contaminants present? How do we effectively address unknowns? Clearly, we can build off of our experience, which has shown us that increasing robustness addresses diversity. To date, we have largely responded reactively to new threats by incorporating additional robustness into our treatment trains. The same approach could be used proactively to cut off this reactionary cycle and provide protection against contaminants of which we are not yet aware. Determining what level of robustness should be used is a topic that the industry will need to address. For example, does the MF, RO, UV/AOP train require an additional barrier? How do the costs of installing additional barriers—such as ozone or biologically active filters—compare with the benefits of additional layers of protection against unknowns? What value does this protection provide us in terms of treatment, regulations, and public perception?

Where addressing a broad variety of contaminants is concerned, robustness is the use of a diversity of barriers to control a diversity of contaminants.

Greater resistance to failure. The multiple-barrier approach, as described by Velz (1970), has been incorporated into numerous regulations and guidance documents for the control of pathogens (NRC, 2012; USEPA, 2006, 1998, 1989). An important benefit of the multiple-barrier approach is increased resistance to failure. This brings us to the second kind of robustness: the ability to resist failures. In this case, robustness protects against catastrophic or "disproportionate" failures, as is shown in the following example (Crittenden et al, 2012b; Starossek, 2006; Trussell et al, 2000).

Consider two treatment trains, each achieving a 6-log removal of a contaminant. The first train uses a single process to achieve the 6-log removal, whereas the second uses three independent processes that each achieve a 2-log removal (Figure 7). Assume each unit process achieves its stated performance 99% of the time, with complete failure (0-log removal) occurring 1% of the time. During the course of a year, train 1 achieves its nominal 6-log performance for 361 days, with 3.7 days of complete failure. In comparison, train 2 has a slight decrease in the nominal 6-log performance (350 versus 361 days) and has approximately 2 weeks of intermediate levels of performance (2- to 4-log removal). When looking at complete failure, however, train 2 significantly reduces this period to 32 seconds per year. Increasing the number of process barriers substantially reduces the risk of total failure in return for a small compromise in the time at which the nominal design performance is achieved. By decreasing the risk of failure, the multiple-barrier approach aids in creating reliable potable reuse systems.

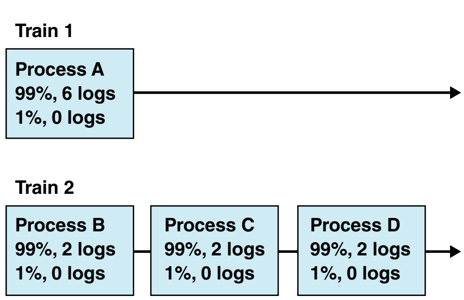
In summary, both robustness and redundancy show how multiple-barrier systems can prevent failures and thereby enhance reliability. Their means of achieving reliability are complementary: redundancy provides multiple barriers against a given contaminant, whereas robustness uses a diversity of barriers against a diversity of contaminants and improves the resistance to failure. The last concept—resilience—approaches the reliability question from another perspective—namely, from the assumption that despite all of our efforts, failures still occur.

RESILIENCE

Up to this point, the discussion has focused on the first pathway to reliability: failure prevention. The fact remains, however, that reliability must be achieved in potable reuse at all times, including during unexpected and rare events. Designing systems to prevent failure under all conditions has obvious limitations; for example, fail-proof design might require RO systems with redundant, oversized units in series, using independent and redundant backup power supplies for each system. The cost of designing a system with this goal may not be justified by the low likelihood of such a failure occurring. In short, potable reuse systems cannot reasonably be

FIGURE 7 (A) Treatment performance and (B) the benefit of the multiple-barrier approach

A



B

Removal	Train 1	Train 2
6 log	361 days	350 days
4 log		11 days
2 log		2.6 hours
0 log	3.7 days	32 seconds

designed to prevent failures under all possible scenarios.

Protecting the system from rare failure events is the domain of resilience, which is defined as the capacity of a potable reuse system to adapt successfully in the face of failures. This is the final key of the reliability framework. Resilience builds systems that are "fail-safe," which does not mean systems that never fail, but that they are designed to cause no harm to public health when failures do occur.

Resilience can be incorporated in two ways. Certain catastrophic failure events are rare but can be anticipated, such as natural disasters (e.g., floods, fires, earthquakes, tornadoes, tsunamis). Although these events rarely occur, preventive strategies can be developed to reduce their effects, such as in the seismic reinforcement of water treatment facilities and infrastructure in earthquake-prone regions or the use of redundant, separated power supplies in tornado-prone regions.

Another form of resilience is in using systems that respond reactively when failures occur. Examples of resilient system design include systems that automatically shunt untreated or undertreated flows to waste during power outages or that include backup power supplies to ensure consistent treatment during power failures. Thus, if power to the system fails for any reason, the system responds with resilience by either diverting untreated water or engaging a reactive response to ensure adequate treatment is maintained. In these scenarios, failure does occur, but the failure does not affect public safety. Such systems can be incorporated to protect against both rare failure events as well as common ones.

CONCLUSIONS

Creating a broad framework for safety in potable reuse is critical given the diversity of treatment approaches that can be used. Although the specific requirements may differ between sites (e.g., treatment criteria, constituents of concern, regulatory setting), certain principles should be applied and extended across all situations. We believe that reliability and its goal of public health protection should be the focus of all potable reuse projects. The concepts of redundancy, robustness, and resilience contribute to such systems by both preventing and responding to failures. These four Rs provide an overarching framework that protects consumers from contaminants and ensures public health.

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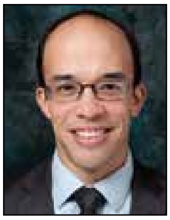

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