Debugging the Plant: Managing Reverse Osmosis Biofouling at a Groundwater Treatment Plant

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Commissioned in 2010, the Arcadia Water Treatment Plant treats local groundwater to provide approximately 10 mgd of treated water as part of the City of Santa Monica’s (Calif.) drinking water supply. The plant removes iron and manganese and then treats a portion of the water with reverse osmosis (RO) as a softening process to achieve desired levels of hardness. Shortly following the plant’s commissioning, biological fouling occurred, first at the pretreatment cartridge filters and then spreading to the RO units.

Chloramine dosing, long established as an effective strategy for RO biological fouling control in wastewater reuse, is not as widespread in groundwater treatment. Previous studies of chloramine use in surface water and groundwater RO systems reported an undesirable increase in salt transport, which can adversely affect treated water quality and decrease usable membrane life. Despite this, successful implementation of chloramine dosing was achieved at the Santa Monica facility, which has overcome fouling.

Keywords: biological fouling, chloramine, groundwater, operation, permeate flush, reverse osmosis

Biological fouling is one of the scourges of reverse osmosis (RO) membrane plant operation. Once established, biological fouling can be difficult and expensive to remove. Even when it is removed, it can quickly reestablish, resulting in increased energy costs, higher chemical costs, loss of production as a result of cleaning downtime, and a significant burden for operation teams.

Chloramine dosing has long been established as an effective strategy for biological fouling control for RO in wastewater reuse applications. While almost ubiquitous in those applications, the use of chloramine is not as widespread for groundwater treatment. Previous research using chloramine on surface and groundwater RO systems showed an undesirable increase in salt transport (Lozier 2005), which can adversely affect treated water quality and decrease usable membrane life. This effect was hypothesized as possibly resulting from iron catalysis of the chloramine to more potent oxidants, such as free chlorine, which may have oxidized the polyamide membrane structure. Further work suggested that iron and aluminum ions catalyze the reduction of chloramine and may form radicals that act to oxidize polyamide membranes (Cran et al. 2011).

The Arcadia Water Treatment Plant in Santa Monica, Calif., treats local groundwater to provide up to 10 mgd of treated water as part of the city’s drinking water supply. The plant removes iron and manganese and then treats a portion of the water with RO as a softening process to achieve desired levels of hardness. Shortly following the plant’s commissioning in 2010, biological fouling occurred first at the pretreatment cartridge filters before spreading to the RO units themselves. As described in this article, a methodical troubleshooting process was undertaken that succeeded in overcoming this fouling and eventually resulted in the successful implementation of chloramine dosing at the Arcadia facility.

PLANT DESCRIPTION

Source water. The Arcadia Water Treatment Plant sources water from a series of groundwater wells, including the Charnock Well Field. Prior to the plant’s construction, the Charnock Well Field had been shut down for more than 14 years because of contamination with methyl-tert-butyl-ether (MTBE), a gasoline additive. Water from the Charnock wells is treated with greensand filtration for iron and manganese removal, followed by granular activated carbon for MTBE removal before the water is combined with flows from other city-owned wells. This combined stream is then pumped to the Arcadia plant.

RO system. At the plant, the combined water stream is dosed with chlorine to aid in oxidation and capture of iron and manganese particles in manganese greensand filters. Following these filters, approximately 75% of the water is directed to the RO system where it is dosed with sulfuric acid and a proprietary antiscalant chemical to minimize the scaling of sparingly soluble salts on the downstream RO. Because the RO membranes are made of a thin-film composite polyamide material, they are not compatible with free chlorine, which can rapidly oxidize the membranes, resulting in greater passage of salt (loss of salt rejection) and, consequently, undesirable levels of dissolved solids in the RO permeate. To prevent this, sodium bisulfite (NaHSO₃) is dosed to quench the remaining free chlorine and protect the membranes.
The final step in pretreatment for the RO system consists of a set of cartridge filters to remove any fine colloidal particles that may foul the RO membrane feed–brine channels. The water is treated by up to three of four RO units (with one unit available in standby) in which the majority of dissolved salts are removed by the membranes. Between 82 and 85% of the water is produced as RO permeate low in total dissolved solids, with the remainder discharged as a concentrated waste stream.

The RO treated water (or permeate) then runs through a decarbonation tower to remove dissolved carbon dioxide before the permeate is reblended with the 25% of water that bypassed the RO. The resulting blend is then dosed with chlorine and ammonia to provide chloramine disinfection before delivery in the drinking water network. A schematic of the Arcadia plant is shown in Figure 1.

The plant has a total of four RO units (three on duty and one on standby), which are configured in a three-staged 39:19:9 pressure vessel configuration. Each pressure vessel is six elements long and is fitted in each stage with thin-film composite membranes. These membranes are in the ultralow-pressure brackish water range for this supplier, with a nominal per-element rejection of 99.5%. Table 1 summarizes the details of the current RO unit configuration at the Arcadia facility.

Each unit has been designed for a maximum recovery of 85% at an average permeate flow of 1,611 gpm. This equates to an average flow per unit area (or flux) of 13.4 gfd. A motor-assisted turbocharger recovers energy from the concentrate stream to provide a boost to the second stage.

**MEMBRANE BIOFOULING**

Since its commissioning, the Arcadia Water Treatment Plant has met overall water quality objectives and provided a valuable supply for the city. The operation of the RO system, however, has not met expectations, with lower production and higher energy consumption than expected, attributable in part to the effects of biological fouling.

The biological fouling was first observed on the RO membranes following a biological fouling episode on the upstream cartridge filters. High differential pressures were noted across the cartridge filters, and on inspection these were found to be covered with a slimy substance with a slight odor. The original plant design provided a dosing location for NaHSO$_3$ upstream of the cartridge filters in order to quench free chlorine (necessary in upstream pretreatment steps) before the RO system in order to avoid membrane damage from oxidation. The lack of a disinfectant at this step resulted in biological fouling of the cartridge filters, which then spread to the downstream RO units. Subsequent RO membrane autopsies confirmed that the foulant was biological in nature. The dosing point was subsequently relocated downstream of the cartridge filters to allow the filters themselves to operate with a chlorine residual, and biofouling was arrested at that location; however, the biofouling had subsequently spread to the downstream RO membranes themselves, where it became more difficult to remove and, more importantly, to prevent.

Figures 2 and 3 offer snapshots of plant performance from October 2013. The figures show the performance of the plant compared with design expectations for the system (as determined from RO projection software and adjusted for membrane age). Although performance across the four units varied, Figure 2 shows an increase of between 5 and 18% additional power consumption than anticipated, whereas Figure 3 indicates that RO unit production was between 7 and 15% lower than anticipated.

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<thead>
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<th>TABLE 1</th>
<th>RO unit configuration</th>
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<tr>
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<td>Stage 1</td>
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<tr>
<td>Number of pressure vessels</td>
<td>39</td>
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<td>Elements per vessel</td>
<td>6</td>
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RO—reverse osmosis
Normalized data. RO operational data were normalized to take into account changes in feedwater conductivity, membrane flux, and water temperature to ensure a representative assessment of membrane condition. Plant staff used proprietary software supplied by a membrane vendor and calculations as specified in ASTM D4516, Standard Practice for Standardizing Reverse Osmosis Data (ASTM International 2010).

A review of normalized differential pressure data from RO unit 1 is instructive in highlighting the effect of biological fouling (Figure 4). With a steady increase from the early phases of operation, the normalized differential pressure more than doubled in all three stages of the RO unit. This corresponded to a blockage of the feed–brine RO element channel in each system and also demonstrated that with time, the effects of biological fouling could be seen across all stages of the RO unit.

An autopsy report conducted for the city in March 2013 by Avista Technologies of San Marcos, Calif., provided further confirmation that biological fouling was present on the membranes and included the following findings:

- Reduced flow—at almost half that of a new membrane—was found at standard test conditions.
- A wet test determined significantly higher differential pressure per membrane than in standard operation (16 psi compared with 3–5 psi).
- The majority of the material collected from the membrane was organic in nature.
- A biological slime was noted on the surface of the membrane.

INITIAL BIOFOULING MITIGATION STEPS

**Cartridge filter chlorine residual.** The original plant configuration included a dose of NaHSO₃ immediately upstream of the RO cartridge filters to quench any residual chlorine from the upstream greensand filters. Following the identification of biological growth in the cartridge filters, plant staff reconfigured the NaHSO₃ dosing to downstream of the cartridge filters, which allowed a chlorine residual to effectively disinfect the cartridge filters themselves. Although biofouling was arrested at that location, however, it had subsequently spread to the downstream RO membranes themselves. Given that thin-film composite polyamide RO membranes will oxidize in the presence of free chlorine, an alternative strategy for biological fouling was required.

**Chemical cleaning.** The increase in differential pressures required significant additional chemical cleaning in order to maintain production. This included frequent high-pH formula cleaners targeting general organic and biological fouling, along with a number of cleaning chemicals specifically targeting the biological fouling itself. While the biologically targeted cleaner showed some short-term improvement, the fouling rapidly returned; consequently, in order to maintain production, up to weekly cleaning per RO unit was required. This cleaning frequency was substantially higher than had been anticipated in the plant design, with a resulting burden both in terms of chemical costs and time spent by plant operations staff.

**RO flushing.** A review was conducted of RO unit flushing to determine whether this could assist in mitigation of the biofouling. RO unit flushing is an automated process that typically occurs as a part of the shutdown sequence. The flush assists by displacing concentrated, sparingly soluble salts from the concentrate end of the unit train that may precipitate as a scale on the membranes. Although antiscalants are designed to minimize scaling in the RO membranes, these merely serve to delay the process and consequently cannot be relied upon to prevent scaling in a shutdown train for any period. In addition, an RO permeate flush can assist in the minimization of biological fouling, with the lower conductivity of the permeate possibly presenting an osmotic shock to the cell structures of the microorganisms as well as displacing any total organic carbon that may have accumulated on the feed side of the membranes.
During the plant flush procedure, the concentrate bypass valve is opened, and RO feedwater passes through all three stages of the RO train at low pressures. This is followed by a second flush using RO permeate. The existing flush sequence used RO feedwater for a duration of 10 min followed by RO permeate water for 4 min. To test the effectiveness of the flush, conductivity measurements of the RO concentrate were taken at various times during the flush period. The intent was to determine at what point the bulk of the saltier water had been displaced by the lower permeate flush.

The original flush duration was found to achieve only a partial reduction in conductivity, from approximately 2,800 µS/cm down to 2,200 µS/cm. As shown in Figure 5, with an extension in the duration of the permeate flush, the final concentrate concentration was able to be substantially reduced to less than 1,000 µS/cm; the more effective flush provided better mitigation to scaling and
biological fouling. At the time that this report was written, there were hydraulic issues that prevented this full duration being enabled at the plant automatically; however, a review was under way to address these issues and achieve a longer flush duration.

DISINFECTION WITH CHLORAMINES

In January 2014, the City of Santa Monica implemented chloramine dosing upstream of the RO as a strategy to combat the biological fouling. Compared with free chlorine, chloramine is a relatively mild oxidant and has been shown to prevent, and in some cases reduce, existing biological fouling without presenting significant damage to the RO membranes. Although chloramine is used ubiquitously in water reuse applications such as the Orange County (Calif.) Water District’s groundwater replenishment system, it has seen less use in groundwater applications.

One reason that chloramine may have not been widely used outside of reuse applications is that previous research testing chloramines on surface and groundwater RO systems showed an undesirable increase in salt transport (Lozier 2005), which can adversely affect treated water quality and decrease usable membrane life. It was hypothesized that this effect possibly resulted from iron catalysis of the chloramine to more potent oxidants, such as free chlorine, which may have oxidized the polyamide membrane structure. An alternative hypothesis (Cran et al. 2011) suggests that metal ions may degrade chloramine and result in the formation of amidogen (NH₃) radicals, which themselves attack the polyamide structure of the membrane. This risk was well understood, but in the case of the Arcadia plant, iron and manganese are removed in the pretreatment process and are at very low levels in the RO feedwater. In addition, the RO system operates with a bypass; consequently, there is some room for an increase in salt passage—which can be managed by blending—that may not be available at other facilities.

Chloramine dosing was implemented at the plant with a target of 1 mg/L as Cl₂. An ammonia dosing point was added upstream of the cartridge filters. Here, the ammonia combines with free chlorine already present at the greensand filters to form chloramine. NaHSO₃ was not dosed in normal operation; in the case of a loss of ammonia dose, however, NaHSO₃ is used to quench any free chlorine.

The modification for chloramine dosing was relatively economical, with a focus on the leveraging of existing assets. Dosing equipment originally configured for a waste stream coagulant dose was repurposed for ammonium sulfate dosing by reconfiguring chemical storage, pipework, and instrumentation to deliver ammonium sulfate upstream of the cartridge filters, where it would combine with chlorine already in the feedwater and form a chloramine residual. The plant post-treatment system was already configured to produce a chloramine residual to the distribution system. Chloramine dosing through the membrane system necessitated only some minor dosing adjustments to the treated water dosing system to maintain the required chloramine target, given that a significant portion (approximately 50%) of the chloramine persists into the RO permeate stream.

PERFORMANCE ASSESSMENT FOLLOWING TROUBLESHOOTING

Overall performance improvement. Following the implementation of chloramine dosing, all four RO units showed significant improvement in terms of both normalized differential pressure and also normalized flow. This clearly indicated that the strategy of implementing chloramine for biofilm control had proved successful. To illustrate the improvement in terms of energy consumption following the successful removal of biological fouling, Figure 6 compares data from October 2013 (i.e., before chloramine dosing) with data from after implementation of chloramine dosing. Figure 7 depicts the normalized pressure before and after chloramine implementation to remove biofilm.

It is instructive to review in closer detail the normalized data taken from before and after chloramine implementation.
Particular improvement was noted following a chemical cleaning that took place after chloramine dosing was implemented (Figure 8, point denoted by red arrow). A significant reduction in overall unit normalized differential pressure was observed, with improvement across all three stages. In addition, following chloramine dosing, the post-clean-in-place differential pressure would be better maintained, demonstrating that bio growth was not returning. Of particular note is that energy consumption was returned to a level similar to that anticipated in the original plant design (Figure 7).

Improvement was also noted in the normalized flow data (Figure 9) with a more subtle effect that can be seen particularly in the first stage, which showed steady improvement followed by stabilized performance. A separate scaling issue (which was not the main focus of this article), was also encountered in the third stage, as can be seen in the normalized data for that stage (Figure 9).

**Effect of chloramine on salt passage.** The effect of chloramine on salt passage was also of interest in this work to determine whether the chloramine resulted in any detrimental consequences with
regard to membrane rejection. For all four RO units, a gradual increase in salt passage across stages 1 and 2 has been observed from the beginning of operation (Figure 10). This is typical with the process of membrane aging and is within normal expectations of system performance. Following the addition of chloramine, this trend has slightly increased, which may be attributable to either more effective cleaning (which exposed more membrane area) or alternatively, some mild oxidation from the chloramine itself.

Significantly higher salt passage was seen in stage 3, likely because of the effects of membrane scaling in the third stage. After the addition of chloramine, an increase in salt passage has been noted following cleaning of the third stage. Following the peak, however, the salt passage returns to an improved level. These peaks appear to occur in line with cleanings.

The RO system at the Arcadia facility principally serves to remove hardness from the water, and the increase in salt passage does not pose a threat to water quality targets in the near term; therefore, no changes to the current blending ratio of feedwater to RO permeate are required. The city will continue to monitor membrane performance and its effect on water quality in the longer term. Given that water quality is blended, even a moderate loss of rejection could be tolerated at this facility without affecting treated water quality. Although chloramine may be accelerating the rate of membrane salt passage increase, in the case of this facility, there is flexibility in plant operation that may allow this tradeoff as a fouling mitigation strategy.

**CONCLUSION**

Following the addition of chloramine, along with improved flush cycles, biological fouling of Santa Monica’s Arcadia RO plant has been significantly reduced. Reduced biological fouling has resulted in significantly lowered RO unit normalized differential pressure, which in turn has reduced the RO feed pressure and RO process energy consumption to levels in line with the facility’s design expectations.

It is acknowledged that chloramine as an oxidant may accelerate the rate of salt passage increase at the membranes. At the Arcadia treatment plant, however, the tradeoff between the rate of salt passage increase and the effect of biological fouling is acceptable because feedwater blending is in place to meet water quality. Chloramines can be effective but must be assessed case by case.

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**ENDNOTE**

1Toray TMG20-430, Toray Membrane USA, Poway, Calif.

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**PEER REVIEW**

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**REFERENCES**

