No Easy Answers: ZLD Improvement Options for a 720-MW Power Generation Facility

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ABSTRACT

The water treatment infrastructure for a relatively new 720-MW power generation facility includes a Zero Liquid Discharge (ZLD) system. The ZLD system receives cooling tower blowdown as the primary feedwater. The ZLD system allowed unrestricted power plant operation for the first three years following initial power plant commissioning, but ZLD system bottlenecks restricted plant operation and required a significant amount of off-site wastewater disposal in subsequent years.

The system as currently configured consists of a fairly typical power plant ZLD system with six basic processes: cold-lime softening, multimedia filtration, wastewater reverse osmosis, brine concentrator, brine crystallizer, and belt filter press (BFP).

This paper examines the plant's ZLD system in detail, focusing on the following questions:

1. Why is the ZLD system a problem now when it wasn't a problem in the past?
2. What process improvements have been attempted in the past and with what results?
3. What options exist for eliminating or mitigating the ZLD process bottlenecks and at what cost?

The discussion answers these questions with the goal of providing a clear understanding where the plant is now, how it got here, where it can go in the future, and how much it will cost to get there.

THE PLANT AND ZLD SYSTEM

The subject plant is a 720-MW facility and consists of two combustion turbine-generators (CTGs), two multi-pressure, supplementary-fired heat recovery steam generators (HRSGs), and a single 3-pressure, reheat, condensing steam turbine-generator (STG). Additional water treatment infrastructure includes a Zero Liquid Discharge (ZLD) system to recover process wastewater to the maximum extent possible.

The ZLD system receives cooling tower blowdown as feedwater. The system as currently configured consists of six basic processes:

1. Clarifier/Softener
2. Multi-media Filters
3. Blowdown Reverse Osmosis System
4. Evaporator (Brine Concentrator)
5. Brine Crystallizer
6. Belt Filter Press

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WHY IS THE ZLD SYSTEM A PROBLEM NOW WHEN IT WASN'T A PROBLEM IN THE PAST?

A simplified process flow diagram appears in Figure 1. Figure 1 shows system design flow and actual system capacity based on operating history. Design flow appears as blue text while actual system capacity appears as red text. The "actual capacity" values indicate the processing capacity of the various process blocks based on the plant's historical data and experience. The figure shows a clear disconnect between "nameplate" design and actual operating capacity.

Figure 2 provides the same drawing, but it compares required treatment capacity to actual treatment capacity. It shows required flow values in blue text. These required flows must be maintained to support continuous plant operation. These flows were determined by evaluating the plant's operating history (power production and dispatch) over 12 months. Data from this time period was analyzed to determine the most limiting operational period in terms of wastewater production. Operation in the months of April through September is most limiting and this operating period was used as the "base case". As with Figure 1, Figure 2 shows a clear disconnect between actual capacity and required capacity. Although none of the process blocks can operate at design capacity, the front-end of the ZLD plant (softener, media filters, and reverse osmosis system) operates closer to the design flow than the back-end (evaporator, brine crystallizer, and belt filter press). Thus, the front-end produces more brine than the back-end of the ZLD plant can process.

The ZLD system design never included the equipment capacity or redundancy required to support continuous plant operation during the April to September time frame. In fact the ZLD system's actual operating capacity is not sufficient to allow continuous plant operation during the remaining months of the year (October through March), but the most limiting case occurs in the months of April through September.

Figure 1: Simplified Process Flow Diagram, Design Capacity vs. Actual Capacity

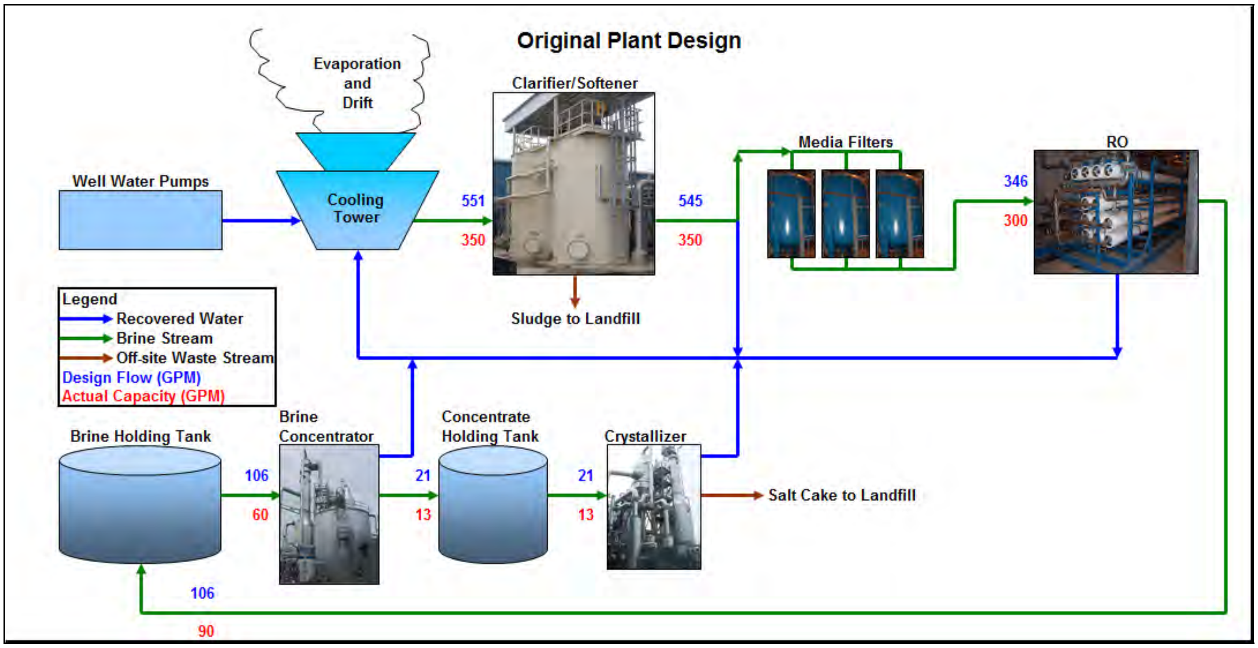
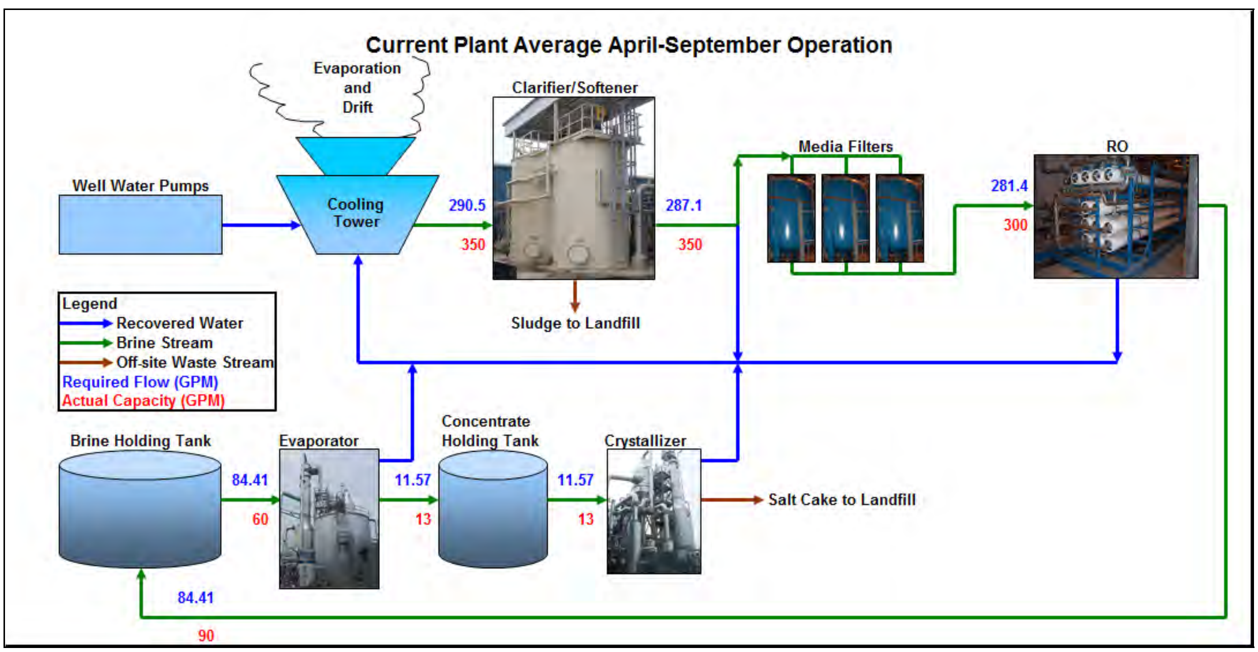


Figure 2: Simplified Process Flow Diagram, Required Treatment Capacity vs. Actual Capacity



Low dispatch masked this issue during the first three years of plant operation. A recent increase in dispatch made visible a problem which had always existed. In the past the plant was shutdown often enough and long enough to allow operators to work off wastewater produced during operation.

It's important to note that the process design basis is sound. The plant's basic ZLD processes can work, but the original equipment package did not include sufficient design margin to account for necessary downtime and performance degradation. Failure or degradation of any single equipment component lowers the capacity of the system as a whole. The single-train design employed at the subject plant magnifies the problem. In general terms the reliability of a serial process is a function of the multiples of the reliability of the individual components of that process. Consider a serial process that consists of six steps and assume that each of these steps exhibits a reliability of approximately 90%. The reliability of the process as a whole is approximately 54%.

This reliability gap can be addressed with storage. Consider the brine holding tank as an example. The evaporator design was intended to process 105 GPM of influent flow. The evaporator can actually process approximately 60 GPM on average. The April through September operating window (base case) generates an average evaporator feed flow of 84.4 GPM. The difference, 24.4 GPM, must be stored until such time as the plant is either shutdown or plant load decreases sufficiently to lower the average inflow to the brine holding tank to less than 60 GPM.

The storage tank level only lowers when inflow to the tank is less than the evaporator influent flow. When the storage tank is full the plant must either curtail production or shutdown in order to process the accumulated volume. The desired storage volume is determined by the number of days of continuous operation desired. The overall process reliability is still limiting – the plant must remain shutdown or curtail production longer in order to account for the lower reliability. Larger storage volumes provide a wider operating window, but the reliability issue remains.

Neither the front-end nor the back-end of the ZLD system operates at the original equipment design capacity. While bottlenecks remain in both portions of the system, the larger problem lies in the back-end of the ZLD system.

Based on data from multiple ZLD installations, the plant's back-end ZLD system is approximately 70% of the size required to support continuous plant operation in the base case. It's important to note that this is a best-case scenario that assumes all of the equipment operates normally. Mechanical problems can actually decrease the back-end system equivalent capacity.

This isn't a new problem. It was a problem in the past, but low plant dispatch made the problem manageable.

The ZLD acceptance test performed during initial system commissioning was not performed with design ZLD system feedwater. The power plant was not operating, so cooling tower cycles of concentration were much lower than design. That being the case, the performance test didn't accurately reflect the ability of the ZLD system to process and remove salt. The acceptance test confirmed that the piping and pumps could handle the design flow, but the test did not determine whether or not the system could handle the design salt loading. It's important to note that this issue arises on almost all ZLD performance tests. No mistakes were made. In an ideal world the ZLD performance test would be conducted with the cooling tower operating at design cycles of concentration and the plant at full load. These operating conditions rarely coincide with the time window available for the performance test.

PROCESS IMPROVEMENTS ATTEMPTED IN THE PAST AND RESULTS

Plant personnel have made many improvements to the front-end of the ZLD process with excellent results. Process improvements lowered front-end system startup time from 7 days to approximately 1-2 days. Improvements also lowered RO cleaning frequency significantly, allowing higher throughput with less downtime. In general terms the RO now operates near its design capacity with an equivalent reliability of approximately 95%. This improvement represents an outstanding accomplishment by the plant staff.

Since operators were able to achieve impressive results with the front-end of the plant's ZLD process, one naturally wonders why the plant staff can't work the same magic on the back-end of the plant's ZLD process.

Reliability and capacity in the front-end of the ZLD process rely substantially on the specific methods by which chemistry is applied and controlled and the rates at which flows and chemistry change, primarily flows and chemistry in the Clarifier/Softener. Many of these methods are within the operators' sphere of control. Operators developed procedures by themselves and their work provided the bulk of the process and reliability improvements. Mechanical changes to the system also provided improvements, but the operators' improved procedural and chemical control provided the bulk of the gains.

While chemical control is critical to control the rate of back-end equipment fouling, operators have relatively little control of this chemistry. Chemistry in the back-end of the system is driven primarily by natural precipitation. That means less opportunity to "tune" the back end to provide higher capacity and reliability. In broad terms the reliability and capacity of the ZLD back-end depend on the heat transfer reliability and capacity of the evaporator and crystallizer. These units foul over time and capacity decreases. Tuning can change the rate at which capacity decreases, but cannot stop it. Operators can't achieve the same gains on the back-end as they have on the front-end simply because they have less with which to work.

WHAT OPTIONS EXIST FOR ELIMINATING OR MITIGATING THE ZLD PROCESS BOTTLENECKS?

It's important to understand and appreciate that there are no easy answers. The plant's back-end ZLD equipment cannot process the wastewater produced during plant operation. The current system requires periodic plant shutdowns to work off accumulated wastewater inventory. This lack of capacity cannot be mitigated through process improvements. Experience with similar ZLD systems indicates that equipment cleaning, changes to chemical feeds, and changes to operating procedures may in total provide single-digit percentage (typically 3-7%) improvements in capacity and/or reliability. Though these improvements are valuable, they will not provide a system capable of supporting continuous plant operation under base case conditions.

Some combination of hauling liquid waste off-site and intermittent plant curtailment or shutdown represents the only realistic short-term solution. There are a host of possible long-term solutions, but the analysis determined that six options should receive a detailed economic evaluation. Many alternatives were modeled including discharge in whole or in part to others, hauling all water off-site, complete demolition and reconstruction of the ZLD system, and hundreds of other scenarios. The six options evaluated capture the broad range of possible scenarios and combinations of scenarios.

There are six basic long-term alternatives. Some, but not all, of these options would support continuous plant operation. The alternatives are:

1. Do nothing (continue with current system)

2. Add storage to the existing system

3. Add another train to the existing front-end

4. Add another train to the existing back-end

5. Install an injection well for RO reject

6. Install an injection well for cooling tower blowdown

The analysis concludes that Option 6 (install an injection well for cooling tower blowdown) would probably provide the lowest total cost and process risk. It also provides the highest reliability and allows continuous plant operation. Table 1 summarizes the options analyzed. The costs presented in Table 1 are preliminary. A detailed economic evaluation of each option should be pursued to review and confirm the economic drivers.

Table 2 provides a valuable summary of the various process improvements attempted and their results. Other plants facing similar issues may find value in what was attempted, what worked and, more importantly, what didn't.

ZLD IMPROVEMENT OPTIONS

The plant's existing equipment necessarily limits ZLD improvement options. A complete demolition and replacement of the existing ZLD system is possible, but at an extremely high capital cost. Even if this is done, operating cost would remain essentially the same. As stated earlier, the ZLD system design is sound. The problems with processing capability occur because the current system lacks redundancy and the back-end thermal equipment (evaporator, crystallizer, and belt filter press) cannot process the flow for which it was designed. The possible improvement options focus on two areas:

- Adding equipment to provide necessary redundancy and capacity

- Deleting components that limit processing capability and replacing them with lower cost and higher reliability alternatives

ZLD engineering often focuses on equipment nameplate capacity and capital cost. Risk analysis may be performed, but it's extremely difficult to quantify risk prior to system operation. That being the case, buyers tend to purchase the least expensive system available with a nameplate capacity equal to the required flow. The ZLD system feed chemistry may be uncertain and any deviation from the design feed chemistry results in a loss of ZLD system capacity. Other factors contribute to capacity and reliability challenges. The result is that ZLD systems seldom meet their nameplate capacities.

Effective system capacity decreases as ZLD system complexity increases because much more can go wrong. Additional capacity must be purchased and installed for more complex systems. Redundancy criteria vary with technology.

The plant has already improved system reliability through better management of spare parts. The plant performed a single-point failure analysis and purchased additional spares. In addition, the plant created contingency plans to address the failure or reduced capacity of the ZLD system.

As stated earlier, there are six options to consider.

DO NOTHING (CONTINUE WITH CURRENT SYSTEM) This scenario assumes that the plant continues to operate with the installed ZLD equipment and that the plant continues to address capacity issues through a combination of limited dispatch and hauling water off-site. Contingency plans are in place to address bottlenecks, but this scenario will not allow continuous plant operation.

Table 1: Options Cost and Risk Summary

Operating Cost (OPEX $/Operating Day)	Current System (Do Nothing)	Add Storage	Add Front-End	Add Back-End	Inject RO Reject	Inject Cooling Tower Blowdown
Maintenance and Outage Costs	$2,227	$2,227	$2,784	$3,341	$1,387	$273
Solid and Liquid Waste Disposal/Haulage	$14,588	$1,473	$14,588	$1,473	$0	$0
Blowdown Clarifier/Softener	$355	$334	$334	$334	$444	$0
Sludge Thickener/Press	$112	$111	$111	$111	$142	$0
Makeup MMF	$3	$3	$3	$3	$3	$3
Blowdown MMF	$13	$13	$13	$13	$13	$0
Cooling Tower	$1,007	$1,007	$1,007	$1,007	$1,037	$1,119
1st Pass RO	$98	$98	$98	$98	$98	$98
2nd Pass RO	$93	$93	$93	$93	$93	$93
EDI	$5	$5	$5	$5	$5	$5
Blowdown Returns to Tower	$0	$0	$0	$0	$0	$0
Blowdown RO	$342	$342	$455	$342	$348	$0
Evaporator	$868	$868	$868	$1,073	$0	$0
Crystallizer	$1,694	$1,694	$1,694	$1,694	$0	$0
Injection Well	$0	$0	$0	$0	$344	$923
HRSG Steam Cycle	$3	$3	$3	$3	$3	$3
Oil/Water Separator	$8.22	$8.22	$8.22	$8.22	$8.22	$8.22
Labor Cost	$849.32	$849.32	$849.32	$849.32	$509.59	$0.00
O&M Cost Summary						
Total O&M Cost	$22,265.70	$9,128.34	$22,912.67	$10,447.40	$4,436.38	$2,525.93
O&M NPV (7% Interest over 30 Years)	$100,848,046	$41,344,972	$103,778,352	$47,319,421	$20,093,686	$11,440,709
Capital and Total Cost ($)						
Total Capital Cost	$560,000	$2,900,000	$2,385,000	$7,959,165	$2,376,999	$5,282,220
Total Cost (Capital + O&M NPV)	**$101,408,046**	**$44,244,972**	**$106,163,352**	**$55,278,586**	**$22,470,685**	**$16,722,929**
Operations Impact and Risk						
Days of Continuous Operation	11.4	85.4	11.4	No Limit	No Limit	No Limit
Allows Continuous Plant Operation (Yes or No)	No	No	No	Yes	Yes	Yes
Risk of Forced Outage	High	Medium	Medium	Medium	Low	Low
Risk of Decreased Capacity	High	High	High	Low	Low	Low
Overall Process Risk	High	High	High	Medium	Low	Low

Table 2: Process Improvements Attempted and Results

Recommendation/Improvement	Result
Send a portion of cooling tower blowdown directly to the brine crystallizer (bypass the evaporator) to minimize the impact of the evaporator bottleneck	Failed – the low temperature of the bypassed water quenched the brine crystallizer and diluted the process resulting in the formation of sloppy cake
Add magnesium oxide to the clarifier/softener to remove silica	Trial in progress, but initial results indicate success. The addition of MgO results in a reduction in silica of approximately 50 ppm in the clarifier/softener. Cooling tower silica lowers as a result
Tune clarifier/softener start-up to provide more rapid return to service of the RO	Success. The clarifier/softener used to require 5-7 days to balance and obtain the chemistry required for the RO to be brought online. The tuning efforts lowered the average time required to bring the RO online to approximately 1-2 days
Tune clarifier/softener chemistry to minimize RO cleaning frequency	Success. RO cleaning frequency used to be approximately once every 4-7 days, sometimes more often. RO cleanings are now required only once or twice a month.
Bypass clarifier/softener (send cooling tower blowdown directly to the RO)	Partial success. Bypassing the softener minimized the time required to bring the RO online and also eliminated the problems associated with balancing softener chemistry. However, the RO recovery had to decrease (to prevent RO scaling and fouling). RO reject flow to the brine tank increased and the evaporator was not able to process the increased flow volume.
Evaluate microfiltration	Not yet attempted. The many improvements in clarifier/softener operation provided the desired results. RO cleaning frequency is now manageable. Microfiltration prior to the RO is no longer necessary.

Recommendation/Improvement	Result
Evaluate option of sending some or all of cooling tower blowdown to others	In progress. Initial modelling focused on sending cooling tower blowdown to a nearby receiver. The results indicated that this scenario will not work – the available receiving entity volume limits operating days to 13-24 and requires the plant to remain shutdown for approximately 28 days once the receiving body is full. Other scenarios still need to be modelled, including sending RO reject and evaporator reject to the receiver.
Remove bleach pump permissive	Success. Running the bleach pumps caused an automatic shutdown of the RO. Rapid changes in clarifier/softener flow resulted in severe turbidity transients, unstable chemistry, and rapid fouling of the RO. Removing the permissive allowed more stable operation of the clarifier/softener and improved chemistry to the RO
Install various flushing lines around the system	Success. Line plugging continues to be a problem, but the installation of many manual flushing connections with hoses allows more rapid clearing and restoration of plugged lines to service.
Feed anti-scalant to the evaporator feed	Success. Feeding anti-scalant to the evaporator feed tank lowered the rate of scale formation in the evaporator preheater and minimized cleaning frequency.
Increase ZLD staffing	Success. During initial operation only one operator managed the ZLD system. Different operators used different strategies to control the various processes. Although well-intended, the difference in operating approaches caused inconsistency and unstable operation. ZLD staffing now includes a lead (on day shift) and two operators on days and nights. This change provided a more stable approach and added process oversight. The system operates much more reliably.

Recommendation/Improvement	**Result**
Added new style hoses with covers to enhance the safety aspect of working around the equipment.	Success. The addition of new style hoses with covers improved safety. The hose covers minimize the risk of personnel exposure to ZLD process water and slurry
Upgraded cooling tower chemical control equipment	Success. The addition of a state-of-the-art cooling tower chemistry control panel provides better control of the cooling tower pH and dispersant. Improved cooling tower chemistry control resulted in fewer clarifier/softener upsets.
Started quarterly addition of non-oxidizing biocide to the cooling tower	Success. The quarterly addition of a non-oxidizing bio-side has improved tower cleanliness.
Added filter aid to media filter	Success. The addition of a filter aid has helped achieve favorable SDI numbers for the RO feed. Lower SDI results in improved RO cleanliness and lowers RO cleaning frequency
Use hydrochloric (HCl) instead of sulfuric acid for cooling tower pH control	Trial in progress. The substitution of HCl is showing promise but it is still too soon to tell.

The risk of forced outages, decreased system capacity, and overall process risk are all high. Specifically, it's likely that the lack of redundancy and the accelerated aging of the ZLD equipment will result in major equipment failures. These failures will likely result in ZLD system shutdowns that may require several days and possibly even weeks to repair. As stated earlier, the current system cannot reliably process the plant's wastewater at a rate sufficient to support continuous operation.

ZLD equipment ages at an accelerated rate. The belt filter press already requires major rework. The loss of a vapor compressor motor could result in several weeks of down-time and could cost several hundred thousand dollars. In general all surfaces with incidental or direct contact with the ZLD process water have corroded and may require replacement. This includes structural steel, chemical feed skids, service lines, and so on. While the capital cost cannot be directly calculated, it's important to understand that the annual capital cost of the current system is at least several hundred thousand dollars per year and may approach a million dollars per year.

All of the current system bottlenecks and operating challenges would remain. The plant has already created contingency plans to minimize the impact on operations from the current system, but these mitigation efforts cannot support continuous plant operation. It's likely that the plant will experience forced outages or will require curtailment, especially during periods of peak power production in the summer.

ADD STORAGE TO THE EXISTING SYSTEM
The plant currently has several Baker tanks onsite to provide additional storage capacity. This scenario would maintain the current system and install additional permanent storage. The additional storage volume was selected to allow approximately 85 days of continuous operation. The additional storage volume (3.12 million gallons total for a working volume of approximately 2.6 million gallons) is in addition to the 400,000 gallons of existing working storage volume.

The ZLD system itself remains as is. This option simply installs additional storage to extend the plant's operating window.

When added together the new and existing storage volumes would increase RO reject storage volume to approximately 3.0 million gallons. This increased storage volume would support approximately 85 days of continuous plant operation under base conditions. It would be sufficient to carry the plant through the summer provided that the ZLD system itself operates continuously.

This scenario assumes that the evaporator operates continuously at an average influent flow of 60 GPM. The evaporator is currently limited to an influent flow of approximately 40 GPM. It's expected that repair work will restore the evaporator average throughput to approximately 60 GPM. The number of days of plant operation supported decrease if evaporator performance does not improve.

The difference between evaporator influent flow capacity and RO reject production must be stored and worked off as plant conditions permit. Assuming a complete plant shutdown (no RO reject production) it would require approximately 35 days to process RO reject once the storage tanks are full.

While the increased storage volume allows longer operation, it's important to note that this scenario suffers the same constraints as those of the current system. Equipment outages, for example, could quickly fill the storage tanks and plant shutdown or curtailment may still be required. The risk of forced outage lowers to "medium" as a consequence of the additional storage, but decreased capacity and overall process risks remain high.

Total cost for this option would be significantly lower than that of the current system. The capital cost associated with the new storage tank(s) is more than offset by savings from the minimization of wastewater hauling. Much of the current wastewater hauling and Baker tank rental would cease.

ADD ANOTHER TRAIN TO THE EXISTING FRONT-END This scenario would remove bottlenecks associated with the front-end of the ZLD system. An additional clarifier/softener would probably not be required. However, the existing media filters and the RO itself would be augmented with the installation of a new train of the same size and flow capacity. This would provide sufficient redundancy to effectively remove any bottleneck associated with front-end ZLD system operation.

System complexity would increase as a result of the new equipment, but front-end reliability would also increase. ZLD plant reliability and capacity would both increase to the extent that front-end processes limit operation. However, this scenario would provide little relief since the front-end of the ZLD system is already operating at a capacity in excess of that required to support continuous operation (thanks to the operators' improvement efforts). The ZLD processing capacity is limited by back-end equipment, so this option would not increase total ZLD processing capacity. The plant would see a slight improvement in reliability, but no improvement in plant operating capacity or average through-put.

Like the current system, this scenario would provide approximately 11 days of continuous operation assuming that the ZLD system operates continuously with no equipment failures or other outages. This scenario would not allow continuous plant operation for an extended period.

This option provides little risk mitigation since the ZLD front-end reliably and consistently operates near its design capacity. The risk of forced outage does lower as a result of the improved redundancy, but that's for the front-end only. The risk of back-end forced outage remains. The risk of capacity loss remains high since this scenario includes no changes to the back-end of the process.

Total cost for this option would be higher than that of the current system since both operating cost and capital cost increase. Operating cost increases as a consequence of the additional equipment. Outages, maintenance, membrane replacement costs all increase.

ADD ANOTHER TRAIN TO THE EXISTING BACK-END This scenario would add a complete train to the back-end of the ZLD system. The new equipment would include an evaporator, crystallizer, belt filter press, and necessary support systems. The plant process flow diagram remains essentially unchanged, but back-end capacity and reliability would both increase as a consequence of the redundant equipment.

Total cost for this option would be lower than that of the current system and lower than that of the "Add Front-end" option, but higher than the other scenarios examined. Operating cost lowers substantially since this option eliminates wastewater hauling. Outage and maintenance costs do increase, but are more than off-set by minimizing or eliminating wastewater hauling. Capital cost increases substantially.

This option would allow continuous operation of the power plant under all conditions assuming no major equipment failures or forced outages. This option would also support extended operation in the event of any single equipment failure on the back-end. For example, this option would support operation with one evaporator out of service for approximately 11 days. This level of redundancy would provide operators with a much larger operating window even in the event of an equipment failure. The current system provides no redundancy. For example, loss of the evaporator under the current system would fill the Brine Storage Tank in approximately three days assuming that the loss occurs when the tank is empty.

In general terms this scenario provides a significant decrease in risk when compared to the current system. There's still a medium risk of a forced outage since the ZLD front-end would remain a single train with no redundancy. The risk of capacity loss is low, however, since this option doubles the back-end ZLD processing capacity. Overall process risk is medium.

INSTALL AN INJECTION WELL FOR RO REJECT This scenario assumes continued operation of the ZLD system front-end. Back-end operation would cease. The existing back-end equipment (evaporator, brine crystallizer, belt filter press) would be shutdown and mothballed.

RO reject and other unrecoverable plant waste streams would be directed to the Brine Holding Tank. The Concentrate Holding Tank would also be adapted to store these waste streams providing an additional 100,000 gallons of storage capacity.

The plant would construct at least one injection well sized for at least 225 GPM. RO reject and other unrecoverable waste streams would be directed to the storage tanks and pumped into the ground as required.

Total cost for this option would be much less than that of the current system. Capital cost is higher, but operating decreases substantially.

Operating cost lowers since the most expensive portion of the ZLD system (the back-end) ceases to operate and wastewater hauling ceases. Outage and maintenance costs decrease by approximately 50%. Parasitic load also lowers substantially.

Capital cost should be estimated in a separate and detailed injection well feasibility study. Key well design characteristics (depth, for example) are unknown. Even assuming very high capital cost, the total cost of this option would be far less than that of the options previously discussed. In fact, it's likely that capital cost of this scenario is at least comparable to and probably less than that of the current system when averaged over several years. Only one scenario (direct injection of cooling tower blowdown, discussed next) offers a lower total cost.

Installing a single injection well for RO reject would allow continuous operation of the power plant under all conditions assuming no major equipment failures or forced outages. This option would also support extended operation in the event of any single equipment failure on the front-end. For example, this option would support operation with the entire front-end of the ZLD system out of service for four days assuming that the brine storage tank is empty when the front-end is removed from service. While this time window is shorter than the "Add Back-End" option, it's important to note that front-end failures are typically of much shorter duration and that front-end equipment can be repaired and returned to service much more quickly than back-end equipment.

This option is much simpler and much more reliable than the current system. In addition, this option would allow direct injection of cooling tower blowdown most of the time. The front-end of the ZLD system could remain idle most of the time and would only be started when the average cooling tower blowdown rate exceeds the injection well capacity (225 GPM).

The simplicity of the well approach and experience with similar wastewater injection wells indicates a low risk of a single injection well failure. For example, one power plant in California has been injecting cooling tower blowdown into the same well since 1995 and has experienced no failures. However, the risk of well failure must be studied in detail. Permeability, transmissivity, aquifer chemistry, and other site-specific conditions impact the longevity of an injection well.

A well failure would remove the plant's wastewater processing capability and would require an extended shutdown to drill another well or repair the existing well. The installation of two wells would mitigate this risk.

There's also a low risk that front-end failure would require direct injection of cooling tower blowdown for the period of time that the front-end is out of service. Operators have demonstrated excellent performance and reliability of the front-end equipment. That being the case, the risk of capacity loss is also low. Overall risk is therefore low. This option presents one of the best in terms of risk reduction and lowest total cost.

INSTALL AN INJECTION WELL FOR COOLING TOWER BLOWDOWN This scenario assumes a complete shutdown of the plant's existing ZLD system (front-end and back-end). The entire ZLD system would be shutdown and either mothballed or salvaged.

Any clean (no significant oil) water with a TDS lower than that of the cooling tower would be directed to the cooling tower for use as makeup water. Cooling tower blowdown would be sent directly to the Brine Holding Tank (bypassing the entire ZLD system). The Concentrate Holding Tank would also be adapted to store cooling tower blowdown providing a total storage capacity of 600,000 gallons.

The plant would construct at least two injection wells with each well sized for at least 250 GPM. Cooling tower blowdown would be directed to these storage tanks and pumped into the ground as required.

This option expands upon the RO Reject Injection option by installing a second well and increasing the well capacity slightly.

Total cost for this option would be the lowest of any option analyzed. Capital cost is higher, but the operating cost savings are greater than any other scenario.

Operating cost lowers since the entire ZLD system ceases to operate. The only operating cost is injection well maintenance. Outage and maintenance costs decrease significantly. Parasitic load also lowers substantially.

As with the RO Reject Injection option, capital cost should be estimated in a separate and detailed injection well feasibility study. Key well design characteristics (depth, for example) are unknown. Even if capital cost is very high, the total cost of this option would probably be far less than that of the options previously discussed. In fact, the capital cost of the injection wells would have to be several times higher than the capital cost of the existing system and even then the injection well option would be less expensive than the options previously discussed.

This option allows continuous operation of the power plant under all conditions. The failure of a single well would still allow continuous operation of the power plant under most conditions. This option provides the least complicated, easiest to operate, and most reliable system of the options evaluated.

The risk of a forced outage and the risk of decreased processing capacity both lower significantly. The model for this scenario predicts cooling tower operation at 8.3 cycles of concentration with a cooling tower blowdown flow rate of approximately 318 GPM under base conditions. The installation of two injection wells, each sized for 250 GPM, provides 2x79% redundancy.

The failure of a single well would result in an increase in the flow to the cooling tower blowdown storage tanks of approximately 70 GPM. As discussed earlier, this option assumes that the existing brine storage tank and the concentrate holding tank would both be used to store cooling tower blowdown for injection. That provides a total storage capacity of 600,000 gallons. Assuming 80% of that storage is available in the event of a single pump failure, the plant could operate continuously under base case conditions for approximately 5 days before the storage tanks are full.

As stated earlier, the simplicity of the well approach and experience with similar wastewater injection wells indicates a low risk of a single injection well failure. Further, this option eliminates the operation of the front-end of the ZLD system and that provides a reliability improvement. Though reliability improves, the risk of well failure is not zero. The risk of well failure must be studied in detail.

The failure of a single well would compromise the plant's wastewater processing capability and could require a plant curtailment or shutdown to work off accumulated cooling tower blowdown. The risk could be mitigated through the installation of 2x100% wells, each sized for 318 GPM.

THE PATH FORWARD

The plant is currently pursuing Option 6 (direct injection of cooling tower blowdown). Well permitting and well studies are in progress. Still, as stated earlier, there are no easy answers. Permitting, development, and commissioning of the injection well system will take approximately two years. In the interim the plant continues to operate, at very high cost, by hauling excess wastewater offsite when cooling tower blowdown flow exceeds the ZLD system's capacity.

The plant currently pays approximately $22,000 per operating day. Over 65% of that cost pays for wastewater hauling alone. ZLD operating and labor expenses comprise approximately 20% of the total. ZLD maintenance and outage costs comprise approximately 10% of the total. Figure 3 shows the breakdown.

These costs are for the plant's water treatment systems only – they do not include any other plant operating costs. That's roughly $4.5 million from April through September. The plant pays this cost, on average, every April – September operating period every year. They'll continue to pay this amount until the injection well system is operational.

Figure 3: Plant Operating Cost Breakdown