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Reduce Project Costs Using Packed Bed Demineralizers

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This paper reviews Packed Bed demineralizer technology. This technology offers significant regenerant and wastewater reductions and cost savings as compared to conventional co-current and counter-current demineralizers. The theory of operation, equipment design, resin selection and overall system performance are reviewed. The major benefits of this technology are described and compared to conventional co-flow demineralizers. Special considerations for packed beds such as influent filtration requirements and uniform particle size resin are discussed. Also, the circumstances that favor modernization of conventional units are discussed. Specific performance benefits of packed beds include higher regeneration efficiency, lower regenerant usage, higher effluent quality, lower rinse water usage, shorter regeneration times and lower waste effluent production. Other benefits include lower life-cycle costs and more efficient use of space in the plant. Two case histories are included to document actual water, regenerant and wastewater cost savings.

Packed Bed, demineralizers, demineralized water, ion exchange, modernization, cost savings

Introduction

Packed Bed demineralizer technology was developed by the Bayer Corporation during the 1970's. During the past decade, the number of manufacturers and installations of packed bed units has risen dramatically. There are many different designs available[1]. Packed beds offer significant regenerant and wastewater reductions and cost savings when compared to both conventional co-current and counter-current demineralizers. The focus of this paper will be to highlight the advantages packed beds have over conventional demineralizers.

Theory of Operation

Packed bed demineralizers are appropriately named, since the resin bed is "packed" with very little freeboard space. The resin bed is not fluidized during any part of the service or regeneration cycle, and there is no full-expansion backwash step. Instead, filtering the influent minimizes the requirement for backwash. Most packed bed systems require transfer of the resin to an external tank for cleaning if the resin becomes fouled with solids. One manufacturer offers a two-chamber unit that allows a portion of the resin in one chamber to be fully expanded and backwashed. Another manufacturer offers a system with an in-situ backwash step of the packed bed without expansion of the resin bed. Generally, bed expansion has been considered crucial to effective backwashing. These backwash claims remain a point of contention among the suppliers of this technology.

Packed bed demineralizers operate in a counter-flow manner, with upflow service and downflow regeneration or visa-versa. (Figure 1).

[1] Hansen, A., Subramanian, R., "Ion Exchange, Packed-Bed Versus Hold-down Ion Exchange," ULTRAPURE WATER®, July/August 1996, pp. 30-38.

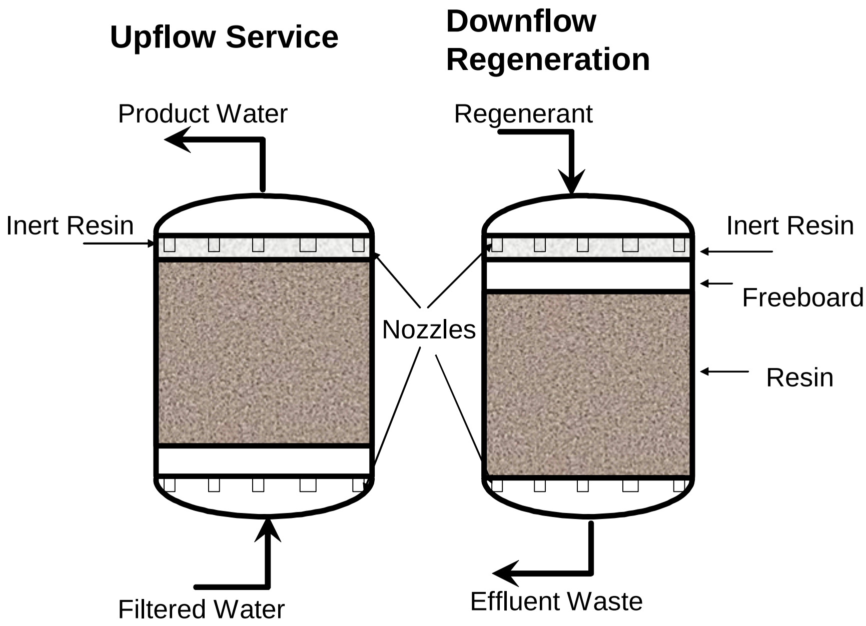

Figure 1 – Packed Beds

The advantages and disadvantages of upflow service and downflow service systems are shown in Table 1.

Table 1 – Capability Review

System	Advantages	Disadvantages
Upflow Service Downflow Regeneration	▪ Higher effluent quality ▪ Less compaction of resin bed, lower pressure drop across bed, and smaller diameter vessels ▪ Lower regenerant flowrates ▪ Less displacement water during regeneration	▪ Must have continuous service flow ▪ For systems with periods of low flow, a recirculation pump may be required for very low flowrates
Downflow Service Upflow Regeneration	▪ Ability to accommodate low service flowrates ▪ Appropriate for layered beds	▪ Uses more water at higher flowrates during regeneration

Upflow Service/Downflow Regeneration

The upflow service/downflow regeneration systems are more common due to the reduced compaction of the bed and lower pressure drop across the bed, allowing for deeper resin beds and smaller diameter vessels. During service, the resin bed is packed against the upper plate. A minimum flowrate must be constantly maintained to avoid resin-bed settling and mixing that would disturb the upper, highly regenerated polishing layer. When the service flowrate falls below the minimum flowrate, some systems automatically stop their service flow and switch to rinse recycle. This allows high quality effluent to be delivered immediately when the service flow demand increases above the minimum flowrate. This control strategy assumes that there is a demineralized water storage tank to ensure a constant supply of high quality water.

Deeper beds increase the overall regeneration efficiency[2]. Downflow regeneration allows greater flexibility in the regenerant flowrates and resin contact time. This increased contact time is particularly important to maximize the

[2] Mommaerts, G. "Ion Exchange, A Review of Packed-Bed Technology Design Parameters," ULTRAPURE WATER®, July/August 1999, pp. 17-24.

elution of organics during a strong base anion regeneration and maximize the efficiency of a hydrochloric acid regeneration of a strong acid cation.

Downflow Service/Upflow Regeneration

The downflow service/upflow regeneration systems are often used when the service flowrate is extremely variable. The resin bed must be packed tightly against the upper plate during upflow regeneration. At the initiation of regeneration, there is a packing step that requires a constant, high flowrate to minimize resin migration and prevent exhausted resin from moving downward into the polishing zone.

Equipment Design

There are several different designs of packed bed demineralizers. Some resin manufacturers have licensed their designs to Original Equipment Manufacturers (OEM's). For example, Bayer Corporation has licensed its technology to Ecodyne, Ltd.. Other equipment manufacturers sell designs that are independent of any resin manufacturer, such as Degrémont or U. S. Filter. The key design characteristics are shown in Table 2.

Table 2 – Key Design Characteristics

Equipment Design	Conventional Co-flow Demineralizers	Packed Bed Demineralizers
Inlet Water Distribution	Hub-laterals or Header-laterals	Nozzle Plate*
Effluent Water Collection	Hub-laterals or Header-laterals or Caps (e.g. Johnson Wedge wire screens)	Nozzle Plate
Regenerant Distribution	Hub-laterals or Header-laterals	Nozzle Plate with orifice distributors, Inert Resin in some units
Fast or Final Rinse	Once through; a few units have fast rinse recirculation	Recirculation System
Backwash System	Reverse flow in-situ during every regeneration cycle	External backwash tank usually required for non-routine use (6 – 12 month interval)

* Required to achieve high regeneration efficiency

Resin Selection /Specification

All resin manufacturers recommend uniform particle size (UPS) resins for packed bed demineralizers. For gel resins (e.g. strong acid cation and strong base anion), UPS resins are manufactured using a "jetting" procedure that is very different from the manufacture of conventional, gaussian-distribution sized resin. The jetting procedure produces a physically stronger bead that is better suited to the higher flowrates and packing processes in packed beds. A stronger bead also produces fewer resin fines, an important characteristic in units that have no routine backwashing to remove these fines.

For macroreticular or macroporous resin, gaussian-distribution resin is screened to eliminate the very large and very small beads. UPS resins are generally premium products, with excellent quality and a higher cost than gaussian-distribution resins but equal in cost to screened resins.

The regeneration efficiency and rinse characteristics of UPS resins are slightly better than conventional resins. UPS resins have a higher void space and, consequently, have a lower total capacity. In other words, UPS resins do not have small beads to fill the voids and will not pack as tightly as resins with a gaussian-distribution. These total capacity and regeneration efficiency differences are small and often dwarfed by the actual operating variables such as influent water quality, resin age, and regeneration concentration. When these operating variables are considered, the actual operating capacity of UPS resins (not the total capacity) is frequently higher than the operating capacity of gaussian-distribution resin. Although distributor design has the greatest impact on rinse time and volumes, there is evidence to support reduced rinse requirements for UPS resins.[3] The primary

[3] Wilson, J. R., McNulty, J. T., "Uniform Particle Size Ion Exchange Resins in Water Demineralization," WaterTech '93

reason for selecting UPS resins for packed beds is the improved physical integrity.

Most packed bed demineralizers have inert resin. In upflow service systems, the purpose of the inert resin is to protect the nozzles from plugging with resin fines. The inert resin improves the distribution of the regenerant during regeneration. Inert resin has a very low density and will float during resin transfer. Inert resin loss should not occur when systems are properly designed and operated.

System Performance

There are several major benefits for packed bed demineralizers over conventional co-current and counter-current units. Packed bed demineralizers have lower regenerant usage than both co-current and counter-current units due to the vessel design (higher aspect ratio of height to diameter) and the greater distribution efficiency of nozzles compared to laterals. Packed beds have a higher effluent quality than co-current units because the regeneration is conducted in a reverse-flow method, creating a zone of highly regenerated resin in the resin bed.

Studies show that full backwashing in conventional units results in minimal mixing or reclassification of resin by size. The small amount of mixing during backwash compromises the effluent quality. Packed beds eliminate routine backwashing, resulting in improved effluent quality. Packed beds have much lower water usage than conventional units because there is no routine backwash and the regenerant volumes are lower. In addition, water usage is lowered by reducing the length of fast or final rinse water step and by recycling the rinse water. There is also a small increase in capacity in packed beds due to the shorter rinse times. The most significant benefits are shown in Table 3.

Table 3 – Comparisons of Operating Metrics

Benefit	Packed Bed Units	Co-Current Units	Counter-Current Units
Lower regenerant usage			
Kilograms of 100% acid per 1000 liter of product water	0.17	0.29	0.19[4]
Kilograms of 100% caustic per 1000 liters product water	0.17	0.42	0.28[5]
Higher effluent quality			
Average Conductivity μS/cm	< 1.0	5 - 10	<5.0[6]
Average Silica (ppb)	<10	20 - 30	20[7]
Lower water usage			
Cubic meters (m^3) of water per 1000 m^3 of product water	73	275 - 500*	165 - 250*

* Assumes no rinse recycle.

The use of a nozzle plate instead of hub-laterals and header-laterals increases the integrity of the vessel internals. Although the initial capital costs for packed beds are higher than conventional units, the life cycle costs are lower. These life cycle costs are lower because of the lower regenerant usage, lower water usage and less production of waste. Most conventional demineralizers have between 50% and 100% freeboard. Packed beds have less than 50% freeboard, resulting in a more efficient use of space and requiring fewer of these vessels for the same throughput of demineralized water.

Special Considerations

Additional influent filtration is usually required for Packed Bed units, especially when the source is surface water (e.g. river water) to prevent resin bed plugging. The specification for water quality is typically described as less than 1 ppm of Total Suspended Solids (TSS). It is difficult to specify the maximum turbidity required for packed beds because there is poor correlation between suspended solids measurements and turbidity. Packed Beds are most vulnerable to fouling during short episodes of high influent solids that occur during periods of heavy rains or snowmelt.

4 Frederick, Ken, "Back to Basics, Countercurrent Regeneration: Principles and Applications," ULTRAPURE WATER®, July/August 1996, pp. 53-56.
5 *Ibid*., pp. 53-56.
6 Kiami, Amin, Rohm & Haas Technical Training, June 1996.
7 *Ibid.*

During these periods, the risk of carryover in the influent clarification systems is the greatest. Consequently, most packed bed manufacturers specify pressurized multi-media filters upstream of the demineralizers.

Even with proper influent filtration, non-routine backwash is often required once every six to twelve months to remove resin fines and colloidal materials that build up over time. In most systems, backwash is conducted by educting between one-third and one-half of the resin volume into an external backwash tank. The resin in the tank is backwashed and the resin remaining in the vessel is fluidized and backwashed. Some packed-bed designs have two external backwash tanks, one for the cation resin and one for the anion resin. However, if plant personnel are careful to remove all of the resin, one tank should be sufficient. The frequency of performing these backwash procedures is highly variable from plant to plant ranging from six months to several years, with many plants performing backwash annually. The external backwash tank can also be used for resin cleaning and to store resin during inspection of the vessel internals.

The two-compartment vessel design from Bayer can be backwashed without a backwash tank. One system is described in the "Mid-Atlantic Paper Mill" case history and another design is shown in the "Gulf Coast Chemical Plant" case history. Another manufacturer offers a system that utilizes a reverse-flow backwash of the packed resin bed. However, these systems usually require external backwash equipment.

Modernization of Existing Demineralizer Plants

The most critical decision required to modernize an existing demineralizer plant is the cost analysis of equipment retrofit (conversion of existing conventional units to packed bed units) versus equipment replacement. In general, retrofit of existing conventional bed demineralizers is time consuming and requires some compromises in effluent quality and regenerant efficiency. Retrofit requires modifications to the vessel internals, the valve settings and the regeneration sequence program. If the existing control system is electro-mechanical, the control system should be replaced with a completely electronic system. In addition, manufacturers can upgrade to a graphic display to monitor and control the system.

If properly designed, the bottom collector or underdrain system may be sufficient for service in the packed-bed mode. The service inlet and service outlet piping are left intact. If the inlet distributor has a simple design such as a splash plate, it will require replacement to a hub-lateral or header-lateral. Due to the increased expense, the inlet distributors are rarely replaced with nozzles, even though nozzles provide a better distribution over the resin bed, better resin retention and lower pressure drop than conventional hub-laterals or header-laterals. A rinse recycle pump always has a favorable economic payback. The majority of conversions result in packed beds with upflow regeneration and downflow service.

A more common modernization project results in the replacement of the existing vessels, valves, piping and control systems. The existing co-flow units can be decommissioned, retained as excess capacity, used as backwash vessels, or converted into weak acid cations, weak base anions or polishers. These projects require a careful process analysis to optimize the re-use of existing assets and match the system design with the needs.

These projects require an alternate source of demineralized water during the installation phase. The plant may have to carefully schedule the installation during a shutdown or other low water usage time or arrange for a mobile water service.

In most cases, the reduction in regenerant and water volumes results in an economic payback of one to two years. Table 3 shows projected theoretical reduction in chemical usage. The case histories illustrate economics and performance that have actually been achieved in the field with packed bed upgrades.

Case Histories

Mid-Atlantic Paper Mill (Westvāco, Luke, MD)

This paper mill produces 9.46 million liters (2.5 million gallons) of demineralized water per day to serve a recovery boiler (0.85 kg/m^2) and two power boilers (2.13 kg/m^2). The raw water source is a mixture of the Potomac and Savage rivers. Raw river water turbidity is typically below 5 NTU (Nephelometric Turbidity Units). The influent chemical treatment consists of alum, an anionic organic polymer and prechlorination for disinfection and iron removal prior to the two parallel treatment trains. The treatment trains consist of a conventional coagulation/flocculation/ sedimentation train and a solids-contact upflow clarifier. Both treatment trains feed a separate set of rapid-gravity sand filters. Caustic is fed to the influent of the treatment trains in the filter plant to raise the pH for more effective alum flocculation and to protect against corrosion of the mild steel transfer lines. The average filtered water quality is shown in Table 4. This water quality was used as the basis for the design of the packed bed units.

Table 4 – Design Basis

Constituent in Filtered Water	Average Concentration
Total Hardness (Ca & Mg)	92 ppm as $CaCO_3$
Sodium (Na)	20 ppm as Na
Carbonate (CO_3)	12 ppm as $CaCO_3$
Chloride (Cl)	14 ppm as Cl
Sulfate (SO_4)	86 ppm as SO_4
Silica (SiO_2)	4 ppm as SiO_2
Total Suspended Solids (TSS)	< 1 NTU

The previous demineralizer plant consisted of four co-current dual beds on a header that were regenerated out-of-train along with two co-flow trains that were regenerated in-train. These dual beds have strong acid cation resin followed by strong base anion resin. There are no polishing units. The primary limitation of these units was high sodium leakage (average 300 ppb (parts per billion)) during service. The primary cause of this leakage is the caustic (NaOH) added to adjust the pH of the filter plant effluent. This high sodium in the demineralized water limited the cycles of concentration and energy efficiency of the 2.13 kg/m^2 (1500 psig) power boilers. Another limitation was the decline in system throughputs during periods of drought due to the increase in chlorides and sulfate (e.g. Free Mineral Acidity (FMA)). During periods of extreme drought, the decline in system throughput was so large that it threatened to curtail steam production. Four of the fluidized demineralizers were 37 years old and the vessels needed re-lining. Another undesirable feature of these four units was their sand and gravel underdrain system. The cost analysis for retrofitting the four older units as compared to replacing them with new packed bed units showed very similar capital costs.

The retrofit option was less desirable because it required installation of header lateral distributors that would not be as efficient as the packed bed nozzle plates.

Another important consideration for the replacement of the trains was the requirement that the new vessels fit in the same footprint and building as the old vessels. Only minor structural modifications of the existing building roof were required because packed bed vessels can accommodate deeper resin beds.

The capacity of each packed bed train is approximately 33% higher than the train it replaced, allowing three new units to produce as much water as four of the older units. Three of the older units were removed and replaced. The other three old co-flow trains remain in standby service to provide peaking capacity during periods of poor influent water quality. Eventually, the oldest remaining train will be retired when major repairs and/or resin replacement becomes necessary.

Normally the river water turbidity is low, but during periods of heavy rain, high solids could reach the demineralizers. It is a standard practice to install pressurized multi-media filters in systems with high influent turbidity. These filters would have increased the cost of the project and significantly increased the payback time. At the customer's request, the manufacturer proposed another option: a modification of the cation design to include a fluidized upper chamber that could be backwashed. During periods of high influent turbidity, this section would trap the particulates during service and remove them during the routine backwash. This would eliminate the need for an external backwash tank and the off-line time for the cation unit backwashing. In addition, the inert resin was eliminated from the upper chamber. As shown in Figure 2, this upper chamber contains one-third of the total resin volume. This design is a modification of the standard Bayer Lift-Bed design and has been described as a "Reverse Lift-Bed." Ecodyne modified the original Bayer design to address the mill's site-specific requirements to minimize solids fouling of the beds.[8]

To address the potential problem of resin fines build-up in the lower chamber, enough freeboard was included in the upper chamber to allow some of the resin from the lower chamber to be transferred to the upper chamber through an integral resin transfer pipe. By transferring some resin from the lower section to the upper section, plant personnel can backwash both chambers. After this non-routine backwash, the resin can be returned to the lower chamber and the unit returned to service. This arrangement eliminates the need for external backwash equipment and greatly reduces the time and potential risks associated with using external equipment.

[8] Ecodyne Limited is a licensee of Bayer Corporation's WS Packed Bed process

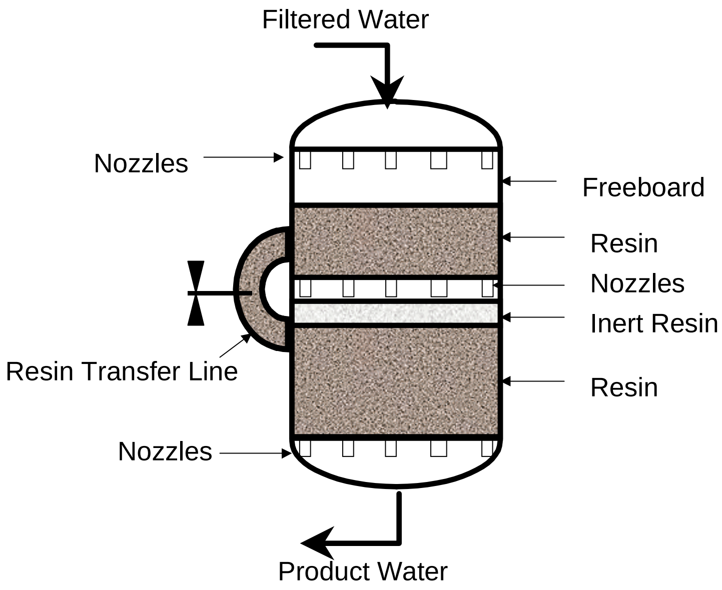

Figure 2 – Downflow Service - Cation and Anion

The designs of the cation and anion vessels are identical, with downflow service and upflow regeneration. Downflow service allows operation during plant flow changes without disrupting the resin beds. There are no solids in the anion unit that would precipitate in the upper compartment, requiring backwash, and therefore, this fluidized compartment needs less freeboard than the cation unit. A small amount of freeboard is required in both anion compartments to accommodate the normal resin volume change that occurs during regeneration.

The effluent sodium concentration has been reduced as shown in Table 5. This reduction in the effluent sodium concentration improved the boiler water quality and allowed the plant to reduce the blowdown flowrate by 61%. Silica leakage has been very low for both the co-flow and packed bed units, and therefore performance data is not presented. In general, silica leakage was lower in the packed beds than the conventional co-current units.

Table 5 – Demineralized Water Quality

Parameter	Average Quality with Co-Current Units	Average Quality with Packed Bed Units
Conductivity	5 μS/cm	<2 μS/cm
Sodium	0.300 ppm as $CaCO_3$	0.050 ppm as $CaCO_3$

The total hardness is approximately 82% of the total cations. Like all cation resin beds, these units are vulnerable to calcium sulfate fouling because the influent calcium concentration is high and sulfuric acid is the cation regenerant. Although a step-wise regeneration procedure was used on both the old and new units, calcium sulfate fouling of the resin beads was experienced in the upper chamber of the new units shortly after start-up. The freeboard in the upper chamber allowed plant personnel to backwash the precipitates out of the unit, adjust the acid concentration algorithm and continue to demineralize water with no production interruption. Reducing the acid concentrations permanently solved the fouling problem. Significant plant production interruption would have occurred without the in-situ backwash capability.

There have been significant reductions in the regenerant usage and wastewater volumes (Table 6).

Table 6 – System Efficiencies

	Annual Percent Reduction for Packed Bed Units
Acid Volume	50%
Caustic Volume	29%
Wastewater Volume	20%

Gulf Coast Chemical Plant (Pasadena, Texas)

This chemical plant produces 9.46 million liters (2.5 million gallons) of demineralized water per day. The raw water source is the Trinity River, filtered and chlorinated by the City of Houston. An adjacent chemical plant cold lime softens, clarifies, filters, and adjusts the pH using sulfuric acid prior to being routed to the plant. The typical turbidity is between 1 and 2 NTU with a maximum value of 5 NTU. The raw water quality varies considerably due to the change in seasons and periods of drought. Operating problems during pre-treatment also causes large fluctuations in raw water quality. The average treated raw water quality used for design of the packed bed units is shown in Table 7.

Table 7 – Filtered Water Quality

Contaminant	Average Concentration (ppm as $CaCO_3$)
Ca	63
Mg	12
Na	50
CO_3	8
HCO_3	22
Cl	34
SO_4	53
SiO_2	7

The old demineralizer units consist of three trains: one co-current two-bed unit (1966) followed by a mixed bed, one counter-current (water block) two-bed unit (1978) followed by a mixed bed and one split-flow counter-current cation, co-current anion three-bed unit (1989). These units are regenerated in-train, had high chemical usage and generated a large volume of waste. It was difficult to control the pH of the stream routed to the wastewater treatment plant because there were no neutralization tanks for the waste regenerant and rinse water. Maintenance costs were high due to the age of these units. There was no fine filtration of the treated raw water. Two of these demineralizers produced water for boilers producing 0.85 kg/m^2 steam and one of these units produced demineralized water for process needs.

The objectives of the packed bed project were to reduce the volume of wastewater from the demineralizers and satisfy the demand for additional demineralized water for process needs. Two packed bed demineralizer trains (cation followed by anion) were installed with a capacity to produce 8.71 million liters per day (2.3 million gallons per day) at an installed cost of $USD 3.0 million. Three pressurized multi-media filters were installed upstream of the cation beds to remove any suspended solids in the incoming raw water. These filters have been very beneficial during upset conditions at the pretreatment plant. The old demineralizers remained in service to provide water to the rest of the plant. They also meet back-up and peaking requirements.

The cation is a Lift-Bed design with upflow service and downflow regeneration as shown in Figure 3. The lower compartment has 50% freeboard in the cation that allows the bed to be backwashed in-situ. The lower compartment is slightly fluidized, resulting in the highest ion exchange efficiency. The upper compartment is 95% full of resin and is tightly packed to ensure the lowest ion leakage. In both units, resin can be transferred from one compartment to the other by using the resin transfer valve.

The cation regenerant is sulfuric acid. Calcium sulfate precipitation occurred in the cation units during startup due to the high concentration of calcium in the influent water. The acid concentrations were adjusted and there were no long-term effects from the calcium sulfate precipitation.

The anion is a VWS design with upflow service and downflow regeneration. The anion regenerant is caustic. The anion vessel has weak base anion resin in the lower compartment and strong base anion resin in the upper compartment. Unlike the cation unit, each compartment has a small amount of freeboard to accommodate the normal volume change that occurs during regeneration. In-situ backwash is not required in the anion unit. Weak base anion is used to remove the high concentrations of naturally occurring organics in the filtered water. The effluent quality meets the plant's specification and mixed bed polishers are not required.

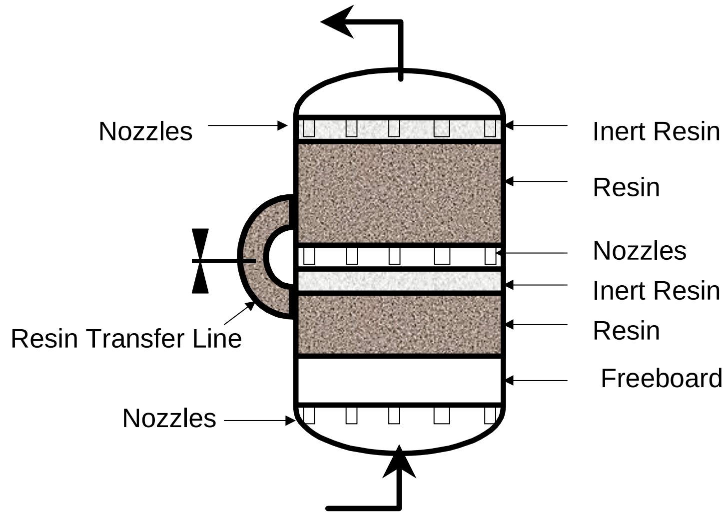

Figure 3 – Service Cycle for Cation and Anion

The benefits of the packed beds for this site are: less wastewater, no additional caustic for waste neutralization, lower acid and caustic usage and less maintenance.[9] In addition, the shorter regeneration time has increased the demineralized water production rate. The cost savings and wastewater savings are summarized in the Table 8.

Table 8 – Economic Analysis

Stream	Annual Savings (U. S. Dollars)
Raw Water and Wastewater	$50,000
Sulfuric Acid	$110,000
Caustic	$240,000
Wastewater Volume Reduction	310 million liters (82 million gallons)

These units have been in service for nearly two years, with no change in system performance. The cation was backwashed after twelve months of service and the anion was backwashed after eighteen months of service. There were very few resin fines in the backwash of either unit. In addition, the effluent water quality and regenerant dosage continue to meet the original system specifications.

[9] Drummonds, David, "Ion Exchange, Minimizing Regenerant Requirements Employing Counter-current Layered and Sandwich Packed-Bed Ion-Exchange Units," ULTRAPURE WATER®, July/August 1999, pp. 70-72.

Acknowledgements

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