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SIZING A WATER SOFTENER FOR AQUIFER THERMAL ENERGY STORAGE

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MASTER

SUMMARY

In aquifer thermal energy storage (ATES) installations, ground water is circulated between an aquifer and heat exchangers via a well field. It is often necessary to soften the water to prevent carbonate scaling in pipes, heat exchangers, and well screens. Most ATES projects requiring water softening will be best served by using synthetic ion-exchange resins.

The size of the resin beds, the resin regeneration cycle, and the amount of NaCl brine used in each regeneration depend on several factors. These are 1) the chemistry of the native ground water, 2) allowable residual hardness after softening, 3) the maximum flow rate of water through the ATES plant, and 4) exchange characteristics of the resin. Example calculations are given for a three-bed water softening system.

CONTENTS

SUMMARY iii

INTRODUCTION 1

EXAMPLE CALCULATIONS 3

WATER CHEMISTRY 3

TANK SIZE 3

REQUIRED RESIN VOLUME 4

REGENERATION CYCLE 6

DECREASING RESIDUAL HARDNESS 6

CONCLUSIONS 9

REFERENCES 13

TABLES

1 Factors for Converting Concentrations of Common Ground-Water Constituents to the $CaCO_3$ Equivalent and to meq/L 4

2 Maximum Service Flow Rate Per Softening Tank 4

3 Effect of the Amount of Salt Used for Regeneration and Total Electrolyte on Resin Exchange Capacity and Residual Effluent Hardness 5

INTRODUCTION

In aquifer thermal energy storage (ATES) systems, ground water is circulated between an aquifer and heat exchangers via a well field. Carbonate scaling in heat exchangers, piping, and wells screens is often a problem. One solution to the problem is to soften the water before it is heated by replacing divalent cations ("hardness" - principally Ca^{++} and Mg^{++}) that can precipitate as carbonates with Na^{+}, whose carbonate salts are highly soluble.

The intent of this report is to illustrate a straightforward method for designing a water softening plant suitable for an ATES system. This report was prepared by Pacific Northwest Laboratory[(a)] at the request of the International Energy Agency (IEA). The U.S. Department of Energy represents the United States in the IEA for Annex VI, which is the IEA task for research and development in ATES.

Softening is commonly done using synthetic ion exchange resins. The resins are charged with Na^{+} at the exchange sites. Then, hard water is passed through a bed of the resin beads, and the divalent ions of the water are exchanged for sodium from the resins. When the resin is depleted of exchangeable sodium, it can be regenerated by contact with a strong NaCl brine solution, which replaces the divalent cations on exchange sites with sodium. The spent brine solution is usually discarded.

The amount of resin used, the number of resin beds, the regeneration cycle, and the amount of NaCl needed in each cycle depend on several factors. These are 1) the chemistry of the native ground water, 2) allowable residual hardness after softening, 3) the maximum flow rate through the ATES plant, and 4) the exchange characteristics of the resin itself.

The exchange capacity of a resin may be expressed as the weight of exchangeable sodium per unit volume of the resin bed, or as the $CaCO_3$ equivalent of the sodium. In design practice, however, the maximum exchange capacity is never used. To do so would yield unacceptably high effluent

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hardness as the capacity of the resin bed approaches exhaustion. Similarly, the resin is not fully recharged with Na^+ during regeneration cycles in order to minimize NaCl consumption.

If intermittent flow through the softener system is acceptable, a design using a single resin bed can be employed. That is, if softened water is only needed (for example) during the day, the bed can be regenerated at night. Similarly, a single-bed design could also be used if a suitable amount of softened water could be stored separately for use during regeneration cycles. However, ATES systems will typically be best served by a multi-bed softener designed specifically for uninterrupted flow of softened water.

In multi-bed systems, one bed can be regenerating while the others are on line. As few as two beds can be used, and three-bed systems are common. In a three-bed system, two on-line resin beds will operate in parallel, so each must be capable of handling one-half of the maximum water flow rate.

In addition to the introduction, this report contains sections providing example calculations, conclusions, and references.

EXAMPLE CALCULATIONS

The following example calculations are based on the water chemistry and flow rate of the ATES system installed at the St. Paul campus of the University of Minnesota. The original bid specifications for this project required 1) a three-bed softener design suitable for continuous flow at 1140 L/min, and 2) beds that could each treat at least 273,000 L before requiring regeneration.

WATER CHEMISTRY

The total hardness of the water is 210 mg/L (calcium and magnesium as $CaCO_3$), based on the following analysis (except pH, all shown as mg/L $CaCO_3$):

Calcium	130
Magnesium	80
Sodium	5
Iron	0.9
Sulfate	9
Chloride	11
Alkalinity	195
pH	7.15

The efficiency of the resin in removing divalent cations depends in part on the total electrolyte (TE) strength of the water to be softened. In this case, the TE is calculated to be 216 mg/L (equal to the sum of the $CaCO_3$ equivalents of the cations).

In the water treatment industry, it is customary to use the calcium carbonate equivalents of aqueous constituents, as illustrated above, to simplify calculations. However, analytical data are most often received in conventional units of mg/L. Further, treatment of the data is sometimes best facilitated using units of meq/L (e.g., a Stiff diagram). Table 1 lists conversion factors for common ground-water ions.

TANK SIZE

Water percolates through the resin bed by gravity flow, and the maximum flow rate is controlled by the surface area of the resin bed. Table 2 shows the useable service flow rates for cylindrical tanks of various diameters.

TABLE 1. Factors for Converting Concentrations (in mg/L) of Common Ground-Water Constituents to the $CaCO_3$ Equivalent and to meq/L

Substance	For $CaCO_3$ equivalent in mg/L multiply by	To convert to meq/L divide by
Calcium	2.50	20.0
Iron (III)	2.69	18.6
Iron (II)	1.79	27.9
Magnesium	4.10	12.2
Manganese	1.82	27.5
Potassium	1.28	39.1
Sodium	2.18	23.0
Bicarbonate	0.82	61.0
Carbonate	1.67	30.0
Chloride	1.41	35.5
Sulfate	1.04	48.0
Fluoride	2.63	19.0

TABLE 2. Maximum Service Flow Rate Per Softening Tank (0.76- bed depth) (After Nalco Chemical Company 1979)

Tank Diameter (m)	Flow Rate (L/min)
0.9	210
1.2	380
1.5	610
1.8	1020
2.1	1170

Inspection of the table shows that 1.5-m-diameter tanks will suffice for a three-bed system at 1140 L/min total flow, with one tank out of service for regeneration.

REQUIRED RESIN VOLUME

At 1140 L/min, the volume of water processed each day will be 1.64×10^6 L. Each resin bed must be capable of softening 273,000 L before regeneration, which is one-sixth of the daily volume. At 210 mg/L hardness, the total daily service load is

$$1.64 \times 10^6 \text{ L/day} \times 210 \text{ mg/L} = 345 \text{ kg } CaCO_3\text{/day}$$

That is, each bed must have a capacity of 57.5 kg $CaCO_3$ (one-sixth of the daily total load).

Table 3 shows the performance of a typical modern resin. Note that both the exchange capacity of the resin and the residual hardness of the effluent vary with the amount of salt used to regenerate the resin and with the total electrolyte strength of the raw water. For the present example, assume that the resin has been regenerated with 96 kg NaCl per m^3 of resin. By extrapolation from the table, the residual hardness in the effluent will be 0.4 to 1.6 mg/L. Also from the table, the capacity of the resin will be 46 kg/m^3. Therefore, the volume of resin needed for each bed is

$$57.5 \text{ kg}/46 \text{ kg-m}^{-3} = 1.26 \text{ m}^3$$

In a 1.5-m-diameter tank, that amount of resin would create a bed 0.71 m deep. However, the resin manufacturer states that the bed must be at least 0.76 m (30 in.) deep to perform properly. Therefore, the volume of resin used is recalculated to be

$$1.26 \text{ m}^3 \times (0.76 \text{ m} / 0.71 \text{ m}) = 1.35 \text{ m}^3$$

The capacity of each bed is also recalculated as

$$46 \text{ kg/m}^3 \times 1.35 \text{ m}^3 = 62.1 \text{ kg.}$$

TABLE 3. Effect of the Amount of Salt Used for Regeneration and Total Electrolyte on Resin Exchange Capacity and Residual Effluent Hardness (After Nalco Chemical Company 1979)

	Salt Applied for Regeneration (kg/m^3)			
	96	128	160	240
Exchange Capacity ($kg\ CaCo_3/m^3$)	46	53	58	69
Effluent Hardness (mg/L as $CaCo_3$)				
100 mg/L TE	0.1 - 0.3	0.1 - 2.0	0.1	0.1
250 mg/L TE	0.5 - 2.0	0.5 - 1.0	0.3 - 0.5	0.1 -0.2
500 mg/L TE	3.0 - 6.0	2.0 - 4.0	1.0 - 3.0	0.5 -1.0
1000 mg/L TE	12.0 - 25.0	8.0 - 15.0	5.0 - 10.0	2.0 -4.0

REGENERATION SCHEDULE

At the total daily load of 345 kg of hardness, and with a 62.1-kg capacity for each of the beds, the service duration for an individual bed is

$$62.1 \text{ kg}/345 \text{ kg-day}^{-1} = 0.18 \text{ day}$$

That is, a bed will be taken off line and regenerated every 4 h and 20 min, for an average of 5.6 regeneration cycles per day.

For each regeneration, the amount of NaCl needed will be

$$96 \text{ kg/m}^3 \times 1.35 \text{ m}^3 = 130 \text{ kg NaCl (as a strong brine)}$$

DECREASING THE RESIDUAL HARDNESS

The residual hardness in the effluent is not constant during the softening cycle. In the example above, it was noted that the residual hardness will be within the approximate range of 0.4 to 1.6 mg/L (as $CaCO_3$). It is possible to both decrease the residual hardness and increase the practical exchange capacity of the resin bed by using more NaCl during the regeneration cycle. The following example illustrates this.

By increasing the amount of NaCl used for regenerating the resin to 240 kg/m^3 (see Table 3), the exchange capacity is increased by 50% to 69 kg/m^3. Further, the residual hardness is reduced to 0.2 mg/L or less.

Because the total flow is still 1140 L/min, the tank diameter remains the same at 1.5 m. Also, the bed depth must still be 0.76 m for the resin to properly perform. Therefore, the volume of resin remains the same, but the capacity of each bed becomes

$$69 \text{ kg/m}^3 \times 1.35 \text{ m}^3 = 93.2 \text{ kg}$$

Thus, the service duration for a bed is

$$93.2 \text{ kg}/345 \text{ kg-day}^{-1} = 0.27 \text{ day}$$

A new cycle of regeneration will therefore be needed every 6 h and 30 min, for an average of 3.7 regeneration cycles per day.

In the first example, with 5.6 cycles per day, the amount of NaCl used is

$$5.6\ day^{-1} \times 130\ kg = 728\ kg/day\ NaCl$$

In the present example, with 3.7 cycles per day, the amount needed is

$$3.7\ day^{-1} \times 324\ kg = 1199\ kg/day\ NaCl$$

Thus, as these examples show, increasing the performance from a minimum 99.2% hardness removal to a minimum of 99.9% removal was accompanied by a 65% increase in NaCl consumption.

CONCLUSIONS

The steps required to design a three-bed water softener may be summarized as follows:

1. Obtain a chemical analysis of the water to be treated. The list of parameters measured should include pH, alkalinity, sodium, potassium, calcium, magnesium, chloride, and sulfate. (At normal ground-water pH, assume that all alkalinity is as bicarbonate.)

2. Convert the analytical results (except pH) to the $CaCO_3$ equivalents. The sum of the cations should equal the sum of the anions within 5% relative error. If the difference is greater, more detailed analysis will be required to determine what other chemical species may be present.

3. Add the divalent cations to obtain total hardness. Add all of the cations to calculate TE.

4. Choose a maximum allowable effluent hardness (beyond the scope of this report), then use Table 3 and TE to choose the amount of NaCl used in regeneration, in terms of kilograms of NaCl per cubic meter of resin, and to determine the exchange capacity. (NOTE: Table 3 provides "typical" resin characteristics, but it is best to obtain performance data for the actual resin that will be used.)

5. Divide the maximum ATES plant throughput by 2, and use Table 2 to determine minimum tank diameter. Assuming a cylindrical tank and a bed depth of 0.76 m, calculate the bed volume:

$$\text{Bed volume in } m^3 = \pi \times 0.76 \text{ m} \times (0.5 \times \text{tank diameter in m})^2$$

6. Determine the total capacity of each bed:

$$\text{Total capacity in kg } CaCO_3 = \text{Bed volume in } m^3 \times \text{Exchange capacity in kg } CaCO_3/m^3$$

7. Calculate the daily hardness load:

$$\text{Total } CaCO_3 \text{ in kg/day} = \text{Water hardness in mg/L} \times \text{flow rate in L/min} \times 0.00144$$

8. Calculate the number of regeneration cycles per day:

$$\text{Cycles per day} = (\text{Total } CaCO_3 \text{ in kg-day}^{-1}/\text{bed capacity in kg } CaCO_3)$$

9. Calculate NaCl usage:

$$\text{NaCl in kg/day} = \text{Cycles per day} \times \text{bed volume in } m^3 \times \text{NaCl requirement in kg/}m^3 \text{ from Table 3}$$

In modern water softening systems, bed switching and regeneration are controlled automatically. The only manual requirement other than periodic inspection and maintenance is to keep the brine tank charged with NaCl. On-line sensors and alarms are available for monitoring liquid levels, flow rates, and chemical parameters.

As the foregoing examples show, the physical size of resin tanks needed for a particular application depends on the flow rate that the bed will be required to handle. The number of tanks needed and the regeneration schedule are dependent on resin capacity, raw water chemistry, and the demand schedule for softened water.

The quality of the softened effluent can be controlled by varying the amount of NaCl used to regenerate the resin beds. Because procurement and handling of NaCl is the major operational cost of a softening system, it is important to determine the quality of effluent that will be actually required for the ATES system.

Disposal of the spent brine needs to be considered. Its principal contents will be a mixture of dissolved sodium, calcium, and magnesium chlorides. While these salts are chemically rather innocuous, large amounts of saline solution may present a disposal problem. In some cases it may be practical to remove the Ca^{++} and Mg^{++} (by precipitation with lime and soda ash) and to recycle the brine for regeneration (Nalco Chemical Company 1979).

Finally, it is possible that the hardness (but not the TE content) of water withdrawn from the aquifer will not be constant. The volume of aquifer that is used for storage of thermally altered water may be considered as a large cell or storage vessel having an output of ground water and an input of softened ground water. The effect of recirculating the water will be a net increase of sodium, and net decrease of divalent cations, within the aquifer. This tendency for a net change in water chemistry will be opposed by the natural movement of native ground water through the storage cell, and may also be opposed by interactions between the softened water and minerals.

Modeling, based on knowledge of aquifer mass transport characteristics and of ATES plant operating cycles, can be used to anticipate a net change in

water hardness. From the standpoint of softener operation, this is not strictly necessary, because the resin beds will perform correctly as long as they have been properly designed with respect to untreated ground water. However, to minimize NaCl consumption, the duration of the service cycle of the resin beds should be lengthened when possible. To do this effectively, it is necessary to monitor the hardness of the water going into the softener as well as the effluent. These data, along with the flow rate and the duration of flow, suffice to calculate the mass of hardness that has been loaded onto a bed. That bed can remain in service until its practical exchange capacity has been reached.

In the example calculations, it has been assumed that the entire throughput of the ATES installation will be softened. However, it is not always necessary or desirable to completely soften the water. If swelling clays (e.g., montmorillonite, known commercially as "bentonite") are present in the aquifer, increasing the sodium content of the ground water can cause clay swelling and dispersion, with a consequent loss of aquifer permeability. The likelihood of swelling and dispersion can be anticipated by calculating the "sodium hazard" (Jackson 1958), which is based on the specific conductivity of the water and the sodium adsorption ration (SAR). The SAR is defined as

$$SAR = (Na)/(Ca + Mg)^{0.5}$$

where the concentrations of sodium, calcium, and magnesium are in meq/L.

Also, even in the absence of swelling clays, partial softening may be adequate for the prevention of significant carbonate scaling. A public domain computer program for calculating the sodium hazard and evaluating water treatment options (including partial softening), H2OTREAT, is available for DOS and UNIX computers (Vail et al. 1993).

Where partial softening is chosen, it is necessary to split the water stream before it enters the softening plant, with part of the water bypassing the plant. The softening plant is then sized based on the daily volume of water that is actually softened. The split flow streams are recombined downstream from the softening plant. As sodium increases in the recycled

water, the sodium content of the recombined effluent stream can be controlled by reducing the fraction of the stream that is passed through the softening plant and by adjusting the regeneration schedule of the individual beds.

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