Ion exchange removes unwanted ions from a raw water by transferring them to a solid material, called an ion exchanger, which accepts them while giving back an equivalent number of a desirable species stored on the ion exchanger skeleton. The ion exchanger has a limited capacity for storage of ions on its skeleton, called its exchange capacity; because of this, the ion exchanger eventually becomes depleted of its desirable ions and saturated with unwanted ions. It is then washed with a strong regenerating solution containing the desirable species of ions, and these then replace the accumulated undesirable ions, returning the exchange material to a usable condition. This operation is a cyclic chemical process, and the complete cycle usually includes backwashing, regeneration, rinsing, and service.

The earliest ion exchangers were inorganic sodium aluminosilicates, some of which were manufactured synthetically and others made by processing natural greensand, which is a mineral called zeolite, into more stable, higher capacity forms. Even though these zeolites now have only limited use for water treatment, the name has persisted, and even synthetic organic ion exchangers are often called zeolites.

The ion exchangers used in water conditioning are skeletonlike structures having many ion exchange sites, as shown in Figure 12.1. The insoluble plastic skeleton is an enormously large ion that is electrically charged to hold ions of opposite charge. As such, the ion exchanger is related to the polyelectrolytes used for coagulation and flocculation (Chapter 8), but deliberately made so high in molecular weight as to be essentially insoluble. Exchangers with negatively charged sites are cation exchangers because they take up positively charged ions. Anion exchangers have positively charged sites and, consequently, take up negative ions. The plastic structure is porous and permeable, so the entire ion exchange particle participates in the process.

**EXCHANGER CAPACITY**

Typical exchangers are in the form of beads, having an approximate size of 20 to 50 mesh (0.8 to 0.3 mm), as illustrated by Figure 12.2. The chemist expresses the strength of a chemical solution in terms of normality; a 1.0 N solution contains 1 g-eq of electrolyte in a liter of solution. Ion exchange beads can be considered as solid solutions; the typical cation exchanger has a normality of approximately 2.0, and the typical strong-base anion exchanger a normality of approximately 1.3.
FIG. 12.1 Model of a cation exchanger, showing negatively charged exchange sites on the skeleton holding sodium ions like grapes on a vine.

FIG. 12.2 Typical commercial exchangers are of two general structures, gel type (left) and macro-porous type (right). These are magnifications.
Capacity is also expressed as milliequivalents per milliliter (meq/mL), which is the same as normality; milliequivalents per dry gram (meq/g); and kilograins per cubic foot (kgr/ft\(^3\)).

In the early history of zeolite softening, it was common to express water hardness in grains per gallon (gr/gal) (1 gr/gal = 17.1 mg/L). Because of this common usage, the capacity of zeolites was rated in kilograins exchange capacity per cubic foot of zeolite, an unfortunately cumbersome term. The factor for conversion of resin normality to kilograins per cubic foot (kgr/ft\(^3\)) is approximately 22, so that a cation exchanger with a capacity of 2.0 meq/mL has an exchange capacity of approximately 44 kgr/ft\(^3\).

Using normality as a basis for expressing the exchange of an ion exchange material and also for expressing the concentration of electrolytes in water, it is very easy to use the classic expression,

\[ V_x N_x = V_w N_w \]

where \( V_x \) = volume of exchange material
\( N_x \) = normality of the exchanger
\( V_w \) = volume of water processed per cycle
\( N_w \) = normality of exchangeable electrolytes in the water

For example, if a water having a total electrolyte content of 200 mg/L as CaCO\(_3\) has a hardness of 150 mg/L, the normality of the exchangeable electrolytes if this water is to be softened is 150/50, or 3.0 meq/L, or 0.003 \( N \). If this is softened through a cation exchanger with a normality of 2.0, then the theoretical volumetric ratio would be

\[ \frac{V_w}{V_x} = \frac{N_x}{N_w} = \frac{2.00}{0.003} = 667 \text{ volumes of water per volume of bed} \]

This is illustrated by Figure 12.3. To make the graph useful, the percentage of total capacity (in normality or kgr/ft\(^3\)) that is actually available under optimum conditions of regeneration must be established. This is covered in a later section of the chapter.

Most commercial ion exchangers are synthetic plastic materials, such as copolymers of styrene and divinyl benzene (Figure 12.4). There is a fine balance between producing a loosely cross-linked polymer that has free access to water for rapid reaction but is slightly soluble, and a tightly cross-linked resin, which would be insoluble, but more difficult to use because of restricted rates of exchange both in exhaustion and regeneration. Water treatment ion exchangers are essentially insoluble and can be expected to last for 5 to 10 years.

To produce cation exchangers, the plastic is reacted with sulfuric acid. Sulfonic groups attach to each nucleus in the skeleton to provide an exchange site. This produces a strong electrolyte, for which a typical reaction with cations in water is shown below:

\[ \text{Na}^+ + \text{R} \cdot \text{SO}_3 \cdot \text{H} \rightarrow \text{R} \cdot \text{SO}_3 \cdot \text{Na} + \text{H}^+ \]  

(1)

In this equation, the resin structure is represented by R. The usual convention omits showing the active group (−\text{SO}_3 \cdot \text{H}) and simply uses the total exchanger molecule, which may be shown as \( Z \) (Na\(_2\)Z, from the historical usage of the word
"zeolite") or X, which is used in this text for the cation exchanger. The above equation is, then, more usually written:

$$2Na^+ + H_2X \rightarrow Na_2X + 2H^+$$ (2)

the X being considered a divalent cation exchange unit. In this example, sodium ions in water are being exchanged for hydrogen ions on the exchanger, a common exchange reaction. This is known as hydrogen cycle operation. On depletion of the hydrogen ion inventory of the exchange resin, called “exhaustion”, the exchanger is regenerated by an acid wash:

$$2HCl + Na_2X \rightarrow H_2X + 2NaCl$$ (3)

Other examples of cation exchange include the following:

Hardness removal, with Na-form exchanger, Na$_2$X:

$$Ca^{2+} + Na_2X \rightarrow CaX + 2Na^+$$ (4)

This is known as sodium cycle operation.

FIG. 12.3 Volumetric capacity of ion exchange resins at 100% utilization.
Iron removal with Na$_2$X:

$$\text{Fe}^{2+} + \text{Na}_2\text{X} \rightarrow \text{FeX} + 2\text{Na}^+ \quad (5)$$

(Note: Of the two species of iron in water, only Fe$^{2+}$ is soluble, requiring an oxygen-free, reducing environment. The ferrous iron is ion exchangeable. However, if oxygen is present either in the water or in the regeneration solution (e.g., brine), the Fe$^{2+}$ will be oxidized to insoluble Fe$^{3+}$, which will precipitate and foul the ion exchanger.)

Nickel recovery from plating waste by H$_2$X:

$$\text{Ni}^{2+} + \text{H}_2\text{X} \rightarrow \text{NiX} + 2\text{H}^+ \quad (6)$$
Cations

Fe$^{3+}$
Al$^{3+}$
Pb$^{2+}$
Ba$^{2+}$
Sr$^{2+}$
Cd$^{2+}$
Zn$^{2+}$
Cu$^{2+}$
Fe$^{2+}$
Mn$^{2+}$
Ca$^{2+}$
Mg$^{2+}$
K$^+$
NH$_4^+$
Na$^+$
H$^+$
Li$^+$

Anions

CrO$_4^{2-}$
SO$_4^{2-}$
SO$_3^{2-}$
HPO$_4^{2-}$
CNS$^-$
CNO$^-$
NO$_3^-$
NO$_2^-$
Br$^-$
C$^-$
Cl$^-$
CN$^-$
HCO$_3^-$
HSiO$_3^-$
OH$^-$
F$^-$

* These ions may be displaced as they are protonated at low pH to: HCrO$_4^-$, HSO$_3^-$, H$_2$PO$_4^-$

Notes: Changes in position may occur between products of different manufacture or having slightly different skeletons or exchange groups. In general, selectivity is affected by:

(a) Ionic valence: $3 > 2 > 1$.
(b) Atomic number: Ba > Sr > Ca > Mg in Group IIA.
(c) Hydrated ionic radius: the larger the radius, the lower the selectivity and exchange capacity.
A more realistic example which illustrates an ion exchanger property called selectivity is hydrogen cycle (H-form exchange) processing of a typical water containing a variety of ions:

\[
\begin{align*}
\text{Ca}^{2+} & \quad \text{Mg}^{2+} \\
\text{Fe}^{2+} & \quad 2\text{Na}^+ \\
2\text{NH}_4^+ 
\end{align*}
\] + \text{H}_2\text{X} \rightarrow
\begin{align*}
\text{CaX} & \quad \text{MgX} \\
\text{FeX} & \quad \text{Na}_2\text{X} \\
(\text{NH}_4)_2\text{X} 
\end{align*}
\] (7)

If this ion exchange process continues to exhaustion, the first ions to appear in the effluent will be \(\text{NH}_4^+\) and \(\text{Na}^+\), and if the exhausted bed is then analyzed, the distribution of ions would be as shown by Figure 12.5. This is due to a selectivity or preference of the cation exchanger for certain ions over others. A typical selectivity list is shown in Table 12.1.

The order of selectivity shown applies to ions in typical water of less than 1000 mg/L TDS. The selectivity is different at high concentrations. For example, in the sodium cycle, the exchanger has a preference for \(\text{Ca}^{2+}\) over \(\text{Na}^+\) at 1000 mg/L; but at 100,000 mg/L its preference is for \(\text{Na}^+\) over \(\text{Ca}^{2+}\) (see Figure 12.6). This is fortunate, as it enhances the efficiency of regeneration with brine.

**FIG. 12.6** \(\text{Na}^+ / \text{Ca}^{2+}\) equilibria for a sulfonic acid cation exchange resin. (Courtesy of T. V. Arden, Surrey, England.)
Returning to the examination of the nature of cation exchangers, there are several materials in addition to the styrene-based material of commercial importance. One is processed greensand—the original zeolite—which is still used effectively for removal of iron and manganese. It can operate only in the sodium cycle over a limited pH range. Another, of increasing importance, is a resin having the carboxyl group (—COOH, with the hydrogen ion exchangeable) as the exchange site. This is called a weak cation exchanger, discussed later in a consideration of hydrogen exchange operations. This material is highly selective for H\(^+\) and divalent cations with hindered ability to exchange Na\(^+\). A third material is a true synthetic zeolite (aluminosilicate) that can be tailored for specific applications (e.g., ammonia removal) and for adsorption of specific molecules (molecular sieves). Other plastic materials are also used, such as acrylic and phenolic resins.

### ANION EXCHANGERS

Anion exchangers may be produced from a variety of resinous or plastic skeletons, including the same styrene-divinyl benzene copolymer as is used for cation exchangers. As with cation exchangers, two general varieties are used commercially, weak base and strong base exchangers. The functional group of an anion exchanger is an amine, the organic equivalent of ammonia. Weak base exchangers contain a secondary or tertiary amine group, RR'—NH or RR'—N—R', which can adsorb strong acids. Strong base exchangers contain a quarternary amine, R R' R'' R'''N\(^+\)—Cl\(^-\), which can exchange all anions. The most common quarternary resin has the formula, −R·N(CH\(_3\))\(_3\)·Cl\(^-\), or structurally

\[
\begin{align*}
\text{CH}_2 \\
\text{(CH}_3\text{)}_3\text{N}^+\text{—(CH}_3\text{)} \\
\text{(CH}_3\text{)} \cdot \text{Cl}^- 
\end{align*}
\]

Weak-base anion exchangers are able to remove only strong mineral acids—HCl, H\(_2\)SO\(_4\), HNO\(_3\)—with practically no exchange capacity for weak acids—such as CO\(_2\), SiO\(_2\), and organic acids. The typical reaction is shown as an adsorption, rather than ion exchange process:

\[
\text{HCl} + \text{A} \rightarrow \text{A} \cdot \text{HCl} \quad (8)
\]

(In this text, the letter A represents an anion exchanger.) The exhausted resin is very efficiently regenerated with any alkali, which simply neutralizes the adsorbed acid and releases it as a neutral salt.

Strong-base exchangers are true ion exchange materials. Several typical reactions are:

- Dealkalization, with Cl-form exchanger, AC\(_2\):

\[
2\text{HCO}_3^- + \text{ACl}_2 \rightarrow \text{A(HCO}_3\text{)_2} + 2\text{Cl}^- \quad (9)
\]
Sulfate removal, with Cl-form exchanger:

$$\text{SO}_4^{2-} + \text{ACl}_2 \rightarrow \text{ASO}_4 + 2\text{Cl}^-$$  \hspace{1cm} (10)

The most common use for strong base exchangers is complete anion removal from hydrogen exchanger effluent, to produce demineralized water:

$$\begin{align*}
\text{H}_2\text{SO}_4 & \quad 2\text{HCl} \\
2\text{H}_2\text{CO}_3 & \quad 2\text{H}_2\text{SiO}_3
\end{align*} \quad + \quad \begin{pmatrix} \text{A(OH)}_2 \\ \text{A(Cl)}_2 \\ \text{A(HCO}_3)_2 \\ \text{A(HSiO}_3)_2 \end{pmatrix} \quad \rightarrow \quad \begin{pmatrix} \text{A SO}_4 \\ \text{A Cl}_2 \\ \text{2H}_2\text{O} \end{pmatrix}$$  \hspace{1cm} (11)

The exchange resin is regenerated with NaOH. In this form, the exchanger can also convert neutral salts to bases, known as salt-splitting.

$$2\text{NaCl} + \text{A(OH)}_2 \rightarrow \text{ACl}_2 + 2\text{NaOH}$$  \hspace{1cm} (12)

The selectivity of the anion exchanger, also shown in Table 12.1, indicates that silica will leak through the bed first, and the exhausted bed will have the composition shown by Figure 12.7.

**PRACTICAL ION EXCHANGE**

In the commercial application of ion exchange to water treatment, there are four important principles:

1. Most ion exchange units are simple vessels containing a bed of ion exchange resin operated downflow on a cyclic basis: (a) a unit is operated to a predetermined leakage level, where it is considered to be exhausted; (b) the unit is then regenerated, first by upflow cleaning (backwash) and then by chemical elution, downflow; (c) the resin bed is then rinsed downflow. Because both water and regenerant flow in the same direction, the water leaving the unit is in contact with the resin having the highest level of contaminating ions, so quality and efficiency both suffer.
2. The ion exchange bed has a considerably higher capacity than is used, because uneconomical excesses of regenerating chemical would be required to convert the resin entirely to the desired ion form. For example, the cation resin may have a capacity of $2 N$ (about 44 kgr/ft$^3$), but only about half of this (20 to 22 kgr/ft$^3$) is used for sodium cycle softening. Therefore, there is always a high concentration of contaminating ions, calcium in this case, on the resin with a potential for spoiling the treated water quality.

3. Because of cyclic operation with cocurrent flow of water and regenerant, chemical utilization in regenerating ion exchange resins is usually poor. This drawback is most pronounced with strong resins—sulfonic-type cation exchangers and quaternary ammonium anion exchangers. For example, in the sodium-cycle, if the utilized capacity is 21 kgr (about 3 lb) as CaCO$_3$ per cubic foot (48 kg/m$^3$) of resin, the salt required is theoretically only $58.5/50 \times 3 = 3.5$ lb NaCl/ft$^3$. The actual salt consumption is typically 6 to 10 lb NaCl ft$^3$, so the efficiency is about 30 to 50%. Acid efficiency for hydrogen exchange using a sulfonic-type resin and H$_2$SO$_4$ for regeneration, and caustic efficiency for regeneration of strong base anion resins are even poorer, about 20 to 40%.

However, weak cation resins (carboxylic type) and weak anion resins (amine type) can be operated at close to 100% chemical efficiency.

4. Most ion exchange materials used in water treatment are in the size range of 20 to 50 mesh, or about 0.5 mm effective size. This makes an ion exchange bed a very effective filter, a characteristic having both advantages and disadvantages. This filtering ability is combined with ion exchange properties in designing industrial condensate polishing systems using ion exchange beds. But the filtering ability also leads to fouling and unpredictable operating runs. Sometimes this is caused by the accumulation of high microbial populations in an exchanger bed, even when operating on a chlorinated municipal water supply.

**AN EVOLVING SCIENCE**

Because of these limitations, in spite of added capital cost and increased sophistication of equipment, ion exchange designs are changing to reduce chemical cost, improve effluent quality, and reduce pollution created by excessive chemical dosages. These improvements are realized by:

1. Countercurrent regeneration techniques
2. Multiple stages of treatment
3. Multiple stages of regeneration
4. Use of weak exchangers wherever possible
5. Pretreatment of water prior to ion exchange (e.g., by lime softening, reverse osmosis) to reduce the ionic load on the ion exchange system
6. Pretreatment to reduce particulates or soluble organic foulants (e.g., by filtration, adsorption)

In subsequent sections, leakage will be mentioned frequently. The term “leakage” implies a slipping of some of the influent ions into the effluent. In fact, unwanted ions reach the effluent by two different processes (see Figure 12.8a).
1. At the beginning of the softening run (using the Na\textsubscript{2}X process as an example) there is appreciable calcium left in the bottom of the resin bed. Water entering at the top gets completely softened, the only cation being sodium. This softened water, in effect a very dilute brine, regenerates the calcium from the bottom of the bed. So at the beginning of the run the hardness in the effluent is due to calcium residue on the exchanger from the previous run.

![Diagram of bed condition and leakage curve](image)

**FIG. 12.8** Leakage through a sodium zeolite softener with cocurrent flows. (a) Bed condition during cycle; (b) leakage curve.

![Diagram of water analysis](image)

**FIG. 12.9** Comparison of results of cocurrent versus countercurrent regeneration of cation exchange resin. (Thompson, J., and Reents, A. C.: "Counterflow Regeneration," Proceedings of 27th International Water Conference, November 1966.)
2. As the bed becomes exhausted, the calcium contamination at the bottom of the bed decreases and the quality continually improves until true leakage—slippage of incoming Ca\(^{2+}\) through the bed into the effluent—begins to appear. The net effect is the leakage curve shown by Figure 12.8b.

This same kind of effect is observed with all exchange processes having cocurrent exhaustion and regeneration. If the bed is regenerated countercurrent to the water flow, this effect is eliminated and leakage is then due to actual ion slippage. The improvement of both quality and efficiency by counterflow regeneration is strikingly illustrated by Figure 12.9, showing a hydrogen cycle operation with downward service flow and upflow regeneration with sulfuric acid.

A final backwash is another procedure for minimizing leakage.

Slippage is easy to appreciate as one consequence of the limited residence time of the water in the ion exchange bed, typically about 1 min.

In an idle unit, there is migration of ions between resin particles. This causes a change of water quality when flow commences again. This migration is also observed during backwash, illustrated in steps 2 and 3 of Figure 12.5.

**SODIUM CYCLE EXCHANGE (ZEOLITE SOFTENING)**

Zeolite softening is the oldest and simplest of the ion exchange processes. It removes hardness from water, including iron and manganese if these constituents can be kept in the reduced ionic form. When the ion exchange bed is saturated with the hardness constituents, the exchanger is regenerated with sodium chloride brine.
FIG. 12.11 With a multiple-unit system, a full flow of soft water is always available. A single regeneration system serves the battery of units, and individual regenerations are staggered to equalize water quality.

During the processing step—the softening run—the hardness of the raw water may vary and the flow rates through the system may change, but the bed continues to operate effectively to produce a soft water.

The equipment design is simple, consisting of a steel shell holding the ion exchange bed and provided with piping and valves to permit the essential operations of softening, backwash, brining, and rinsing (Figure 12.10). Instrumentation may be provided to help the operator anticipate exhaustion of the bed, so that the bed can be regenerated before the effluent quality depreciates beyond acceptable limits. Almost all sodium zeolite units include a meter for measuring water flow, usually equipped with an alarm so that when the gallonage corresponding to the capacity of the bed has been reached, the operator will be warned of the need to regenerate. More sophisticated units, required by higher quality limits, include automatic hardness analyzers.

If storage capacity is provided for softened water, a single unit may be adequate for the plant needs. In larger plants it is common to have more than one unit, so that one can be taken out of service for regeneration without interrupting the flow of soft water.

A diagram of a multiple unit system is shown in Figure 12.11. This system uses steel tanks to saturate the brine solution and then to measure it for application to the ion exchange bed. Larger systems, where salt can be more conveniently purchased in truckload quantities than in bags, are designed to have a large concrete salt-saturating basin located adjacent to a track or roadway where brine can be brought to the plant in bulk and simply dumped into the underground salt storage and brine saturation basin. A typical design of the salt storage facility for these larger installations is shown in Figure 12.12.

Figures 12.13 and 12.14 illustrate several typical installations, the first being a simple zeolite softener treating city water as boiler makeup, and the second a sodium zeolite softener especially designed for high-temperature service and installed in a plant to follow a hot process lime softener and filter system.
FIG. 12.12  Wet salt storage basin for bulk truckload or carload deliveries of sale.  (Courtesy of Cochrane Division, the Crane Company.)

FIG. 12.13  Multiple-unit sodium zeolite installation for continuous delivery of softened water.  (Courtesy of The Permutit Company.)
The chemical reactions for the sodium zeolite process are shown below:

Softening (exhaustion):

\[
\begin{align*}
\text{Ca}^{2+} + \text{Na}_2\text{X} & \rightarrow \text{CaX} + 2\text{Na}^+ \\
\text{Mg}^{2+} + \text{Na}_2\text{X} & \rightarrow \text{MgX} + 2\text{Na}^+
\end{align*}
\] (13) (14)

*Note:* The selectivity of the exchanger favors \( \text{Ca}^{2+} \) over \( \text{Mg}^{2+} \). Therefore, Mg hardness predominates at the point of breakthrough.

Regeneration (brining):

\[
\begin{align*}
2\text{NaCl} + \text{CaX} & \rightarrow \text{Na}_2\text{X} + \text{CaCl}_2 \\
2\text{NaCl} + \text{MgX} & \rightarrow \text{Na}_2\text{X} + \text{MgCl}_2
\end{align*}
\] (15) (16)

The amount of salt applied to the individual zeolite bed for regeneration is determined by the acceptable effluent quality limits and the capacity the plant wishes to achieve to properly schedule regeneration of the system based on available labor. The greater the salt dosage, the lower is the hardness leakage and the higher the capacity. However, the higher salt dosage also results in poorer chemical economy and greater quantities of spent brine to be handled through the waste disposal system. (See Table 12.2.)

As mentioned briefly earlier, countercurrent regeneration is one technique used to improve both effluent quality and regenerant efficiency; this will be covered in more detail in a later section of this chapter. Another technique is multiple-stage regenerant application at high chemical dosages. For example, salt could be applied for regeneration of a sodium exchanger at 15 lb/ft\(^3\). The initial dis-
TABLE 12.3 Sample Calculation of Sodium Exchange System

Water Analysis: See Figure 12.15. Total hardness = 200 mg/L, allowable leakage = 3 mg/L, TE = 300 mg/L.

Plant Requirements: 1,200,000 gal/day = average flow of 1,200,000/1440 = 833 gal/min; must accommodate extended peak flow of 1200 gal/min.

1. Calculation of required size to handle 1200 gal/min. (See Table 12.4.) Use three 10 ft diameter units.

2. Calculation of required resin volume.
   a. Required capacity in kilograins:
      Hardness = 200 mg/L; 200/17.1 = 11.7 gr/gal,
      1,200,000 X 11.7/1000 = 14,035 kgr/day
      Schedule all 3 units to be regenerated each shift.
      \[ \text{Required capacity} = \frac{14,035}{3} = 4678 \text{ kgr total} \]
      4678/3 units = 1560 kgr/unit.

   b. Allowable leakage = 3 mg/L:
      This leakage can be achieved at 6 lb NaCl/ft³. (Table 12.2)
      (Actual leakage at 6 lb/ft³ will be only 1.5 mg/L hardness)
      Capacity at 6 lb/ft³ = 20 kgr/ft³ (Table 12.2)
      \[ \text{Required resin} = \frac{1560}{20} = 78 \text{ ft}³ \text{ minimum per unit.} \]

   c. Bed depth: Area of 10 ft diameter unit = 78.5 ft². Therefore, bed would be approximately 1 ft deep. To achieve the desired leakage, minimum bed depth is 30 in. Therefore, each unit requires:
      \[ 2.5 \text{ ft deep} \times 78.5 \text{ ft}² \text{ area} = 195 \text{ ft}³ \]

   d. The actual service run will be:
      \[ \frac{196 \text{ ft}³ \times 3 \text{ units} \times 20 \text{ kgr/ft}³}{14,035 \text{ kgr/day}} = 0.84 \text{ day} \]
      \[ 0.84 \times 24 = 20 \text{ h} \]
      or one unit will be regenerated every 6 h, 40 min.

3. Salt consumption at 6 lb salt—20 kgr/ft³
   \[ \frac{6}{20} = 0.3 \text{ lb/kgr (2.1 mg/L salt/mg/L hardness), (theoretical = 0.167 lb/kgr)} \]
   \[ 14,035 \text{ kgr/day} \times 0.3 \text{ lb NaCl/kgr} = 4200 \text{ lb NaCl} \]
   This requires bulk deliveries for practical handling by plant labor.
The charge of spent brine will be high in Ca and Mg hardness, but after passage of a brine volume equivalent to perhaps 5 to 6 lb/ft³ the hardness concentration of the discharge usually drops sharply; at this point, the subsequent brine discharge can be diverted from sewer to a reclaim tank to be used as the first step of the next regeneration cycle. This same principle has been applied to acid and caustic regenerations in water treatment and has been used extensively in metallurgical applications of ion exchange, such as uranium recovery.

An example is worked out completely in Table 12.3 to give a perspective on the relative size of the equipment, the choice between salt dosage, capacity, and leakage, and the volumes of waste produced. Note that NaCl utilization of 0.3 lb/kt compared to a theoretical (stoichiometric) of 0.167 corresponds to an efficiency of only about 56%.

Identification of Analyses Tabulated Below:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>CaCO₃</td>
<td>150</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>&quot;</td>
<td>50</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>Sodium</td>
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<tr>
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<td>CaCO₃</td>
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<td>300</td>
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<td></td>
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<tr>
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<td></td>
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<tr>
<td>Sulfate</td>
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<td>50</td>
<td></td>
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<td></td>
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<tr>
<td>Chloride</td>
<td>&quot;</td>
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<td>50</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>&quot;</td>
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<td>200</td>
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<tr>
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<td>&quot;</td>
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</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>0.2</td>
<td>Nil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>Nil</td>
<td>Nil</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TDS *</td>
<td>350</td>
<td>370</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>Nil</td>
<td>Nil</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* Note the increase in TDS due to higher equivalent weight of sodium (23) compared to Ca (20) and Mg (12.2)

FIG. 12.15  Expected results of simple sodium zeolite treatment.
Service flow is based on rates of 6 gal/min/ft\(^2\), single unit maximum rate, and 8 gal/min/ft\(^2\) short term rate, on multiple units when one unit is out of service for regeneration. To provide a continuous supply of treated water, most plants use two units, so that while one is being regenerated, the other continues to provide finished water. Plants having variable demand store finished water to eliminate surges in flow, minimizing equipment size. Treated water storage permits smaller plants to install only a single unit, relying on stored water to provide requirements during regeneration. This is risky, since it provides no margin for error or for normal maintenance.

Backwash rate of 3 gal/min/ft\(^2\) for anion resins at 70\(^\circ\)F.

Backwash rate of 6 gal/min/ft\(^2\) for cation resins at 70\(^\circ\)F.

Backwash rate of 12 gal/min/ft\(^2\) for cation resins at 220\(^\circ\)F.

The zeolite softener simply removes hardness when used for treatment of a raw water supply. A typical analysis showing raw water and treated water is given in Figure 12.15. However, the system is also used for cleanup of process condensates in industrial operations, such as paper mill condensate, chemical plant condensate, and central heating station condensate, where the units are operated at very high flow rates and remove not only traces of hardness that enter the system from leakage of heat exchangers, but also particulate matter, such as corrosion products.

The wastes from regeneration of an ion exchange system are convenient in that they are in solution form. However, they increase the dissolved solids content of the effluent from the waste treatment plant through which they are processed. If this saline water is a problem, it can be treated with lime and soda ash to precipitate the hardness, producing a brine which can then be reused. This process, which converts the liquid saline waste to a solid waste, has been proposed for installations in the southwest where the spent brine may lower the quality of the receiving streams and where the climatic conditions are favorable for drying of solid waste.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Area, ft(^2)</th>
<th>Min. resin, ft(^3) at 30 in</th>
<th>Backwash, gal/min</th>
<th>Service flow, gal/min max.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 ft-0 in</td>
<td>3.14</td>
<td>8</td>
<td>9</td>
<td>19</td>
</tr>
<tr>
<td>2 ft-6 in</td>
<td>4.91</td>
<td>12</td>
<td>15</td>
<td>30</td>
</tr>
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<td>3 ft-0 in</td>
<td>7.07</td>
<td>18</td>
<td>21</td>
<td>42</td>
</tr>
<tr>
<td>3 ft-6 in</td>
<td>9.62</td>
<td>24</td>
<td>29</td>
<td>58</td>
</tr>
<tr>
<td>4 ft-0 in</td>
<td>12.6</td>
<td>32</td>
<td>38</td>
<td>75</td>
</tr>
<tr>
<td>4 ft-6 in</td>
<td>15.9</td>
<td>40</td>
<td>48</td>
<td>95</td>
</tr>
<tr>
<td>5 ft-0 in</td>
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<td>49</td>
<td>59</td>
<td>118</td>
</tr>
<tr>
<td>5 ft-6 in</td>
<td>23.8</td>
<td>60</td>
<td>71</td>
<td>143</td>
</tr>
<tr>
<td>6 ft-0 in</td>
<td>28.3</td>
<td>71</td>
<td>85</td>
<td>170</td>
</tr>
<tr>
<td>6 ft-6 in</td>
<td>33.2</td>
<td>83</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>7 ft-0 in</td>
<td>38.5</td>
<td>96</td>
<td>115</td>
<td>230</td>
</tr>
<tr>
<td>7 ft-6 in</td>
<td>44.2</td>
<td>110</td>
<td>132</td>
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<td>150</td>
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<td>56.8</td>
<td>142</td>
<td>170</td>
<td>340</td>
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<tr>
<td>9 ft-0 in</td>
<td>63.6</td>
<td>160</td>
<td>190</td>
<td>380</td>
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<tr>
<td>9 ft-6 in</td>
<td>70.9</td>
<td>176</td>
<td>213</td>
<td>425</td>
</tr>
<tr>
<td>10 ft-0 in</td>
<td>78.5</td>
<td>196</td>
<td>235</td>
<td>470</td>
</tr>
<tr>
<td>11 ft-0 in</td>
<td>95</td>
<td>240</td>
<td>285</td>
<td>570</td>
</tr>
</tbody>
</table>

* Service flow is based on rates of 6 gal/min/ft\(^2\), single unit maximum rate, and 8 gal/min/ft\(^2\) short term rate, on multiple units when one unit is out of service for regeneration. To provide a continuous supply of treated water, most plants use two units, so that while one is being regenerated, the other continues to provide finished water. Plants having variable demand store finished water to eliminate surges in flow, minimizing equipment size. Treated water storage permits smaller plants to install only a single unit, relying on stored water to provide requirements during regeneration. This is risky, since it provides no margin for error or for normal maintenance.

† Backwash rate of 3 gal/min/ft\(^2\) for anion resins at 70\(^\circ\)F.

‡ Backwash rate of 6 gal/min/ft\(^2\) for cation resins at 70\(^\circ\)F.

§ Backwash rate of 12 gal/min/ft\(^2\) for cation resins at 220\(^\circ\)F.