SOFTENER PERFORMANCE

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by

G.F. Yuzwa, P.Eng.

H2O ENGINEERING LTD.
539 Edgemont Bay N.W.
Calgary, Alberta
T3A 2K7

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Types of Hardness Salts

All natural water supplies, either in their raw state or after treatment by a municipality, contain dissolved mineral matter. The mineral constituents differ greatly in the amounts and proportions from one water supply to another; however, the most abundant are the bicarbonates, sulphates, and chlorides of calcium, magnesium, and sodium.

There are two types of hardness, namely "temporary hardness" and "permanent hardness".

Temporary hardness, or carbonate hardness, is the hardness that is associated with the bicarbonates of calcium and magnesium. Its name is derived from the fact that when water containing this type of hardness is heated, the soluble bicarbonates break down to form insoluble carbonate salts. In effect, the hardness is precipitated, thus resulting in soft water, as illustrated with equations 1 & 2 below.

$$\mathrm{Ca(HCO_3)_2} + \text{heat} = \mathrm{CaCO_3} + \mathrm{CO_2} + \mathrm{H_2O} \qquad (1)$$

Calcium + heat = Calcium (scale) + Carbon (gas) + Water (soft)
Bicarbonate Carbonate Dioxide

$$\mathrm{Mg(HCO_3)_2} + \text{heat} = \mathrm{MgCO_3} + \mathrm{CO_2} + \mathrm{H_2O} \qquad (2)$$

Magnesium + heat = Magnesium (scale) + Carbon (gas) + Water (soft)
Bicarbonate Carbonate Dioxide

Permanent hardness, or noncarbonate hardness, is the hardness that is associated with the sulphates, chlorides, and nitrates of calcium and magnesium. Water with this type of hardness is corrosive in steam boilers because of their reaction with water to form corrosive compounds such as hydrochloric acid, magnesium hydroxide, etc.

The total hardness concentration is equal to the sum of the carbonate and noncarbonate hardness concentrations.

The amounts of carbonate and noncarbonate hardness are determined by inspection of the water analysis report as follows:

(1) if the M-alkalinity equals or exceeds the total hardness, all of the hardness is carbonate hardness;

(2) if the M-alkalinity is less than the total hardness, the carbonate hardness equals the M-alkalinity, and the noncarbonate hardness equals the total hardness minus the M-alkalinity.

In most areas of the Province of Alberta, the natural water consists largely of carbonate hardness.

Properties of Hardness Scale

As indicated previously, when water containing carbonate hardness is heated, the soluble bicarbonates of calcium & magnesium are converted to their insoluble carbonates.

As illustrated in Table 1 overleaf, calcium & magnesium bicarbonate are very soluble (ie., 1,620 ppm & 37,100 ppm at 32 °F, respectively), whereas their respective carbonates have a solubility of only 13 ppm & 75 ppm respectively at 212 °F. This means for example that if water containing 100 ppm hardness as calcium bicarbonate is heated to boiling, 87 pounds of scale (ie., 100 - 13 = 87) will be precipitated for every million pounds of water.

Also as indicated in Table 1, the permanent hardness salts are very soluble, except for calcium sulphate, (eg. solubility of calcium chloride is 554,000 ppm at 212 °F); however, as indicated previously, these salts are very corrosive because of the acids/bases they form when they react with water.

Table 1: Solubility of Hardness Salts

Hardness Salt Common Name	Hardness Salt Chemical Formula	Solubility at Indicated Temperature (ppm $CaCO_3$)
Carbonate Hardness		
Calcium Bicarbonate	$Ca(HCO_3)_2$	1,620 (at 32 °F)
Magnesium Bicarbonate	$Mg(HCO_3)_2$	37,100 (at 32 °F)
Calcium Carbonate	$CaCO_3$	13 (at 212 °F)
Magnesium Carbonate	$MgCO_3$	75 (at 212 °F)
Noncarbonate Hardness		
Calcium Sulphate	$CaSO_4$	1,246 (at 212 °F)
Calcium Chloride	$CaCl_2$	554,000 (at 212 °F)
Magnesium Sulphate	$MgSO_4$	356,000 (at 212 °F)
Magnesium Chloride	$MgCl_2$	443,000 (at 212 °F)

The solubilities of the carbonate hardness salts and calcium sulphate are inversely proportional to the temperature of the water. That is, their solubilities decrease as the temperature of the water increases.

With the exception of calcium sulphate, the solubilities of the noncarbonate hardness salts are directly proportional to the temperature of the water. That is, their solubilities increase as the temperature of the water increases.

Effects of Hardness Scale in a Heating System

The thermal conductivity of hard water scales is in the order of 0.2 to 1.5 Btu/ft^2/ft/hr/°F depending on its porosity. By comparison, the thermal conductivity of fire brick is about 0.75, and that of steel is about 26. Therefore, hard water scales therefore have about the same insulating value as fire brick.

The maximum safe operating temperature for mild boiler steel is considered to be about 900 °F, since temperatures above this level will result in metal failure.

As illustrated in Table 2 below, the heat insulating effect of hardness scale becomes more pronounced as the heat rate increases. That is, hardness scale is more tolerable in boilers with a lower heat rate. For example, in a boiler with a typical heat rate of 10,000 Btu/ft^2/hr, a scale thickness of only 0.10 inch will cause a temperature differential of 111 °F, whereas in a boiler with a heat rate of 2,000 Btu/ft^2/hr, a scale thickness of 0.10 inch will cause a temperature differential of only 22 °F.

Table 2: Effect of Scale on Boiler Heating Surface

Boiler Heat Rate (Btu/ft^2/hr)	Temperature Differential Caused by 0.10 inch of Scale with a Thermal Conductivity of 0.75 Btu/ft^2/ft/hr/°F (F°)
2,000	22
5,000	56
10,000	111
20,000	222

Hardness Removal by Softening

Since sodium salts are extremely soluble in cold and hot water, they do not form scale, unless evaporation is taken to undue lengths. Therefore, scale prevention may be accomplished by converting hardness salts to sodium salts.

This process utilizes ion exchange resin and is referred to as softening the water. Hard water is passed through a bed of sodium form cation exchange resin, which replaces the calcium & magnesium ions with sodium ions, thus yielding soft water. When the capacity of the resin for absorbing calcium & magnesium ions is exhausted, the resin is regenerated with a salt solution, usually sodium chloride.

A typical water analysis report will indicate hardness concentration as either ppm or mg/l $CaCO_3$; however, in the softener industry, hardness concentration is indicated as either grains/gallon, or simply grains. Since a grain is 1/7000th of a pound, the conversion factor is 1/14.3 to convert ppm to grains per imperial gallon. For example, a total hardness concentration of 143 ppm is equivalent to 10 grains of hardness per imperial gallon, and is said to be 10 grains hard.

The exchange capacity of softener resin is expressed as kilograins (ie., kgrn), and the design run for a softener may be calculated as follows:

$$Q = E \text{ X } V \text{ X } 14.3/TH \tag{3}$$

where, Q is the volume of water softened, IG (ie., imperial gallons)
E is the exchange capacity of the resin, kgrn/ft^3 resin
V is the volume of resin, ft^3
TH is the raw water total hardness concentration, ppm $CaCO_3$

For example, a 30 kgrn softener will remove 30,000 grains of hardness, and its design run for water with a hardness concentration of 143 ppm is 3,000 IG.

However, the field capacity of the softener is dependent on factors such as the raw water TDS concentration and the regeneration salt dosage, as illustrated in Table 3 below.

Table 3: Softener Exchange Capacity

Raw Water TDS (mg/l)	Exchange Capacity (kgrn/ft^3)				
	Salt Dosage (lb/ft^3)				
	20	15	10	5	2.5
200	34	34.5	33	23.5	20
400	32	31.5	29	21	18
800	28	25.5	24	19	16
1200	24	22.5	21	14	11

Example 1: When a water with a TDS concentration of 400 ppm is regenerated at a salt dosage of 5 lb/ft^3 of resin in a softener that contains 5 ft^3 of resin, the total exchange capacity will be 105 kgrn (ie., 5 ft^3 X 21 kgrn/ft^3, from table 3). With this example, the softener will soften 10,500 IG of water that has a hardness concentration of 143 ppm, using equation 3 on page 6.

Example 2: If the water has a TDS concentration of 1200 ppm and the same hardness concentration of 143 ppm, the same softener with 5 ft^3 of resin will soften only 7,000 IG of water using the same salt dosage of 5 lb/ft^3 of resin.

By inspection of the exchange capacities indicated in Table 3, the salt dosage for example 2 must be doubled from 5 lb/ft^3 resin to 10 lb/ft^3 resin in order to obtain the same softener exchange capacity as for example 1.

Salt Efficiency

Salt efficiency is obtained by dividing the softener total exchange capacity (ie., kgrns) by the amount of salt (ie., pounds) that is used for its regeneration. As indicated in Table 4 below, the salt efficiency increases as the salt dosage decreases, for all TDS levels (note that when the salt dosage is reduced to zero, the salt efficiency is obviously also zero). That is, for a TDS level of 200 mg/l, the salt efficiency is increased from 2.3 kgrn/lb at a regeneration level of 15 lb/ft^3 to 8.0 kgrn/lb at a regeneration level of 2.5 lb/ft^3.

However, the high salt efficiency at the reduced regeneration level unfortunately results in hardness leakage into the treated water. The higher the salt efficiency, the higher the hardness leakage. Therefore, the application determines the salt dosage rate. That is, when the softener is used for softening the feed water to a steam boiler, hardness leakage must be minimized; therefore, a high salt dosage of 10-15 lb/ft^3 is used, thus sacrificing salt efficiency. Conversely, hardness leakage from a home softening unit is usually acceptable; therefore, the salt dosage may be reduced to about 5 lb/ft^3 in order to maximize the salt efficiency.

Table 4: Salt Efficiency

Raw Water TDS (mg/l)	Salt Efficiency (kgrn/lb)				
	Salt Dosage (lb/ft^3)				
	20	15	10	5	2.5
200	1.7	2.3	3.3	4.7	8.0
400	1.6	2.1	2.9	4.2	7.2
800	1.4	1.7	2.4	3.8	6.4
1200	1.2	1.5	2.1	2.8	4.4

Volume of Brine for Regeneration

The volume of brine required for a regeneration may be calculated as follows:

$$B = S \times V \times 1/C \qquad (4)$$

where, B is the volume of brine required for regeneration (USG)
S is the salt dosage (lb/ft^3 resin)
V is the volume of resin, ft^3
C is the salt concentration (lb/USG)

Example 3: A softener with 1 ft^3 of resin which is regenerated at a salt dosage of 15 lb/ft^3 will require **7.6 USG of brine** at a salt concentration of 1.98 lb/USG.

In order to minimize the volume of brine used for regeneration, and also the regeneration time, the brine concentration in the brine tank must be at least 80% of saturation before a regeneration is attempted. Otherwise, an inordinate volume of brine is required for the regeneration. That is, if the brine concentration is only 50% of saturation, the salt concentration is only 1.24 lb/USG (see Table 5 blow); therefore, **12.1 USG of brine** will be required to regenerate the same softener given in Example 3.

Table 5: Salt Concentration

Salimeter Reading (%)	Salt Concentration (lb/USG)
100	2.48
80	1.98
50	1.24
25	0.62

Softener Control Limits

Service Influent Chlorine:	1 ppm max.
Service Effluent Hardness:	1 ppm max.
Service Flow Rate:	2 USG/ft^3 resin
Backwash Flow Rate:	4-6 USG/ft^3 resin
Regenerant Concentration:	10% NaCl (at vessel inlet)
Regenerant Flow Rate:	1 USG/ft^3 resin
Regenerant Time:	15 minutes min.
Rinse Flow Rate:	1 USG/ft^3 resin (initial) 1.5 USG/ft^3 resin (final)
Rinse Water Requirements:	25-75 USG/ft^3 resin
Brine Concentration:	80% saturation min. (in brine tank)