



Ion Exchange Design – Hand calculation

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Introduction

Before design programmes were introduced, every engineer had to calculate the design by hand using resin manufacturers data. Each engineer had their own way to carry out in their calculation.

Before starting the design ideally you need to know some basic information:

1. Maximum / Average / Minimum flow rate and roughly how many hours per day the maximum flow rate is required (m^3/h).
2. Daily requirement (m^3/day) over how many hours.
3. Design water analysis
4. Cation regenerant (sulphuric or hydrochloric acid)

Flow rate

1. If the maximum demand is for a short period, or if there is a wide range of operating flow rates, then you can design the plant on the average demand and include a larger treated water storage to cater for the maximum flow rate or variations in demand.
2. It is always to keep the plant in operation rather than operating on an “on-off” basis with lots of stopping and starting.
3. Resins can operate over a range of flow rates, but the design of ion exchange columns is often very basic and many cannot accommodate very low flow rates. Poor distribution / collection is often encountered at low flow rates leading to channelling and poor performance.

Cycle Time / No of Streams

The cycle time for each cation – anion pairing is determined by the water analysis, flow rate and number of streams. Where demineralised water is critical to the sites operation then normally the client will require a standby stream to cover for regeneration time of the other stream(s) and allow some basic maintenance.

Most commonly encountered plants are therefore 2 x 100% or 3 x 50% duty, but where very high flow rates are encountered 4 x 33% duty and 5 x 25% duty streams have been supplied.

A cation – anion pair can be regenerated in under 2 hours if simultaneous regeneration is employed and with short cycle plant it is even quicker. Mixed beds are more complicated, but are regenerated less frequently and usually take 2 to 3 hours.

Cycle Time / No of Streams

Ignoring short cycle plants, then classical designs are often based on 8 or 12 hours on line between regenerations depending on the water analysis used for the design.

Longer cycle times are encountered when the raw water TDS is low. Such thin waters often see plants designed on 24 hours on line or even longer.

We will now select the basis for our design calculations.

Design Analysis

1. Knowledge of the maximum and typical analysis is critical when choosing the cycle time.

No point choosing short cycle time on the design analysis if the worst water has a much higher TDS. This will mean the time between regenerations is too short.

2. The analysis should balance i.e. The cations and anions expressed as mg/l CaCO₃ or in meq/l should be very similar (within 5%)

3. You have to design the plant to cope with the worst water, but if that water is very infrequently seen then all design operating costs and design decisions need to be based on the typical water analysis.

Maximum Water Analysis (Worst Water)

If designed on the worst water analysis presented by the end user the water may not balance as the client may have “cherry picked” the highest recorded level for each ion. These highest level for all ions will not occur on the same day and hence it will not balance.

Then you can round down the highest category to give the balanced analysis as naturally occurring waters must balance.

In our calculation the end user has given us the analysis of his anticipated worst water.

Design Basis for this Calculation

Flow Rate – 60 m³/h (for 24 hours per day)

Important application so standby stream required – 2 x 100% duty.

Hydrochloric acid for cation regeneration. Water temp 10 centigrade.

Worst Water Analysis from client (all expressed in mg/l as CaCO₃.)

<u>Cations</u>		<u>Anions</u>	
Calcium (Ca)	110	Bicarbonate (HCO ₃)	100
Magnesium (Mg)	55	Sulphate (SO ₄)	50
Sodium (Na)	100	Chloride (Cl)	75
Potassium (K)	11	Nitrate (NO ₃)	25
TOTAL CATIONS	276	TOTAL ANIONS	250

Greater than 10% difference!

Design Basis – Corrected Analysis

Corrected Worst Water Analysis to balance
(all expressed in mg/l as CaCO₃)

<u>Cations</u>		<u>Anions</u>	
Calcium (Ca)	100	Bicarbonate (HCO ₃)	100
Magnesium (Mg)	50	Sulphate (SO ₄)	50
Sodium (Na)	90	Chloride (Cl)	75
Potassium (K)	10	Nitrate (NO ₃)	25
TOTAL CATIONS	250	TOTAL ANIONS	250

Design analysis to go forward

In addition we will assume a Reactive Silica of 5 mg/l as CaCO₃.
It is a ground water and contains negligible dissolved organics.

Degassing tower

The inclusion of a degassing tower to remove the bicarbonate after the cation, when it is converted to carbonic acid, has to be decided before the design is commenced.

If the bicarbonate level is above 40 mg/l as CaCO_3 then it is normally cost effective to include a degasser, this is particularly the case on engineered design where a neutral effluent is often required from the waste water produced and plant costs are greater.

However, on small, low flow rate, standard plants many companies do not supply a degasser as the capital cost associated with the tower, degassed water pumps (stainless steel) makes the pay back period less attractive and here all the bicarbonate load is often removed by the anion stage.

On this design with 150 mg/l bicarbonate we will have a degasser tower.

Design Approach

In all cases however you have to design from the back of the plant.

If you have a cation – anion – mixed bed system then you start with mixed bed calculation, then anion and then the cation.

This way you can calculate or estimate the waste water required which must pass through the preceding unit during the design.

For this example I will assume a simple co-flow regenerated system of cation – anion followed by a polishing mixed bed.

Counter flow regeneration is a little more complicated as you have to estimate the additional treated water required for regenerant injection and slow rinses on the cation and anion beds.

Polishing Mixed Bed - Design basis

After SAC / SBA resins the loading on to polishing mixed beds is very low and so these units are sized on flow rate which makes it very simple. The basis I use is:

- Vessel sizing based on specific velocity of $60 \text{ m}^3/\text{m}^2/\text{h}$.
- 600 mm minimum bed depth for cation / anion components.
- Anion regeneration level 65 g/l – with cation regen level designed to give substantially self neutralising effluent.
Depending on cation load, approx. 62 g/l for HCl and 80 g/l for sulphuric acid gives a neutral effluent.
If not worried about neutral effluent then regen levels as low as 60 g/l NaOH and 48 g/l HCl or H_2SO_4 have been used.

Polishing Mixed Bed - Sizing

Applying these parameters to 60 m³/h flow rate then:

60 m³/h divided by 60 m/h = Minimum area 1 m² required.

Hence based on UK vessel sizing = 1219 mm diameter (1.16 m²)

Resin volume per unit = 0.6 m x 1.16 m² = 0.696 m³ (696 litres)

Rounded up to the nearest 25 litres = 700 litres of each component.

Caustic applied at 65g/l regen level = 65g/l x 700 / 1000 = 45.5 Kg
(as 100% NaOH).

HCl applied at 63 g/l regen level = 63 g/l x 700 / 1000 = 44.1 Kg
(as 100% HCl).

(Metric Sizing 1200 mm diameter with 675 litres of each resin)

Polishing Mixed Bed - Operation

Mixed beds should never be run near to exhaustion – due to the long run length this has little effect on plant operating costs.

Historically I tend to use the following guide capacities to determine run length of a polishing mixed bed based on the cation / anion leakage.

Anion reactive silica loading should not exceed 9 g/l (6 g/l used by some)

Cation sodium loading should not exceed 15 g/l.

These are highly conservative. Hence good quality obtained at all times!

Anion Design – Anion analysis after Degasser Tower

After the degassing tower the bicarbonate anion loading will be reduced typically to $< 5 \text{ mg/l CO}_2$ as CaCO_3

Therefore the anion load based on the original raw water will now be:

Anions

Sulphate (SO_4)	50
Chloride (Cl)	75
Nitrate (NO_3)	25
Reactive Silica	5
Carbon Dioxide	5

Anion Load = 160 mg/l as CaCO_3

Anion Design – Gross water production per cycle

Early we chose 8 hour on line for the worst water.

Therefore volume of water treated per cycle would be:

(8 hours x 60 m) + MB regen water

(Note MB normally uses between 12 and 20 BV of water per regen.)
We will use 15 BV for the calculation, so with 1400 litres of resin per mixed bed it needs $15 \times 1400 = 21000$ litres (21 m^3)

Therefore anion volume of treated water = $(8 \times 60) + 21 \text{ m}^3$

$$= 501 \text{ m}^3$$

Anion Design – Anion load per cycle

$$\begin{aligned}\text{Therefore anion volume of treated water} &= (8 \times 60) + 21 \text{ m}^3 \\ &= 501 \text{ m}^3\end{aligned}$$

$$\begin{aligned}\text{The anion ionic load per cycle is therefore} & 501 \text{ m}^3 \times 160 \text{ mg/l} / 1000 \\ &= 80.160 \text{ Kg as CaCO}_3\end{aligned}$$

Now we have the load per cycle to calculate the resin volume we need to now calculate from the resin manufacturers data the working capacity of the resin.

For the basis of this calculation, with a low organics content I am basing on a gel, polystyrenic, anion resin with a high capacity. This type of product is available from all the leading suppliers.

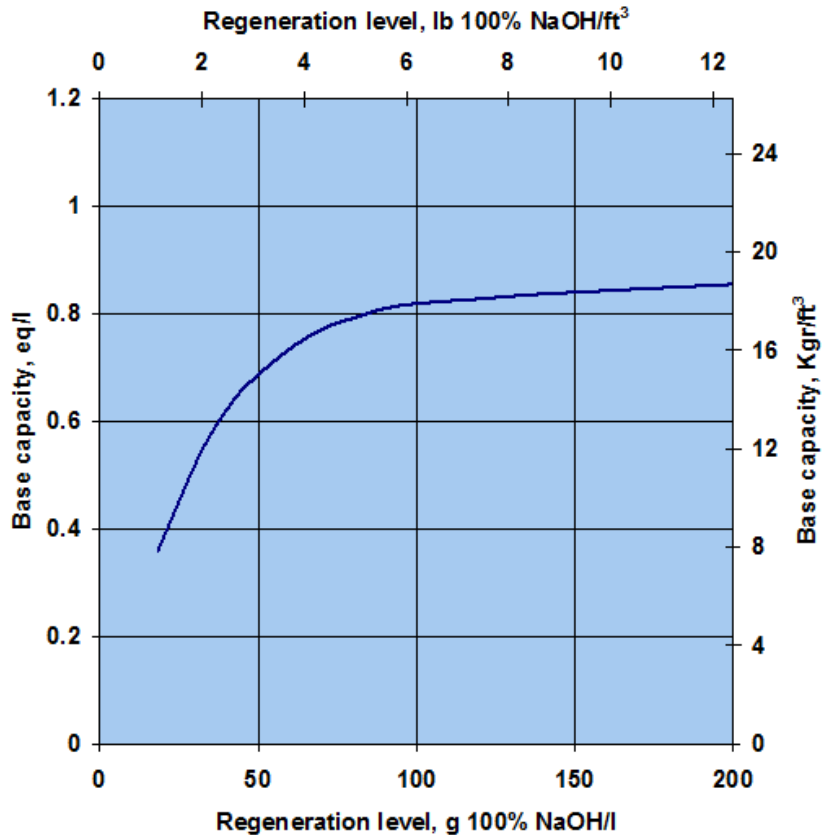
Anion Design – Capacity Correction Factors

For a type 2, gel, polystyrenic, anion resin the working capacity is determined by a base capacity dependent on regen level (amount of caustic applied). This capacity then has various correction factors applied **and each manufacturers graphs presented differently.**

- The percentage sulphate in the anion load.
- The percentage CO₂ in the anion load.
- The silica endpoint for regeneration.
- The bed depth (if shallow below 0.7 m). We can ignore this with our design as with the size of plant our bed depth will be between 1 and 1.5 m.
- The percentage silica in the anion load and regenerant temperature.

Co-flow plant regen levels tend to be between 55 and 80 g/l. However, regen levels are sometimes encountered outside this range.

Anion Design – Base Resin Capacity

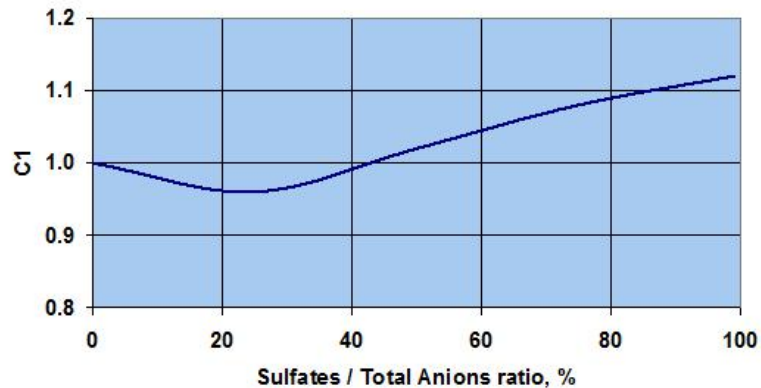


For this co-flow regenerated design I have chosen a regeneration level of 60 g/l NaOH.

From the resin engineering bulletin this gives a base working capacity of 0.75 eq/l. This is 37.5 g/l as CaCO_3 (0.75 x 50)

Anion Design – Anion Capacity Adjustment

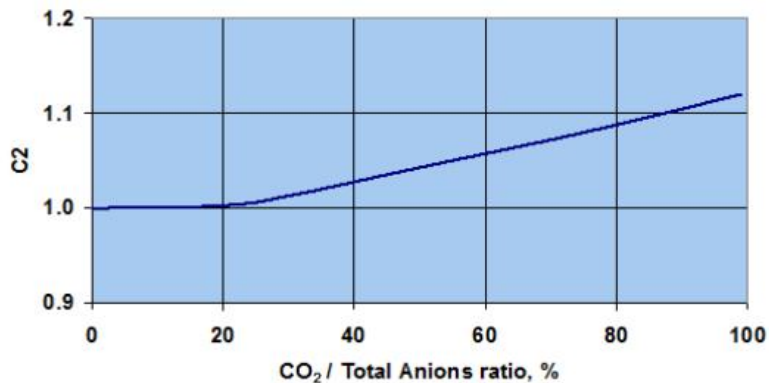
C1 - Capacity correction factor
Sulfates / Total Anions



Sulphate percentage in anion load $50 \text{ mg/l} / 160 \text{ mg/l} \times 100 = 31.25\%$.

From graph correction factor = 0.95

C2 - Capacity correction factor
CO₂ / Total Anions

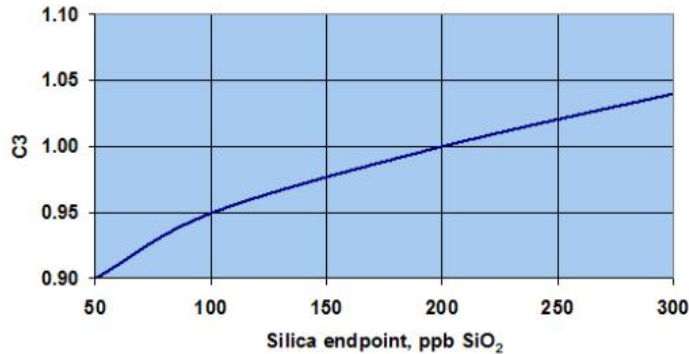


Carbon Dioxide percentage in anion load $5 \text{ mg/l} / 160 \text{ mg/l} \times 100 = 3.125\%$.

From graph correction factor = 1.00 (no effect)

Anion Design – Anion Capacity Adjustment

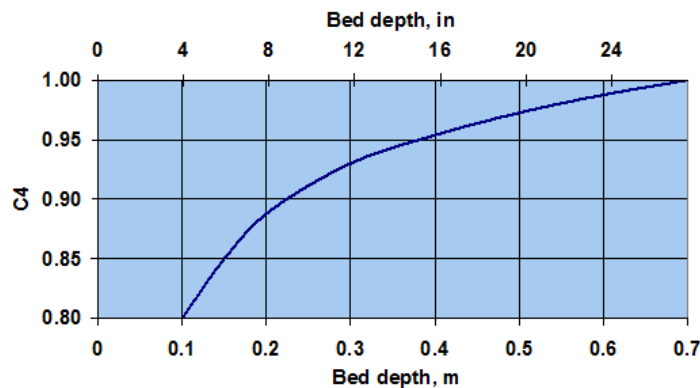
C3 - Capacity correction factor
Silica endpoint



We can operate to a 200 ppb endpoint.

From graph correction factor = 1.00 (No effect)

C4 - Capacity correction factor
for bed depth

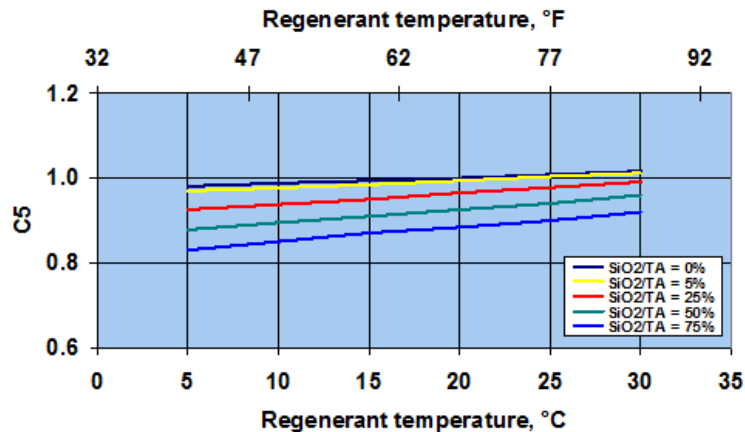


We will have a bed depth above 0.7 m.

From graph correction factor = 1.00 (No effect)

Anion Design Capacity (Theoretical)

C5 - Capacity correction factor for Silica and Regeneration temperature



Silica percentage equates to 3.1% of Anion load. If we assume regenerant temperature of 10 C then from graph correction factor = 0.965

If we now apply all these correction factors to the base capacity we will obtain the theoretical working capacity (Ignoring those which are 1.0 as they have no effect).

Theoretical Working capacity = $37.5 \text{ g/l} \times 0.95 \times 0.965 = 34.37 \text{ g/l}$ as CaCO_3

Anion Design – Rinse Correction

Now I need to correct the capacity for the loading on to the bed caused when the resin is rinsed after regeneration with decaionised water. For a co-flow regenerated anion resin I would use 6 BV final rinse (when new). Therefore the rinse correction in g/l as CaCO₃ is:

$$6 \text{ (bed volumes)} \times 160 \text{ (mg/l anion load)} / 1000 = 0.96 \text{ g/l}$$

Therefore revised working capacity is now $34.37 - 0.96 = 33.41 \text{ g/l}$

Depending on the design / actual knowledge of the water, and the engineering system being used, a smart engineer will now apply a design margin to ensure the resin manufacturers performance can be guaranteed for an operating plant for the warranty period.

Anion Design – Design Margin / Working Capacity

The selection of and the amount of design margin is critical to a well designed reliable plant. When I am doing these calculations I favour taking a larger design margin on the anion resin over the cation resin. This is because I want the plant to be cation limiting making conductivity control of the plant on exhaustion easier and also because anion resin performance usually falls off at a quicker rate than cation performance. **I therefore tend to take a 10 to 15% design margin on the anion capacity and correspondingly lower 5 to 10% on the cation resin.**

Many engineers just take 10% design margin on both to make the plant more competitively priced etc. **On this example I will apply 10% to both.**

Therefore anion working capacity = $33.41 \times 0.9 = 30.07$ g/l.

Anion Design – Resin Volume

If you recall we calculated back on slide 17 we calculated the anion load as 80.160 Kg as CaCO_3

The resin volume required (in litres) is therefore the ionic load / the working capacity of the resin x 1000:

$$(80.160 / 30.07) / 1000 = 2665 \text{ litres}$$

We normally round up to nearest 25 litre bag quantity hence:

2675 litres required

Anion regen level was 60 g/l. Therefore caustic applied per regen is $60 \times 2675 / 1000 = 160.5 \text{ Kg}$ as 100% NaOH.

Cation Design – Design Analysis and Water Production

The cation load based on the original raw water will now be:

Cations

Calcium (Ca)	100
Magnesium (Mg)	50
Sodium (Na)	90
Potassium (K)	10

Cation Load = 250 mg/l as CaCO₃

The volume of water treated per cycle would be:

(8 hours x 60 m) + Anion regen water + MB regen water (21 m³)

(Note: a co-flow anion normally uses between 10 and 12 BV of water per regen.) We will use 12 BV for the calculation, so with 2675 litres of resin per anion unit, it needs 12 x 2700 litres = 32100 litres (32.1 m³)

Cation Design - Cationic Load

$$\begin{aligned}\text{Therefore cation volume of treated water} &= (8 \times 60) + 32 \text{ m}^3 + 21 \text{ m}^3 \\ &= 533 \text{ m}^3\end{aligned}$$

$$\begin{aligned}\text{The cation load per cycle is therefore} & 533 \text{ m}^3 \times 250 \text{ mg/l} / 1000 \\ &= 133.25 \text{ Kg as CaCO}_3\end{aligned}$$

Now we have the load per cycle to calculate the resin volume we need to now calculate from the resin manufacturers data the working capacity of the resin.

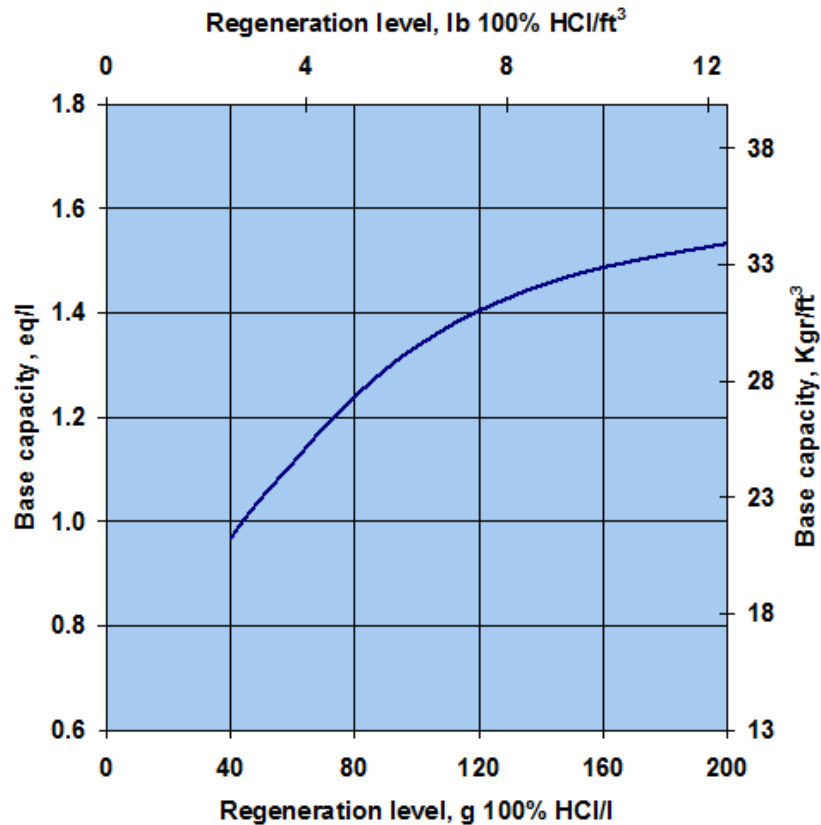
For the basis of this calculation, I am basing on an 8% DVB cross linked, gel, polystyrenic, standard grade strong acid cation resin with a high capacity. Similar product available from all the leading suppliers.

Cation Design - Capacity Correction Factors

For this type of resin the working capacity is determined from a base capacity dependent on regen level (amount of acid applied). This capacity then has various correction factors applied dependent on the following:

- The percentage bicarbonate present in influent water.
- The temperature of the water treated.
- The percentage sodium in the cation load.
- The kinetic loading. This will not apply as this is mainly linked to high TDS waters or high BV/h flow rates.

Cation Design – Base Resin Capacity

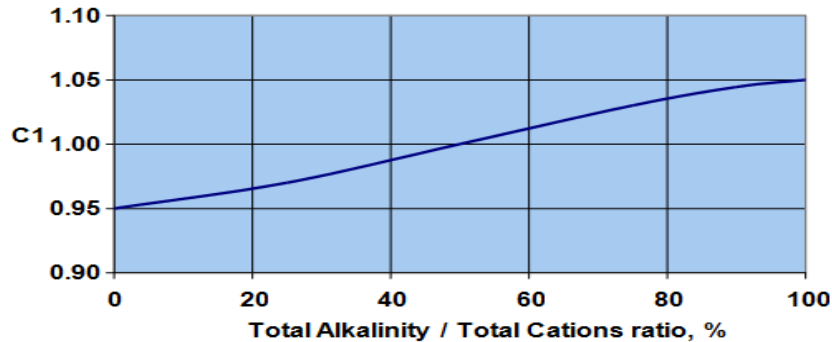


For this co-flow regenerated design I have chosen a regeneration level of 66 g/l HCl.

This corresponds from the cation engineering bulletin to a base working capacity of 1.14 eq/l. This is 57 g/l as CaCO_3 (1.14×50)

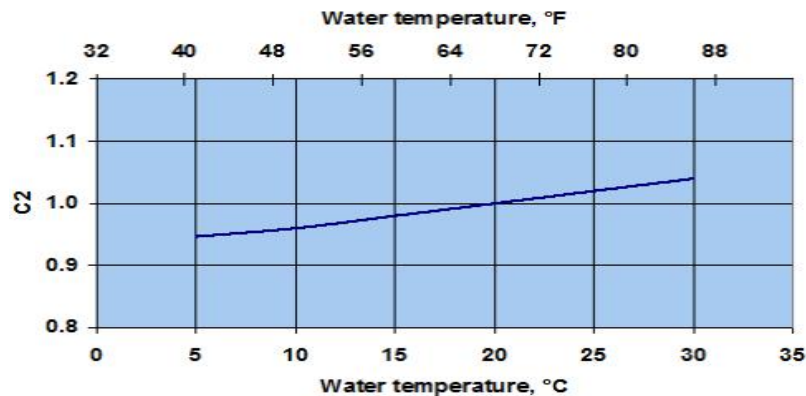
Cation Design – Cation Capacity Adjustment

Figure 2
C1 - Capacity correction factor
Total Alkalinity / Total Cations



Bicarbonate percentage in
Cation load 100 mg/l / 250 mg/l
 $\times 100 = 40\%$.
From graph correction factor =
0.97

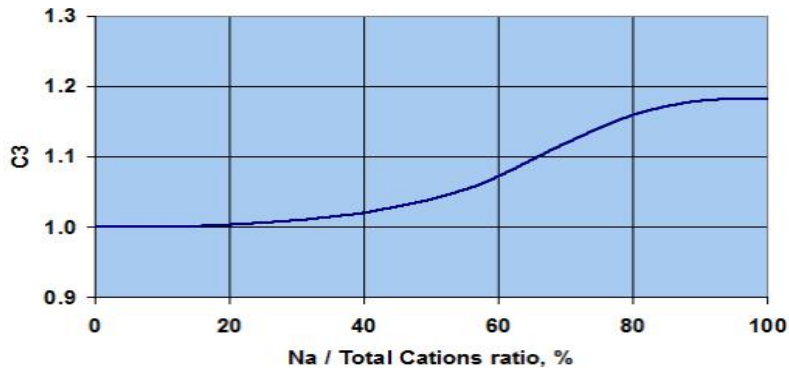
Figure 3
C2 - Capacity correction factor for temperature



Design water temperature 10 C
(minimum water temp)
From graph correction factor =
0.96

Cation Design- Cation Capacity Adjustment

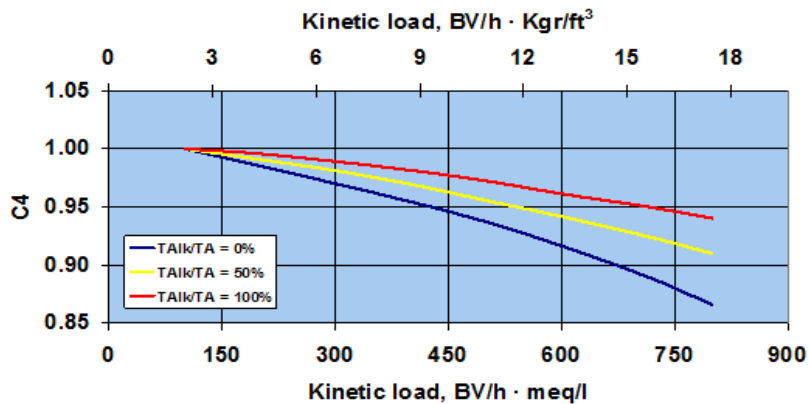
Figure 4
C3 - Capacity correction factor
for Na / Total Cations



Sodium percentage in cation load $100 \text{ mg/l} / 250 \text{ mg/l} \times 100 = 40\%$.

From graph correction factor = 1.025

Figure 5
C4 - Capacity correction factor for
kinetic load (Specific flow rate · Total Cations)



This graph applies to high TDS or high BV/h flow rates. In this design it does not apply as we are to the LHS of the graph where the factor is 1.0 (No effect).

Cation Design – Working Capacity

If we now apply all these correction factors to the base capacity we will obtain the theoretical working capacity (Ignoring those which are 1.0 as they have no effect).

$$\text{Theoretical Working capacity} = 57 \text{ g/l} \times 0.97 \times 0.96 \times 1.025 = 54.40$$

If we now apply rinse correction for co-flow cation. I tend to use 5 BV for this calculation for a co-flow regenerated cation.

$$\begin{aligned} &= 5 \text{ BV} \times 250 \text{ mg/l cation load} / 1000 \\ &= 1.25 \text{ g/l as CaCO}_3 \end{aligned}$$

This gives a theoretical capacity of $54.40 - 1.25 = 53.15 \text{ g/l as CaCO}_3$

If we then apply 10% design margin we have a working capacity of:

$$53.15 \times 0.9 = 47.83 \text{ g/l as CaCO}_3$$

Cation Design – Resin Volume

If you recall we calculated back on slide 27 we calculated the cation load as 133.25 Kg as CaCO_3

The resin volume required (in litres) is therefore the ionic load / the working capacity of the resin x 1000:

$$(133.25 / 47.83) / 1000 = 2785 \text{ litres}$$

We normally round up to nearest 25 litre bag quantity hence:

2800 litres required

Cation regen level was 66 g/l. Therefore acid applied per regen is $66 \times 2800 / 1000 = 184.8 \text{ Kg as } 100\% \text{ HCl}$.

Checking for Neutral Effluent (Taken from earlier slides)

Cation load	=	133.250 Kg as CaCO ₃
Anion load	=	80.160 Kg as CaCO ₃
Cation acid applied	=	184.800 Kg as 100% HCl
Caustic applied	=	160.500 Kg as 100% NaOH

If we convert the chemicals applied to as CaCO₃ we can establish the excess acid and caustic generated from a regeneration (Conversion factor for HCl is x 1.37 and for NaOH it is x 1.25).

Acid applied = $184.80 \times 1.37 = 253.2$ Kg. Therefore excess acid is the $253.2 - 133.25 = \mathbf{119.95}$ Kg as CaCO₃

Caustic applied = $160.5 \times 1.25 = 200.62$ Kg. Therefore excess acid is the $200.62 - 80.160 = \mathbf{120.46}$ Kg as CaCO₃

The two excesses are similar – therefore neutral effluent!

Checking for Neutral Effluent

I CHEATED

I did the calculation first before preparing the slides and this is why I selected a cation regen level of 66 g/l. I knew it gave me a neutral effluent for the calculation/presentation

Otherwise this part of the hand calculation takes some time to resolve. You have to draw a graph on which you plot regeneration level against excess regenerant generated and regeneration level against resin volume. Based on this graph it is then possible to interpret the results to reach a neutral effluent but it takes some time! Probably the subject of a another presentation.

THIS IS WHERE DESIGN PROGRAMMES HELP SO MUCH

Vessel Sizing – Design Parameters

Fortunately in this example co-flow cation and anion have very similar resin volumes so the sizing will be almost identical (2.675 m³ in the anion and 2.800 m³ in the cation. For insitu regenerated co-flow regenerated plant I use the following parameters for my vessel sizing:

Maximum service velocity. 50 m³/m²/h (m/h)

Minimum service velocity. 12 m³/m²/h (m/h)

Guide to maximum pressure drop at minimum temperature for a fully classified bed to allow for some compaction/fouling. 100 to 122 Kpa.

Maximise bed depth within pressure drop guide but rarely would the bed depth exceed 1.75 m and preferably more than 1.0 m and never below 0.6 m.

50 to 60% freeboard above resin for co-flow backwash.

Vessel Sizing

Using these parameters and the pressure drop curves for each resin the vessel size I would have selected the same vessel size for both columns:

Metric 1600 mm diameter x 2250 mm i/s.

This corresponds to 1.40 m cation and 1.34 m anion bed depth (installed) and a service velocity of 30 m³/m²/h (m/h)

UK 5 feet diameter x 8.25 feet i/s

This corresponds to 1.54 m cation and 1.47 m anion bed depth (installed) and a service velocity of 33 m³/m²/h (m/h)

Pressure Drop Across Resin Beds

We know the bed depths 1.4 m (cation) and 1.34 m (anion) and because the vessels are the same diameter the velocity of the water through each bed is the same ($30 \text{ m}^3/\text{m}^2/\text{h}$ (m/h)).

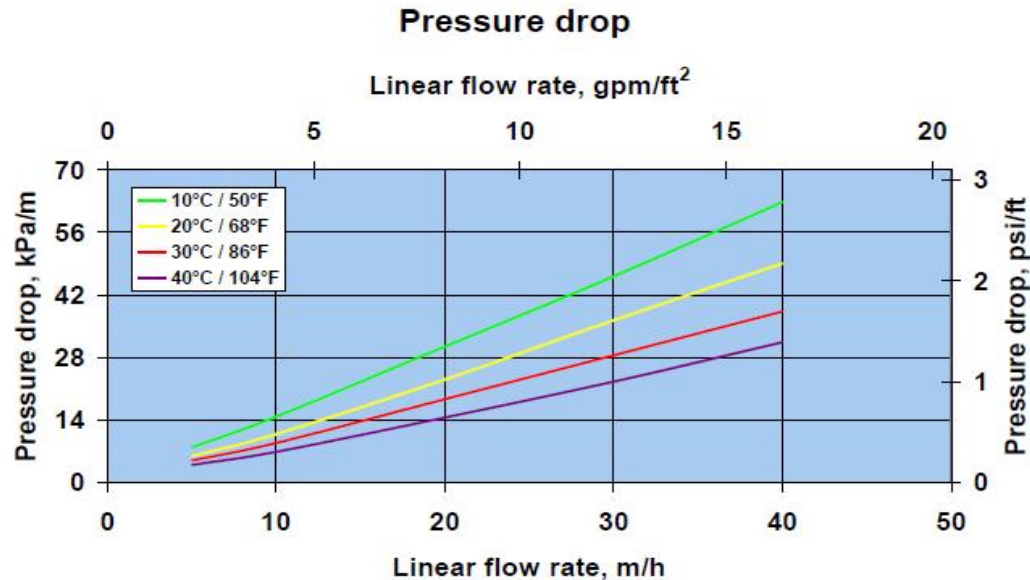
If we assume the minimum water temperature is 10 C in the winter, we can now calculate the pressure drop from a single graph for each resin which is based on the.

Velocity

Water Temperature

Bed Depth

Pressure Drop Across Resin Beds – Anion Resin Example



Different graph for cation resin

At a velocity of 30 m/h and temperature of 10 C (green line) we can read of the pressure drop. In this case the answer is 46 kPa/m. Our bed depth is 1.34 m so pressure drop across a clean, fully classified, not compacted bed is $46 \times 1.34 = 61.64$ Kpa. For my pump calculations I add a safety margin between 10 and 20% depending on how free of solids the water is, cycle length (compaction), resin ageing etc. Therefore pressure loss for pump is around 70 Kpa – within limit.

Leakage from Resin Beds – Cation Resin Example

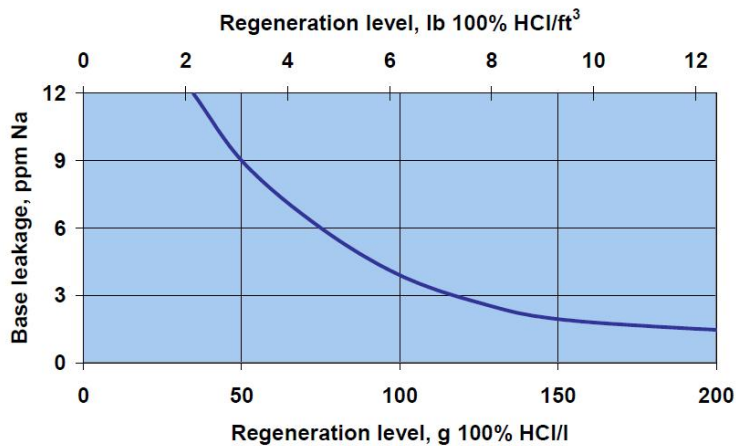
From the cation regen level selected, and the raw water analysis we can calculate the sodium leakage from the cation resin which allows us to establish the conductivity exit the anion. Reactive silica leakage from anion makes no contribution to the anion outlet conductivity.

Similar to the capacity calculation the leakage starts with the base leakage based on the regeneration level. Then we apply factors. In this case the factors are:

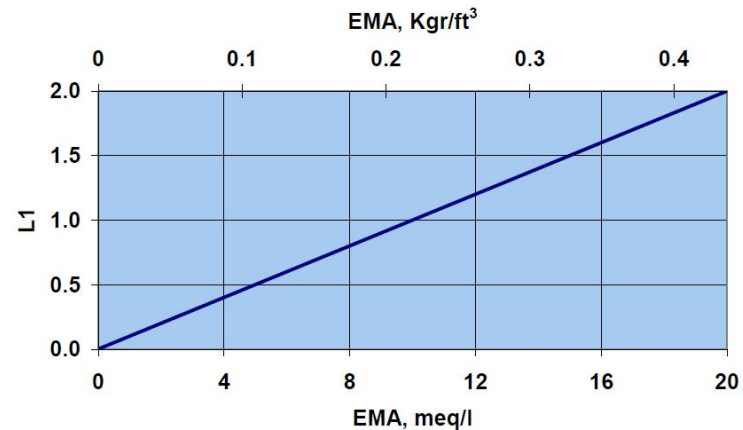
1. **The EMA present in the feed in meq/l.
(EMA = Sulphate + Nitrate + Chloride)**
2. **The % Sodium in the feed as CaCO₃.**

Leakage from Resin Beds – Cation Resin Example

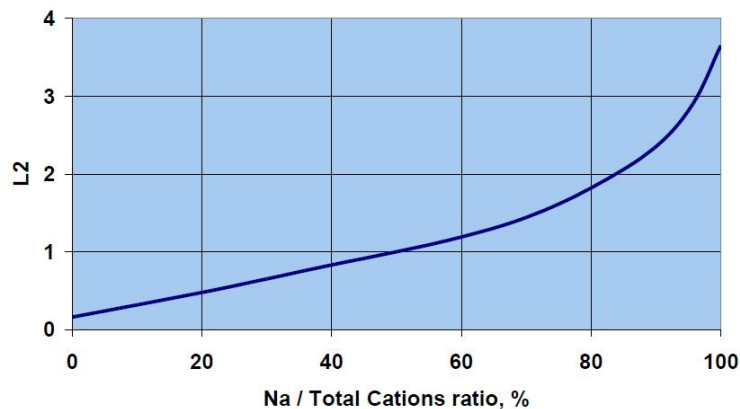
Base Sodium Leakage



L1 - Capacity correction factor for Equivalent Mineral Acidity



L2 - Leakage correction factor for Na / Total Cations



Regen level selected 66g/l.

From slide 9:

Sodium % in feed $90/250 = 36\%$

EMA level in meq/l $150 \text{ mg/l} / 50 = 3.0$

Sodium Leakage

$7 \text{ mg/l} \times 0.35 \times 0.75 = 1.83 \text{ mg/l}$

Therefore average leakage 2 mg/l as Na

Leakage from Resin Beds – Anion Resin

From the anion regen level selected, and the raw water analysis we can calculate the reactive silica leakage from the anion resin.

Similar to the cation calculation the leakage starts with the base leakage based on the regeneration level. Then we apply factors. In this case there are five factors which are:

- 1. The % Reactive Silica to Total Anions.**
- 2. Feed Water Temperature
(Highest temp gives highest leakage correction).**
- 3. Regenerant Temperature
(Highest temp gives lowest leakage correction).**
- 4. Sodium leakage from cation in mg/l Na.**
- 5. Silica end point.**



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