Introduction to High Purity Treatment Trains

by Peter S. Cartwright, CWS-VI, PE

A treatment train is a sequence of water treatment stages where each stage is a specific treatment technology. The output of one treatment stage becomes the input for the next treatment stage. Treatment trains can be subdivided into three components:

1. Primary treatment, where water is brought to the final quality needed at the point of use.
2. Pre-treatment, which protects the primary treatment technology and equipment.
3. Post-treatment, which removes any impurities picked up in storage or the distribution system and acts as a barrier for any debris that the upstream treatment equipment any unexpectedly shed.

Treatment train design requires a consideration of both the water quality and the flow rate that needs to be produced. Once the required water quality has been determined, the starting point of any treatment system design is a thorough analysis of the raw water. This analysis is critical in order to properly identify the contaminants and remove them with the most expedient technology.

Contaminants can be divided into four categories:

1. Microorganisms
2. Particulates (typically indicated as Total Suspended Solids, TSS, although they may also appear on a water analysis as turbidity)
3. Dissolved and Ionized (Total Dissolved Solids, TDS)
4. Organic (Total Organic Carbon, TOC). TOC primarily is a measurement of the concentration of dissolved organic molecules, but in reality it also includes the microbiological contaminants.

It is important to remember that it is impossible to remove all of any contaminant from the water supply. The goal of water treatment is to produce water that meets the client's water quality requirements.

An example of a water quality parameter that is of particular interest in high purity and ultrapure water is resistivity. Resistivity is the opposite of the conductance of water. Water conducts electricity as a result of the dissolved salts in it. When very high quantities of dissolved salts are removed from water, the resulting conductivity is easier to measure as the reciprocal, which is resistivity. Typically, the highest resistivity that can be obtained in high purity water is just over 18 million ohm centimeters, also known as megohm centimeters (MΩ-cm).

Silica is another contaminant that is important in high purity water, because of the problems it can cause and because of its removal difficulty. TOC is also a parameter that may be of significant concern.

Seasonal variances in raw water quality and parameters such as temperature can impact treatment processes. Some municipal water suppliers may alternate between surface water and ground water, or may blend the two. Often, the municipality will treat the water before it is released into the distribution system. The water may be treated with alum (aluminum sulfate), a common flocculent, to lower the suspended solids concentration. Although the treated water is then allowed to sit in a settling tank, some residual alum may still be present in water supplied to the customer's facility.

Virtually all municipal water supplies in the US are treated with some sort of chemical disinfectant, such as chlorine (or chloramines), which leaves a residual concentration. Some municipalities will also adjust the pH of the water by injecting a base such as sodium hydroxide, add orthophosphates to inhibit corrosion, or polyphosphate to control the effects of dissolved iron or hardness minerals. All of these additions can affect the operation of water treatment equipment at the customer's site.

Table 1 is an example of a complete water analysis that may be obtained for a high purity water application. All the contaminant classes are represented with the exception of TOC, although color can be an indicator of the presence of organic substances. The place count indicates the bacterial concentration. The dissolved solids are listed alphabetically. Conductivity is also an indication of total dissolved solids content, often measured in microseimens per centimeter, or micromho per centimeter. pH is the indication of acidity or basicity of water. Turbidity, indicating suspended solids content, is measured as NTU, nephelometric turbidity units. The TDS and TSS values are also given.

Introduction to High Purity Treatment Trains

continued from page 26

Table 1: Sample Water Analysis

Parameter	Results	MDL
Ammonia	0.51 mg/L	0.01 mg/L
Arsenic	ND	0.005 mg/L
Calcium	6.71 mg/L	0.008 mg/L
Chloride	33.18 mg/L	1 mg/L
Chlorine	ND	0.01 mg/L
Copper	0.17 mg/L	0.006 mg/L
Iron	0.10 mg/L	0.005 mg/L
Lead	ND	0.005 mg/L
Magnesium	1.59 mg/L	0.005 mg/L
Manganese	0.02 mg/L	0.005 mg/L
Microorganisms	TNTC	0 cfu/mL
Nitrate	0.31 mg/L	0.1 mg/L
Nitrite	ND mg/L	0.01 mg/L
Potassium	1.30 mg/L	0.02 mg/L
Sodium	37.12 mg/L	0.05 mg/L
Sulfate	18.40 mg/L	1 mg/L
Hardness	23.29 mg/L as $CaCO_3$	1 mg/L
Color	0 color units	1 color unit
Conductivity	172 micromho/cm	1 micromho/cm
pH	8.02 units	0.1 units
Turbidity	0.75 NTU	0.3 NTU
Alkalinity	55 mg/L as $CaCO_3$	2.5 mg/L as $CaCO_3$
Sediment	Absent	Present/Absent
Silica	3 mg/L	0.05 mg/L
TDS	103.20 mg/L	5 mg/L
TSS	5 mg/L	1 mg/L

ND = Not Detected
TNTC = Too numerous to count > 200 cfu/mL
MDL = Minimum detection level
cfu/mL = colony forming units per milliliter
TDS = Total Dissolved Solids
TSS = Total Suspended Solids

Once the raw water has been analyzed and the customer's water quality parameters have been determined, the treatment technologies for the primary, pre-, and post-treatment components of the treatment train can be selected.

Pre-Treatment

Because pre-treatment prepares the raw water for the primary treatment operation, the goal is to remove those contaminants that could affect the performance of the primary treatment technologies and equipment. The pre-treatment technologies will depend on which primary technology is chosen, but typically, they remove suspended solids or slightly soluble dissolved solids which can turn into suspended solids downstream. Pretreatment may also include chemicals that can improve performance of downstream equipment and processes.

Several technologies can be used as pre-treatment. The first of these is often media filtration to remove suspended solids. It could be a cartridge filter or media housed in a pressurized tank. The media itself could be sand, anthracite, etc, or some combination.

The second often-used pre-treatment technology is softening to remove calcium carbonate, magnesium carbonate, and possibly slightly soluble salt compounds such as iron and manganese. Finally, many pre-treatment systems will use granular activated carbon (GAC) filters to remove residual disinfectant. Virtually all disinfectants are oxidizing agents and will attack reverse osmosis membranes, softener resin, and possibly plastic or synthetic rubber components. GAC may also be used to lower TOC concentration.

The placement of the GAC filter in the treatment train depends on what the GAC is being used to address. If TOC is present in significant concentrations, it should be removed prior to the ion exchange softener to avoid fouling the resin. On the other hand, if GAC is used to remove chlorine, it will often be placed after the softener so that the disinfectant can be used to suppress bacterial growth in the softener. While resin will degrade after sufficient exposure to oxidizers like chlorine, bacterial growth in the softener is often considered as a more immediate threat.

In addition to treating what is normally in the raw water, the pre-treatment provides protection against unexpected events, such as municipal maintenance procedures on the distribution lines, which could release suspended solids, an accidentally high concentration of disinfectant added at the treatment plant, or other.

Municipal water supplies are guaranteed to have biofilm. When the municipality performs its scheduled hydrant flushing, much of the biofilm can be released

Introduction to High Purity Treatment Trains

continued from page 27

into the distribution piping, becoming a contaminant.

Let's look at how a particular application can dictate which treatment technologies would be used.

The customer manufactures integrated circuits and requires very high quality water for the rinsing process. Because integrated circuits have very tiny line widths, even bacteria in the water will affect the device. Table 2 lists the treated water quality requirements.

Table 2: Electronics Rinse Water Requirements

Parameter	Result
Resistivity (MΩ-cm)	18 MΩ-cm
Silica (mg/L)	5 µg/L
Particulates	2 µm/mL
Microorganisms	1 cfu/mL
TOC	50 µg/L
Copper	50 µg/L
Chloride	2 µg/L
Potassium	2 µg/L
Sodium	1 µg/L
Zinc	5 µg/L
Residual Solids	10 µg/L

Notice that resistivity is 18 MΩ-cm and the allowed silica concentration is less than 5 micrograms per liter, or ppb. All of the requirements listed in Table 2 are voluntary industry standards, unlike some of the Food & Drug Administration-mandated parameters in pharmaceutical manufacturing, but they're used routinely throughout the electronics manufacturing industry.

Figure 1 is an example of a treatment system created to produce this quality of water. In this case, the raw water analysis (Table 1) indicated dissolved iron, hardness and chlorine in sufficient concentrations to necessitate treatment. The iron and hardness may form solids under the right conditions downstream, such as during the reverse osmosis (RO) treatment process. An oxidizing filtration medium (Manganese Greensand) is used to treat the iron in the feed water and allow the softener technology to be directed toward hardness removal. Carbon filters are used to remove any chlorine to also protect the downstream RO. The water softener is used as pretreatment for the RO stage, which removes the bulk of the hardness to produce a reasonable quality water.

Electrodeionization (EDI) follows the RO to bring the water up to final 18 MΩ-cm quality. The treated water is directed to a storage tank to help meet peak demand. A pump delivers the water through an ultraviolet treatment unit to further reduce organics, including the bacteria.

Figure 1: Treatment System for Rinse Water in Electronics Manufacturing

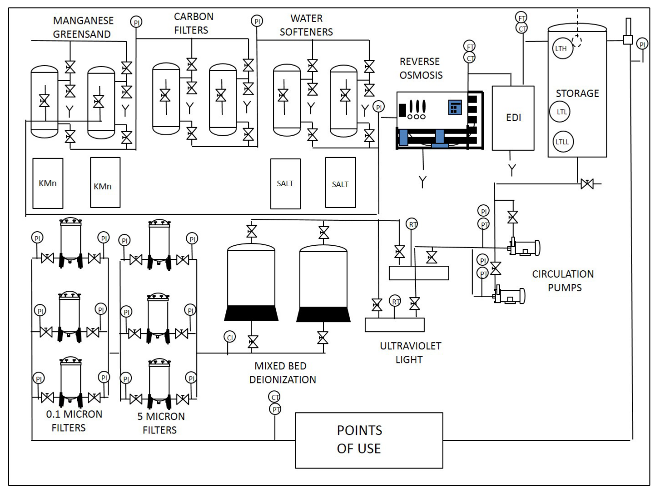
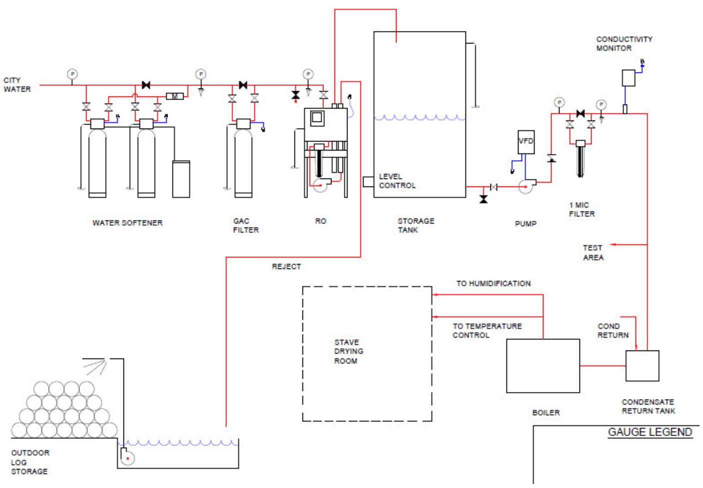


Figure 2 is an example of an application that prepares water for boiler feed. After steam generation, impurities in the water will be left behind inside the boiler. The result may be scaling, reduced energy efficiency, potential corrosion, and water inefficiency due to the need for more frequent boiler blowdown operations to reduce contaminants. The higher the boiler's operating pressure, the more rigorous the water quality requirements. In this example, the primary treatment is RO, which is a commonly applied technology for boiler water treatment. The raw water analysis did not show a significant iron concentration, but did indicate hardness and chlorine. As a result, the pretreatment is a water softener to ensure a reduction in slightly soluble salts that could foul the RO membrane, and a carbon filter to remove chlorine.

Intro to High Purity Treatment Trains

continued from page 28

Figure 2: Boiler Water Treatment System



Another high purity water application is kidney dialysis. Hemodialysis is the activity that replaces kidney functions in people whose kidneys are no longer working correctly, or in people who have undergone trauma and are in need of it temporarily. Hemodialysis is a large consumer of high purity water treatment technologies because of the water quality requirements. The treated water is fed into an artificial kidney, which is also running the patient's blood through it. The two streams are separated by a diffusion dialysis membrane. Various components are put into the water, such as heparin, that diffuse across into the blood stream. At the same time, the waste products that are in the blood stream diffuse into the water stream and are discharged.

In hemodialysis, two of the most important treated water quality parameters are bacteria and endotoxins, which are pieces of microorganisms. Both can cross the dialysis membrane and cause serious illness or possible death of the patient. Chlorine and chloramines can also be of significant concern as they too can diffuse through the dialysis membrane and result in hemolysis (destruction of red blood cells) and death.

Table 3 is a raw water analysis for this example application. Table 4 lists product water quality standards from the American Association of Medical Instrumentation (AAMI), which are mandatory and enforced. A comparison of the two reveals that the raw water analysis is incomplete and missing the endotoxin and bacteria counts as well as disinfectant residual concentration; however, the illustrated technologies will easily produce the desired treated water quality from normal water supplies.

Table 3: Raw water analysis - hemodialysis

Parameter	Results
pH	7.29 units
Hardness	8 gpg
Alkalinity	7 gpg
Sulfates	14.0 mg/L
Iron	0.7 mg/L
TDS	265 mg/L
Turbidity	1.6 NTU

Table 4: Product Water Standards (AAMI), as of 2012

Parameter	Max Allowable Concentration
Aluminum	0.01 ppm
Calcium	2 ppm
Chloramines	0.1 ppm
Chlorine	0.4 ppm
Fluoride	0.2 ppm
Magnesium	4 ppm
Nitrate	2 ppm
Potassium	8 ppm
Sodium	70 ppm
Sulfate	100 ppm
Bacteria	50 cfu/mL (action)
Endotoxins	0.125 eu/ml* (action)

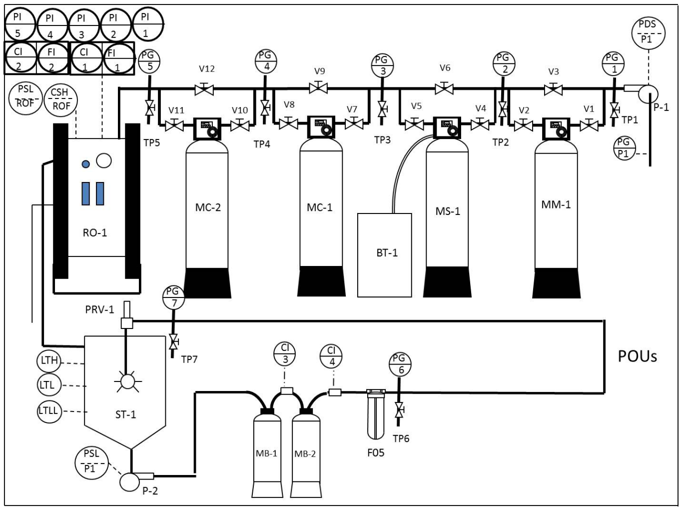
*eu=endotoxin unit

Turbidity in the raw water, as well as iron and hardness, are addressed in the pre-treatment component of the hemodialysis treatment train (illustrated in Figure 3) by the sediment filter and the water softener. Notice that two activated carbon filters follow the softener. The removal of chlorine and chloramines is critical and the health of the patient is at stake. The second filter provides a back up to the first in case of failure and it provides the additional contact time needed to remove chloramines.

Intro to High Purity Treatment Trains

continued from page 29

Figure 3: Treatment System for Hemodialysis



MM = Multi-media filter
MS = Softener
BT = Brine tank
MC = Carbon tanks
RO = Reverse osmosis system
ST = Storage tank
MB = Mixed bed DI tanks
F = Submicron filter

Primary Treatment

Primary treatment is the stage where the concentration of remaining dissolved solids (TDS), large molecular weight organics (TOC), dissolved gasses, and microorganisms are reduced to the levels acceptable for the application. For example, in the eletronics rinsing application (Figure 1), both reverse osmosis and electrodeionization are utilized. Reverse osmosis alone will not produce water with 18 MΩ-cm resistivity. It can remove up to 99.8% of the dissolved salts concentration, but in most cases, that's not sufficient. A "polishing" technology is needed, and one of the more commonly used is electrodeionization.

In the boiler feed water treatment and the hemodialysis applications (Figures 2 and 3, respectively), reverse osmosis alone is sufficient to achieve the required water quality.

Post Treatment

Finally, let's look at the post treatment. Most high purity water applications have varying water usage rates and require storage of treated water for times of peak usage demand. The higher the purity of the treated water, the greater its ability to dissolve anything it contacts, such as the materials used to store the water, convey it or pump it. The role of post-treatment is to remove contaminants the treated water may have picked up from the storage and distribution system and bring the water quality back to the level achieved in primary treatment.

Water quality deteriorates when the water is sitting in the storage tank and piping, although pumps can also impart contamination. The storage tank feeds the distribution system, the treated water goes out to some point of use, but part of it is recirculated to the storage tank.

Some examples of treatment technologies used in post-treatment are disposable submicron cartridge filters to remove particulates and ultraviolet irradiation to inactivate microorganisms or break down organic substances that may have gotten into the system. Bacteria is of particular concern in the storage and distribution system as they can grow under virtually any condition, and any residual disinfectant was removed upstream. Theoretically, bacteria-free water can be made, but it won't stay that way.

Typically, submicron filter cartridges (less than 0.2 micron rating) are pretty effective at removing bacteria. If the system is not going to be used for any period of time, then it is wise to put a disinfectant in the storage and distribution loop just to keep this bacterial concentration at a relatively low level. Spray balls can be used with the recirculation process to help uniformly distribute the recirculated water throughout the storage tank. A nitrogen blanket is used in the storage tank to keep oxygen and carbon dioxide out of the treated water in applications requiring very high quality water, such as electronics rinsing. In this application, gasses can affect the product quality.

In the sample treatment systems for electronics rinsing (Figure 1), the treated water from the storage tank goes through ultraviolet irradiation, mixed bed deionization, and a 5 micron guard filter. A "guard" filter is meant to block potential contaminants coming from the treatment process, such as particles of resin beads. The final filter in this case is a 0.1 micron cartridge filter. The water then travels through the distribution loop, and back into the storage tank.

Introduction to High Purity Treatment Trains

continued from page 30

In the boiler feed water application (Figure 2), the 1 micron filter following the storage tank serves as the post-treatment. In the dialysis application (Figure 3), the post-treatment technologies are easily identified once you find the storage tank and determine the direction of water flow.

In the diagram in Figure 3, the mixed bed deionization system and the submicron filter are typical of what's used in the hemodialysis industry. The submicron filter in this case, is not only to remove any resin fines, but also to remove any bacteria that may have grown in the mixed bed polishing tanks. The designation, "POUs" indicates the individual dialysis stations.

In addition to making sure the treatment system is providing water that meets the quality requirement, it is also essential to make sure the quantity requirement for the water is being met. Not only does sufficient water flow rate have to be available at the point of use, but enough flow needs to be available for the various cleaning processes required by the treatment equipment.

Media filters, for example, require regular backwashing. It's not a good idea to use the raw water for backwashing because it could contain suspended solids. To provide the treated water for cleaning, the media filter is sized to provide an excess of treated water. Some of that filtered water is collected and used for backwash.

Water softeners also require some water for backwashing, but even more importantly, for regeneration. Treated water is also needed to carry away the little bit of concentrate formed in the EDI system. Likewise, some portion of the RO feedwater is needed to carry the rejected salts away from the surface of the RO membrane. Typically, large reverse osmosis systems may only require 15% or so of the feedwater volume to be used to carry away the salts that have been rejected. Smaller ones can require as much as 40%. This, too, needs to be taken into consideration when sizing the RO system.

The primary treatment of the treatment system is normally sized to meet the total daily requirements, and the pre-treatment equipment size is based on the primary treatment plus the needed backwashing and regeneration volume. The instantaneous flow rate requirements at the point of use are used to size the storage tank and distribution system.

About the author
In 1980, Peter Cartwright started his own consulting engineering company and has performed consulting services for more than 250 clients in virtually all aspects of water and wastewater treatment. He has authored over 150 articles, several book chapters, and is currently writing a book on membrane technologies.