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Making Decisions about Water and Wastewater Processes

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Introduction

Water is one of the most important liquids used in cleaning processes. Users should be concerned about water purity at each stage of a process to make the best decisions about water and wastewater and the solid waste generated by a parts cleaning process. As new technologies are introduced, users have more options in source (tap) water and wastewater treatment than ever before. This usually adds to the complexity of decision making, especially if the most effective, least-cost solution is the objective. In this chapter, water treatment terms are defined and various water processes are explained and compared. It is designed as an introduction for those new to the water treatment field, as well as a reference for experienced users.

Water and Wastewater Operational Factors

The following list of factors begins with the most important a new user should consider first. For example, discharge regulations are the first factor because if no wastewater can be discharged or the facility is near a stream of water, lake, or other sensitive discharge area, it will be much more difficult and expensive for management. The next most important factor is the wastewater volume. If the volume is small, the wastewater can be hauled at a low cost except in a remote location. If the volume is large, hauling or evaporation, unless solar, can be very expensive. Source (tap) water availability can be a serious concern—especially future changes in availability. Also, it is very difficult to treat water such as brackish water with very high total dissolved solids (TDS). A new plant location can be greatly affected by these two factors alone.

To achieve the optimal washing system at the lowest cost, users must consider source (tap) water, wastewater treatment, and solid waste disposal. By using the list below, the cost consequences of a wrong decision decrease substantially. Potential factors include the following, which correspond to major sections in this chapter:

- Discharge regulations
- Wastewater volume
- Water purity specification
- Source (tap) water treatment
- Wastewater treatment
- Wastewater treatment for new processes
- Overcapacity of the current wastewater treatment system

Discharge Regulations

Usually, regulations are discussed after wastewater treatment designs are presented. Since regulations can substantially affect the optimal design of a wastewater treatment system for a parts washing operation, they should be considered early in the design process.

Water and Wastewater

For water treatment specialists, the word “water” generally refers to water obtained from a variety of sources, while wastewater refers to any water used in a process that is reused or discharged. For example, water used simply as cooling water through a heat exchanger without any treatment other than transferring heat through a metal tube can be referred to as either water or wastewater in the industry. There is no absolute convention about this. All wastewater and solid waste, including sludge from processes, must comply with federal, state, and local regulations.

As regulations increase, it becomes more difficult to discharge wastewater without treatment. Throughout the United States, discharge of wastewater is controlled by three categories of regulations: POTW, ground water (septic system or well), and surface water (streams, rivers, ponds, and lakes). (POTW is a publicly owned treatment works or municipal sewer district.) At a minimum, state and local agencies must comply with federal regulations. State regulations might be more stringent than federal regulations, and local regulations might be more stringent than state regulations. For discharge to surface water, a NPDES (National Pollutant Discharge Elimination System) permit must be obtained from both federal and state agencies. Sometimes a local community might require that no industrial wastewater be discharged, even if the water or wastewater meets federal drinking water standards.

In many places in the United States, a permit is required to discharge wastewater from an industrial process even for a small batch-type cleaner (like a household dishwasher). Even if a user has tested his wastewater and it is in compliance with regulations, a local agency will usually still require a permit. A user is strongly advised to notify local regulatory agencies to avoid future issues and fines after the fact.

In the past, testing samples were usually taken at the end of the sewer pipe from the building. However, in increasingly more states, wastewater is tested as it comes from the equipment within a user's facility. This makes compliance more difficult. The old adage, "The solution to pollution is dilution," which is the illegal action of diluting wastewater from a process with source (tap) water to meet discharge regulations, has been declining for decades.

User concerns include

- Can I discharge any wastewater at all to the POTW, ground water, or surface water?
- Is a permit required? Are there regulations?
- What wastewater is acceptable for discharge? What is the concentration of contaminants?
- What permits might be required and air pollutants regulated for an evaporator?

Solid Waste

Federal regulations define solid waste as a solid material, liquid, or sludge, for example, the sludge from an evaporator. Users generating solid waste with toxic metals are liable for any of their solid waste hauler's or regenerator's violations of environmental laws from the time the wastewater or solid waste leaves the generator's facility (toxic metal generated by the original company's manufacturing process) to the ultimate disposal site. The expression, "cradle to grave," is commonly used to describe this concept. Any entity between the generator and the end user, knowingly or unknowingly, can be liable for damages or a sensitive user's losses.

Sensitive users and generators of toxic metals who rent or own deionizer (DI) tanks that are sent back and forth to a regeneration vendor to treat or replace their spent granular media (activated carbon and resin) must be greatly concerned. The typical design of most DI operations is to have one activated carbon tank followed by two or more deionized (DI) tanks. During this operation, there are two sources of toxic metal cross contamination. The first is the used (spent) activated carbon. In the regenerator's facility, after the carbon is removed from the tank(s), there is always residual carbon with toxic metal contamination inside crevices in the tanks. Also, once the carbon is removed, there is a possibility that the new carbon is put into the wrong tank that contains residual toxic metals in tank crevices and shipped to a sensitive user.

> Sensitive users include kidney dialysis, biotech, hospital, residential, medical research, or other applications. Such toxic metal cross contamination can have serious and even catastrophic effects, not affects on humans, major medical research studies, or manufacturing processes.

The second source of contamination is from ion exchange resin tanks used to make high-purity deionized water. The vendor regenerates the resin tank(s) so the resin regains its ability to deionize water. There are two methods to treat the resin inside the same tanks or have it bulk regenerated. In bulk regeneration, spent resins from one user or many users are blended together and chemically treated.

There are three sources of toxic metal contamination during regeneration (chemical) of the spent resin. The first and second are the same as described with activated carbon. The third occurs when toxic metal resin from bulk regeneration is combined in error with a sensitive user's resin and then put into the sensitive user's tanks. Also, even though most of the toxic metals are removed during the regeneration process, they are *never* completely removed.

The best way to eliminate the potentially catastrophic threat of toxic metal cross-contamination is to use a vendor that only treats toxic metal wastewater and does not treat source (tap) water for sensitive users using rental DI tank services. The next best possibility is doing what a nationwide vendor does in providing rental DI services to both toxic metal and sensitive users. It has one facility just for toxic metals because of concern about liability. The vendor also takes other precautions, for example, having tank connections with reverse fittings to make sure that a casual user does not make an error by using tanks that should only be used for sensitive users.

There are four characteristics (federally mandated) of solid waste that a user must comply with: ignitability, reactivity, corrosivity, and toxicity, to determine if it is hazardous or not before disposal. (See EPA "Code of Federal Regulations," "Protection of the Environment," Section 40.) The two most frequently used characteristics are corrosivity and toxicity. The pH of the waste determines the corrosivity, while TCLP (toxicity characteristic leaching procedure) measures the amount of toxic metal. Sometimes, the wash chemical has a high pH and the washing process might clean parts containing toxic metals. The TCLP test is the minimum compliance requirement throughout the United States. Certain states might have a more stringent TCLP procedure.

The TCLP test identifies eight toxic heavy metals—cadmium, barium, silver, chromium, lead, arsenic, mercury, selenium (my acronym is "CBS CLAMS")—with allowable concentrations. For example, in the washing process for electronic assemblies (see "Closed-Loop Design"), the parts are soldered with solder that usually contains lead and silver. In this washing process, all of the consumable parts of the process, such as filters, activated carbon, ion exchange resin, and other solid waste, must be tested to determine whether they are toxic or not before disposal. The solid waste and the wastewater from this process must be compliant with two different metal regulations (lead and silver) and the solid waste used in the process must also meet the minimum TCLP requirements. Hauling hazardous waste usually costs up to about several hundred dollars per drum, while hauling nonhazardous waste usually costs up to about $50 per drum.

Occasionally, an entire process generating solid waste is defined as hazardous even though parts of it are not, according to the TCLP test. For example, a user might have an electroplating process with one of the eight toxic metals. Even though the ion exchange resin (solid waste) used on the rinse water is not hazardous according to the TCLP test, the ion exchange resin is still considered hazardous because the entire process has been designated by the EPA to be hazardous. In the electronic assembly example (see "Closed-Loop Design"), the process could have as many as two toxic metals (lead and silver). The entire washing process is not designated as hazardous waste; however, the resin and carbon must be tested to ensure that the concentration of both toxic metals does not exceed the TCLP test limits. Whenever toxic metals are present, the user must prove that the solid waste does not exceed regulatory limits before disposal.

Wastewater Volume

Determining the volume of wastewater from a cleaning process is very important because it can have a major influence on handling the water, wastewater, and solid waste generated by the process. For small volumes, cleaning processes generating less than about 25–75 gal/week of wastewater, if hazardous, are likely best hauled by a licensed carrier. For larger volumes, recycling all wastewater or discharging to the POTW, ground water, or surface water supply might be used.

Water Purity Specification

Determining the water purity specification is not easy in many cases and some investigation is often necessary. Information from trade associations, competitors, or related processes is very helpful. If these sources are inadequate, a user might have to experiment on a small scale or make the determination during the actual production process. The latter situation has a downside risk of too many part failures.

Measuring Water Purity

In many applications, a user must be concerned about measuring those characteristics of source water (tap water or raw water) from a lake, river, well, or wastewater that affect the quality of the parts being cleaned. In many applications, two characteristics are measured—dissolved and undissolved contaminants. In addition, another contaminant, colloids (see "Reverse Osmosis"), has characteristics of both dissolved and undissolved contaminants (See Table 32.1).

Dissolved Contaminants

Dissolved contaminants include ionic compounds such as sodium chloride, calcium carbonate, and many others that form ions in water. They are measured by a total dissolved solids (TDS), conductivity, or resistivity meter. Other dissolved contaminants such as sugar, starches, and other water-soluble organic compounds are not ionic and cannot be detected by these three types of meters.

Low-purity water is usually expressed in conductivity or TDS, while high-purity water is usually expressed in resistivity. Conductivity or TDS measurements are often used to determine the capacity of ion exchange resins or the rejection capability of membrane systems using nanofilters (NF) and reverse osmosis (RO).

TABLE 32.1 Resistivity, Conductivity, and TDS Conversion Chart

Resistivity (Ohm cm) at 25°C	Conductivity (μS/cm) at 25°C	Dissolved Solids (ppm)	Approximate (GPG) as $CaCO_3$
18,000,000	0.056	0.0277	0.00164
15,000,000	0.067	0.0333	0.00193
12,000,000	0.084	0.0417	0.00240
10,000,000	0.100	0.0500	0.00292
5,000,000	0.200	0.100	0.00585
2,000,000	0.500	0.250	0.0146
1,000,000	1.00	0.500	0.0292
500,000	2.00	1.00	0.0585
300,000	3.33	1.67	0.0971
200,000	5.0	2.50	0.146
100,000	10.0	5.00	0.292
50,000	20.0	10.0	0.585
30,000	33.3	16.7	0.971
20,000	50.0	25.0	1.46
10,000	100.0	50.0	2.92
5,000	200	100	5.85
3,000	333	167	9.71
2,000	500	250	14.6
1,000	1,000	500	29.2
500	2,000	1,000	58.5
300	3,300	1,670	97.1
200	5,000	2,500	146
100	10,000	5,000	292

Source: Owens, D.L., *Practical Principles of Ion Exchange Water Treatment*, Tall Oaks Publishing, Littleton, CO, 1995. With permission.

Note: Approximate grains/gallon calculated by dividing ppm column by 17.1.

Most meter manufacturers use different algorithms to convert the conductivity electrical measurement to a TDS scale reading. The conversion factor from several sources can vary from about 0.4 to 0.7.[1–6] Thus, it is likely that different meters will give different results. The reason for the differences between meters is that source (tap) water throughout the United States at different locations is different in composition. Then, add the additional complexity of wastewater that has a far greater number of compositions than source (tap) water. Even if the TDS of the two different water samples were the same, they could still have a different effect on resin capacities because of the different weights and charges of the ions in the water or wastewater samples. If TDS is not accurate enough, a complete water analysis can be performed.

For simplicity, all TDS readings used in this chapter are determined by multiplying the conductivity readings by a conversion factor of 0.50. A simple correlation to remember is that a conductivity reading of one microsiemens (1 μS/cm) = resistivity of 1 megohm cm = approximately 0.50 ppm TDS (see Table 32.1). Since wastewater might contain ions that differ substantially from natural water supplies, this conversion will likely be even less accurate.

Higher dissolved ionic content (higher TDS) means higher conductivity or lower resistivity of the water or wastewater. A conductivity meter is best for water approximately 1 μS/cm or higher. For lower conductivity (lower TDS), resistivity is the preferred measurement. In both examples, accuracy and readability of the meter are improved.

Another important consideration is that readings from approximately 1–18.2 megohm cm are best made with a resistivity meter with its cell inserted in a flowing stream of water. (18.2 megohm cm is the highest water purity possible.) At 10 megohm cm or higher, this is the only way to make an accurate measurement. Stagnant water absorbs ionic impurities from the plastic or metal pipe and reduces the water purity reading.

Undissolved Contaminants

Undissolved contaminants do not affect the electrical properties of source (tap) water and wastewater, and are measured by different methods. There are far more different kinds of contaminants in wastewater than in source (tap) water. Some of the most common contaminants are measured by:

- *Total suspended solids* (TSS) measures the weight of all particles that do not pass through a 0.45 μm absolute rated membrane filter. This helps a user determine the particle loading of the water or wastewater to design a filtration system for a washing application.
- *Fat, oil, and grease* (FOG) measures any compound (vegetable or animal fats, petroleum and synthetic oils, lubricants, and some sulfur compounds) extracted by a fat-soluble solvent. It is used to determine whether a user complies with the discharge regulations of a POTW.
- *Biological oxygen demand* (BOD) is a measure of the amount of oxygen required by aerobic microorganisms to decompose organic matter in a given period of time. This is usually used for discharge compliance.
- *Chemical oxygen demand* (COD) is a measure of the amount of oxygen required to oxidize compounds such as sulfides, salts of metals, and organic compounds with potassium permanganate. This is used for discharge compliance, but much less often than BOD.
- *Total organic carbon* (TOC) is usually a measure of the total amount of oxidizable organic matter in high-purity water.

pH

pH is a measure of the acidity, neutrality, or basicity of water and is expressed as the negative log of the hydrogen ion concentration, or $-\log [H^{+1}]$. A pH reading below 7 is an acid condition, 7 is a neutral condition, and above 7 is a basic condition. In certain applications, the pH of the source water for wash chemicals and rinse water can be very important.

Source (Tap) Water Treatment Options

All water processes require an initial charge of source (tap) water from a well, river, lake, or a transported supply of water (bottled or from a tanker truck). Many operations might require a continuous supply. Two options for source (tap) water are no treatment and dissolved solids (ions) removal. Other options such as mechanical filtration, water softening, and others (see "Other Treatment Options").

IMPORTANT: Materials of Construction Used in Water and Wastewater Systems

> It is best to use corrosion-resistant materials for wetted surfaces in any system with water or wastewater with very low or very high TDS. If low TDS water (resistivity of about 100,000 ohm cm and higher or conductivity of 10 μS/cm and lower) is in contact with any material that is not plastic, or 304 stainless steel or better, corrosion might result. At 10 megohm cm and higher, corrosion will result; fluorocarbons (Teflon® and others) and 316 stainless steel are superior. Materials like Teflon are superior to 316 stainless steel. High TDS water like seawater (about 30,000 ppm) is well known to be corrosive to many different metals.

No Treatment

Sometimes the source (tap) water is of sufficient purity that no treatment is necessary. Laboratory scale or pilot testing can help provide guidance for this determination. If a pilot scale test is not practical for some reason, it might be necessary to go to a full production scale with a backup plan to treat the source water as quickly as possible if this option is insufficient.

Dissolved Solids (Ions) Removal

Industrial water treatment commonly uses RO, deionization (DI), and much less often, electrodeionization (EDI) to reduce dissolved solids (sometimes called minerals) and ions from water or wastewater. RO removes far more dissolved solids than a nanofiltration (NF) membrane process. It is essentially identical in design to RO except for the membranes and other incidental differences. NF is used for water softening, industrial wastewater treatment processes, and other specialty applications where RO water is not necessary.

Reverse Osmosis

RO is a membrane process that removes all particles, molecules, colloids (ranging in size from about 0.1–0.001 μm),[7] ions and other species down to a size of about 200 molecular weight and larger from water or wastewater. Even though RO removes all particles, it is used primarily for dissolved solids, not particle removal. It is not designed to remove significant amounts of microorganisms or colloids.

RO is a process in which a pump is used to force water or wastewater through a permeable membrane barrier, as shown in Figure 32.1. The key component of an RO unit is the membrane, which is made from a thin film of specially treated plastic, most often constructed in the form of a spiral. Membranes vary in size from about 2–12 in. in diameter to several feet long. Water is forced through the membrane at pressures as high as about 1000 lb/in.^{2}

RO separates the source (tap) water or wastewater into a permeate stream (product water for use in a process) and a wastewater stream (wastewater to a POTW). There are two key performance characteristics describing an RO system—% recovery and % rejection. The first is the percentage of lower ionic content water recovered (permeate) of the total amount treated by the RO. The second is the percentage

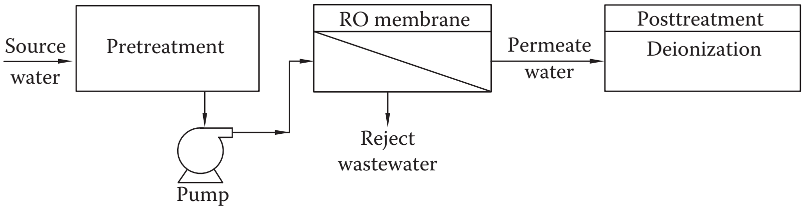


FIGURE 32.1 Single-pass RO system.

of much higher ionic content water rejected by the membrane. Essentially, an RO removes ions from water, concentrates them, and then discharges them to a POTW.

For the first performance characteristic (% recovery), an RO system usually recovers from 15% to 75% of all water or wastewater the RO treats. (15% is the typical recovery of a household RO drinking water system.) Therefore, from 85% to 25% goes to a POTW. As a membrane ages, its ability to reject dissolved solids decreases; the practical life of a membrane is from 3 to 5 years. In wastewater applications, the life could be substantially reduced. In the second performance characteristic, an RO usually rejects from 85% to 99% of all ions. Ionic concentration is very often the most important factor in distinguishing the different grades of water purity used in industrial applications. Ions have a wide variety of weights, shapes, and charges that determine the percentage rejection. For example, a higher charged ion like sulfate (SO^{-2}) has about a 95% rejection percentage, while a lower charged ion like sodium (Na^{+1}) has about a 90% rejection rate.[8]

Colloid reduction is very important when treating water and wastewater with RO because the colloids will likely irreversibly foul membranes, even sometimes in small quantities. These contaminants have a size between particles and ions, but are not truly soluble in water, as salt is. Typically, they do not settle as fast as larger particles do, but under the right conditions, they agglomerate like colloidal iron in source (tap) water. If there are substantial amounts of colloids, more pretreatment is required to prevent possible irreversible fouling of the membranes, often requiring special cleaning or replacement. Membranes can be cleaned, depending on the cost effectiveness of the procedure—additional equipment, labor, number of membranes, ability of getting adequate additional life, and other factors.

A typical RO system might consist of a pretreatment stage using one or more of the following: mechanical filters (multimedia filter, filter cartridges, or other), adsorptive media (activated carbon), anti-scaling chemical, pH treatment, and water softening. This is followed by a high-pressure pump, membrane(s), and storage tank. The posttreatment might include an ultraviolet light, repressurization pump, and, if higher purity water is required, DI (deionization) or EDI (electrodeionization) could follow. Sometimes cartridge membrane filters down to 0.2 µm could follow. The selection of these processes depends on a source water analysis and the water purity objective.

Another RO design is a double-pass RO, which is an RO followed by another RO in a single unit. This process can be followed by either DI or EDI. Usually, the sensitivity of an RO to increased costs from treating water or wastewater is much less than for an ion exchange system. This is why RO is often used as pretreatment before an ion exchange system when dissolved solids increase substantially. For example, the cost to treat 100 or 1000 gal with RO is much lower in terms of the cost of membrane life as compared to ion exchange resin whose operating cost would be about 10 times greater.

RO rejects essentially the same percentage of ions whether the incoming water to the RO has hundreds of parts per million TDS or thousands of parts per million of TDS. For example, the incoming water to an RO might have a TDS of 200 ppm with 95% rejection. In another example, the incoming water might have a TDS of 2000 ppm with the same rejection. The amount of minerals remaining in the product water (reject stream) from the 2000 ppm incoming water will be about 10 times greater than in the 200 ppm water.

Deionization

Deionization (DI) is a process using ion exchange resin to remove dissolved solids (ions) from water and wastewater.

> Ions are charged atoms in water. For example, when table salt, sodium chloride (NaCl), is dissolved in water, the ions form loosely held pairs, Na^+ and Cl^-. This occurs with many other compounds (mostly salts) that dissolve in water.

Occasionally, DI is referred to as demineralization, an older term used less frequently today. DI water is any water treated by a deionizer from which dissolved solids are removed, water resistivity increases, and TDS and conductivity decrease. There is no specific water purity measurement that defines the term, deionized water. Even though RO removes dissolved solids similar to DI, it is not referred to as deionized water, but RO water. Usually deionization does not require a similar amount of pretreatment as RO does. DI cannot remove the fine particles that RO can.

There are three basic deionizer designs:

- Two-bed weak base
- Two-bed strong base
- Mixed bed

Each deionizer design uses cation and anion ion exchange resin. There is weak acid and strong acid cation resin and weak base and strong base anion resin. Weak acid cation resin is used in specialty applications and will not be discussed. The lowest purity deionized water is produced by a strong acid cation and a weak base anion resin in series; a strong acid cation and strong base anion resin produces the next higher purity; and a mixed bed (composed of a mixture of strong acid and strong base resin) produces the highest purity water. These last three resin combinations are most often used (Table 32.2).

Both weak and strong base anion resins are the same except that the molecules have different functional groups, which give each a unique ionic removal property. Strong base anion, most commonly used, removes dissolved carbon dioxide and silica in addition to what weak base anion resin removes.

Strong acid cation and strong base anion resins are made of polystyrene and are cross-linked with divinylbenzene. Cation resin has a great number of spherical beads with a diameter of about 0.025 in. Each resin sphere is composed of an even far greater number of polystyrene molecules with negatively charged sulfonic acid functional groups with a positively charged hydrogen (H^{+1}) ion attached. Strong base anion resin is very similar, except that it has positively charged quaternary ammonium functional groups with a negatively charged hydroxyl (OH^{-1}) ion attached.

DI water is produced in a two bed deionizer in two steps. Cations in a source (tap) water or wastewater are removed and replaced with hydrogen ions, while all of the anions in the water or wastewater remain the same. This produces very low pH water from the acids created during the exchange process.

TABLE 32.2 Deionizer Designs vs. Water Characteristics

Water Characteristics	Two-Bed Weak Base Deionizer	Two-Bed Strong Base Deionizer	Mixed Bed Deionizer
Purity (megohm cm)[a]	0.02–0.6	0.1–0.9	1.0–18.2
pH	6 or lower	8.0+	Close to 7
Carbon dioxide and silica removal	No	Yes	Yes
BOD and COD reduction	Essentially none	Essentially none	Essentially none

Source: Otten, G., *American Laboratory*, July 1972.

[a] These are the typical ranges of water purity that are dependent upon feedwater characteristics.

For example, the cation resin removes the sodium (Na^+) ion from sodium chloride (NaCl) and replaces it with a hydrogen ion (H^{+1}) to become hydrochloric acid (HCl). (This is the reason the word "exchange" is used to describe this process.) There are cations such as potassium (K^{+1}), calcium (Ca^{+2}), ferrous iron (Fe^{+2}), and many others. In the second step, the acid enters the anion tank and the resin removes the chloride ion (Cl^{-1}) from the hydrochloric acid and replaces it with a hydroxyl ion (OH^{-1}). One H^{+1} ion from the cation resin and one OH^{-1} ion from the anion resin make water (H_2O). There are anions such as sulfate (SO_4^{-2}), nitrate (NO_3^{-2}), silica (in a variety of compositions and charges), and many others. The above chemical reactions occur in one tank in a mixed bed deionizer containing both cation and anion resin.

A *two-bed weak base* deionizer produces the lowest resistivity (higher conductivity and TDS) water. The resin capacity—number of gallons of water treated per ft^3 of ion exchange resin—depends on the capacity of the cation and anion resin. Both have a nominal capacity of about 30,000–40,000 grains/ft^3. (A range is given for these capacities because it better represents a typical user's experience.) At the endpoint, the water purity drops off somewhat sharply. For wastewater, it is not unusual for the decline to be much more gradual. This is also characteristic of the two bed strong base and mixed bed designs, which follow.

A *two-bed strong base* deionizer uses the same cation resin as a two bed weak base deionizer. However, the strong base anion resin increases the purity of the water more than a two bed weak base. The higher water purity is achieved by removing dissolved carbon dioxide (carbonic acid) and silica ions, causing the resistivity of the water to increase. The higher removal of ions by the anion ion exchange resin reduces the nominal capacity to about 20,000–30,000 grains/ft^3.

A *mixed bed* deionizer contains exactly the same resin used for a two bed strong base design, except that cation and anion resins are intimately mixed in one tank. It produces the same effect as multiple two bed strong base deionizers in series. It is commonly used when water purity above one megohm cm is required and has a nominal capacity of about 10,000–13,000 grains/ft^3.

Even though TDS is an approximation of the capacity of a deionizer, a water analysis is better when designing a large system over about 10 gpm. For a two bed deionizer, the higher the flow rate, the more important a water analysis is in optimizing system design. Regardless of these factors, if the TDS is too high at about 500–1000 ppm, the cost of replacing or regenerating the resin becomes prohibitive unless the amount of wastewater treated is small and infrequent. So, RO alone or as pretreatment to the ion exchange resin makes the process much more economical.

Ion exchange resins have specific capacities, that is, the ability to remove ions from a given number of gallons of water. The capacity is inversely proportional to the TDS of the water. For example, if the TDS goes from 100 to 300 ppm, the capacity of the resin is decreased to one-third of its original capacity. For example, for 30,000 grains/ft^3 resin, the new capacity would be 10,000 grains/ft^3. The capacity of resin mostly depends on, in no specific order, concentration of different ions, concentration of foulants (e.g., colloids), flow rate, volume, depth and cross-sectional area of the resin in a tank, water purity, amount of chemical used to regenerate the resin, and temperature of water. In the preceding discussions, the highest resin capacity numbers stated are theoretical and are typical for several ion exchange resin manufacturers under ideal conditions.

For higher water purity, some of these resin capacity factors reduce the full utilization of the theoretical capacity of the resin and have an increased adverse effect on the resin's ability to produce high-purity water. This is commonly observed when treating lake water supplies in the Northeastern part of the United States. Universal colloids, as they are sometimes called, are very long chain molecules up to about one million molecular weight that prevent and interfere by blocking the accessibility of ions to resin sites, thereby reducing capacity. However, the mechanism for the reduction of water purity is different. In this case, colloids most often have ions bound on the molecules that are not easily removed by standard resins. These long-chained molecules with few ionic charges on them are very susceptible to removal because of the low ionic charge per unit weight of the molecule. When the molecules are released from the resin, the resistivity meter can detect the ionic charges on the molecules as the water passes through the cell of the resistivity meter.

Calculating Ion Exchange Resin Capacity

A TDS meter (see "Dissolved Contaminants") is most often used. It is much simpler than getting a complete water analysis, which is far more accurate, but much more expensive and time consuming. To be useful, all readings from a TDS meter have to be divided by 17.1 as calcium carbonate.[9] Therefore, 1 grain/gal = 17.1 ppm/grain (as calcium carbonate). For example, a water sample has a TDS of 100 ppm (as calcium carbonate). (Grain is an ancient unit of weight measurement referring to average size grains of dry wheat. 7000 grains of wheat equals one pound.)[9] To convert the ions to grains/gal, the following calculation is made: 100 ppm/gal ÷ 17.1 ppm/grain = 5.8 grains/gal. Therefore, in 1 gal of water there are 5.8 grains of TDS (total dissolved solids). Thus, 30,000 grains/ft^3 (resin capacity) ÷ 5.8 grains/gal = 5,172 gal/ft^3 of DI water produced before the resin is exhausted, requiring replacement or regeneration. This calculation applies to two bed strong base, mixed bed, and water softening processes.

Deionizer Resin Operating Options

An important variable that affects the capacity of ion exchange resin is whether it is used to treat source (tap) water or wastewater. Source (tap) water resin can be regenerated many times and still have good capacity for about 10 years for water softeners and 5 years for deionizers before replacement with virgin (new) resin. However, resin capacity varies greatly for wastewater because it usually has to treat a far greater concentration of foulants and oxidizers. This resin might not be regenerated economically or produce high-purity water, or both; thus requiring frequent replacement of virgin resin as often as each time it is used. Operating experience is the best way to determine whether to use regenerated resin or virgin (new) resin each time. Resin options include

- Off-site regenerated
- On-site regenerable
- Disposable

Regeneration is a process of chemically treating spent ion exchange resin to restore its capacity to remove dissolved solids. There are two ways that resin can be regenerated—off-site and on-site.

Off-site regenerated resin is a method in which a vendor takes the exhausted tanks to his facility and regenerates the resins with acid and caustic chemicals. The vendor then returns the tanks to the customer.

On-site regenerable resin is typically used for large volume users with more than about 20 gpm (gallons per minute). The resins are regenerated inside tanks at the user's facility with the same chemicals as used for off-site regeneration. The user might have to treat the wastewater produced by the regeneration process for pH. If any toxic metals are present, the user treats the toxic metals to meet federal, state, and local regulations.

Disposable resin has no waste stream to treat at a user's facility since the contaminants are held on the resin. After the resin is used once, it is discarded to a nonregulated or hazardous landfill after it is tested according to federal, state, and local regulations, as discussed earlier.

RO or DI or Both

Generally, RO is preferred when

- Requiring lower operating costs for reduction of TDS from source (tap) water containing 200 ppm or more (the higher, the more economical)
- Eliminating use of strong acid and caustic chemicals used to regenerate DI resins
- Requiring much lower concentration of small, nonionic substances

Generally, DI is preferred when

- Requiring no wastewater to be discharged
- Existing wastewater treatment system is at over-capacity
- Waiting for a wastewater discharge permit for an RO

- Requiring higher water purity that RO alone cannot produce
- Requiring a simple, flexible pilot system
- Producing similar water purity even when input water quality varies greatly
- Requiring flexibility in supplying water purity at a range of flow rates with the same equipment
- Requiring elaborate pretreatment for an RO system to operate cost effectively
- Requiring a simple system for low flow rate application

Generally, both RO and DI are preferred when

- Reducing TDS using an RO to make DI more economical

Case Histories

- *RO-only application*: In 2002, a customer with an RO-only application used well water with a conductivity of about 476 µS/cm and hardness of about 210 ppm. The untreated water compromised the chemical bath performance and caused spotting that would affect further surface treatment of the metal parts. In the final RO design, the hardness was too high, so a chemical anti-scalant was used to prevent fouling the RO membrane with hardness (calcium and magnesium carbonate scale). Otherwise, the RO would not produce the proper amount of treated water. The final design included a source (tap) water storage tank, and then an RO that produced permeate (product water) directly to the operations without a storage tank (called a direct feed design). The final water purity produced was about 15–25 µS/cm. System cost was $15,200.
- *DI-only application:* Our customers used closed-loop DI for electronics assembly operations. (See the first case history in "Closed-Loop Design.") System costs range from several thousand to $70,000.
- *Both RO and DI application*: In 2001, a customer who worked with automotive glass specified an RO and DI equipment to meet a water purity specification of 10–15 megohm cm at 5–7 gpm. The design used an RO to pretreat the water into mixed bed DI tanks and then into a storage tank. (The storage tank provided for periodic peak flow demands during cleaning operations.) The water continuously recirculated in a loop from the storage tank back to the storage tank to maintain high purity. The loop had another mixed bed, a UV light, and a 0.2 µm absolute membrane cartridge filter. It might have been possible to achieve the water purity specification with only DI. However, if lake water were used, colloids could make it much more difficult for DI to achieve the water purity. System cost was $32,100.
- *RO or DI application:* A washer manufacturer's customer wanted to remove lubricants from strip steel. The washer manufacturer tried high-purity DI water, which was a typical solution for all of their washing applications. However, even though DI water produced a spot free rinse, it caused another condition called "flash" rusting. This happens when steel parts are rinsed with higher water purity than necessary to achieve spot-free rinsing. The problem was eliminated when either a two bed weak base deionizer or an RO was used to produce low water purity, followed by an air blower.

Wastewater Treatment Options

The following decision making is the most complicated part of the selection process. Each of the options has to be analyzed to determine its cost effectiveness in meeting a user's objectives. It is very important in this evaluation that the entire process be reviewed initially to decide the critical success factors and margin of safety. After these are listed, another review must be made of the next most important variables. This method ensures that all key variables are considered; otherwise, much time and resources can be lost because they were not identified earlier in the evaluation. Typically, a closed-loop system uses the lowest amount of makeup water, while a cleaning process without any water reuse requires the largest amount of water.

For example, consider including a provision for future products that might require cleaning parts at a higher level of cleanliness than is customarily used in the original design. In another example, a user

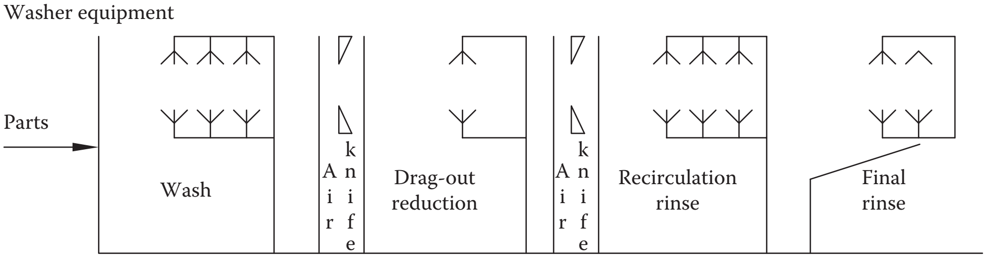


FIGURE 32.2 Conveyorized washer design. Note: This schematic represents a conveyorized washer. It can also be visualized as a multistage cabinet washer where all of the parts remain stationary and are subjected to each cleaning step. The parts are moved manually or automatically from one cleaning step to another in a dip tank cleaning process.

might inquire about future regulations for the contaminants being complied with and make accommodations for them. Regulations very seldom become less stringent.

Cleaning operations can use the sequence of operations as shown in Figure 32.2 for a conveyorized washer. This schematic shows the same processing steps that would be used for a series of dip tanks or a multistage cabinet (like a dishwasher). These other two designs look quite different from the conveyorized design.

No-Discharge Wastewater Option

The key to any no-discharge wastewater option is the ability to reuse wastewater and generate the least amount of solid waste. Sometimes wastewater from one application can be considered acceptable source water for another process. Cascade counter-flow rinses are very often used; they are a good example of wastewater reuse in the same process. With this method, the highest-purity water is used at the end to rinse the parts in the process. The wastewater flows in the opposite direction to the parts being cleaned as it cascades to the previous step in the process. Each time the wastewater is reused, the overall cost of water for the process and the amount of wastewater generated decreases as compared with using the highest purity water for each rinse stage and dumping it to drain.

A user might decide not to discharge wastewater because

- Return on a no-discharge system's capital equipment investment and operating cost are very favorable.
- Federal, state, or local regulatory agencies prohibit discharge of industrial wastewater.
- High cost of wastewater treatment.
- Restriction in volume of wastewater discharge.
- Uncertainty of water availability.
- Liability for ground or surface water contamination.
- High monitoring cost for discharging wastewater.

Closed-Loop Design

The design in Figure 32.3 allows no wastewater discharge to a POTW because it is all recycled to the same process. A closed loop is not easily attained, but for some processes, it is the most cost-effective, ideal solution.

Closed-loop design benefits include

- Recovery of high-cost DI water
- No wastewater discharge to POTW
- No wastewater tests, permits, inspections, and reports
- Wastewater converted to hot, DI water

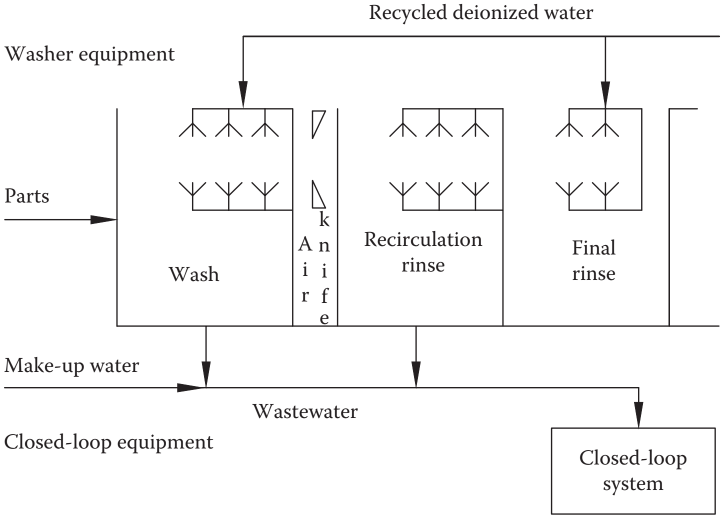


FIGURE 32.3 Washer and closed-loop wastewater system design.

- Wastewater recycled nearly indefinitely
- Reduction of energy and water usage by at least 90%
- Minimal amount of new source (tap) water
- Water purity ranging from low to high
- Solid waste is not hazardous in standard applications

Case Histories

- From the mid-1980s to today, over 450 electronic assembly customers worldwide have greatly benefited from our closed-loop water recycling system designs. All wastewater is recycled back to the washing process after it is treated. In an electronics assembly application, a manufacturer takes printed circuit boards, inserts numerous electronic devices on the boards, fluxes the boards, and then solders the devices. The flux is sometimes removed with DI water, and the wastewater from the washing process is processed by a closed-loop system. Today it is the design standard in this industry.[10] However, for many nonelectronic-assembly applications, the capital cost might be similar, but the operating cost for such a closed-loop system is often prohibitive because of the high dissolved solids (ions) in the wastewater. This causes a high operating cost because of the consumption of activated carbon and ion exchange resin.

This closed-loop design results in substantial savings. The return on investment is achieved within 6–12 months, after which the cash flow is positive.[11] That is, the cost to operate will be less than for a system that discharges all of the wastewater to a POTW. For example, suppose the TDS of the source (tap) water is about 300. In a once-through system, the source (tap) water with the same TDS is continuously fed to the parts washer, and then to waste treatment and a POTW or just to a POTW. However, in a closed-loop system, the water returns to the closed-loop system at 20–50 ppm instead. (The range depends on the soldering chemistries used in the process.) The saving is the difference between the cost of deionizing water at 300 and at 20–50 ppm. Also, there are savings from the energy recovered from recycling heated water used in the washing process, which ordinarily goes to the drain in a once-through system and there is minimal need for new source (tap) water. However, as much as 200 gal/day of source (tap) water is required because of the DI water that evaporates from board drying while operating 8 h/day. Some of this water-laden air can be economically recovered in some cases. The higher the TDS of the source (tap) water, the greater the return on a user's investment.

This closed-loop design uses a combination of particle, organic, and ionic removal media, allowing the water to be completely reused. Depending on the level of reliability required of an electronic assembly, the media is replaced after the resistivity drops below the water purity specification. The life of the ionic removal media depends on the soldering materials used in the process. Operating experience has demonstrated that soldering fluxes alone can cause the operating costs to vary as much as 50%.[12] Depending on the amount of certain soldering materials, such as water soluble tape, temporary mask, defoamers, dissopads, or other materials used, the operating costs can be so high that it is prohibitive to operate. A thorough knowledge of the soldering materials' impact on the operating cost of the system is crucial in achieving the lowest operating cost.

The solid waste (particle-removal filters, activated carbon and ionic removal media) generated must be tested (TCLP test) to determine compliance with federal, state, and local regulations prior to disposal. The key toxic contaminants generated by this process are lead and, sometimes, silver, both of which are regulated. From numerous installed operating systems, it has been found that the first particle-removal filter can be hazardous waste because of the solder balls being washed off the boards during the soldering process. Usually, the organic removal media and the ionic removal media are considered nonhazardous.

- In 1999, a customer required a recycling system to remove dissolved chrome from the rinse water using ion exchange resin. This process eliminates wastewater treatment, does not discharge wastewater, and substantially reduces water consumption, while providing chrome-free rinse water. System cost was $5100.
- In 2002, a nozzle manufacturing customer tested nozzles at multiple test stations to ensure they allowed water to flow within an acceptable range. The specification required continuous warm water in a narrow range, no odor from the water, water purity in the proper range to produce a spot free rinse, yet not too high to cause corrosion, and a specific air saturation of the water. The final design consisted of mixed bed DI tanks, deaerator, ozonation, ultraviolet radiation, and water storage tank. Our customer was very concerned about odors from the water, so both an ozonator and UV radiation were used. Most often one or the other is sufficient. System cost was $151,700. (Note: Detailed specifications are not stated to maintain confidentiality.)
- In 2009, a fuel cell customer was using an ink matrix in their process that required the wastewater to be hauled. The company wanted to substantially reduce the amount of waste to haul. The objective was achieved by using a UF membrane and DI. The UF membrane system produced two streams, the reject stream that contained the concentrated solid contaminants and the product water that was recovered from the wastewater. This product water was deionized and used again in the process. The solid waste generated by the UF was a small fraction of the amount of wastewater previously hauled. System cost was $75,300.

Zero-Wastewater Discharge Design

In the previous section, an electronics assembly case history was discussed using a closed-loop design. Many other parts are also washed, such as automotive, computer, and others, which might have oil and other contaminants. In these applications, the amount of dissolved solids (ions) or TDS in a wash tank are far greater than in electronics assembly applications. This makes the capital and operating cost of a closed-loop design prohibitive unless substantial design changes are made. Even with such changes, the costs are higher than for a closed-loop system.

Figure 32.4 shows a zero-wastewater discharge design that represents the typical stages of a variety of washer designs. Parts can be washed in a series of dip tanks, multi-stage cabinet design (dishwasher style), or conveyorized design. This design, like the electronics assembly closed-loop design discussed in "Closed-Loop Design," does not allow wastewater discharge to the POTW. In the electronics application, the solid waste had the toxic metals, lead and silver, but passed the TCLP test, making it nonhazardous. In nonelectronics applications, the solid waste is usually an alkaline wash chemical, which might be hazardous, depending on the pH, oil, or other characteristics.

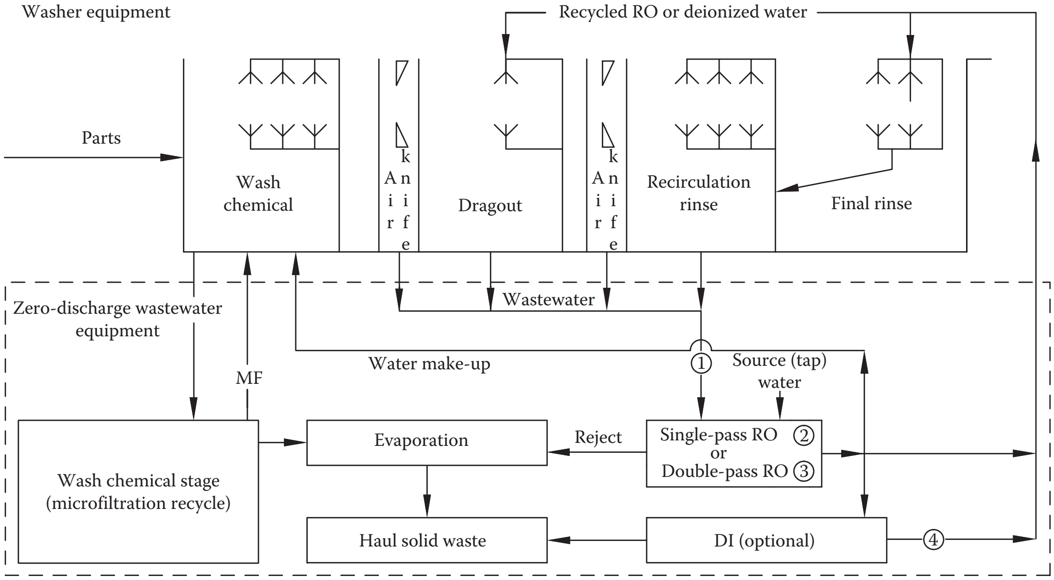


FIGURE 32.4 Washer and zero-discharge wastewater system design.

The first section is the wash chemical stage, which is designed to remove oil and other contaminants. If there is emulsified oil, recycling through a microfiltration membrane system (mechanical process) removes it. (Emulsified oil is an intimate mixture of oil and alkaline wash chemistry that does not separate.) It will separate into two components if mechanical or chemical methods are used. Free oil can be removed by numerous mechanical devices that allow the oil to accumulate at the top and be removed. In low-volume applications, it is most cost effective to haul away the wastewater.

The second section is the dragout stage, which is designed to reduce the amount of dissolved solids (ions) with the least amount of rinse water. One or more mechanical techniques are used, including air knives, rinse water spray, misting, and letting the excess wash chemistry drip off the parts. (An air knife is a long, narrow, slotted device that spans the width of a conveyorized washer. High-pressure air is forced through the slot to more effectively remove water from blind holes and other areas of a part.)

The third section is the final rinse water stage, which is used to rinse the parts with a recirculation rinse and final rinse with the highest purity water. Usually the final rinse cascades back to the previous recirculation rinse section.

Wash Chemical Stage

There are three general methods of handling wash chemical wastewater without discharging to a POTW—hauling, evaporation, recycling, or a combination.

The best method depends on four factors:

- Volume of wastewater
- Cost of hauling wastewater
- Cost of evaporation
- Cost of recycling

The cost of hauling, evaporation, and recycling are dependent upon local conditions. The discussions that follow provide guidance on what to consider. In addition, the stringency of discharge regulations and whether or not the wastewater and solid waste are hazardous can be significant factors.[13]

Volume of Wastewater

The volume of wastewater is the key factor for the next three methods for disposing of the unusable wash chemical. Estimates have to be made of the volume of wastewater to determine which is most cost effective.

Hauling

Hauling is most economical for low-volume applications because it eliminates the need for any capital equipment for treatment. A common carrier is allowed to haul waste as long as the wastewater is not hazardous. Otherwise, the solid waste must be manifested and hauled by a licensed trucking company to an authorized facility. In addition, even though federal, state, and local regulatory agencies might not classify the solid waste as hazardous, a local landfill owner might have his own regulation disallowing this solid waste. In some cases, for a new process, hauling might be used as a temporary measure until a final decision is made.

Evaporation

Evaporation is a method of separating a liquid from solids, typically by heating the wastewater with gas, electricity, solar energy, or vacuum distillation. When the amount of wastewater is much larger, hauling is not cost effective unless evaporation is used to reduce the volume, making it cost effective. It can greatly reduce the amount of wastewater to be disposed of by about 70%–95%. This is usually an energy-intensive process and the cost of the energy must be considered. If there are other processes in a plant producing excess heat that can be used, or if solar energy is available, evaporation can be very economical.

After evaporating the volatiles, the remaining contaminants might be solid waste with toxic metals or have a very high pH (regulations vary throughout the United States) that makes it a hazardous waste. The water vapor from evaporators (electric or gas) is like distilled water and has a water purity similar to medium purity DI or RO that can be reused in the washing process. An analysis of the cost of condensing the water vapor and the usefulness of the higher purity water can be made to determine its cost-effectiveness. The cost of evaporation and hauling is not significantly affected by the concentration of the toxic metals in the wastewater. Therefore, concentrating the liquid might be best. Depending on the regulations in some states or local areas, the vapors can be highly regulated and an air discharge permit required. These areas are sensitive air pollution regions of the United States.

Recycling

Recycling can be accomplished by using either a microfilter or an ultrafilter membrane.[14,15] (See Table 32.2 for particle size removal ranges.) These filters are made of polymeric, ceramic, or stainless steel materials. There are advantages and disadvantages of each of these materials. The ultrafilter is made only of polymeric materials in order to achieve removal of shorter chain molecules that the microfilter cannot remove very effectively. The membrane separates the alkaline wash into two streams: (permeate) alkaline chemistry and (reject) concentrated emulsified oil and free oil (small amounts). Depending on the molecular size of the components of the wash chemical, either a microfilter or ultrafilter can be very effective. In most cases, a microfilter at a nominal rating of 0.2 µm is very effective for higher molecular weight contaminants and it operates at a much higher flow rate than an ultrafilter. It is best to remove the free floating unemulsified oil before either microfiltration or ultrafiltration (UF) processing; otherwise, the flow rate through either could be substantially reduced and could even irreversibly foul the membranes.

During either microfiltration or UF (especially), some of the larger molecules (key ingredients) of the alkaline wash chemistry are removed. The amount of passage depends on the size of the molecules in the wash chemistry components and the membrane porosity. Some chemical suppliers offer an add-back package to rebalance the alkaline wash chemistry. Experience from operating such systems has shown that the life of a wash chemical is extended from three to ten times.

Recycling design benefits include

- Maintain a consistent wash chemistry
- Reduce average levels of emulsified oil on parts
- Reduce maintenance cost by not replacing the wash chemistry as frequently
- Reduce chemical consumption by extending the life of wash chemical
- Reduce water consumption from less frequent wash chemical replacement
- Reduce solid waste and wastewater hauling costs

A user's ability to achieve these benefits depends on a careful evaluation of the parts washer, cleaning chemistry, membrane unit, oil-based contaminants, and other factors. First, review the entire process, user's objectives, and potential benefits. Next, demonstrate the recyclability of the wash chemistry on a laboratory scale. A pilot test is performed at the user's facility to corroborate the benefits of recycling on a larger scale, and for the customer's understanding of the operating requirements of the membrane unit. Other chemicals and membranes might be tested to achieve optimum results. After this procedure is followed, the user can have complete confidence in the successful operation of a full-scale production washing process.

Case History

In 1998, a manufacturer of metal computer parts had difficulty removing water soluble oils and suspended particles that coated metal parts before electroplating. Even though the wash chemical was being replaced frequently, the failure rate of the next process step (electroplating) was too high. Neither an oil skimmer nor a coalescer reduced the failure rate because they could not remove the emulsified oil that caused the problem. Replacing the wash chemical even more frequently was too expensive. A pilot system was shipped to the manufacturer to ensure the equipment would achieve its purpose and the equipment operation was understood by the user. Even though the wash chemical bath was at 170°F, the temperature could have been even higher. The microfilter was very successful in maintaining both the emulsified oil concentration at a continuous low level. Other benefits such as reduced chemical costs, maintenance downtime, and others mentioned above contributed to making this a very cost-effective solution. The life of the chemical bath was extended by more than five times. System cost was $27,600.

Dragout Stage

The dragout stage uses mechanical methods to reduce the amount of wastewater coming from the wash chemistry tank before it gets to the next stage. The greater the volume of water produced, the larger the RO pretreatment system, and the more costly the zero-wastewater discharge equipment. Therefore, an effort should be made to achieve the highest concentration of contaminants in a given amount of dragout water.

The dragout method for a series of dip tanks could consist of orienting parts with blind holes to drain, holding wet parts over the wash tank for a period of time, air spraying parts, and other techniques. All actions are performed over the wash tank to reduce the amount of wastewater generated that has to be treated and chemicals required to replenish the wash tank. The parts can also be briefly sprayed with rinse water over an empty tank just before immersing in a rinse tank. For a multi-stage cabinet design (dishwasher style) orient parts with blind holes to drain and hold wet parts before going to the next stage to allow better drainage. For small parts in large quantities, the orientation of the blind holes to drain might not be practical. A brief rinse will be very effective.

For a conveyorized washer, the dragout stage is illustrated in Figure 32.4: an air knife, a low flow rinse spray, and another air knife. An old conveyorized washer without these features might be modified. As the washed parts enter the dragout stage, the air knives remove excess wash water from the parts and return it to the wash tank for reuse. They simultaneously reduce the amount of additional chemistry required to replenish the wash tank. A brief rinse removes more of the wash chemistry to reduce the TDS, allowing the RO to attain higher water purity. The final air knife removes more of the rinse water off the parts. Most of the rinse wastewater from any of these three washing system designs (dip tanks, multi-stage cabinet, or conveyorized), can be used as makeup water to the wash tank. Conserving water and chemicals is the best way to achieve the lowest operating cost system.

Rinse Water Stage

TDS reduction process options include

- Single-pass RO
- Double-pass RO
- Single-pass or double-pass RO followed by DI

Table 32.3 lists ways to produce low, medium, and high water purity as predicted by different treatment methods using incoming wastewater at 5000 ppm TDS (1). 5000 ppm is an arbitrary TDS of the wastewater in Figure 32.4 coming from air knife, dragout, air knife and recirculation rinse going to a single-pass or double-pass RO. It allows sample calculations to be made for illustrative purpose.

The final rinse water treatment method depends on the amount of TDS dragged out of the wastewater. For example, if the dragout stage is very effective, a single-pass RO might be adequate; otherwise, use a double-pass RO. With an installed washer, a user might have to consider the cost of modifying the washer's dragout section, if possible. The additional benefit of a double-pass RO is that a user might be able to achieve the specified water purity without requiring a DI closed loop. It is better to use a double-pass RO only, rather than a single-pass RO followed with a DI unit; otherwise it will be more costly. In all cases the lower the TDS of the wastewater to the TDS reduction process, the less extensive the treatment equipment and the lower the operating cost.

Calculating Water Purity Specifications

The following sample calculations allow a user to make an evaluation of different technologies, designs, and capability. These three water purity specifications are arbitrary and are not industry standard:

- *Low purity* (2): Depending on the wastewater TDS, a single-pass RO might achieve this specification. As an example, the wastewater has 5000 ppm TDS and the RO rejection rate for dissolved solids is 95%. Therefore, 5000 ppm × 5% (100% – 95% = 5%) = 250 ppm of the dissolved solids remaining in the product water. The remaining contaminants become the waste stream. Using the conversion factor of 0.5 (see "Dissolved Contaminants"), 250 ppm ÷ 0.5 ppm/µS/cm = 500 µS/cm (2000 ohm cm).
- *Medium purity* (3): If low-purity water is not acceptable, a double-pass RO raises the resistivity from the single-pass RO to about 40,000 ohm cm. Take the 250 ppm from the above low-purity option and recalculate: 250 ppm × 5% = 12.5 ppm ÷ 0.5 ppm/µS/cm = 25 µS/cm (40,000 ohm cm).

TABLE 32.3 Zero-Discharge Wastewater to Produce Low, Medium, or High Purity Rinse Water

	Washer Stages		
Water Purity	Wash Chemical (1) (ppm)	Dragout (ppm)	Recirculation and Final Rinse Water Stage (Ohm cm)
Low purity (2)	5,000	Depends on process	Single-pass RO 2,000 (250 ppm)
Medium purity (3)	5,000	Depends on process	Double-pass RO 40,000 (12.5 ppm)
High purity (4)	5,000	Depends on process	Double-pass RO plus DI 1,000,000+ (less than 0.5 ppm)

- *High purity* (4): Adding a final closed-loop DI (conventional mixed bed DI or EDI) to either a single-pass RO (see low water purity) or a double-pass RO (see medium water purity) will achieve this specification. The water purity will be above 1,000,000 ohm cm (1 megohm cm).

Both single-pass and double-pass RO designs have a reject stream that goes to an evaporator. This eliminates the final wastewater stream from the process, thereby attaining a zero-discharge wastewater design. The solid waste produced is not likely to be hazardous unless it contains one or more of the eight toxic metals mentioned in “Solid Waste.” If they are present, the waste must be subjected to a TCLP test to determine the concentration and whether any of the toxic metals exceed the regulation limit. If even one metal exceeds the regulation, the solid waste must be hauled by a licensed carrier as hazardous solid waste. Also, too low or too high pH is a regulatory concern.

Discharge Wastewater Option

A user might discharge wastewater because

- Wastewater meets discharge regulations directly without any treatment
- No-discharge wastewater option does not meet corporate return on investment objective
- Ability to treat wastewater for discharge at low cost
- Availability of source (tap) water at low cost
- Hauling costs for wastewater are too high
- Lack of interest in pioneering water conservation, reducing the amount of contaminated wastewater or solid waste

The following sections describe appropriate wastewater discharge options for various contaminants and conditions.

Fat, Oil, and Grease

Some washing applications might have any of these three kinds of contaminants, fat, oil, and grease (FOG), coming off the parts being cleaned. Usually, the contaminants produce free-floating oil and some emulsified oil. Free-floating oil forms on the surface of the wash chemical, while emulsified oil forms throughout the wash chemical. Usually emulsified oil appears milky white in larger quantities (dyes will change the color); in smaller quantities, it might be cloudy or not visible.

The ability to remove oil, fat, or grease contaminants as free floating, dispersed, and/or emulsified forms with the proper method depends upon a few key factors: amount and type of contaminants, temperature, and wash chemical (emulsifiers and surfactants). Some factors in selecting equipment include available space, maintenance, capital and maintenance costs, operating skills required, and other operating conditions.

The following is a summary of the most common technologies and techniques used to remove free and emulsified oil from water with an indication of the capabilities of each:

	Free Oil	Emulsified Oils
Decanter	Yes	No
Oil skimmer	Yes	No
Coalescer	Yes	No
Thin-film oil separation	Yes	No
Centrifugation	Yes	No
Activated carbon	Yes (very limited)	Yes (very limited)
Chemical precipitation	Yes	Yes
Dissolved air flotation	Yes (no chemical)	Yes (with chemical)
Microfiltration	Low amounts	Yes
Ultrafiltration	Low amounts	Yes

Free Oil

Free oil or unemulsified oil is always considered free-floating oil. There are many proven, long-used methods and even a newer technology, thin film oil control, which can be used:

- *Decanter* (gravity separator) allows the free oil to rise to the surface, separating it from water, and spilling over a weir into a container.
- *Oil skimmer* includes an oil-attracting material in the form of a belt, disk, or similar device to remove free oil from the surface of the wastewater.
- *Coalescer* is a device constructed of materials, usually polymeric media that allows the adherence of very small droplets of oil that grow in size and are released to the surface of the water when large enough, and then removed by a decanter.
- *Thin-film oil separation* equipment is a newer method that utilizes Bernoulli's principle. In the three step process, the oil is concentrated, and then allowed to flow over a weir for disposal. There are no moving parts or consumables.
- *Centrifugation* spins the wastewater at a high velocity forcing the densest particles and organic compounds to separate from other particles and compounds.
- *Activated carbon* is available in a granular or cartridge design and is effective for very low amounts of free oil; otherwise it would be prohibitive in cost.

Chemical precipitation, dissolved air floatation and microfiltration and UF will be discussed in the next section.

Emulsified Oil

Here are three methods that use chemicals and membranes to separate emulsified oil from water:

- *Chemicals* are used as a general purpose method for small or large amounts of emulsified oils.
- *Dissolved air flotation* (DAF) is a completely different design used most effectively for large operations. This design uses air that attaches to free or dispersed oil and facilitates its rise to the wastewater surface for easy removal. Chemicals are used to allow removal of the emulsified oil.
- *Membrane filtration,* such as microfilters and ultrafilters, are ceramic, metal, or polymeric, and are very effective in meeting local discharge regulations. A microfilter can process much larger volumes of wastewater than an ultrafilter on an equal basis of surface area of the membrane. Therefore, it is better suited for large flow rate applications. However, an ultrafilter has a smaller pore size, so it is more effective in removing low-molecular-weight organic molecules. Both of these technologies are increasingly competing with chemical precipitation and even DAF for large flow applications. Membranes can only process small amounts of free oil before the flow rate through the membranes is reduced. However, a free oil removal device eliminates this restriction. There are several important variables that must be considered when making a decision about whether a membrane or DAF is best.

pH

Sometimes the wash tank of a cleaning operation contains alkaline wash chemistry with a pH higher than the local discharge limit. This condition can be corrected by using an acid pH chemical control unit. Less frequently, the use of an alkaline chemical control is necessary for applications with a low pH.

Biological Oxygen Demand and Chemical Oxygen Demand

Often state and local regulatory agencies have discharge limits for BOD (biological oxygen demand) and, to a much lesser extent, COD (chemical oxygen demand). The BOD test method determines the amount of oxygen consumed by microorganisms to decompose organic matter in water or wastewater.

The COD test method uses a chemical oxidant to determine indirectly the amount of oxygen required to oxidize both organic and inorganic contaminants in water.

COD contamination sometimes requires chemical oxidant, carbon adsorption, ultraviolet oxidation, or ozonation to achieve further reduction. A membrane process such as UF or NF can be used, but they are more often used in a recycling process where the permeate would be reused; otherwise the waste stream must be hauled or evaporated and then hauled.

Toxic Metals

The following methods are widely used to remove different toxic metals to meet discharge limits. In many cases, there is not one single form of a metal; rather, there are two or more forms simultaneously. It is not unusual that as many as three of these technologies are used together:

- Mechanical filtration (particulate)
- Chemical precipitation (particulate, colloidal, and chelated)
- Membrane filtration (particulate and others)
- Ion exchange resin (ionic)

Mechanical filters are useful for particles of about 1 μm and larger, at low concentration levels, and small to moderate volumes of wastewater treated. Filter replacement cost is the most important factor. This is a low capital cost option with the smallest space requirement.

Chemical precipitation is most often used for large volumes because it is economical. It is designed to remove chelated, non-chelated, and colloidal toxic metals. A chelate is a metal ion that is chemically bound by other ions, making it difficult to separate. With a few exceptions, this process can be used to remove chelated toxic metals too. This is the next highest capital cost option, which occupies a larger space than mechanical filters.

Membrane filtration is very effective, especially for moderate to large applications for all forms of these contaminants. There are three types of membranes that can be used, depending on the state of the toxic metal. RO can be used for dissolved metals, but the user must be careful of the chelated forms of metals, which might be colloidal, and which could irreversibly foul the membranes (see "Reverse Osmosis"). Neither UF nor MF can remove ionic forms of metals. UF can remove suspended, colloidal, and chelated forms of metals. MF's effectiveness is limited in removing colloidal and chelated forms of metals. Membranes are very flexible in their removal capability, but are usually the higher capital cost systems in this grouping. In large applications, chemical precipitation and membrane filtration must be studied carefully to determine the most cost-effective approach.

Ion exchange is a very simple method used primarily for two reasons: The ionic metal concentration cannot be removed by any of the three other methods and other forms of the metal (colloidal and chelated) do not exceed the discharge regulations. Neither chelated nor colloidal forms are effectively removed by resin. Under these conditions, a UF membrane will eliminate the problem. If suspended solids contain metals, they can be removed by mechanical filters before the particles get to the ion exchange process.

There are three types of resins used: standard deionizing (cation and anion or mixed bed), specific heavy metal, and cation or anion with other combinations of resin. There are two criteria in making the decision about which to choose—cost and capacity. The standard resins are less expensive, but have a lower capacity; while the specific heavy-metal resin is more expensive, it has a higher capacity. The key difference between these two is that the deionizing resin removes ions that do not have to be removed, while the specific heavy-metal resin does not. The key question is, "Does the higher capacity resin justify its cost in terms of the amount of metal it removes?" For low-volume applications the standard resin is probably best. But at higher volumes, since the cost becomes significant, the best action is to either do pilot testing or just try the different resins in the actual production operation. The last type, cation or anion with other combinations of resin, is too specific to the conditions, usually with several solutions, and is too complicated to discuss here. In all of these decisions, pH, TDS, competing ions, and other factors, each or all of them together, could have a major impact upon the effectiveness of the resins used.

The final selection of the best method or combination depends on the type of metal form (particulate, colloidal, ionic, chelated, or a combination), flow rate, total flow per day, concentration of contaminants, and other factors. In some membrane applications, the wastewater processed could be reused. The waste stream would contain the concentrated metal and the oils would be hauled as hazardous waste.

Case Histories

- In 1998, a customer was washing beryllium copper strips that had water-soluble stamping oils and metal particles on the surfaces. An oil skimmer and coalescer were used to remove the free-floating oils. However, there were bare spots causing poor adhesion, resulting in later post cleaning plating part failures. After reviewing the entire cleaning process, the chemical cleaner was changed along with adding a chemical recycling system that could remove the emulsified oil that could not be removed previously. Reductions in chemistry use, physical labor, waste disposal, and product rejects led to an annual cost saving of almost $120,000 per year. System cost was $29,800.
- In 2005, a customer decided to discharge wastewater to a POTW because it was not economical to recycle the wastewater. The wastewater stream flowing at 4 gal/min had a zinc concentration that was above the local regulatory discharge limit. Zinc-selective ion exchange resin was the best solution to remove the heavy metal. Two systems cost $6400 each.
- 1n 2008, a large military aerospace R&D center for advanced electronics had toxic metals in their process that would violate local discharge to a POTW if not treated. Four of these toxic metals had to meet these regulations. The technologies that were pilot tested proved that an ultrafilter and ion exchange would solve the problem. The ultrafilter was necessary because of the small particle size and ion exchange was used for the ionic forms of some of the metals. System cost was $44,500.

Other Treatment Options

Other treatment options can be used individually or with the treatment methods discussed previously. The following sections describe some of the most common.

Distilled Water

Distilled water is a common, low-TDS water, similar to what RO and ion exchange can produce. It is produced by simply heating water to boiling and condensing the vapor, which then becomes distilled water. It is used most often for pharmaceutical and laboratory applications where bacteria-free water is necessary. It is usually not economical for industrial applications as compared with the other options described previously. It is mentioned here because it is used in many small applications and readily available in small quantities.

Water Softening

There are some applications in which softened water is sufficient to achieve a cleanliness specification. This process might be used alone to treat the source (tap) water for washing parts or, more often, as pretreatment to RO.

Water softening is a process of removing mostly hardness minerals (ions), calcium and magnesium, and to a much lesser extent, dissolved iron or manganese and replacing them with sodium cations. The key component of a water softener, as in a deionizer, is the ion exchange resin inside a tank (Figure 32.5). The cation ion exchange resin is the same as used for deionization, except that it is in a different form—sodium (Na^{+1}) instead of hydrogen (H^{+1}). Softening the source (tap) water has essentially no effect on the TDS, conductivity, or resistivity of the water.

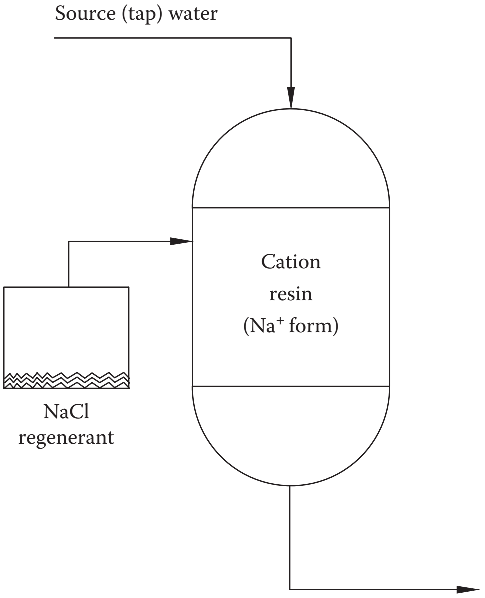


FIGURE 32.5 Water softener.

After all of the ions are exchanged, the ion exchange resin becomes spent. The resin is regenerated (reversing the process) by flowing concentrated sodium or potassium chloride through the resin during a multistage process, performed manually or automatically. During the regeneration process, the sodium (from sodium chloride salt) or potassium (from potassium chloride salt) replaces the hardness cations that the softener removed. This process is very inexpensive compared to regenerating a deionizer. There are factors such as regenerant concentration, iron fouling of the resin, and others that can significantly influence the actual capacity of the resin. The minerals remaining after softening do not cause a hard scale or soap curds (bath ring) to form on the sides of the tank containing the softened water. The amount of soap, detergent or alkaline cleaner required to wash parts is greatly reduced.

Soft water can achieve visually spot-free parts as long as minerals are lower than about 50 ppm and depending on other factors, especially the surface shininess of the parts. A drop of source (tap) water or wastewater allowed to evaporate on a shiny test metal panel will usually leave a more observable residue than with softened water. The appearance of any residue is highly dependent on the level of polish of the part. The more highly polished, the more observable any residue or spots are. The great saving as compared with DI water makes this technology worthwhile to evaluate.

The ion exchange resin capacity calculation for a water softener is the same as for a deionizer (see "Deionization").

Electrodeionization

Electrodeionization (EDI) is an ion exchange process that produces high-purity water greater than 1 megohm cm resistivity (1 μS/cm) without the use of chemical regenerants—hydrochloric acid and sodium hydroxide. However, pretreatment is far more important than for a conventional deionization system. Also, it is most often used as a posttreatment to an RO membrane process. It is used far less often in industrial processes instead of conventional DI, but is increasingly gaining popularity because it does not use hazardous chemicals.

Mechanical Filters

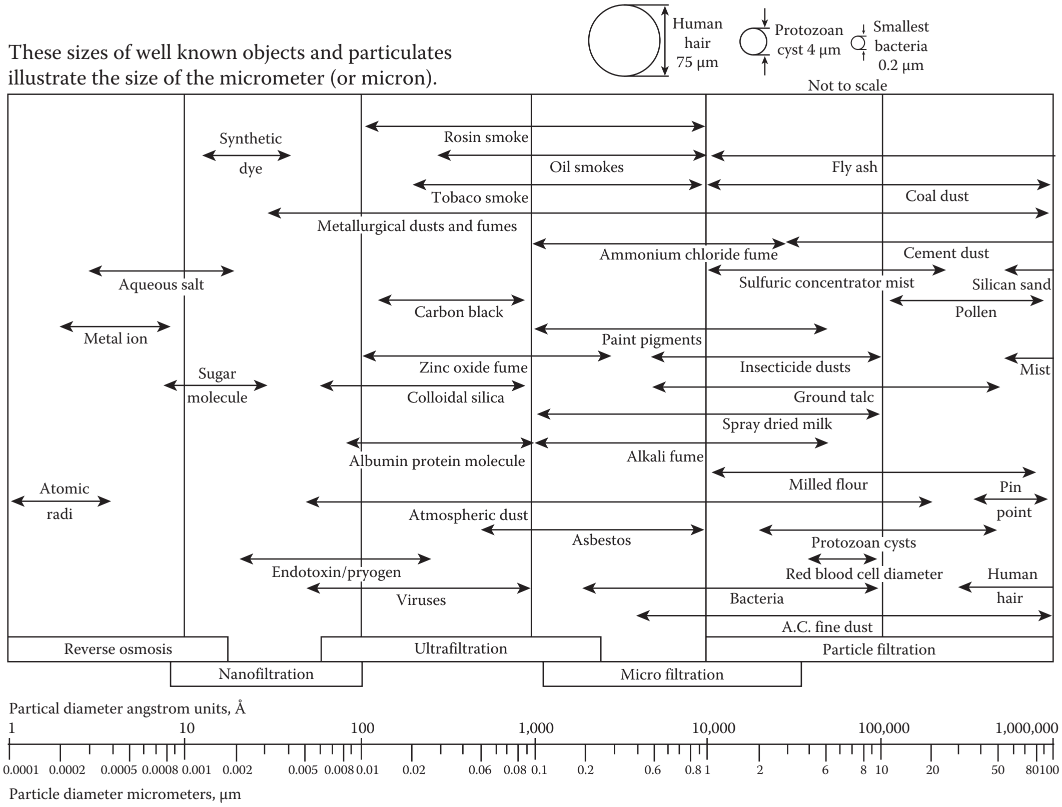
Mechanical filters are physical barriers for removing particles from water. Mechanical filtration is the most common method used to remove particles from water and wastewater in washing processes. The particles can vary from very coarse to a sub-micrometer (sub-micron) level, that is, less than 1 µm in size. There can be a very large overlap in the removal capabilities of the various technologies that follow. See Table 32.4 for a chart of the different types of contaminants and the separation technologies used.

There is neither an industry-wide micrometer nor filtration efficiency rating that defines all of these filters. For example, a 10 µm rated bag filter might have an efficiency rating of 70%, that is, 70% of all 10 µm particles are removed, while a 10 µm cartridge filter (non-membrane type) might remove 90%. Beta ratios are sometimes used to rate the effectiveness and efficiency of filters. If the beta ratio is 10, the filter has an efficiency rating of 90%, while a filter with a beta ratio of 100 has a 99% efficiency rating. There is far more reliability of filter micrometer ratings and efficiencies for a given manufacturer. Also, there are certain industries that use standard criteria accepted only within that industry.

As a general rule, the rank order from high to low flows of the four most common filter designs is granular media, bag, and the two cartridge types. However, depending on the application, it is possible to operate any of the following four designs at flow rates as low as a few gallons per minute:

- *Granular media filters* are composed of a single media or multimedia with various grades of sand and other minerals. They are used primarily to remove suspended particles from 20 to 40 µm in size and larger from source (tap) water. They can remove much finer particles, but not as effectively. As a reference point, a grain of table salt is about 125 µm.

TABLE 32.4 Particle Size Removal Range by Filtration



Source: Courtesy of Water Quality Association (WQA), Lisle, IL.

- *Bag filters* are manufactured from felt materials, both woven and nonwoven, and typically have a higher contaminant loading and a lower cost per pound of contamination removal than cartridge filters. They are the most commonly used filters in industry. They are primarily designed for higher flow and higher solids loading applications. Usually, they are not as effective and reliable as cartridge filters for particles in the lower micrometer sizes.
- *Cartridge filters* are commonly used filters made from a wide variety of plastic and natural fibers, such as polypropylene and cotton, in a large variety of designs such as molded, fiber wound, and pleated paper. They are most often used for lower flow rates and higher efficiency, low micrometer removal applications. Efficiency is defined as the ability of a filter to remove particles at a stated micrometer (micron) rating. For high-flow-rate and high-volume applications, granular or bag filters are most often used first and sometimes followed by cartridge filters, if needed.
- *Cartridge membrane filters* are manufactured from a variety of plastic and inorganic materials with different shapes (flat sheets, tubes, spiral wound tubes, and other forms). They are designed to remove very small particles and organic molecules from a liquid stream. Microfilters (MF) are rated at about 0.05–1.0 μm. Ultrafilters (UF) are rated to remove essentially all particles and molecules from about 10,000 to 1,000,000 molecular weight from water.

Sometimes a microfilter from one manufacturer is called an ultrafilter by another manufacturer. To compare one membrane with another, a user must determine the test method the manufacturer used for the rating. This rating problem can be extreme, for example, a membrane manufactured from a plastic material, such as polysulfone, polypropylene, or nylon, rated at 0.2 μm might reject 99.999% (beta ratio of 10,000) of all bacteria, whereas a ceramic membrane with the same rating will have dramatically lower removal efficiency and be unable to significantly remove any bacteria.

Membranes are available in many shapes, sizes, and with varying removal effectiveness. They can be in a disk, cartridge (5–30 in. long), or in large microfiltration systems with one or several membranes and many other configurations. This allows a user the ability to test a filtration application on a small scale at a very low cost.

None of these membranes remove dissolved solids (ions) from water. However, for example, an ultrafilter will effectively remove colloids and other high-molecular-weight substances, such as surfactants, while a microfilter membrane will not do so effectively. However, both types can be used to recycle wash chemicals (alkaline cleaners). Ultrafilter membranes are much more effective than microfilters in removing large organic molecules (macromolecules and lower-molecular-weight petroleum products). This is desirable for discharge to a POTW, but not for recycling a wash chemical. This will result in more add-back chemical additions. Membranes are also mentioned in "Recycling" in the "Wash Chemical Stage" section and in "Emulsified Oil" in the "Fat, Oil, and Grease" section.

Adsorption (Activated Carbon)

Adsorptive technology uses large surface areas to remove contamination. Activated carbon is one of several adsorptive materials used. It is a granular media made by heating carbon-containing materials, such as coal, coconut shells, and similar substances, in the absence of air, producing a porous material with a very large surface area. It is usually used as a pretreatment method to remove chlorine and long-chained organic molecules (primarily decayed vegetation in reservoirs and lakes) prior to ion exchange resins and some RO systems. Activated carbon has a catalytic corrosion effect on stainless steel tanks used to hold the carbon. The carbon can cause pinhole leaks; lining the tanks with plastic solves this problem.

Oxidation

Oxidation is a process, with or without a chemical, that can oxidize chemicals, dissolved species, deactivate microorganisms (bacteria, viruses, and others), and reduce the amount of organics and many other species and substances in water or wastewater. Even air alone can be used effectively, for example, oxidization of dissolved iron and manganese to form particles that are removed by mechanical filtration prior to an RO. Oxidation is usually achieved by a chemical or air.

Ozonation is a nonchemical oxidation process that uses ozone gas, a powerful oxidant, to greatly reduce the concentration of microorganisms, organic compounds, and other chemical compounds in water. This method can eliminate the need for chemical dosing used for chlorine, potassium permanganate, and others.

Ultraviolet Radiation

Ultraviolet radiation (UV) sanitizes (not sterilizes) water or wastewater to control microorganisms. (In the medical, pharmaceutical, and similar fields, sterilization means a 100% kill rate of all microorganisms.) UV units are too often referred to as "sterilizers," implying that they have the ability to produce microorganism-free water. However, UV sanitizers do greatly reduce the numbers of a wide range of microorganisms with a wide range of degree of effectiveness. There are two types of lamps, 254 nm wavelength, the most common, and 184 nm. The latter produce a slight amount of ozone in addition to their sanitizing ability, thus increasing their effectiveness against microorganisms. If unfiltered water or wastewater is used, it might drastically reduce the effectiveness, because the particles or contamination block the UV radiation and reduce the ozone's effectiveness before it reaches the microorganisms. Prefiltration is important to ensure continuous optimum operation. It can be used alone or as a post-treatment to a DI water system, pre- or post-RO, or alone.

Wastewater Treatment for New Process

First, it is advisable to have a water treatment specialist involved in the early stages of process decisions. Second, to reduce the uncertainty of wastewater treatment decisions, a user should determine the local source water conditions, similar processes in the industry (competitors), availability of hauling, allowance of temporary discharge to define the process, and piloting the process, all of which greatly prevent overdesign costs. The less that is known about a process, the greater the margin of safety that is usually necessary to ensure a treatment system that will meet a user's requirements. A user should attain maximum flexibility before buying a permanent system. A user should be concerned about the following three areas.

Source Water Treatment

If a water sample is available, it is best to have it analyzed, especially if high-purity water is necessary. It is best to wait for the results of the analysis before renting a long-term system or buying a permanent system, unless the uncertainty of the treatment process is minimal. Any water can be treated to meet a user's need; it is a matter of cost.

No-Discharge Wastewater

It is difficult to achieve an economical wastewater treatment system for a no-discharge wastewater design because of unknowns, for example, type of wash chemical, specific contamination generated by the process, surface quality of the parts, and other factors. For small volume applications, the entire wash tank and rinse water could be hauled. For large volumes of wastewater, where hauling might be a problem and the user is on a POTW, it might be possible to discharge it with minimal treatment with a waiver from the local regulatory agency until the final design is achieved. If on a septic system, river, or other body of water, hauling is the only practical way. Another alternative for any of the above could be a temporary treatment system alone or along with hauling until enough data are gathered to define the final, permanent treatment system.

Wastewater Discharge

If a user has decided to discharge to a POTW, it is necessary to obtain the discharge regulations to determine the wastewater conditions that must be met to obtain a permit as soon as possible. It is easier to prepare for this application than for a zero-discharge design because there are far fewer conditions affecting the final design. For example, for most alkaline cleaning applications, pH and oil are the two key concerns. For pH adjustment, equipment is usually easily obtainable on relatively short notice. The amount of oil in the wastewater is more difficult to assess and could lead to a large, unnecessary initial expenditure if a large margin of safety is required, such as considering a UF membrane or chemical treatment system. In such cases, a discharge waiver from a POTW would be of great value until the final effluent is tested.

Overcapacity of the Current Wastewater Treatment System

Usually in such applications, treatment at the source of the discharge can be a primary solution. The cost of expanding the entire wastewater treatment system is usually much more than trying to reduce the amount of wastewater going to the central treatment system. A careful evaluation of all discharge sources should be made to determine the most viable option from a cost standpoint. For temporary overcapacity applications, hauling might be most economical.

Conclusion

Selecting the best source water and wastewater treatment processes for cleaning applications requires a methodical approach. It is best to make a quick review of the entire process while moving forward toward the final design. There might be a critical interdependency of some parts of the cleaning process and wastewater treatment system. A user does not want to miss a critical item in the analysis, especially early in the analyzing process. Sometimes a simple change can alter the entire economic equation, changing a previously uneconomical solution into an economical one or vice versa. The general trend is toward increasing stringency of discharge regulations. Continual vigilance by users in maintaining their knowledge of current water and wastewater treatment practices will ensure the most effective, low-cost design in the future. Most important of all is to make selecting the best wastewater treatment system a team effort; there will be fewer errors and recriminations later.

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