Reducing waste is one of the greatest challenges facing the chemical process industries (CPI) today. Because water is one of industry's major waste products, the ability to reclaim wastewater for reuse would be a giant step toward overall waste reduction.

The systematic approach to water reuse presented here involves understanding, evaluating, and selecting appropriate water reclamation technologies. This process consists of comparing competing technologies in terms of performance capabilities, production of residues, life-cycle costs, and operation and maintenance requirements.

This article offers screening guidance on how to select the appropriate water reclamation technology or technologies for a specific application, and it provides brief summaries of specific technologies—biological treatment, carbon adsorption, centrifugal separation, chemical oxidation, crystallization, electrodialysis, evaporation, filtration, flotation, gravity separation, ion exchange, membrane separation, precipitation, solidification and stabilization, solvent extraction, stripping, and thermal treatment.

Some of the technologies discussed (for example, solidification and stabilization, and thermal treatment) do not by themselves produce a water stream that can be reused, but may be used to treat residue streams from other water-reuse processes. Any waste streams or residuals (gaseous, aqueous, or solid waste) created by a treatment are important because of their impact on multimedia pollution prevention.

Wastewater characteristics

When selecting a technology for the potential reuse or reclamation of water and wastewater, the following information about the waste stream should be considered:

- basic chemical aspects of organic, inorganic, and biological constituents;
- phase state of the compounds; and
- quality of the stream.

The selection of a specific process generally requires the integration of wastewater characteristic data with water quality requirements. Frequently, bench and/or pilot testing is conducted prior to final process selection and design.

Contaminants can be classified into six basic categories that are representative of the key water-quality issues associated with water and wastewater reclamation and reuse:

This article is based on the book “How to Implement Industrial Water Reuse: A Systematic Approach,” published by AIChE’s Center for Waste Reduction Technologies (CWRT), an industry-based group that focuses on emerging environmental and process technologies. For more information, contact Dr. Joseph Rogers, CWRT Director, 212/705-7727, jorogers@aiche.org.
In organics generally encompass those compounds not possessing carbon-hydrogen bonds. They include elemental ions, transition metal complexes, and various hydrides and oxides of metalloids and nonmetals. Inorganics that often require treatment in water reuse applications are listed in Table 1.

Organics include petroleum (aliphatic and aromatic) hydrocarbons, alcohols, aldehydes, ketones, ethers, carboxylic acids, esters, amides, and complex organics such as pesticides, lignin, pharmaceuticals, and so on. Other types of organic constituents are the noncompound-specific measurements, such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), and total organic carbon (TOC). Some of the organics that are often relevant in water reuse applications are listed in Table 1.

Dissolved components are smaller than colloidal particles (about 0.1 micron) and are dispersed as individual molecules or ions throughout the solution (water). Suspended solids are particles that are larger than about 0.1 micron and that can be filtered from solution. Some suspended solids are of sufficient size and density to be settleable solids. Others that remain in suspension in a quiescent solution (e.g., colloids) are termed nonsettleable solids and are frequently measured with units of turbidity.

Biological constituents include bacteria, fungi, algae, protozoa, viruses, and possibly pathogenic organisms that can render a water nonpotable or can be detrimental to a water system.

pH is the measurement of the hydrogen ion concentration of a stream, and it can be affected by the presence of any of the five contaminant types discussed above. It is a crucial water-quality parameter because water reuse or discharge applications usually have restrictions on the acceptable pH range of the stream. Most of the technologies discussed here either require preliminary pH adjustment to optimize the process, or affect pH through the addition of chemicals or change in the waste stream quality by treatment. Therefore, pH is not considered further as a contaminant type because of its universal applicability.

Table 1. Typical species monitored for water reclamation applications.

<table>
<thead>
<tr>
<th>Inorganics</th>
<th>Organics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalinity (CO$_3^{2-}$, HCO$_3^{-}$)</td>
<td>Chemical Oxygen Demand (COD)*</td>
</tr>
<tr>
<td>Hardness (Ca, Mg)</td>
<td>Biochemical Oxygen Demand (BOD)*</td>
</tr>
<tr>
<td>Fe $^{2+}$</td>
<td>Total Organic Carbon (TOC)</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>Volatile Organic Compounds (VOCs)</td>
</tr>
<tr>
<td>Cl $^{-}$</td>
<td>Phenols</td>
</tr>
<tr>
<td>NO$_3^{-}$</td>
<td>Oil and Grease</td>
</tr>
<tr>
<td>NH$_4$</td>
<td>Turbidity</td>
</tr>
<tr>
<td>Total Dissolved Solids (TDS)</td>
<td>Total Halogenated Organics/Adsorbable Organic</td>
</tr>
<tr>
<td>Total Suspended Solids (TSS)</td>
<td>Haloens (TOX/ADOX)</td>
</tr>
</tbody>
</table>

* Inorganic constituents can also contribute to COD and BOD.
† Can sometimes be contributed by organics.
‡ Contributed by suspended inorganics and organics.

The following sections discuss the types of processes applicable to water reclamation. The list is not exhaustive; rather, it summarizes the major technology types available for water reuse applications. Other technologies that might be considered for water reuse applications that are not covered here include: physical control measures for stormwater or pro-
Table 2. Applicability of treatment technologies for different types of contaminants.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Inorganic</th>
<th>Organic</th>
<th>Dissolved</th>
<th>Suspended</th>
<th>Biological</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological Treatment</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Carbon Treatment</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Centrifugal Separation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Chemical Oxidation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Crystallization</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Electrodialysis</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Filtration</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>Flotation</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Gravity Separation</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>Ion Exchange</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Membrane Separation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Solidification and Stabilization</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Stripping</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Thermal Treatment</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
<td>Yes*</td>
</tr>
</tbody>
</table>

*Primarily biosolids

Table 3. Suitability of wastewater technologies for different types of applications.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Source Reduction</th>
<th>Water Treatment</th>
<th>Recycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological Treatment</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Carbon Treatment</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Centrifugal Separation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Chemical Oxidation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Crystallization</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Electrodialysis</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Filtration</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Flotation</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gravity Separation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Ion Exchange</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Membrane Separation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Solidification and Stabilization</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Stripping</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Thermal Treatment</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

cess water collection and containment; innovative and emerging technologies with limited application experience or a demonstrated record of performance; ecological treatment, such as constructed wetlands; and sludge reuse and recycling technologies, such as land application or incorporation into building materials.
Biological treatment

Biological biotreatment (1, 2, 3, 4, 5) employs a biological reactor that maintains a high concentration of either suspended or attached microorganisms. Water is passed through the reactor. Microorganisms metabolize organic compounds and can alter the properties of some inorganic compounds. Technology variations include aerobic, anaerobic, nitrification, and other processes.

In order to be a candidate for biotreatment, the water should contain no toxic organics or inorganics. In addition, there are maximum concentration limits for some compounds (for example, total dissolved solids (TDS) 16,000 mg/L, heavy metals 2 mg/L, cyanides 60 mg/L, phenols 140 mg/L, copper 1 mg/L, chromium 5 mg/L, and total oil 50 mg/L (6)). And, influent conditions should be as stable as possible, because excessive concentration and temperature changes can be detrimental.

Aerobic processes can generate significant quantities of biosolids that require removal and management. Anaerobic processes usually generate methane and hydrogen sulfide, which require special off-gas handling. The effluent produced from biotreatment may need filtration and/or disinfection prior to reuse.

Biotreatment is effective for treating water with dissolved and suspended organics (BOD, COD, volatile organic compounds (VOCs), and semivolatile organic compounds (SVOCs)) and inorganics (nitrates, phosphates, cyanide, and hydrogen sulfide), as well as biosolids. It is ineffective for some organic compounds, such as halogenated solvents and aliphatics. Concentrations of degradable organics are typically reduced by more than 90%.

Biotreatment can be used for water treatment and for water recycle and reuse. Common applications include the treatment of industrial wastewater for reduction of BOD, COD, nitrogen, and phosphorous, treatment of refinery wastewater for removal of phenol, and digestion of primary and secondary biological treatment sludges.

Capital costs of biological treatment systems can be high. Treatment costs range from $40 to $500 per million gallons treated for low-strength wastestreams (typically less than 1,000 mg/L BOD) and are usually more than $1,000 per million gallons treated for high-strength waste streams (typically greater than 5,000 mg/L BOD).

Carbon adsorption

In a carbon adsorption system (1, 2, 4, 7, 8, 9), water is passed through a vessel containing a sorbing medium, such as activated carbon (or polyvinyl resin), that has an affinity for the target contaminants. The sorption phenomenon is a function of the type and particle size of the medium, pH, temperature, contact time, and types and concentrations of contaminants.

The presence of suspended solids, oil, or grease can reduce treatment efficiency and cause maintenance problems. Prefiltration is commonly employed to avoid such problems.

Some organics are not readily treated using carbon adsorption. These include alcohols, low-molecular-weight ketones, acids, and aldehydes. However, some inorganics, such as arsenic, chromium, tin, chlorine, and bromine, do have high adsorption potential. Temperature, pH, and other competing adsorbates all affect removal efficiency.

Concentrations of dissolved organics can be reduced by more than 90%, and BOD and COD can be reduced by 30–60%.

A disadvantage of carbon adsorption is that it requires periodic regeneration as the carbon becomes spent. Most regeneration occurs off-site, but large-quantity carbon regeneration can be performed on-site. On-site regeneration requires additional facilities for carbon and off-gas treatment. The spent sorbent may be a hazardous waste.

Carbon adsorption can be used for source reduction, water treatment, and water recycle and reuse. Common applications for carbon adsorption include the treatment of refinery wastewater to remove phenol, removal of color from wastewater effluent, and post-biological treatment of high-strength organic-containing wastewaters.

Costs range from $70 to over $1,000 per million gallons treated.

Centrifugal separation

Centrifugal separation (2, 5, 10, 11) uses elevated gravitational forces created in a rotating bowl to separate solids from a liquid. A solids-laden stream enters a centrifuge and is forced against the bowl’s outer wall, forming a pool of liquid and sludge solids. Differences in density cause the liquid and sludge solids to separate into distinct layers, which are then separately discharged from the bowl. Different types of centrifuges are available, including basket, solid-bowl, countercurrent-flow, and cocurrent-flow designs.

Centrifugal separation is effective for the removal of suspended noncolloidal solids with particle sizes ranging from 1 to 5,000 micron. Streams with particles that are larger than 5 mm usually require pretreatment with an upstream grit removal unit or grinder.

Total solids capture generally exceeds 85%. Depending on the sludge, the centrifuge type, and the chemical conditioning used, a wet cake in excess of 30% solids may be produced.

Centrifugal separation can be used for source reduction, water treatment, and water recycle and reuse. A common water-treatment application is the thickening of biological treatment sludge and dewatering of thickened biological and chemical treatment sludges. Other applications include the separation
of oil and water mixtures, and dewatering of fibrous solids, such as paper pulp, chemical fibers, and food processing wastes.

The costs for centrifugal separation range from $60 to more than $2,000 per million gallons of water treated.

Chemical oxidation

Chemical oxidation (1, 2, 3, 4, 12, 13) is the partial or complete conversion of organic compounds into carbon dioxide and water. In the case of partial conversion, the original organic compounds may be partially oxidized to substances that are more biodegradable than the parent compounds, such as alcohols, aldehydes, ketones, and carboxylic acids.

Common oxidants include ozone, chlorine, chlorine dioxide, peroxide, air, supercritical water, and potassium permanganate. Advanced oxidation processes generate OH− radicals that oxidize the contaminants.

Some chemical oxidation methods require careful control of pH, and high-strength (generally much greater than 1,000 mg/L) COD-bearing wastewaters require pretreatment to reduce the amount of oxidizing chemical required. In addition, advanced oxidation using ultraviolet light is prone to scaling and fouling; so, the UV lamps will need periodic wiping or cleaning. The presence of either iron or alkalinity in the influent promotes scaling. Some oxidation methods may leave residual oxidant in solution. Frequently, excess oxidant is required to drive the reaction.

Chemical oxidation is effective for treating inorganics (NH₃, CN, sulfides, and mercaptans), organics (phenols and hydrocarbons), and biological contaminants (pathogens, bacteria, and viruses). Concentrations of organics can be reduced by more than 80% using chemical oxidation.

Chemical oxidation can be used for water treatment and water recycle and reuse, and sometimes for source reduction. Applications include the disinfection of domestic and industrial wastewater (commonly via chlorination or ozonation), removal of phenol and COD from refinery wastewaters, and removal of chlorinated alkanes, pentachlorophenol (PCP), nitrogen-containing organics, ethers, cyanides, acetone, methyl ethyl ketone (MEK), COD, TOC, and adsorbable organic halogens (AOX) from process wastewater streams.

Chemical oxidation costs from $200 to $10,000 per million gallons of water treated.

Crystallization

Crystallization (2, 10) is a process that consists of evaporating a quantity of the liquid phase or lowering the temperature of the liquid phase to increase the solids concentration of the remaining brine to the point where salts contained in the wastewater crystallize out. Crystalizers produce a moist solids stream (instead of a concentrated brine, as in evaporation) and a high-quality distillate. Several crystallizer configurations are available, including fluidized-suspension, forced-circulation, draft-tube baffle, and surface-cooled crystallizers.

Crystallization is effective for waters containing dissolved organics (except VOCs) and inorganic salts. It is very effective for use with high-TDS waters and wastewaters. The influent TDS concentration should be as high as possible (1–10% TDS) to minimize energy requirements. Certain decomposable or volatile constituents in the influent, such as ammonia, bicarbonate, and sulfate, may break down or evaporate, affecting distillate quality and suitability of the water for reuse and producing scale that can reduce the process effectiveness. Sometimes, pH control can be used to suppress volatilization.

Crystallization can produce distillate whose quality is near that of distilled water. Impurities in the distillate tend to consist of volatile reactive gases (CO₂, NH₃, SO₂, HCN, and H₂S). Distillate solids are typically less than 100 mg/L. Depending on the crystallized solid impurity, the effluent may be a reusable product.

Crystallization is used for source reduction and water recycle and reuse. It is commonly used for treatment of cooling tower blowdown, water reclamation from liquid hazardous waste, treatment of wastewater from coal-fired or gas-fired utility boilers, and treatment of pulp-and-paper bleach-plant and deinking effluent.

Crystallization costs are typically more than $5,000 per million gallons of water treated.

![Figure 1. An electrodialysis stack consists of alternating anion- and cation-exchange membranes.](image-url)
Electrodialysis

Electrodialysis (ED) (2, 3, 5, 10, 14) is a method for concentrating water containing 1,000 to 10,000 ppm dissolved solids using electrically driven ion-selective semipermeable membranes. Ions in solution move through the membranes into concentrate cells within the membranes. Concentrated and dilute solutions are collected via separate manifolds.

An electrodialysis stack consists of anion and cation exchange membranes assembled in alternating order and separated by spacers through which the solution flows (Figure 1). Electricity is applied as a direct current from the anode through the stack to the cathode. Cations in solution flow toward the cathode and anions flow toward the anode. When the solution is in contact with a membrane, the membrane properties determine whether the ion is rejected or passed through (cations pass through the cationic membrane but not through the anionic membrane). There are alternating cells of concentrated and dilute solutions that are formed between the cation and anion membranes. Most packaged ED units have between 10 and 100 cells. ED systems are not suitable for once-through treatment, and typically will require a recovery tank for capture of the solution for recycle through the ED system.

Electrodialysis reversal (EDR) was developed to eliminate the common problem of fouling or scaling of the membranes and other surfaces. EDR involves reversing the polarity of the electrodes on a frequent basis (three or four times per hour) and exchanging fresh water and the concentrate wastewater within the membrane stack to remove fouling and scaling.

To be a candidate for use of ED, solutions should have TDS concentrations greater than 1,000 mg/L. The presence of colloidal and suspended solids can reduce treatment efficiency and cause maintenance problems, making pretreatment, such as by filtration, necessary in these cases. ED systems require turbulent flow for operation.

The advantages of ED are its relatively low energy consumption, and its ability to produce a highly concentrated stream for recovery (if that is the application). The disadvantage is that, like most membrane processes, periodic maintenance requirements must be adhered to for proper operation. Electrodialysis can be used for source reduction, water treatment, and water recycle and reuse. It is effective for treating water with dissolved inorganics (ionic species and metals).

ED has been extensively used for desalination and water treatment, and as a purification process for industrial process streams or baths. Other applications include the recovery of metals from electroplating baths, concentration of reverse osmosis brine, treatment of water for steam generation, cooling-tower blowdown treatment, purification and recovery of spent alkaline process streams, desalting and deacidification of food materials, and phosphoric acid recovery.

The cost for electrodialysis ranges from $50 to more than $1,000 per million gallons treated.

Evaporation

Evaporation (2, 5) reduces the volume of a liquid waste stream, thereby lowering its final disposal cost. There are two primary types of evaporators: mechanical evaporators and evaporation ponds. Mechanical evaporators are operated by either steam or electric power (or both) and recover water for potential reuse. Evaporation ponds do not require a power source, but they do not provide the opportunity for water recovery. Figure 2 is a schematic of a typical mechanical evaporation process.

Evaporation is well-suited for waters containing primarily inorganic salts and heavy metals, and it can be used with special care for wastes containing significant concentrations of organic contaminants, except VOCs. It is effective on waste streams with any concentration of dissolved solids. The brine is usually very high in suspended (1 to 10%) and dissolved (5 to 20%) solids. Vacuum evaporation can produce an effluent with a dissolved solids concentration that is typically less than 200 mg/L. The presence of suspended solids and carbonate in the feed can reduce treatment efficiency and cause maintenance problems, which can be minimized through pretreatment (e.g., filtration).

The advantage of atmospheric evaporation is that it is a simple, reliable, and robust technology. Evaporation is highly effective for concen-
Figure 3. Dissolved air flotation and induced air flotation are useful for removing suspended solids.

Costs for evaporation range from approximately $20 (ponds) to more than $10,000 (thermomechanical evaporation) per million gallons treated. The energy requirements for mechanical evaporation are 0.1 to 0.4 kWh/gal, depending on system type.

Filtration

Filtration (1, 2, 3, 4, 5, 10) reduces suspended solids and/or oil and grease to relatively low levels. It is either used as a pretreatment for another process or as a final effluent-polishing step prior to discharge or reuse. Several different types of filters are available, including granular-media, cartridge, membrane, and diatomaceous-earth precoat filters.

Filtration is effective for removing suspended inorganic, organic, or biological solids. It is most effective for the removal of particles larger than approximately 1 micron in diameter. When streams contain suspended solids concentrations greater than 100 mg/L or oil and grease concentrations above 25 mg/L, pretreatment is usually required.

Suspended solids concentrations can be reduced by 90–99%, and oil and grease can be removed to less than 5 mg/L.

This technology can be simple to operate. Its main disadvantages are that backwash from some filtration processes (particularly granular media) can be very high in suspended solids and often require separate treatment, and that cartridge filters produce spent cartridges that require disposal or incineration.

Filtration can be used for source reduction, water treatment, and water recycle and reuse. It has been extensively used for cooling tower and boiler blowdown. Other specific applications include the reduction of alkali, fertilizer, petroleum, pharmaceutical, and food processing wastes, reduction of membrane treatment concentrates, ion-exchange regeneration and demineralizer waste reduction, recovery and reuse of plating solutions and rinsewaters, and reduction and recovery of oily compressor water and other wastewaters.
Flotation

Flotation (1, 2, 3, 5, 15) is a process in which small gas bubbles are entrained in the water stream by mechanical or diffused aeration, or by suddenly reducing the pressure of a supersaturated portion of the water stream, causing the excess gas to come out of solution as bubbles. Bubbles rising through the water adhere to suspended particles or oil globules, decreasing the specific gravity of the particle/bubble combination to less than that of water. As a result, the particles rise to a surface “froth,” and from there they are skimmed off. Dissolved air flotation (DAF) and induced air flotation (IAF) are the two principal types of flotation employed for wastewater treatment (Figure 3).

Flotation is effective for the removal of suspended inorganic, organic, or biological solids. Some influent wastestreams may require pretreatment, for example, by chemical addition or pH adjustment to break chemical and mechanical emulsions, or by gravity separation to remove high slugs of solids and oils.

Suspended solids concentrations can be reduced by more than 75%, and oil and grease can be reduced by more than 90% (with chemical addition).

Skimmed solids require additional management in the form of dewatering and disposal. Sometimes, the skimmed oil can be used as fuel. The effluent water that is produced is usually not suitable for reuse without additional polishing.

Flotation can be used for water treatment and for water recycle and reuse. It is commonly used in the pulp and paper industry for whitewater recycle and in petroleum refineries for oil and grease removal.

Flotation costs range from approximately $20 to more than $100 per million gallons treated. Bench- or pilot-scale treatment testing is often necessary to determine optimal treatment conditions and chemical addition rates.

Gravity separation

Gravity separation (1, 2, 3, 4, 5) removes oil and solids from wastewater based on the different densities of immiscible oil, water, and solids. The wastewater stream is fed into a vessel sized to provide a quiescent zone of sufficient retention time to allow the various phases to separate. Gravity separation works best when the densities of the different phases are very different from that of water.

Gravity separation can reduce oil concentrations by 60–99%. Suspended solids concentrations can be reduced by 10–50% for primary treatment, and more than 70% when used as a unit process for coagulation and flocculation. Sometimes chemical addition or pH adjustment is employed to aid separation and settling, or to break oil emulsions.

The settled solids that are produced are typically 1–2% solids by weight. These settled solids may be considered a listed hazardous waste for some industries.

Oils will most often float to the top of a gravity separator and are skimmed for removal. The oil skimmings may have sufficient heat of combustion content for economical reuse as fuel.

Gravity separation is suitable for influent streams of very poor quality (suspended solids and heavy metals). It can be applied to removal of organics, heavy metals, and other suspended solids such as grit and silt.

Gravity separation is used for source reduction, water treatment, and water recycle and reuse. It is commonly used for the recycling of whitewater in the pulp and paper industry, as a component of chemical coagulation/flocculation facilities used for sludge removal, to remove floating oil from wastewater, process water, and stormwater, and in commercial Lurgi gasification facilities for the removal of tars and oils from process condensate.

Gravity separation can cost from approximately $50 to $500 per million gallons of water treated.

Ion exchange

Ion exchange (1, 2, 3, 8, 10) is the reversible exchange of ions between an insoluble solid salt (an ion-exchange resin) and a liquid in contact with that solid. It is generally used as a polishing step to remove low-concentration constituents from a wastewater stream. The ion exchange resin is a natural or synthetic organic material with active exchange sites on its surface, usually in the form of beads or particles.

Ion exchange is effective for the treatment of dissolved ionic inorganic species and organics in the form of TOC and COD. The upper concentration limit for exchangeable ions is approximately 2,500 mg/L. Ion exchange is very good for separating low concentrations of ionic contaminants from dilute wastewater, such as purifying rinsewaters from electroplating, where concentrations of ionic species are on the order of 1 to several hundred ppm. Pretreatment is required to remove any suspended solids or oil and grease that are present, since these substances can reduce treatment efficiency and cause maintenance problems such as clogging of the resin. In some applications, the pH of the inlet water has to be adjusted.

Concentrations of most inorganic constituents are typically reduced by more than 90%, and organic constituents can be reduced by 20–80%. High concentrations or slug loads of target contaminants can significantly decrease removal efficiency.

The advantages of ion exchange are its relatively low energy consumption and its ability to produce a highly concentrated stream through regeneration for recovery if that is the application. The disadvantage is that large volumes of wastewater are produced during resin regeneration.

Ion exchange can be used for source reduction, water treatment, and water recycle and reuse. Common applications include the demineralization of boiler feedwater, and treatment of industrial wastewa-
ter to remove heavy metals, nitrate, sulfate, and chloride.

Technology costs range from $250 to more than $1,000 per million gallons treated.

**Membrane technologies**

Membrane processes (2, 3, 4, 5, 7, 10, 16, 17) employ a semipermeable (selective) membrane and a driving force (pressure, concentration, etc.) across the membrane to separate target constituents from a feed liquid. Water passes through the membrane, forming a treated water stream (permeate) and leaving behind the other constituents in a concentrate.

Different types of membrane processes can remove dissolved and colloidal constituents in the size range of 0.0001 to 1 micron. The commercially available membrane processes include microfiltration, ultrafiltration, reverse osmosis, membrane electrolysis, and diffusion dialysis. The technologies operate differently, and each is best suited for specific applications. They all are useful for separation of molecular mixtures.

**Microfiltration and ultrafiltration.** Microfiltration and ultrafiltration are variations of cross-flow microfiltration (CMF). In CMF, the fluid to be filtered flows parallel to the filtration surface — that is, cross-flow with respect to the flow of the filtrate. The cross-flow generates shearing forces and turbulence across the filter medium and limits the thickness of the particle deposits on the filtration surface. Because of the nature of flows within a tubular surface, a gradient in the particle concentration perpendicular to the surface is established.

Microfiltration removes constituents between approximately 0.05 and 2 micron, while ultrafiltration removes constituents between approximately 0.005 micron (molecular weight of 500) and 0.1 micron.

**Reverse osmosis.** Reverse osmosis is a pressure-driven membrane process used to separate water from all other substances — particles, macromolecules, and low-molecular-weight compounds — of a solution in order to concentrate the solution or to generate clean water for process reuse (or both). This is accomplished by applying a hydrostatic pressure greater than the osmotic pressure of the feed solution. The osmotic pressure of a solution varies directly with the concentration of the solution.

Reverse osmosis generally removes constituents with molecular weights above 200.

In typical applications, feed solutions have a significant osmotic pressure, which must be overcome by the hydrostatic pressure applied as the driving force. The applied pressure is generally between 140 and 700 psi, and in some cases may be as high as 1,000–2,000 psi (1). This pressure requirement limits the practical application of this technology.

**Membrane electrolysis.** Membrane electrolysis (Figure 4) is driven by an electrical potential that is applied across a membrane. The membranes are ion-permeable and
selective, permitting ions of a given electrical charge to pass through.

Depending on the chemistry and the specific application, membrane electrolysis systems are designed either with cation- or anion-exchange membranes. Cation-exchange membranes allow only cations, such as copper or aluminum, to pass through, while anion-exchange membranes allow only anions, such as sulfates or chlorides, to pass through.

**Diffusion dialysis.** Diffusion dialysis (Figure 5) is a membrane-based ion-exchange technology that is used mostly for the purification of metal-contaminated acids. The metals are separated from the acid via an acid concentration gradient. The concentration gradient that exists between the two liquids is the driving force for the diffusion reaction, which is known as Donnan diffusion. The specific anion-exchange membrane allows the diffusion of highly dissociated acids (anions) through the polymer structure while cations (metals) are rejected because of their positive electrical charge.

In any membrane process, the presence of suspended solids can cause maintenance problems; so, filtration may be necessary. A scale inhibitor and pH adjustment are sometimes required.

Depending on the characteristics of the dissolved substances and the practical operation of the equipment, the contaminants are rejected differently. The rate at which each is rejected is known as the membrane rejection rate. The fraction of nonrejected substances is called leakage, and its rate depends on the size of the molecules, the radius of the ion, the electrical load of the ions, and the interacting forces between the ions and the solvent.

Membrane processes can be used for source reduction, water treatment, and water recycle and reuse.

Membrane electrolysis is used mainly in surface finishing operations for the regeneration of etching and stripping solutions (2, 3), purification and regeneration of chromium plating baths, the recycle and maintenance of chrome conversion coating solutions (4, 5), and reactivation and removal of metals from deoxidizing solutions.

Applications for reverse osmosis include purification of water for use as make-up water, desalination of sea water and brackish water, concentration of milk in the dairy industry, and the dehydration of liquid food (4).

Microfiltration is used to treat reactor washdown water, phosphate rinse discharge, and soluble oily wastewater, and to concentrate dilute oils (such as fuel-cutting oils and die lube oils) for reuse.

The costs for membrane technologies range from $30 to more than $2,000 per million gallons treated.

**Precipitation**

Chemical precipitation (1, 2, 4, 5, 7, 8, 10) is a process by which the chemical equilibrium of a solution is altered to reduce the solubility of the constituents of concern. The dissolved compounds are converted to insoluble precipitates, which are taken out of solution by solids removal processes. Chemical precipitation reactions are usually induced by: adding substances that react directly with the dissolved compound(s) in solution to form a less soluble compound; adding substances that shift the solubility equilibrium to a point at which an insoluble precipitate of the compound is formed; or changing the temperature of the solution in the direction of decreased compound solubility.

Precipitation is effective for treating water containing dissolved and suspended inorganics (ionic species and metals) and organics. It can handle a wide variety of influent stream conditions and contaminant concentrations. The presence of surfactants, oils, or greases can interfere with treatment by causing precipitates to adhere to surfaces or even become buoyant. Chelated metals will require a chemical pretreatment step to break the chelated bond that would hold the contaminant in solution. Many wastewaters have complex process chemistries, and there is potential for competing precipitation reactions; this can be evaluated by using ion ratios to predict the order of precipitation (18).

Some contaminants can be removed down to the parts per billion range. Removal is a function of solubility of the salt that is formed as a result of the reaction. Treatability testing is often necessary to confirm and optimize process selection, and to determine chemical usage requirements.

A solids removal step such as filtration is usually necessary following precipitation. Sludges produced from precipitation will require further management (dewatering and disposal). Some sludges may be a characteristic or listed hazardous waste.

Precipitation can be used for water treatment and for water recycle and reuse. Specific applications include scrubber effluent treatment and reuse, treatment of industrial wastewater for softening and removal of heavy metals, arsenic and phosphate, removal of contaminants from electroless nickel plating baths, and precipitation of chloride from chromium plating baths.

The costs for precipitation range from $50 to more than $2,000 per million gallons treated.

**Solidification and stabilization**

Solidification/stabilization (2, 5, 19, 20) is generally used to treat the byproducts of other water reclamation technologies that cannot be managed by other practices. A solidification agent, such as portland cement, is combined with soluble silicates and the concentrated waste (i.e., brine, crystallization solids, or sludge) to form a fast-setting, relatively nonleaching, inert solid.

The process is amenable to a wide variety of wastes, and the leachability of contaminants from
the solid can be controlled through the selection of the solidification agents and the use of additives. The solid produced is usually suitable for landfilling in a commercial, industrial, or hazardous waste landfill.

Solidification/stabilization is a very robust technology that can be applied to wastes with a wide range of characteristics. The disadvantage is the generation of large volumes of waste that require disposal.

Solidification/stabilization can be used for wastewater treatment. It is effective for treating water with dissolved inorganics (most heavy metals) and organics. It has been extensively used for solidification of crystallizer sludges and highly toxic organic or heavy metal concentrates.

Costs for solidification/stabilization range from $10 to $1,000 per ton of waste. The costs are driven by the required degree of contaminant fixation in the solid and the types of additives required.

**Solvent extraction**

Solvent extraction (2, 10, 11, 21, 22, 23, 24) is an indirect separation technique in which two immiscible liquid phases are contacted and the impurities from one phase are transferred to the other phase. Feed is usually contacted countercurrently with an immiscible solvent. The extract produced contains the solvent and the constituents that were extracted from the feed solution. The raffinate (feed water and some solvent) can then be passed to a distillation column where the solvent is recovered. A typical solvent extraction system is illustrated in Figure 6.

Solvent extraction is effective for treating water with dissolved inorganics (actinide chemicals and metals) and dissolved organics (but not VOCs or azeotropes).

In order to be an economically viable candidate for solvent extraction, a solution should contain at least 2,000 mg/L of extractable organics and have a flow rate of at least 50 gal/min. The presence of suspended
WATER REUSE

solids can cause maintenance problems; pretreatment, such as filtration, will be necessary. Emission controls may be necessary if VOCs are present.

Concentrations of extractable organics can be reduced by more than 60%, some up to 99%. Both the purified extract and the purified raffinate may be viable for reuse.

Solvent extraction can be used for source reduction, water treatment, and water recycle and reuse. It has been extensively used for product recovery or refining in chemical process plants. Other specific applications include the removal of phenols from coking and gasification plant aqueous streams, and recovery of acetic acid in pulping and cellulose plants.

Costs typically range from $1,000 to $10,000 per million gallons of treated water. However, these costs may be offset if the extract has a recovery value.

Stripping

Stripping (2, 3, 5, 11, 25) is a mass-transfer process in which air or steam is passed, generally countercurrently, through a waste stream. It typically takes place in a tower filled with a packing medium that provides high surface area for contact between the air or steam and water and a low resistance to flow (pressure drop). Figure 7 depicts an air stripping process.

The efficiency of the stripping process is based primarily on the equilibrium ratio (or Henry's constant) for a particular contaminant, the ratio of air or steam to water, and the characteristics and height of the packing medium. The elevated temperatures associated with steam stripping make it more effective than air stripping.

The presence of suspended solids can reduce treatment efficiency and cause maintenance problems; pretreatment, such as filtration, is necessary to remove these solids. The presence of VOCs and/or acid gases will often require the addition of air-pollution control equipment.

Stripping efficiency is a function of flow rate, temperature of the influent feedwater, temperature of the influent gas, and gas-to-water flow ratio. Often, heating the influent water stream or the stripping gas will increase removal efficiencies.

Stripping is effective for dissolved inorganics (hydrogen sulfide, ammonia, carbon dioxide, and hydrogen cyanide) and dissolved organics (VOCs and light hydrocarbons). Concentrations of volatile compounds and ammonia may be reduced by more than 95%. Nonvolatile organics will pass unaffected through the process.

Stripping can be used for source reduction and water treatment. Applications include removal of VOCs from wastewater, removal of ammonia from biological treatment plant effluent, and treatment of sour petroleum wastewaters.

Costs range from $40 to $250 per million gallons treated.

Thermal treatment

Incineration (2, 5, 26) is a thermal combustion process with controlled fuel and air flows. The fuel is predominately waste material supplemented with natural gas or fuel oil.

The basic process chemistry of incineration consists of oxidation (partial or complete) of the organic constituents in the waste material to form carbon dioxide, water vapor, elemental oxides, and hydrogen halides, and partial oxidation of byproducts. The different types of incinerators used for waste treatment include multiple hearth furnaces, liquid-injection incinerators, rotary kilns, and fluidized-bed systems.

Thermal treatment is effective for organics and biological contamination. The types of waste that can be incinerated include concentrated wastewater, liquid waste, solid waste, gases, and sludge.

Concentrations of most organics are typically reduced by more than 99%, and destruction and removal efficiencies of more than 99.99% are achievable.

The particle size of any solids in the waste will dictate pretreatment requirements and incinerator selection. The presence of halogens, sulfur, phosphorous, and some metals will often predicate the addition of air-pollution control.

Combustion gases may contain particulates, heavy metals, acid gases, carbon monoxide, nitrogen oxides, and nonmethane hydrocarbons, and may generate an aqueous scrubber blowdown that is high in heavy metals and TDS. In addition, the ash produced may have high concentrations of heavy metals, which necessitate special disposal requirements.

Thermal treatment can be used for wastewater treatment. Applications include wastewater sludge combustion, and destruction of liquid hazardous and biological waste.

Costs are more than $1 per gallon treated.

Economics

When considering the use of any of these technologies, one needs to evaluate it both technically and economically. The implementation of water reuse is primarily driven by economics. More often, though, industry evaluates a number of factors to determine the feasibility of reuse, including:

- cost of treated raw water;
- cost of wastewater treatment;
- cost of compliance and environmental liability;
- capital costs of water reuse technology; and
- operating costs of water reuse technology.

In addition, the implementation of certain technologies will result in steadier-state operation of processes, increased productivity by minimizing rework, and, sometimes, less process downtime.

The costs presented for each technology are life-cycle costs (in dol-
lars per quantity of water processed). These costs include installed capital costs, chemicals, and power costs. They do not include a cost comparison with traditional treat-and-discharge. We recommend that a facility conduct an economic evaluation of all reuse opportunities by calculating a return on investment (ROI) or by using some other comparative economic tool.

G. A. ZIMNUS is a chemical engineer and project manager with CH2M HILL, Corvallis, OR (541/752-4271; Fax: 541/752-0276; E-mail: gzimnus@ch2m.com). He has 12 years of experience as a chemical engineer and manager for a number of industrial clients in identifying, designing, and implementing pollution prevention projects. He is currently managing the development of the CH2M HILL Engineered Systems group that provides advanced separations technologies for water and chemical recovery, purification, and reuse. He holds a BS in chemical engineering from Northeastern Univ. He is a member of the American Electroplaters and Surface Finishers Society.

W. D. BYERS is vice president, energy, environment, and systems with CH2M HILL, Corvallis, OR (541/752-4271; Fax: 541/752-0276; E-mail: byersw@ch2m.com). In his 17 years with CH2M HILL, he has designed a wide variety of systems for water reuse and chemical recovery for the CPI. He earned a BS in chemical engineering from Oregon State Univ. and an MBA from the Univ. of Oregon. He is currently a Director of AICHE, a Diplomate of the American Academy of Environmental Engineers, and a professional engineer licensed in both chemical engineering and environmental engineering in the state of Oregon. He also serves on the Advisory Board for Oregon State University's Chemical Engineering Dept.

W. W. DOERR, PhD, is a research specialist with Factory Mutual Research Corp., Norwood, MA (781/762-4300). He has over 20 years of experience with industry, federal facilities, and academia. His areas of expertise include pollution prevention, process chemical safety (OSHA PSM and EPA RMP), source-term evaluations, and process engineering. He has authored over 20 papers and presentations in pollution prevention, process safety, and process systems. He has been a Visiting Assistant Professor at the Massachusetts Institute of Technology (MIT) and is on the Editorial Advisory Board for Chemical Engineering Progress. He has a PhD and SM from MIT and a BSCH and BA from Tufts Univ. He is an active member of AICHE.

Literature Cited


Further Reading


Introducing a breakthrough in on-line analysis of hardness, alkalinity, nitrate and ammonia.

Maximum performance.

Minimum maintenance.

The new APA 6000.

Our new APA 6000 Analyzers just might be your best party excuse to come around in years. With models for hardness, alkalinity, nitrate and ammonia, these next-generation analyzers have been designed from the ground up to reduce the effort and cost of process monitoring and control. They're accurate and reliable—self-cleaning, self-priming, and self-calibrating. They're compact and fast—reduced sample volume requires less reagent, less standard, and less analysis time. And they're versatile. You can sample up to three streams with one analyzer, and you can network multiple analyzers together. Add it all up and you've got the control solution you've been waiting for. Start the celebration by calling 800-227-4224 and requesting literature number 1504.