choice. The dual distribution system of the City of Altamonte Springs, Florida, operates with constant-speed supply pumps and two elevated storage tanks, and pressures range between 55 and 60 psi (380 kPa and 410 kPa). The urban system of the Marin Municipal Water District, in California, operates at a system pressure of 50 to 130 psi (350 kPa and 900 kPa), depending upon elevation and distance from the point of supply, while Apopka, Florida, operates its reuse system at a pressure of 60 psi (410 kPa).

The system should be designed with the flexibility to institute some form of usage control when necessary and provide for the potential resulting increase in the peak hourly demand. One such form of usage control would be to vary the days per week that schools, parks, golf courses and residential areas are irrigated. In addition, large users, such as golf courses, will have a major impact on the shape of the reclaimed water daily demand curve and hence on the peak hourly demand, depending upon how the water is delivered to them. The reclaimed water daily demand curve may be "flattened" and the peak hourly demand reduced if the reclaimed water is discharged to golf course ponds over a 24-hour period or during the daytime hours when demand for residential landscape irrigation is low. These methods of operation can reduce peak demands, thereby reducing storage requirements.

3.3 Industrial Reuse

Industrial reuse represents a significant potential market for reclaimed water in the U.S. and other developed countries. Although industrial uses accounted for only about 8 percent of the total U.S. water demands in 1985, in some states, industrial demands accounted for as much as 43 percent of a state's total water demands. Reclaimed water is ideal for many industries where processes do not require water of potable quality. Also, industries are often located near populated areas where centralized wastewater treatment facilities already generate an available source of reclaimed water.

Reclaimed water for industrial reuse may be derived from in-plant recycling of industrial wastewaters and/or municipal water reclamation facilities.

Recycling within an industrial plant is usually an integral part of the industrial process and must be developed on a case-by-case basis. Industries, such as steel mills, breweries, electronics, and many others, treat and recycle their own wastewater either to conserve water or to meet or avoid stringent regulatory standards for effluent discharges. This document does not discuss in-plant recycling; however, ample information and guidelines are available from industrial associations and regulatory authorities.

Industrial uses for reclaimed water include:

- Evaporative cooling water,
- Boiler-feed water
- Process water, and
- Irrigation and maintenance of plant grounds.

Of these uses, cooling water is currently the predominant industrial reuse application. In most industries, cooling creates the single largest demand for water within a plant. According to Keen and Puckorius (1988), a small petroleum refinery (40,000 barrels/d) or a 250-MW utility power plant will need about 1 to 2 mgd (44-88 L/s) of makeup water for a recirculating cooling system. Worldwide, the majority of industrial plants using reclaimed water for cooling are utility power stations.

3.3.1 Cooling Water

3.3.1.1 Once-Through Cooling Systems

Once-through cooling systems use water to cool the process equipment and then discharge the heated water after a single use. Because once-through cooling systems use such large volumes of water, reclaimed water is rarely considered a feasible source. For instance, flow for a once-through cooling system at a typical 1,000-MW fossil fuel power plant would be approximately 650 mgd (28,500 L/s), as compared to recirculating systems, such as wet towers and cooling ponds that would use approximately 9 and 6.5 mgd (395 and 285 L/s), respectively (Breitstein and Tucker, 1986).

In the largest single industrial reuse project in the U.S., the Bethlehem Steel Company in Baltimore, Maryland, uses approximately 100 mgd (4,380 L/s) of treated wastewater effluent from Baltimore's Back River WWTF for processing and cooling in a once-through system (Water Pollution Control Federation, 1989). Generally, however, once-through cooling systems require too large a volume of water to rely on public water supplies. Because water quality requirements for these cooling systems are generally not restrictive, large lakes, rivers, and even saltwater can be used, in some cases with little, if any, treatment.

3.3.1.2 Recirculating Cooling Systems

Recirculating cooling systems use water to absorb process heat, then transfer the heat from the water by evaporation, and recirculate the water for additional cooling cycles. This recirculating cooling process may employ cooling towers or cooling ponds.

Manual, Guidelines for Water Re-use, US EPA EPA/625/R-92/004 September 1992

a. Cooling Towers

Cooling towers are designed to take advantage of the water's high heat of evaporation, i.e., one volume of evaporated water will cause 100 volumes to drop in temperature by approximately 10°F. Dry air is brought through the sides or bottom of the tower while water is pumped to the top of the tower's packing material. The water is broken into droplets to increase air/water contact, and then brought into contact with the upcoming air, which causes a portion of the water to evaporate. The cooled water droplets collect at the bottom of the tower and then are recycled.

Evaporation and wind action at the top of the tower (drift) result in a water loss that must be replaced. To prevent an unacceptable build-up of salt contaminants due to evaporation, a portion of the recirculating water is also continuously wasted as "blowdown," and a source of make-up water is required. Makeup water must be of high quality since any contaminants in the water are concentrated many times during the cooling cycle (Asano and Mujeriego, 1988).

Cooling tower make-up water constitutes a large percentage of the total water used (from 25 to 50 percent) in such industries as electric power stations, chemical plants, metal factories, and oil refineries. The cooling tower recirculating water system is almost always a closed loop system that is operated as a separate process with its own characteristic water quality requirements. The water quality is determined by ascertaining the concentration of the potential precipitants within the make-up.

The cycles of concentration, which is defined as the ratio of a concentration of a given ion or compound in the blowdown cooling water to the concentration in the make-up water, is indicative of the number of times that the cooling water is recirculated. According to Keen and Puckorius (1988), most cooling systems are operated in the range of 5 to 10 cycles of concentration. Above this range, the small amount of water conserved is rarely justified by the increased risk of scaling and SS deposition.

Regulatory constraints on waste discharges often require treatment of the blowdown water. Treatment methods vary according to the specific discharge standards and may include temperature and pH adjustments and ion exchange for metals removal. The discharge limits and the costs of removing the contaminants can place limits on the cycles of concentration.

b. Cooling Ponds

Cooling ponds may also be used as closed recirculating cooling systems. The pond water serves as the source of cooling water, and surface evaporation from the pond is the mechanism for cooling the heat-exchanged water. The critical parameter in pond design is the surface area required for cooling the heated water. The approximation used for power plant cooling ponds is 1 to 3 ac (2.5-7.5 ha)/MW of generated electricity (Gehm, 1976). Cooling ponds are attractive because of their low capital costs, large storage capacity, and ability to function without makeup water for extended periods. However, their drawbacks include potential groundwater contamination, large land requirements, and maintenance problems involving algae and weeds.

The City of Fort Collins, Colorado, supplies reclaimed water to the Platte River Power Authority for cooling the 250-MW Rawhide energy station (Fooks *et al.*, 1987). The recirculating cooling system includes a 5.2-billion gal (20 million m^3) cooling pond to supply 170,000 gpm (10,700 L/s) to the condenser and auxiliary heat exchangers. The water reclamation facility provides complete-mix activated sludge treatment with provisions for polymer addition, followed by final clarification, chlorination, and dechlorination with sulfur dioxide. Additional treatment for phosphorus removal is provided at the energy station to deliver a maximum phosphorus concentration of 0.2 mg/L. After about 2 years of operation, the cooling lake deteriorated in aesthetic appearance and chemical quality, and a limnological management program was instituted to provide aeration and minnow control in the cooling lake.

3.3.1.3 Cooling Water Quality Requirements

The most frequent water quality problems in cooling water systems are scaling, corrosion, biological growth, fouling, and foaming. These problems arise from contaminants in potable water as well as reclaimed water, but the concentrations of some contaminants in reclaimed water may be higher. Table 13 lists water quality criteria for cooling water supplies.

In Burbank, California, about 5 mgd (219 L/s) of municipal secondary effluent has been successfully utilized for cooling water make-up in the city's power generating plant since 1967. The effluent is of such good quality that treatment consisting of additional chlorine, acid, and corrosion inhibitors makes the reclaimed water nearly equal in quality to fresh water.

The City of Las Vegas and Clark County Sanitation District used 90 mgd (3,940 L/s) of secondary effluent to supply 35 percent of the water demand in power generating stations operated by the Nevada Power

Table 13. **Recommended Cooling Water Quality Criteria for Make-Up Water to Recirculating Systems**

Parameter[a]	Recommended Limit[b]
Cl	500
TDS	500
Hardness	650
Alkalinity	350
pH[c]	6.9-9.0
COD	75
TSS	100
Turbidity[c]	50
BOD[c]	25
Organics[d]	1.0
NH4 - N[c]	1.0
PO_4[c]	4
SiO_2	50
Al	0.1
Fe	0.5
Mn	0.5
Ca	50
Mg	0.5
HCO3	24
SO4	200

[a]All values in mg/L except pH.
[b]Water Pollution Control Federation, 1989.
[c] From Goldstein *et al.*, 1979.
[d]Methylene blue active substances.

Company. The power company provides additional treatment consisting of two-stage lime softening, filtration, and chlorination prior to use as cooling tower make-up. A reclaimed water reservoir provides backup for the water supply.

In Odessa, Texas, three industries have used approximately 2.5 mgd (110 L/s) of municipal effluent for cooling tower make-up and boiler feed for over 20 years. Secondary effluent is treated by cold lime softening followed by filtration prior to use by the industries. This water is used directly for cooling tower make-up; water use for boiler feed is treated by two-bed demineralization before use (Water Pollution Control Federation, 1989).

a. Scaling
The cooling water must not lead to the formation of scale, i.e. hard deposits. Such deposits reduce the efficiency of the heat exchange. The principal causes of scaling are calcium (as carbonate, sulfate, and phosphate) and magnesium (as carbonate and phosphate) deposits.

Scale control for reclaimed water is achieved through chemical means and sedimentation. Acidification or addition of scale inhibitors can control scaling. Acids (sulfuric, hydrochloric, and citric acids and acid gases such as carbon dioxide and sulfur dioxide) and other chemicals (chelants such as EDTA and polymeric inorganic phosphates) are often added to increase the water solubility of scale-forming constituents, such as calcium and magnesium (Strauss and Puckorius, 1984).

Lime softening, commonly used to treat reclaimed water for cooling systems, significantly increases the cycles of concentration. The lime removes carbonate hardness and the soda ash removes the noncarbonate hardness. Other methods used to control scaling are alum treatment and sodium ion exchange, but the higher costs of these processes limit their use.

b. Corrosion
The recirculated water must not be corrosive to metal in the cooling system. High total dissolved solids (TDS) promotes corrosion by increasing the electrical conductivity of the water. The concentrations of TDS in municipally treated reclaimed water, generally two to five times higher than in potable water, can increase electrical conductivity and promote corrosion. Dissolved gases and certain metals with high oxidation states also promote corrosion.

Corrosion may also occur when acidic conditions develop in the cooling water. The Jones Station power plant in Lubbock, Texas, reported that the ammonia present in reclaimed water was converted to nitrates in the recirculating cooling water, resulting in a lowering of the pH from a range of 7.4 to 7.9 to a value of 6.5 or less. The pH was adjusted by adding carbon dioxide to increase the bicarbonate alkalinity of the cooling water (Treweek *et al.*, 1981).

Corrosion inhibitors such as chromates, polyphosphates, zinc, and polysilicates can also be used to reduce the corrosion potential of the cooling water. These substances may need to be removed from the blowdown prior to discharge. The alternative to chemical addition is ion exchange or reverse osmosis, but high costs limit their use (Strauss and Puckorius, 1984).

c. Biological Growth
Reclaimed water used in cooling systems must not supply nutrients or organics [biochemical oxygen demand (BOD)] that promote the growth of slime-forming organisms. The moist environment in the cooling tower is conducive to biological growth. Microorganisms can significantly reduce the heat transfer efficiency, reduce water flow, and in some cases generate corrosive by-products (Troscinski and Watson, 1970; California State Water Resources Control Board, 1980; Goldstein *et al.*, 1979).

The reduction of BOD and nutrients during treatment reduces the potential of the reclaimed water to sustain microorganisms. Chlorine is the most common biocide used to control biological growth because of its low cost, availability, and ease of operation. Chlorination is also used as a disinfectant to reduce potential pathogens in the reclaimed water. Frequent chlorination and shock treatment is generally adequate. Chlorine gas (purchased as liquid chlorine) is used most often, but it may also be applied as sodium hypochlorite as a liquid or solid. Chlorine dioxide is also frequently used.

At the City of Lakeland, Florida, which uses reclaimed water from a secondary treatment facility for power plant cooling, the system design of four to six cycles was reduced significantly due to biological growth and fouling of the cooling tower. Biological mass accumulated in the tower to such an extent that structural stability was threatened. The problem was solved by instituting a pretreatment program to reduce BOD, phosphorus, and SS (Libey and Webb, 1985).

On the other hand, the Orlando (Florida) Utilities Commission has reported no biological accumulation or fouling problems in the cooling system of the C.H. Stanton energy facility, which uses approximately 5 mgd (219 L/s) of highly treated reclaimed water (5 mg/L BOD, 5 mg/L TSS, 2 mg/L TN and 1 mg/L P) from an Orange County WWTF. Prior to use, the energy facility also provides pH adjustment, rechlorination, scale inhibitors, and anti-foaming agents.

In Hillsborough County, Florida, a municipal water reclamation facility provides reclaimed water for cooling a 1,200-ton/d, waste-to-energy facility and treats the blowdown water wasted from the cooling towers. The reclaimed water from the advanced treatment system meets the following water quality standards: BOD, 20 mg/L; TSS, 5 mg/L; total nitrogen, 20 mg/L; fecal coliform, $<1/100$ mL; and pH, 6 to 8.5. The reclaimed water is treated with additional chemicals at the waste-to-energy facility to prevent algae growth and biological buildup in the cooling system. Approximately 330,000 gpd (14 L/s) of used cooling water is discharged back to the wastewater treatment plant (Tortora and Hobel, 1990).

d. Fouling

Fouling is controlled by preventing the formation and settling of particulate matter. Chemical coagulation and filtration during the phosphorus removal treatment phase significantly reduce the contaminants that can lead to fouling. Chemical dispersants are also used as required.

3.3.2 Boiler-Feed Water

The use of reclaimed water differs little from the use of conventional public supplies for boiler-feed water; both require extensive additional treatment. Quality requirements for boiler-feed make-up water are dependent upon the pressure at which the boiler is operated as shown in Table 14. Generally the higher the pressure, the higher the quality of water required. Very high pressure boilers require makeup water of distilled quality.

In general, both potable water and reclaimed water used for boiler water makeup must be treated to reduce the hardness of the boiler-feed water to close to zero. Removal or control of insoluble salts of calcium and magnesium and control of silica and aluminum are required since these are the principal causes of scale build-up in boilers. Depending on the characteristics of the reclaimed water, lime treatment (including flocculation, sedimentation, and recarbonation) might be followed by multi-media filtration, carbon adsorption, and nitrogen removal. High purity boiler-feed water for high-pressure boilers might also require treatment by reverse osmosis or ion exchange. High alkalinity may contribute to foaming, resulting in deposits in superheater, reheater, and turbines. Bicarbonate alkalinity, under the influence of boiler heat, may lead to the release of carbon dioxide, which is a source of corrosion in steam-using equipment. The considerable treatment and the relatively small amounts of makeup required, make boiler-feed a poor candidate for reclaimed water.

3.3.3 Industrial Process Water

The suitability of reclaimed water for use in industrial processes depends upon the particular use. For example, the electronics industry requires water of almost distilled quality for washing circuit boards and other electronic components. On the other hand, the tanning industry can use relatively low-quality water. Requirements for textiles, pulp and paper, and metal fabricating are intermediate. Thus, in investigating the feasibility of industrial reuse with reclaimed water, the potential users must be contacted to determine specific requirements for process water. Table 15 presents industrial process water quality requirements for a variety of industries. Table 16 summarizes some of the water quality concerns for industrial water reuse and potential treatment processes.

3.3.3.1 Pulp and Paper

Reuse of reclaimed water in the paper and pulp industry is a function of cost and grade of paper. The higher the quality of paper, the more sensitive to water quality. Impurities found in water, particularly certain metal ions and color bodies, can cause the paper produced to change color with age.