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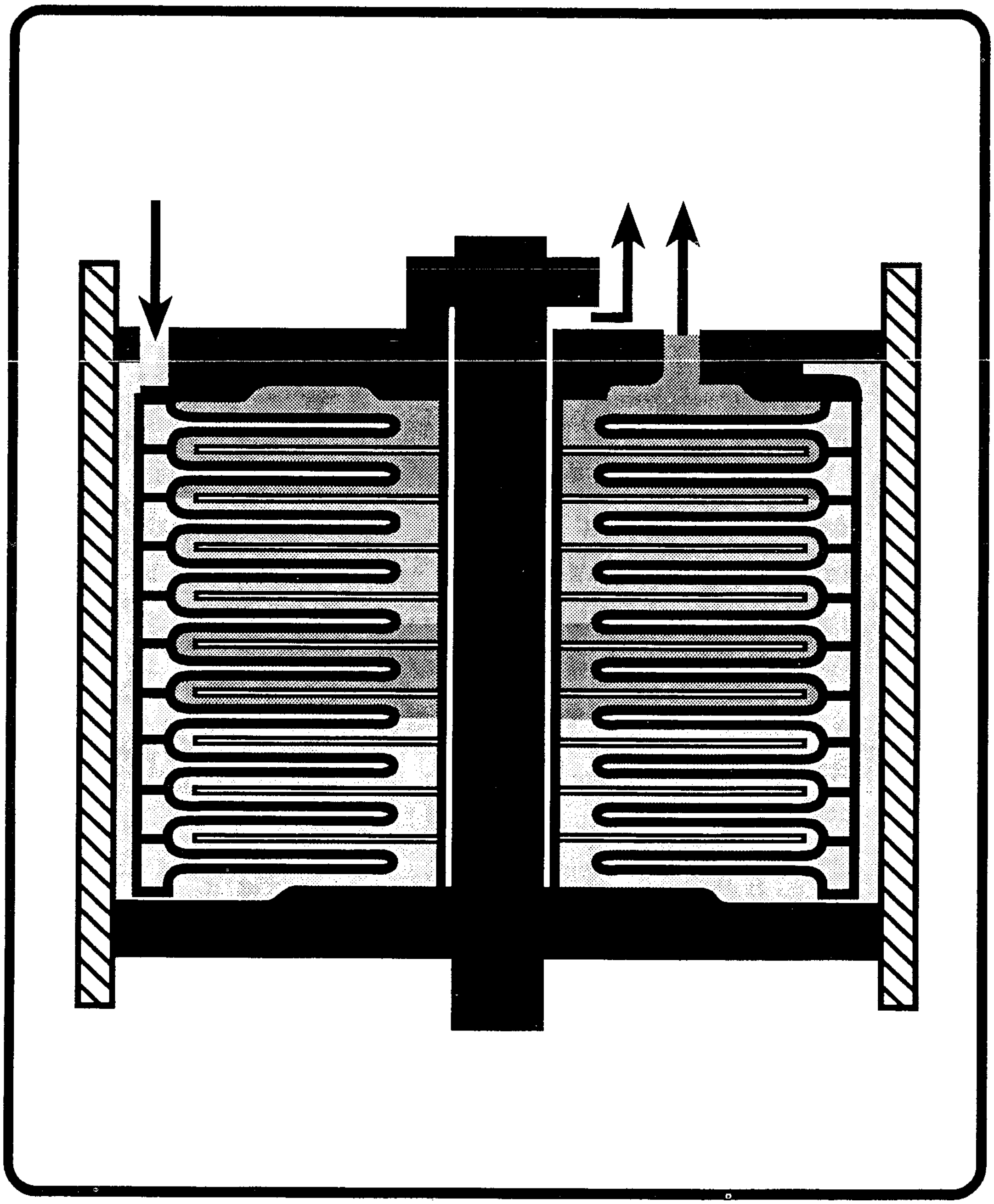
Capsule Report

Reverse Osmosis Process



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Center for Environmental Research Information
National Risk Management Research Laboratory
Office of Research and Development
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Cincinnati OH 45268

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Introduction

A failure analysis has been completed for the reverse osmosis (RO) process. The focus was on process failures that result in releases of liquids and vapors to the environment. The report includes the following:

- A description of RO and coverage of the principles behind the process.
- Applications of RO for treatment of effluent waters from the metal finishing industry.
- Descriptions of equipment and operating and maintenance procedures.
- Failure analysis that includes types of failures and causes.
- Key questions that can be used for software development.
- A bibliography on RO applications in the metal finishing industry.

Reverse Osmosis Process

Process Description

In the reverse osmosis (RO) process, water passes through a membrane, leaving behind a solution with a smaller volume and a higher concentration of solutes. The solutes can be contaminants or useful chemicals or reagents, such as copper, nickel, and chromium compounds, which can be recycled for further use in metals plating or other metal finishing processes. The recovered water **(permeate)** can be recycled or treated downstream, depending on the quality of the water and the needs of the plant. As shown in Figure 1, the water that passes through the membrane is defined as ***permeate*** and the concentrated solution left behind is defined as ***retentate*** (or concentrate).

The RO process does not require thermal energy, only an electrically driven feed pump. RO processes have simple flow sheets and a high energy efficiency. However, RO membranes can be fouled or damaged. This can result in holes in the membrane and passage of the concentrated solution to clean water, and thus a release to the environment. In addition, some membrane materials are susceptible to attack by oxidizing agents, such as free chlorine.

The flux of component A through an RO membrane is given by Equation (1):

$$N_A = P_A\left(\frac{\Delta\Phi}{L}\right) \qquad (1)$$

where

N_A = Flux of component A through the membrane, **mass/time-length²**.

P_A = Permeability of A, mass-length/time-force.

DF= Driving force of A across the membrane, either pressure difference or concentration difference, force/length^2 or **mass/length³**.

L = Membrane thickness, length.

At equilibrium, the pressure difference between the two sides of the RO membrane equals the osmotic pressure difference. At low solute concentrations, the osmotic pressure (p) of a solution is given by Equation (2):

$$\pi = C_S RT \qquad (2)$$

where

p = Osmotic pressure, force/**length²**.

C_S = Concentration of solutes in solution, **moles/length³**.

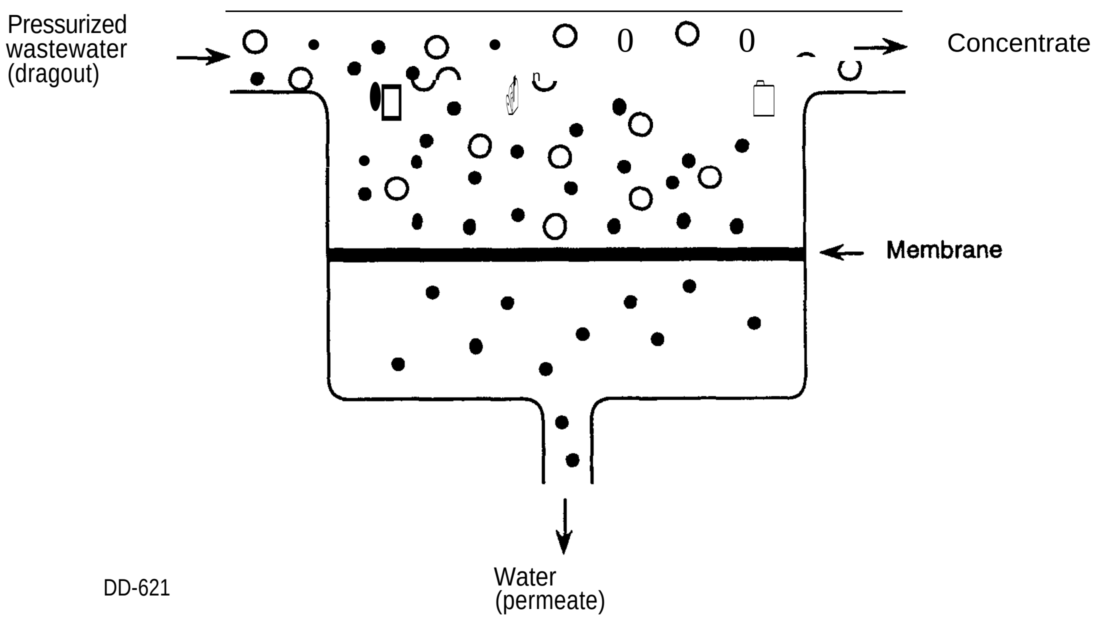

Figure 1. Reverse osmosis process.

R = Ideal Gas Constant, (force-length)/(mass-temperature).

T = Absolute temperature, °K or °R.

As a mixture is concentrated by passing water through the membrane, osmotic pressure of the solution increases, thereby reducing the driving force for further water passage. An accurate characterization of the pressure to drive the RO process must be based on an osmotic pressure computed from the average of the feed and retentate stream compositions. The water recovery of an RO process may be expressed by Equation (3):

$$REC = (Q_P/Q_F) \times 100 \quad (3)$$

where

REC = Water recovery, %.

Q_P = Permeate flow rate, length³/time.

Q_F = Feed flow rate, length³/time.

Water recovery is determined by temperature, operating pressure, and membrane surface area. Rejection of contaminants determines permeate purity, while water recovery primarily determines the volume reduction of the feed or the amount of permeate produced. Generally, for concentration of waters from the metal finishing industry, greater water recoveries are desirable to obtain overall greater volume reduction.

Applications

Nickel plating rinsewaters can be treated with RO with over 90% of the rinsewater recovered, with suitable quality for reuse. Plant payback for a 5 cubic meter per hour recovery RO plant has been estimated at 1.3 years in the case of 2,000 mg/l nickel in the feed (Shoeman et al., 1992; Cross and Evans, 1991). There are at least 150 RO systems operating on various types of nickel baths; most use cellulose acetate membranes (Cartwright, 1984).

At least 12 RO systems are operating on various copper sulfate rinses. These systems use both hollow-fiber polyamide and cellulose triacetate membranes and spiral-wound, thin-film composite types, and offer a membrane life of 1 to 3 years.

One effective RO system, which is being used on a zinc sulfate rinse, employs spiral-wound thin-film composite membranes at a feed rate of 45 gal/hr and at a water recovery of 88%. The membrane concentrate is further reduced in volume in an evaporator and returned to the process (Kinman, 1985; Cartwright, 1984).

Approximately five RO systems are operating on various types of brass cyanide rinses. Both polyamide and cellulose triacetate hollow-fiber membrane elements are used.

An RO system is being used after contact plating on printed circuit boards. The rinse is fed to a polyamide hollow-fiber membrane element at the rate of 210 gal/hr. The system is operating at a water recovery of about 90%; part of the concentrate is recycled to the plating bath and the remainder is routed to the waste treatment system. All of the membrane permeate is reused as a rinsewater (Cartwright, 1984).

Cadmium and chromium rinsewaters are also treated with RO. Membrane fouling has been experienced for the cadmium rinsewaters, but little fouling has been experienced for chromium rinsewater applications. Preliminary results show that payback for 5 cubic meters per hour RO cadmium/water and RO chromium/water recovery plants are three and seven years, respectively (Shoeman et al., 1992).

In other industries, RO is used for production of potable water from seawater and brines, for water recovery from landfill leachates, and for concentration of industrial wastewaters and brines. RO is sometimes used as a pre-concentrator for evaporators to lower energy requirements and increase process efficiency. RO has also found many applications in the food and dairy industries; it is used in the food industry to concentrate apple juice and in the dairy industry to concentrate cheese whey.

Equipment

The module is the housing that contains the membrane. With regard to failure analyses, module configuration is important because some types of modules are more reliable than others. Membrane modules are commercially available in four configurations:

- Plate-and-Frame
- Spiral-Wound
- Hollow-Fiber
- Tubular

Plate-And-Frame Modules

As shown in Figure 2, plate-and-frame modules use flat sheet membranes that are layered between spacers and supports. The supports also form a flow channel for the permeate water. The feed water flows across the flat sheets and from one layer to the next. Recent innovations have increased the packing densities for new design of plate-and-frame modules. Maintenance on plate-and-frame modules is possible due to the nature of their assembly. They offer high recoveries with their long feed channels and are used to treat feed streams that often cause fouling problems. Only recently advanced designs of plate-and-frame modules capable of operating up to 25% dissolved solids and operating pressures up to 4500 psia have been placed in operation in Germany (Stanford and Miller, 1994). This development opens new opportunities for the use of reverse osmosis for concentration of metal finishing wastewaters.

Spiral-Wound Modules

Spiral-wound modules use a sandwich of flat sheet membranes and supports, wrapped spirally around a collection tube (see Figure 3). The feed flows in against one end of the rolled spiral and along one side of the membrane sandwich. The support layers are designed to minimize pressure drop and allow a high packing density. Additionally, the spiral-wound modules can be designed by equipment suppliers to promote turbulence and therefore increase the mass transfer across the membrane or to provide an uninterrupted flow path to decrease membrane fouling. Spiral-wound modules offer greater packing densities, but maintenance is difficult.

Hollow-Fiber Modules

As shown in Figure 4, hollow-fiber modules consist of small diameter membrane fibers bundled within cylindrical pressure vessels. The fibers are pressurized from the outside. The permeate flows to the interior bore or lumen of the fiber and down the length of the fiber to the product header. Fibers can also be pressurized from the inside, but greater mechanical strength of the fibers is necessary to prevent fiber rupture. By feeding on

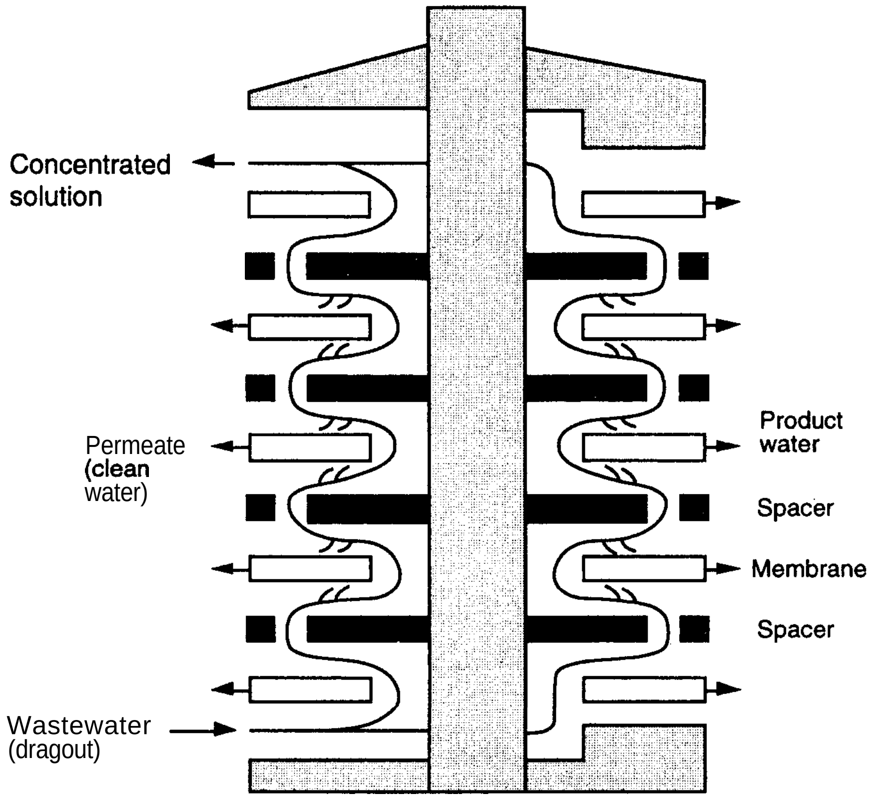

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Figure 2. Plate-and-frame reverse osmosis module.

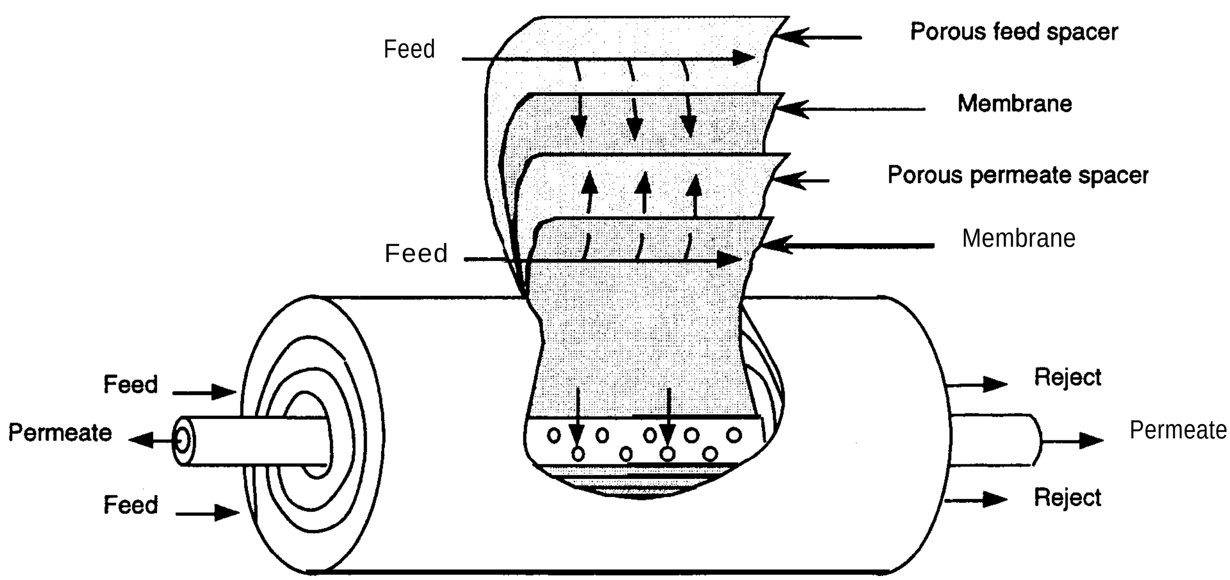

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Figure 3. Spiral-wound module.

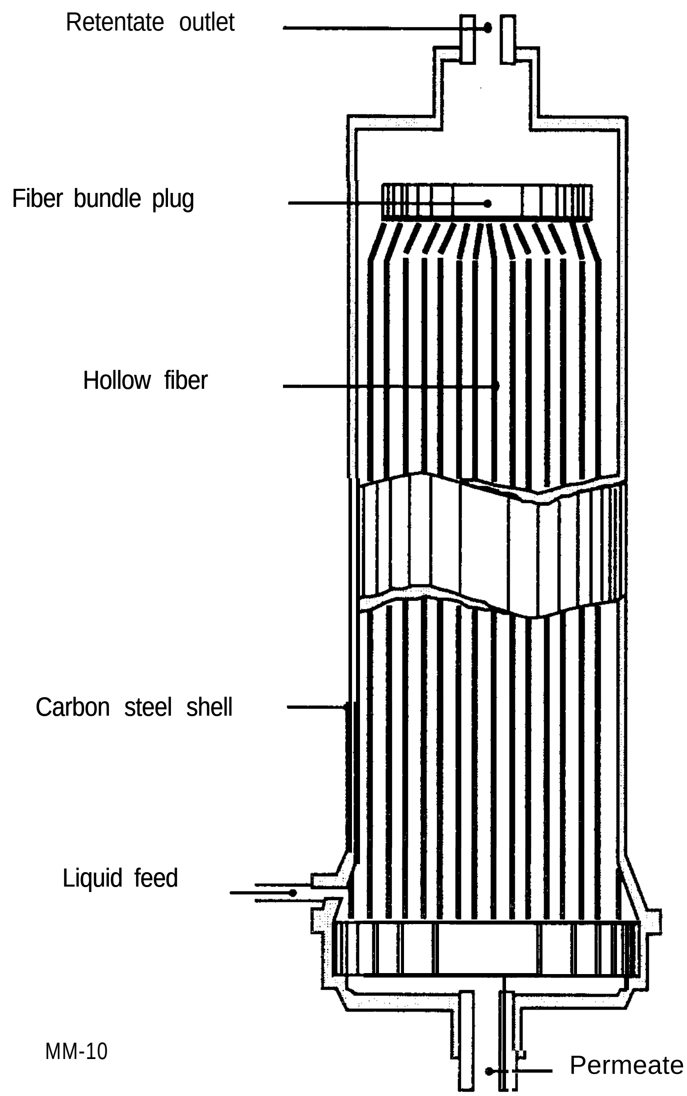

Figure 4. Hollow-fiber module.

the shell side of the fibers, a lower pressure drop is encountered down the bore of the fiber since the permeate flow rate is less than the feed flow rate. Hollow-fiber modules offer the greatest packing densities of the configurations described.

Tubular Modules

Tubular modules have membranes supported within the inner part of tubes. The operator can easily service feed and permeate channels to remove fouling layers. Tubular modules are somewhat resistant to fouling when operated with a turbulent feed flow. This is accomplished with larger flow channels than those used with hollow-fiber and spiral-wound modules. The drawbacks of tubular modules are their high energy requirements for pumping large volumes of water, high capital costs, and low membrane surface area per unit volume of module (see Figure 5).

Operation And Maintenance

To maintain membrane performance and extend membrane life, pretreatment chemicals may be necessary, depending on the characteristics of the wastewater. In addition, chemicals may be required to achieve clean water specifications. Filtering wastewater may be necessary to remove suspended solids before wastewater is fed to the RO modules. Membrane performance can be enhanced by control of pH, removal of certain dissolved species and colloidal materials such as clays and oils, and dissolved or suspended organics. In any RO system, depending on the capacity and size of modules, a number of parallel modules may be needed.

Membrane fouling can result from the formation of a fouling layer on the membrane surface, or from internal changes of the membrane material. Both forms of fouling can cause membrane permeability to decline. Scaling is a form of fouling that occurs when dissolved species are concentrated in excess of their solubility limit. Chemical agents can be added to slow the formation of precipitates. Acidification is used to prevent the formation of carbonates of low solubility, such as magnesium carbonate. An ion exchanger is sometimes used to trade cations of low solubility salts for cations that are more soluble, for example, sodium sulfate may be traded for calcium sulfate.

Prevention of biological growth is necessary to prevent damage to the membrane. Biological growth can be inhibited with chlorination, but some RO membranes are chlorine sensitive, so water must be dechlorinated before entering the RO module. Other disinfectants are ozone, formaldehyde, ultraviolet light, copper sulfate, and sodium bisulfate. A schematic of an RO system with four modules in parallel, chemical pretreatment, and an up-front filtration step is shown in Figure 6.

Staging RO Systems

RO can be used as a one or two-stage process, depending on requirements for purity of the water removed (permeate). In the two stage process, the permeate from the first stage is "polished" by the second, producing a higher purity water than is possible with one stage alone. As indicated in Table 1, solute concentration in the permeate may be reduced from about 500 ppm for one stage to 6 ppm in two stages. The flow diagram for the two-stage RO process is shown in Figure 7.

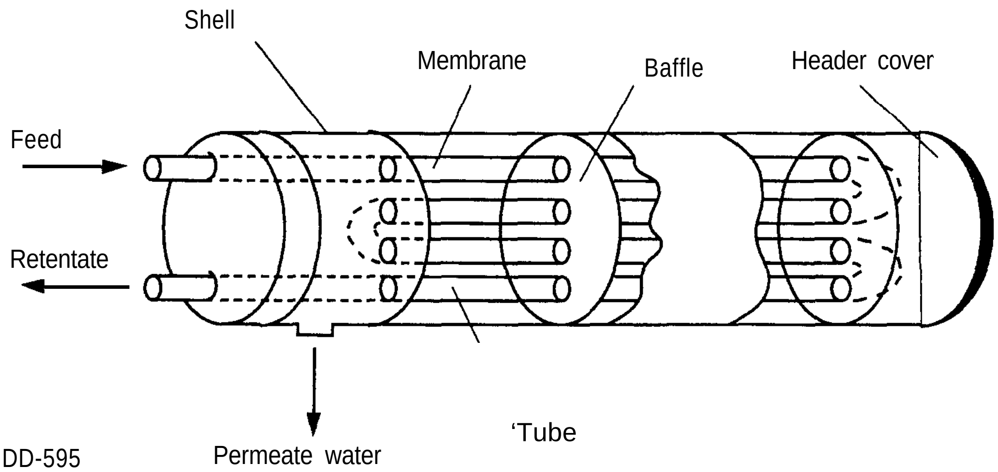

Figure 5. Tubular module.

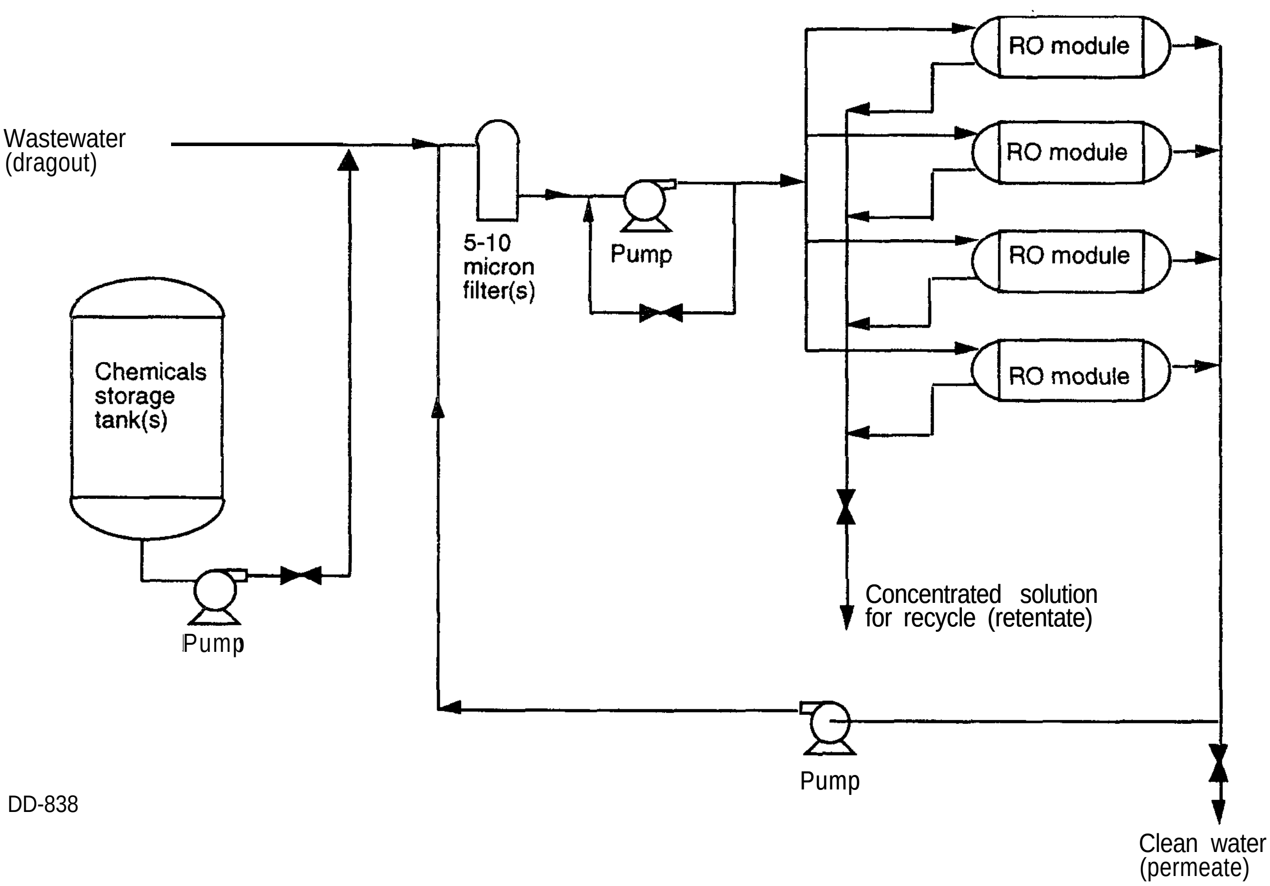

Figure 6. Reverse osmosis system.

Table 1. **Reverse Osmosis: One- and Two-Stage Processes, Water Recovery, and Purity**

Configuration	Water Recovery,%	Water purity, ppm
RO—one stage	77	500
RO-two stage	77	6

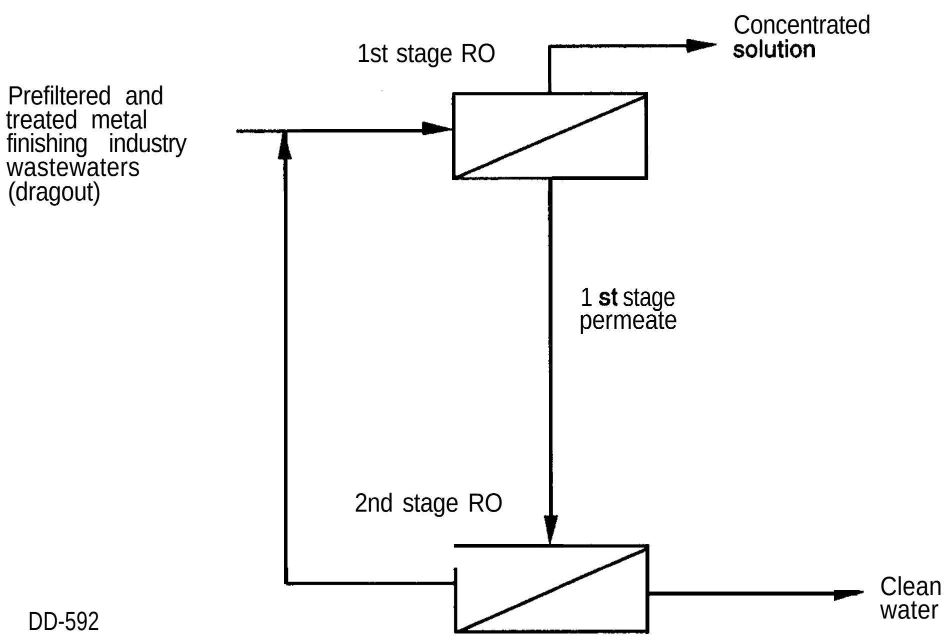

Figure 7. Two-stage reverse osmosis process.

Failure Analysis

A failure analysis is presented below for the RO process when used to treat waters from the metal finishing industry. As shown below, the failures are categorized as to probability of occurrence (high, moderate, and low). To our knowledge there are no published data that further quantify the frequency of occurrence of these failures.

High Probability

Relief Valves (Liquid)

Liquid relief valves are included in RO (and other processes) to protect the piping from overpressure. Overpressure frequently occurs during startups, shutdowns, and upsets. Overpressures can result from control valves failing in the closed position, and from the plugging of valves, piping, and membrane modules. Plate-and-frame and tubular modules are not as susceptible to plugging as hollow-fiber and spiral-wound modules.

Seals

Seal or o-ring failures may occur in the membrane feed pump, chemical feed pump, or the air compressor that delivers instrument air to instruments and control valves. Possible causes of seal failures include overheating and mechanical stress. Visual inspection can confirm spraying or leaking of wastewater at the pumps or compressor.

Valves and Pipe Fittings

These failures are more prevalent in older plants than in newer ones. Causes include mechanical stress, improper maintenance procedures, and freezing during cold weather. Visual observations can confirm leaks of wastewater or chemicals from valve stems and fittings.

Miscellaneous Spills During Daily Operations

Spills of chemicals or wastewater frequently occur when tanks are replenished or when the system is shut down for maintenance. For RO systems, chemical spills can include acids, bases, phosphates, and chlorine.

Relief Valves (Vapor)

Storage and run down tanks are equipped with vapor relief valves to maintain a constant pressure. These valves release contaminated vapors to the atmosphere as tank levels (and tank pressures) increase. These releases are small, but they can occur frequently.

Moderate Probability

Tank Overflows

Tank overflows can result in significant releases of wastewaters or chemicals to the environment. They occur mostly during startups, shutdowns, and plant upsets.

Membrane Failures

Holes may develop in the membrane material, allowing wastewater to escape to contaminate the clean water permeate. The potting material that attaches the membrane material to the module housing may also fail and result in contamination of the clean water permeate. If the upstream filters fail, solids can escape and damage the membrane. And the membrane can be defective when it is delivered from the supplier. In addition, corrosive chemicals, such as chlorine, can attack some types of membranes, though some membrane materials are more durable than others. For example, ceramics are more durable than polymer membranes. An indication of membrane failure is a sudden reduction in pressure drop across the membrane.

Low Probability

Tank Ruptures

A tank can rupture, possibly because of mechanical failure or freeze damage. Though this type of failure is rare, a rupture can result in the release of a large quantity of wastewater or chemicals to the environment.

Piping Ruptures

Piping is typically strong and not likely to rupture. Possible causes of rupture include mechanical stress, freezing, and improper maintenance procedures. Large leaks are possible with this type of failure.

A summary of the types and causes of failures and the associated questions for later software development are presented in Table 2.

Table 2. Failure Analyses for Reverse Osmosis System

Failure	Cause(s)	Questions for Software Development
	High Probability	
Relief valves (liquid)	- Overpressures during start-ups, upsets, and shutdowns - Key control valves failing in closed position. - Plugging of valves, piping, and membrane modules due to buildup of solids. Hollow-fiber and spiral membrane modules are most susceptible to fouling.	What is the expected quantity of leaks through the liquid relief valves (gallons)? What is the disposition of these leaks (i.e., Do they go to a capture system, process sewer, or are they lost directly to the environment)?
Seals	- Overheating - Mechanical stress - Abrasive wear	What is the expected quantity of leaks through seals (gallons)? What is the disposition of these leaks?
Valves and pipe fittings	- Mechanical stress - Improper maintenance procedures - Freezing	What is the expected quantity of leaks through valves and pipe fittings (gallons)? What is the disposition of these leaks?
Miscellaneous spills during daily operations	- Spills during filling of tanks (due to faulty gages and equipment and mistakes by operators). Spills can include pretreatment chemicals (such as acids, bases, and phosphates). - Faulty maintenance procedures	What is the expected quantity of leaks from spills (gallons)? (Base on plant experience and operating records). What is the disposition of these spills?
Relief valves (vapor)	- Increases in tank levels - Changes in ambient temperature	What is the expected quantity of leaks through vapor relief valves (standard cubic feet/hour)? What is the disposition of these leaks?
	Moderate Probability	
Tank overflows	- Occur mostly during unstable conditions (during startups and shutdowns). Overflows can include pretreatment chemicals (such as acids, bases, and phosphates).	What is the expected quantity of tank overflows (gallons)? (Base on plant experience and records). What is the disposition of these overflows?
Membrane module failures	- Membrane defective - Module potting material defective - Presence of corrosive chemicals - Presence of solids	What is the expected quantity of leaks through membrane modules (gallons)? What is the disposition of these leaks?
	Low Probability	
Tank ruptures	- Mechanical failures - Freezing	What is the expected quantity of releases due to tank failures (gallons)? (Be sure to include the concentrated waste if it is stored onsite). What is the disposition of these releases?
Piping ruptures	- Mechanical failures - Freezing	What is the expected quantity of losses due to pipe ruptures (gallons)? What is the disposition of these losses?

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