

Electrodialysis and Electrodialysis Reversal

Second Edition



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Electrodialysis and Electrodialysis Reversal

Second edition



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Manual of Water Supply Practices—M38, Second Edition

Electrodialysis and Electrodialysis Reversal

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Preface



This second edition of AWWA Manual M38 provides detailed information on the classical electrodialysis (ED) and the electrodialysis reversal (EDR) processes and systems. ED and EDR systems employ electrochemical and membrane cell technologies to separate ionic materials in aqueous solutions. These systems have proven useful in food processing, medical applications, and other specialized industrial uses, with major applications being the production of drinking water or pure industrial process water from brackish, saline, or mineralized sources.

Directed to engineers and operators of ED and EDR systems, this manual provides detailed background information on ED and EDR as they relate to water treatment processes. The manual explains process principles, equipment information, electrodialysis technology, and system design. Information on water chemistry is included to enhance understanding of water processing.

It is hoped that this manual will also assist water process engineers and treatment plant decision makers in understanding the value of ED and EDR technology applied to their water treatment needs.

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Chapter **1**

Introduction

By W. Shane Walker

Overview of the Electrodialysis Process

Electrodialysis (ED) is an electrically driven membrane process used to demineralize or desalinate brackish and saline water. Brackish waters lie under approximately two-thirds of the United States, and some inland rivers, such as portions of the Rio Grande and the Colorado, are also brackish. Water is generally classified as brackish when mineral content ranges between that of fresh drinking water and that of seawater; brackish water contains more than 500 mg/L of total dissolved solids (TDS), and seawater contains more than 30,000 mg/L TDS. ED systems are capable of treating variable source water quality while producing a consistent finished water quality.

According to the Global Water Intelligence (GWI) DesalData website (incorporating the IDA Desalting Plants Inventory), the installed worldwide capacity of ED membrane treatment plants increased from 2 mgd (315 m³/h) in 1955 to more than 200 mgd (31,545 m³/h) in 1992 and more than 758 mgd (119,556 m³/h) in 2019.

Reduction of Salinity (Total Dissolved Solids)

An overview of membrane process target applications based on size and molecular weights of contaminants is shown in Figure 1-1. ED processes remove total dissolved solids in the form of ions, or salinity, which may also be removed by reverse osmosis (RO) or nanofiltration (NF). RO operates by passing *water* through the membrane and rejecting dissolved contaminants, whereas ED processes operate by passing *ions* (charged compounds) through the membranes (as water flows parallel to the membranes). As a result, ED systems are generally more robust with respect to fouling and scaling than RO, and ED systems can generally be designed for higher recovery than RO systems.

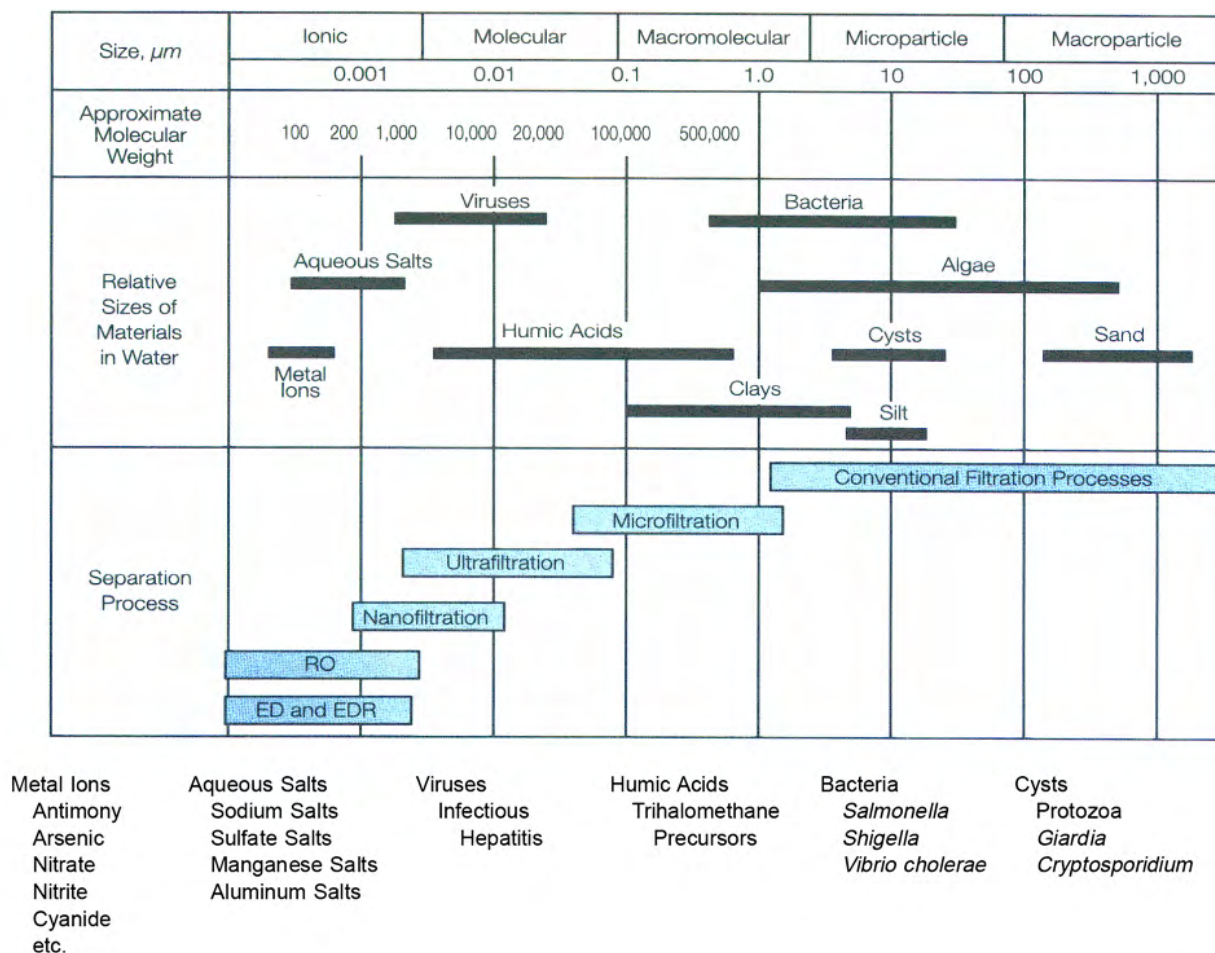


Figure 1-1 Membrane processes overview

While RO and NF processes typically remove a fixed fraction (e.g., 90–99 percent) of dissolved solids, electrodialysis plants can be designed to remove a targeted fraction (typically from 50–99 percent) of dissolved solids. Source water salinities of 100 mg/L to greater than 100,000 mg/L TDS can be successfully treated with ED with tailored salinity removal ratios of 50–90 percent, and ED can also be used to treat brackish concentrates, as well as seawater (Tanaka 2015). In addition to overall TDS reduction, ED and EDR systems can effectively treat source water with problems such as saltwater intrusion; high hardness; high nitrate/nitrite and selenium levels from agricultural contamination; high, naturally occurring arsenic or fluoride levels; and heavy metals contamination.

Review of Water Chemistry

A basic understanding of the composition of solutes in water whether salts, ions, or polar compounds is necessary to understand the design, operation, and maintenance of an electrodialysis treatment system. A brief review of water chemistry concepts is provided here, but several texts are available that provide more in-depth discussion of the topic (Bard et al. 2001, Newman & Thomas-Alyea 2004, Robinson & Stokes 2002, Wright 2007).

Table 1-1 Common ions found in natural waters

Cations (+)	Anions (-)
Sodium (Na^+)	Chloride (Cl^-)
Potassium (K^+)	Bicarbonate (HCO_3^-)
Magnesium (Mg^{+2})	Carbonate (CO_3^{2-})
Calcium (Ca^{+2})	Fluoride (F^-)
Strontium (Sr^{2+})	Sulfate (SO_4^{2-})
Barium (Ba^{2+})	Nitrate (NO_3^-), Nitrite (NO_2^-)
Iron (Fe^{2+} , Fe^{3+})	Phosphate (PO_4^{3-})

Ionic Solutions

An *ion* is a charged atom (e.g., sodium) or polyatomic compound (e.g., sulfate), and a mixture of ions in water is an electrolyte solution. An *electron* is a subatomic particle that, by convention, has an assigned charge of negative one (-1). A neutral atom that gains an electron will have a net charge of -1 , and conversely, a neutral atom that loses an electron will have a net charge of $+1$. These charged atoms are called *ions*. Positively (+) charged ions are called *cations*, and negatively ($-$) charged ions are called *anions*. These two types of ions can dissociate in water. Some common ions that may be found in natural waters are shown in Table 1-1.

Ionic compounds, such as salts, minerals, acids, and bases (e.g., sodium chloride, NaCl , or table salt), are composed of charged atoms (e.g., Na^+ and Cl^-) that are held together by electrically attractive forces. If a crystal of sodium chloride is dissolved in water, the two atoms separate into two electrically charged particles, one with a positive charge (e.g., Na^+) and one with a negative charge (e.g., Cl^-). In addition to the ions shown in Table 1-1, ED may also be used to remove ionic species of metals such as cadmium, chromium, copper, mercury, selenium, and uranium.

Electrical Conductivity

With respect to ED, an important property of an ionic solution is its ability to conduct electricity. When two electrodes are connected to a direct current (DC) power supply (e.g., a battery) and immersed in pure water, negligible electric current passes between the electrodes because of a lack of ions in the solution to transport the electrical current. In a solution with sufficient concentration of ions, however, the dissociated ions are forced to move by the electric field, and their movement constitutes the electric current between the two electrodes. The ability of a solution to carry an electric current is known as *electrical conductivity*, and the conductivity of fresh and brackish water is typically reported in units of microsiemens per centimeter ($\mu\text{S}/\text{cm}$). The SI unit siemens is the reciprocal of an ohm, and the archaic term for this unit is the mho (ohm spelled backwards).

Conductivity is affected by the concentration of ions, the composition of ions, and the temperature of the solution in the following ways:

- Increasing ion concentration (salinity) increases electrical conductivity (i.e., decreases electrical resistance for concentrations less than several mol/L).
- Ions contribute differently to the overall conductivity depending on size and charge.
- Increasing the temperature increases ion mobility, resulting in an increase in conductivity.

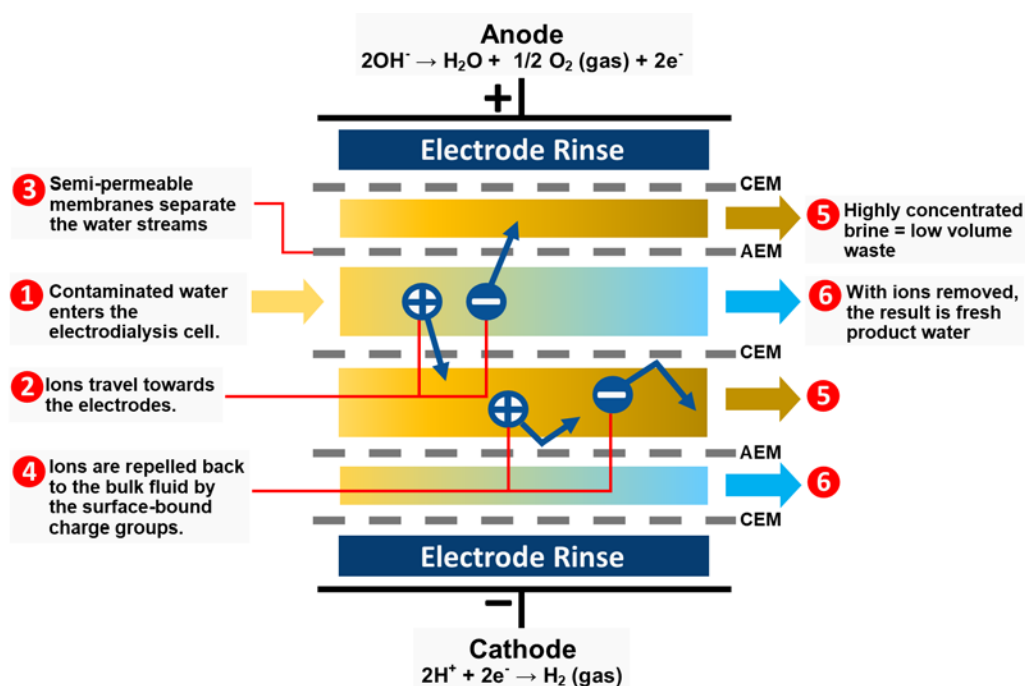
Operating Principles of Electrodialysis

Electrodialysis (ED) is an electrochemical separation process in which ions are transferred through ion exchange membranes by means of an applied DC voltage. The ED process was developed in the 1950s and '60s (Mintz 1963, Solan et. al. 1971, Sonin & Probst 1968) and has been described more generally over the past half-century (Benjamin & Lawler 2013, Davis et. al. 1997, Green & Perry 2018, Metcalf & Eddy 2014, Strathmann 2004, Tanaka 2015).

Ion Exchange Membranes

A basic electrodialysis stack is composed of two electrodes (cathode and anode) and repeating pairs of ion exchange membranes (cation and anion), as shown in Figure 1-2. The ion exchange (more correctly called *ion transfer*) membranes used in ED are described as either cation exchange (transfer) or anion exchange (transfer) membranes. These membranes are thin and flat with a relatively smooth surface, similar in appearance to a plastic sheet. The ions that are being removed diffuse through the water that is trapped inside the membranes, pulled by the electric field. The water that is being treated flows across the surface of the membranes; it is not pushed through the membranes as is the case in pressure-driven membrane processes.

Cation transfer membrane. The cation transfer membrane is a sheet composed of cation exchange media. This membrane allows the passage of cations while blocking the passage of water and anions, as shown in Figure 1-2. The membrane contains fixed, negative charges, which repel the negative ions while allowing the positive ions to pass through the membrane.



Adapted from Strathmann 2004

Figure 1-2 Electrodialysis stack operation (adapted from Strathmann)

Anion transfer membrane. The anion transfer membrane is a sheet composed of anion exchange media. This membrane allows the passage of anions while blocking passage of both cations and water. The membrane contains fixed, positive charges, which repel positively charged ions and allow negatively charged ions to pass through the membrane.

Operation

As feedwater flows parallel to the membranes (as shown in Figure 1-2), positively charged ions (e.g., Na^+ and Ca^{2+}) are attracted toward the negatively charged cathode, and negatively charged ions (e.g., Cl^- and SO_4^{2-}) are attracted to the positively charged anode. The desalination (separation) processes is described for each of the compartments:

- *Electrode rinse.* Cells 1 and 8 contain electrodes where reduction (cathode) and oxidation (anode) reactions occur.
- *Diluate.* Cells 2, 4, and 6 — Anions (e.g., Cl^-) are attracted toward the anode and pass through the anion membranes (A) into adjacent concentrate cells, while cations (e.g., Na^+) are attracted to the cathode and pass through the cation membranes (C) into adjacent concentrate cells.
- *Concentrate.* Cells 3, 5, and 7 — Anions (e.g., Cl^-) are attracted toward the anode but are repelled by the cation membranes (C) and are retained in the concentrate cells; while cations (e.g., Na^+) are attracted to the cathode but are repelled by the anion membranes (A) and are retained in the concentrate cells.

Thus, compartments 2, 4, and 6 are depleted of ions (known as *diluate* cells), whereas compartments 3, 5, and 7 have increased concentration of ions (known as *concentrate* cells). The flow through all of the diluate cells is collected in a diluate manifold to produce one effluent diluate (demineralized, product) stream, and the flow through all of the concentrate cells is collected in a concentrate manifold to produce one effluent concentrate (waste) stream. In full-scale operation, up to several hundred of these compartments may be assembled into a membrane stack.

Metal electrodes may be used to drive the electrical current through the stack by generating redox reactions at the electrode surface. At the cathode (-), water is reduced to consume electrons and produce hydrogen gas and hydroxide ions. At the anode (+), water is oxidized to produce electrons, oxygen gas, and hydrogen ions (protons); some chloride may be oxidized to chlorine gas (see Chapter 2). Because of the acidic and oxidizing environment of the anode compartments, anodes are normally constructed of inert materials, such as platinum-coated titanium. Some researchers are exploring the use of non-Faradaic (capacitive) electrodes for electrodialysis, but these are not yet widely used commercially.

Configurations of electrically driven membrane processes

Electrodialysis (Batch and Continuous)

The first type of commercial ED system was the batch system. In this ED system, source water is recirculated from a holding tank through the demineralizing spacers of a single membrane stack and back to the holding tank until the final purity is obtained. The production rate is dependent on the dissolved minerals concentration in the source water and on the degree of demineralization required. The concentrate stream is also recirculated to reduce wastewater volume, and continuous addition of acid might be required to prevent membrane stack scaling, depending on the ionic composition of the source water.

The second type of commercially available system was the continuous-flow ED. The demineralized stream makes a single pass through the stack and exits as product

water. Higher salinity removal ratios can be achieved by arranging multiple stacks in series with the diluate effluent from the one stage entering the diluate to the following stage. The concentrate stream may be partially recycled to reduce wastewater volume, and scaling may be prevented by dosing the concentrate with antiscalant compounds and/or acid (depending on feed water composition). Control of scale and fouling is critical to all membrane systems — ED, EDR, RO, etc. Costs to install, operate, and maintain chemical feed systems as well as chemical storage facilities can significantly add to the costs of any membrane-based system.

Electrodialysis Reversal (EDR)

EDR systems, first developed in the 1960s, incorporate electrical polarity reversal to control membrane scaling and fouling. These systems are designed to produce demineralized water quasi-continuously without continuous chemical addition during normal operation.

In EDR systems, the polarity of the electrodes is typically reversed two to four times per hour. When polarity is reversed, the charge of the electrodes is reversed (i.e., the cathode switches to the anode, and the anode switches to the cathode). Thus, the diluate cells become concentrate cells, and the concentrate cells become diluate cells. After reversing polarity, valves in the system automatically switch so that water flowing through the new diluate cells now goes to the process, while water flowing through the new concentrate cells now goes to waste (or recycle).

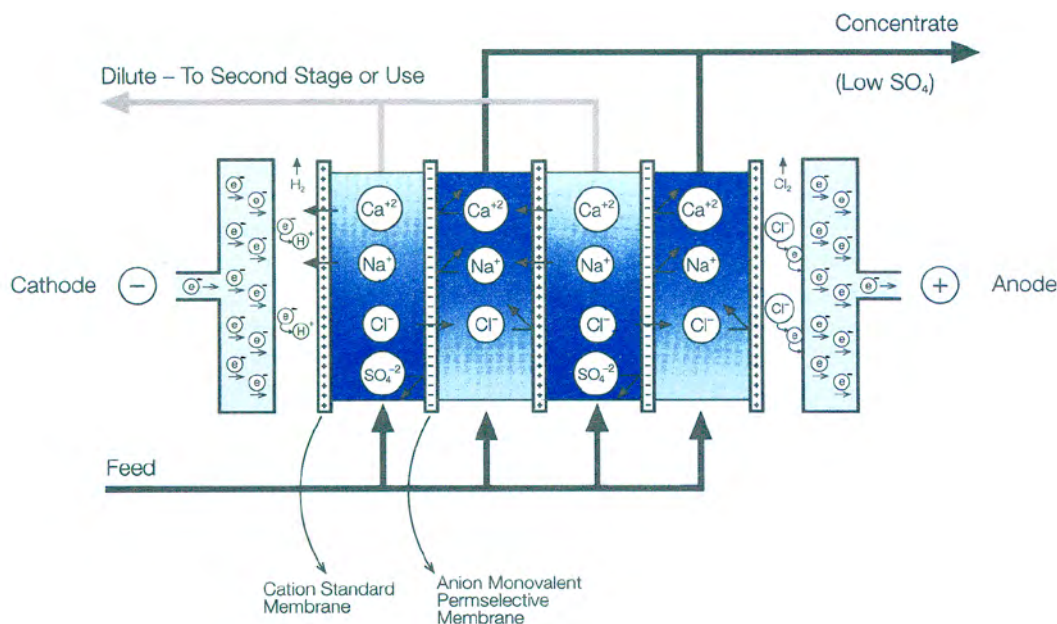
In EDR, all electrodes must be tolerant of both the anode and cathode conditions. The polarity-reversal process affects the operation of a membrane system by

- detaching polarization films
- breaking up freshly precipitated scale or seeds of scale before they can cause damage
- reducing slime formations on membrane surfaces reducing problems associated with the use of chemicals
- cleaning electrodes with acid generated during anodic operation

Colloidal particles or slimes that are slightly electronegative may accumulate on the anion membrane and cause membrane fouling. This problem is common to most classes of ED systems. These fouling agents are removed by flushing with cleaning systems or by periodic polarity reversal as previously described.

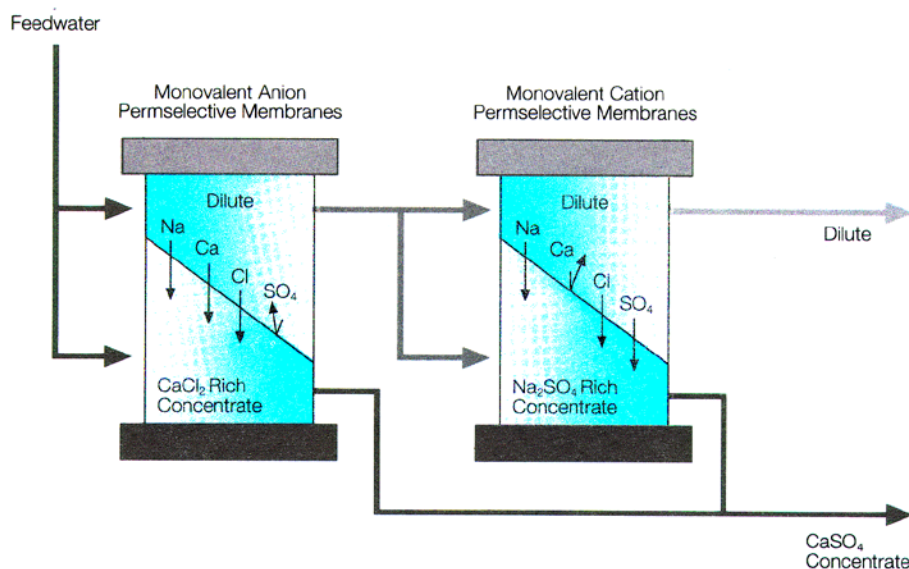
Electrodialysis with permselective membranes

Permselective membranes can be tailored to inhibit the passage of divalent anions or cations, such as sulfates, calcium, and magnesium. Permselective refers to the ability of an ED membrane to discriminate between different ions allowing passage or permeation through the membrane. For example, some membranes show good permeation (high transport numbers) for monovalent anions, such as Cl^- or NO_3^- , but have low transport numbers and show significantly lower permeation for divalent or trivalent ions, such as SO_4^{2-} , PO_4^{3-} , or similar anions, as shown in Figure 1-3. This is achieved by treating the anion membrane, and the effect can be exploited to separate various ions. Existing commercial membranes include monovalent anion specific, monovalent cation specific, or hydrogen ion specific. The relative specificities vary, with the monovalent anion membrane showing the greatest specificity (e.g., the ratio of chloride to sulfate ion transport numbers). Figure 1-3 shows the use of a standard membrane with a monovalent anion permselective membrane; the concentrate stream is very low in sulfate (i.e., approximately equal to or slightly greater than the feedwater), while the chloride and sodium concentrations, for example, could be many times higher than the feedwater.



Source: Thomas D. Wolfe

Figure 1-3 Principle of monovalent permselective electrodesialysis



Source: Thomas D. Wolfe

Figure 1-4 Use of monovalent permselective ED membranes for high recovery (e.g., concentration of calcium sulfate in saturated waters)

Through the use of proper staging, with monovalent and divalent permselective membranes, the development of high calcium sulfate in the concentrate side of the membranes can be forestalled and scale formation prevented, as illustrated in Figure 1-4. In the first stage, relatively little sulfate passes through the membrane, and so the concentrate is rich in calcium chloride. Rather than passing this concentrate to stage 2, the stage 2 system concentrate is made up from fresh feed or another source. Here, the passage of calcium ions is retarded, and the concentrate is rich in sodium sulfate. Neither stage ever

exceeds the calcium sulfate solubility limits. Yet, when the two concentrate streams are combined, together they can far exceed the calcium sulfate limit. In fact, precipitation can result on mixing.

In other schemes, the concentrate can be made up from a separate water source that is already low in sulfate (for example, reverse osmosis permeate or ED dilute water) to increase water recovery.

Electrodeionization (EDI)

Electrodeionization (EDI) was first commercialized in 1987 by the Process Water Division of Millipore Corporation (now Evoqua Water Technologies). EDI is a well-established process for the production of ultrapure water for several markets, including pharmaceutical/biotechnology, power generation (boiler feed water), and microelectronics/semiconductor. The process of EDI is a hybrid of two well-known separation processes—electrodialysis and ion exchange deionization. Like ED, EDI uses alternating anion-exchange and cation-exchange membranes, with spaces between the membranes configured to create liquid flow compartments with inlets and outlets. A direct current (DC) electric field is applied by an external power supply using electrodes at the ends of the membranes and compartments. The main construction difference between ED and EDI is that in EDI some or all of the compartments between the ion exchange membranes contain an electroactive, conductive filler—typically ion-exchange resin beads, as shown in Figure 1-5. For this reason, EDI has also been referred to as *filled-cell electrodialysis*.

The reason for the construction difference is a functional difference between the two processes. While ED is a bulk salt removal process typically used to produce drinking water from a brackish water feed, EDI is a polishing process most often used to make ultrapure deionized water from reverse osmosis permeate. In ED/EDR, when the feed solution is very dilute, the electrical resistance of the ED stack increases significantly, and it becomes difficult to pass DC and therefore, to remove the last traces of salt. In ED, the practical lower limit of product water conductivity is around 20 $\mu\text{S}/\text{cm}$ —which is a typical feed water conductivity for an EDI system. The resin filler in EDI devices provides two modes of ion removal that allow the EDI process to produce effluent approaching the theoretical minimum water conductivity of 0.055 $\mu\text{S}/\text{cm}$ at 25°C. In the first mode, transport of ions in the dilute solution is enhanced by the electroactive media, which helps conduct the ions to the surface of the membranes and then into the concentrating compartments (illustrated in Figure 1-5). The second mode involves operating with sufficient DC power to cause splitting of water into hydrogen and hydroxyl ions, thus electrochemically regenerating a portion of the ion exchange resin filler in the product water compartments. The water splitting and electroregeneration allow for the removal of weakly ionized species such as carbon dioxide, silica, and boron—which are not effectively removed by ED.

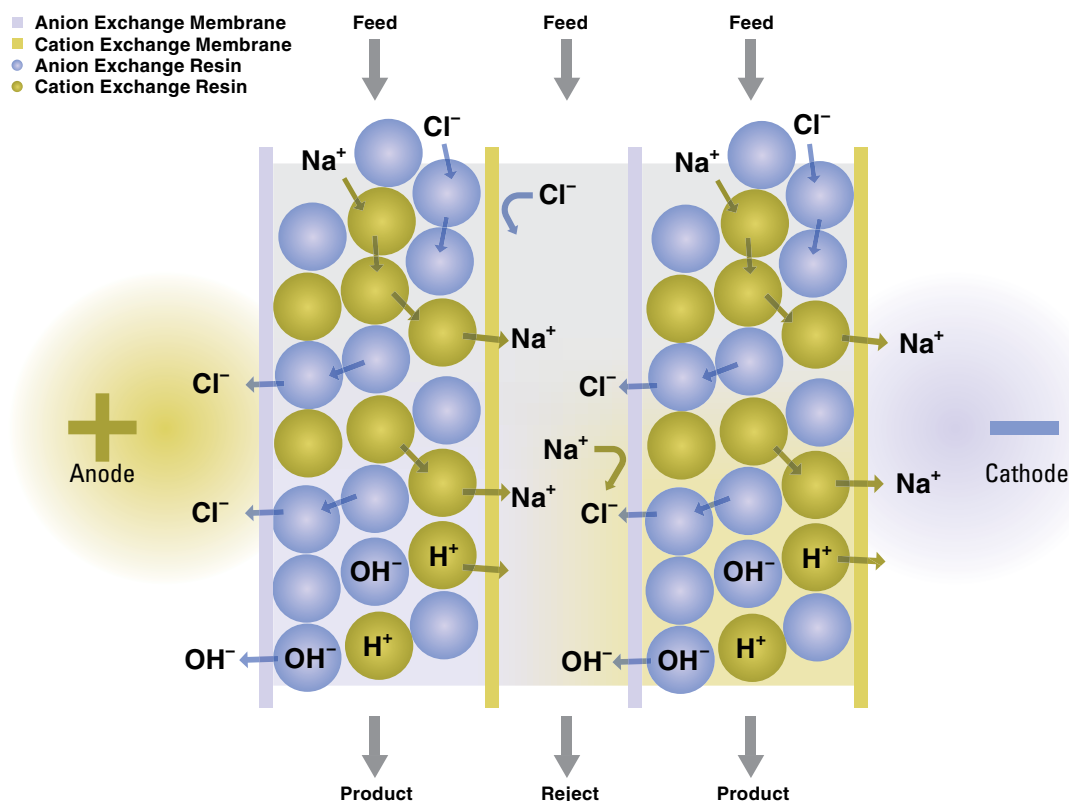


Figure 1-5 Ion transport and electrochemical regeneration in an EDI cell

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Chapter 2

Applications and Process Design

By Jonathan Wood

Both ED and EDR are electrically driven membrane processes that selectively remove soluble ionic constituents carrying electrical charges that pass through semi-permeable ion exchange membranes. The natural electrical conductivity of water allows ED and EDR processes to be applied to a wide range of water treatment objectives.

In ED and EDR systems, the water being treated flows past, not through the membranes, so these systems do not present a barrier to remove bacteria or uncharged contaminants. In contrast, RO and NF systems pass water through membranes designed to reject contaminants in the molecular and ionic size ranges, effectively rejecting cysts (such as *Giardia* and *Cryptosporidium*), enteric viruses and bacteria. RO can be used in combination with ED and EDR to remove these contaminants and to further concentrate the waste stream.

Chapter 1 introduced conventional ion exchange membranes, also called ion-transfer membranes. These have a single type of charge (positive or negative) that allows them to exclude ions of the same charge. There are also membranes that contain both positive and negative charges and are thus called *bipolar membranes*. Applications for each are described in the following section.

APPLICATIONS OF MONOPOLAR MEMBRANE ELECTRODIALYSIS

Brackish Water Desalination

Reduction of TDS to meet drinking water standards is the most common application of ED and EDR technology. Plants treating brackish sources that contain up to 10,000 mg/L TDS can reliably and economically yield product water containing less than 500 mg/L TDS. For example, an EDR plant in Sarasota County, Fla., treats brackish well water with 2,500 mg/L TDS and yields product water of less than 350 mg/L TDS—an overall reduction in dissolved solids of 86 percent—with 85 percent recovery. The same plant can produce product water with 500 mg/L TDS from source waters containing as much as 3,600 mg/L TDS at the same rate of recovery. This flexibility is particularly important in applications for which multiple or variable source waters are used. The ability to control the product water quality by adjusting the applied DC voltage is an additional advantage of ED and EDR over other desalination processes such as reverse osmosis, which would typically employ blending to control product water quality to allow minimizing power consumption.

RO Reject Recovery

Electrodialysis can be used to treat the concentrate stream of reverse osmosis systems, in order to increase overall system water recovery. Because electrodialysis operates by removing ions from brackish water (instead of removing water, as in the case of reverse osmosis), in some cases higher recoveries can be achieved (Walker et al. 2014). This use of ED is of particular interest in zero-liquid-discharge systems, where it is desirable to reduce the volume of the RO brine stream due to the high cost of downstream brine concentrators. In some cases, the RO reject is softened before processing by electrodialysis, but polarity reversal has also been shown to be effective at preventing scaling of the ED (Wiesner et al. 2010). The fact that ED does not concentrate silica may be an advantage in some of these applications.

Seawater Desalination

While electrodialysis has been widely used for desalination of brackish water as previously mentioned, historically it has not often been applied commercially for the desalination of sea water. The most commonly stated reasons are high power consumption due to the high electrical resistance of the ion exchange membranes and diluting compartments as well as back diffusion due to the salinity difference between the concentrate and dilute streams.

In recent years, there have been technological advances that suggest there is a future for electrodialysis in desalination of seawater to make drinking water. Such improvements as counterflow, multi-stage operation, and the reduction of inter-membrane spacing was shown to reduce energy use to about 6 kW·h/m³ (Turek 2002). With new lower-resistance ion exchange membranes, ED power consumption of 1.8 kW·h/m³ has been demonstrated on a pilot scale (Shaw et al. 2011). This is comparable to the energy consumption of a state-of-the-art reverse osmosis system (Elimelech & Phillip 2011).

Table Salt Production

For many decades it has been common practice in Japan (which has no natural salt deposits) to use ED to concentrate seawater prior to evaporation to obtain salt crystals. The ED process can concentrate seawater from 3.5 percent by weight up to about 20 percent (near saturation). Acid is added to the seawater to minimize CaCO₃ scaling, and special monovalent selective membranes (which preferentially pass monovalent ions over polyvalents) help avoid CaSO₄ precipitation in the concentrate (Tanaka 2015).

Food Processing

Electrodialysis has found a number of applications in the food industry such as deacidification of fruit juice, removal of tartaric acid from wine, and demineralization of products such as soy sauce, sugar molasses, amino acids, and cheese whey. By far, the largest market share of these applications is the demineralization of cheese whey and skimmed milk.

Whey is a byproduct that is produced in considerable amounts during production of cheese (about 9:1 whey to cheese ratio) and can present a waste disposal problem. While the whey is an excellent source of protein, lactose, vitamins and minerals, its high salt content makes it unsuitable as a food. ED has the ability to reduce the salt content of the whey without denaturing the proteins or causing decomposition of the vitamins. When the salt concentrations are reduced, the whey is similar in composition to human milk and useful in baby food products.

Desalting of whey or skimmed milk requires ion exchange membranes that are resistant to organic fouling. They must also be stable at both high and low pH, to tolerate the frequent chemical sanitization that is necessary to control growth of microorganisms. A typical system employs four electrodialysis stages (in series) and would achieve an overall salt reduction of 90 percent for whey and 70 percent for skimmed milk (Strathmann 2004).

Deionization

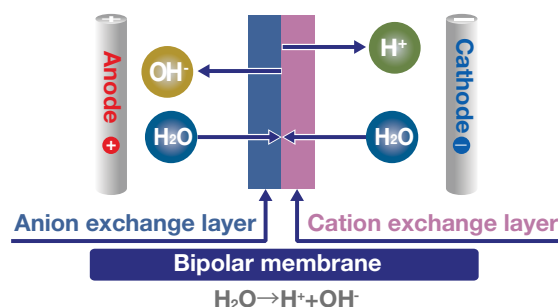
Electrodeionization (EDI) was first commercialized in 1987 by the Process Water Division of Millipore Corporation (now Evoqua Water Technologies). EDI (described in more detail in chapter 1) is now a well-established process for the production of ultrapure water for several markets, including pharmaceutical/biotechnology, power generation (boiler feed water), and microelectronics/semiconductor. EDI can treat water with relatively low electrical conductivity (e.g., 20 $\mu\text{S}/\text{cm}$) and produce high purity water approaching 0.055 $\mu\text{S}/\text{cm}$.

APPLICATIONS OF BIPOLAR MEMBRANE ELECTRODIALYSIS

Ion exchange membranes are selectively permeable. They contain fixed charges (anionic or cationic) and will allow the passage of counter-ions (opposite of the fixed charges) but not co-ions (of the same charge as the fixed charges). A cationic (positively charged) membrane will allow the passage of anions and is called an anion-permeable or anion-exchange membrane. An anionic (negatively charged) membrane will allow the passage of cations and is termed a cation-permeable or cation-exchange membrane. Normal electrodialysis stacks contain an alternating arrangement of separate anion exchange membranes (AEM) and cation exchange membranes (CEM).

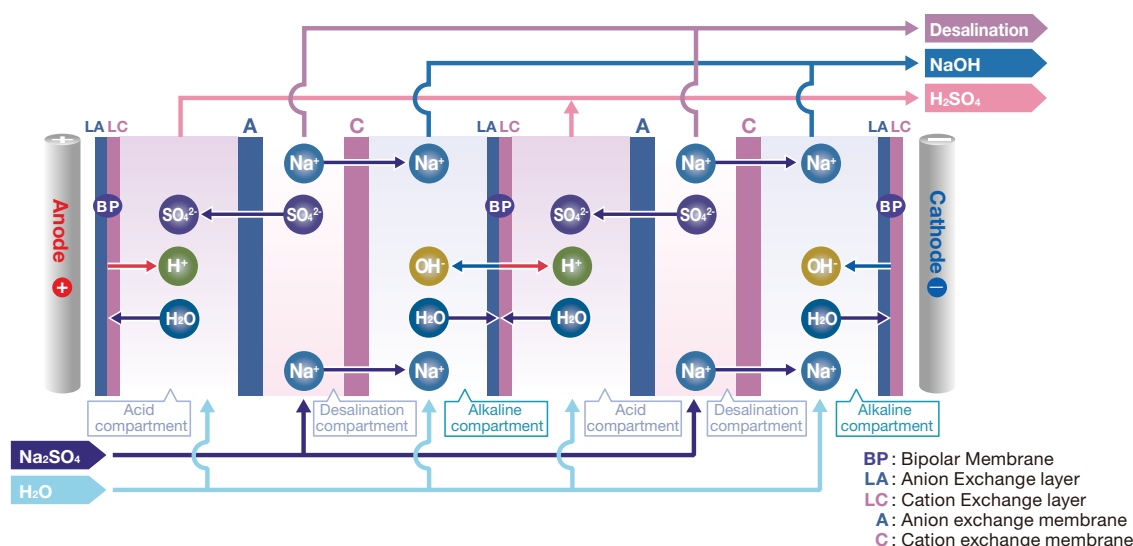
A bipolar membrane contains an anion selective layer and a cation selective layer laminated together with some sort of transition region between the two. Application of an electric field will first remove salt ions from the transition region, and when these have been removed further transport of current can only be accomplished by hydrogen and hydroxyl ions resulting from splitting (dissociation) of water. The hydroxyl ions become available on the anode side of the bipolar membrane, and protons on the cathode side. Water is transported into the transition region from the solutions on either side of the bipolar membranes, as shown in Figure 2.1.

The process of bipolar membrane electrodialysis (BMED) combines bipolar membranes with monopolar anion-exchange and cation-exchange membranes to allow conversion of a salt to its corresponding acid and base. In such a case the repeating unit, or cell triplet, comprises a bipolar membrane, an acid compartment, an anion-exchange membrane, a salt compartment, a cation-exchange membrane and a base compartment. This arrangement is shown in Figure 2-2.



Source: ASTOM Corp. Website

Figure 2-1 Water splitting in a bipolar membrane



Source: ASTOM Corp. Website

Figure 2-2 Production of acid and base from salt by BMED

The use of bipolar membranes has been widely investigated, for such wide-ranging applications as production of acid and caustic for regeneration of ion exchange resins; recovery of organic acids from fermentation processes; removal of sulfur dioxide from flue gas; recycling of acids from steel pickling solutions; and dissociation of alcohols for production of alkoxides, to name a few. However, the BMED process has not been widely practiced commercially. The most frequently mentioned reasons are the relatively poor chemical stability of both the bipolar and monopolar membranes which results in fairly short service life, and poor permselectivity leading to product contamination (Strathmann 2004).

ALTERNATIVE SOURCES OF DC POWER

The most common way to power an electrodialysis stack is to take alternating current (AC) power from the grid through an electrical subsystem as discussed in chapter 4. The