DEIONIZATION

A COMPARISON OF EDI TECHNOLOGIES

Electrodeionization (EDI) is the high-purity water treatment process that polishes reverse osmosis (RO) permeate without chemical regeneration. EDI has been in existence for more than 60 years, and has been commercially available for more than 27 years. Over time, EDI has become a proven and acceptable technology for all industrial water treatment users that require high-purity water. The process of operating an EDI system is extremely simple. EDI is continuous in nature and sometimes referred to as continuous electrodeionization (CEDI) or continuous deionization (CDI). There are several different commercially available EDI products with varying design, but all operate using the same principles of chemistry.

EDI modules are electrochemical devices, driven by electrical energy from an external DC power supply. Each EDI module consists of five primary components: ion exchange (IX) resin, 2 IX membranes (cation and anion exchange), and 2 electrodes (cathode and anode). Figure 1 shows a schematic diagram of the internal process of one type of EDI device. Two electrodes are on the ends of multiple cell pairs. Cell pairs include one diluting chamber and one concentrating chamber. As water flows through the EDI module, and power is applied, there are three processes occurring simultaneously: 1. The deionization process where the water is purified by IX; 2. ion migration where the ions are removed from the resin; and 3. continuous regeneration of the resin.

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Diluting chambers (D-Chambers) are the portion of a cell pair that contains mixed-bed IX resin where water is purified or diluted of ions. Concentrating chambers (C-Chambers) are the areas where water is concentrated of ions, and becomes wastewater. The D-chambers contain both cation-exchange resin and anion-exchange resin. The D- and C-chambers are separated by ion-selective membranes. The membranes are similar in material and charge to the IX resin. Cation-exchange membranes only allow cations to pass, and anion-exchange membranes only allow anions to pass. Water and oppositely charged ions may not pass across the IX membrane used in EDI.

Deionization is the removal of ions; both positively charge cations and negatively charged anions. Cations are positively charges ions because they have a loss of one or more negatively charged electrons. For example, the sodium ion (Na^+) is positive because the ion lost one electron. Calcium (Ca^{++}) has twice the positive charge of sodium because it has lost two electrons. Anions contain a negative charge because they contain one or more additional electrons.

Figure 2 shows the IX process where resin in the regenerated hydrogen (H^+) or hydroxide (OH^-) form allow the exchange of contaminant cations and anions with hydrogen or hydroxide ions. The released hydrogen and hydroxide ions bond to form water. Water is purified or deionized by the removal of the cations and anions as it flows through the mixed resin bed.

Ion migration. The second simultaneous process in EDI is ion migration. This differs from chemically regenerated IX as EDI continuously removes the ions from the resin, rather than remaining exhausted until chemical regeneration occurs. Once bonded with the resin, the electrical charge applied at the electrodes attracts the oppositely charged ions. The cations are attracted to the negative cathode and anions are attracted to the positive anode. Positively charged ions will migrate through the cation resin bed, through the cation exchange membrane and into the concentrate chamber because of their attraction to the cathode.

Negatively charged ions will migrate through the anion-resin bed, through the anion-exchange membrane and into the concentrate chamber because of their

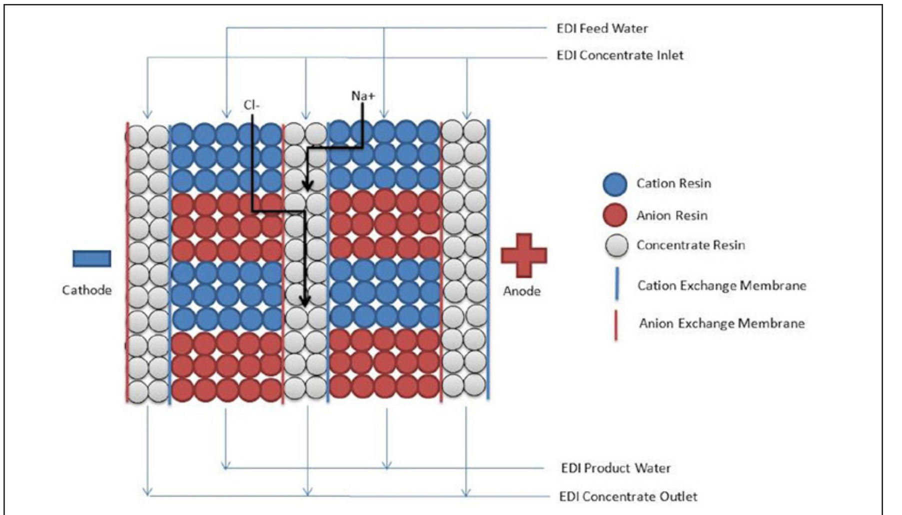

Figure 1. Schematic diagram of the internal process of one type of EDI device.

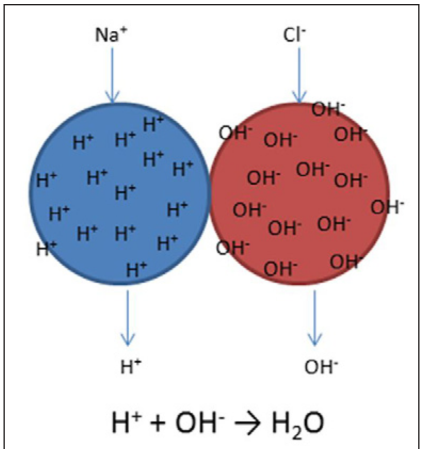

Figure 2. Illustration of the IX process where the regenerated resin allows for the exchange of the contaminant ions.

TABLE A
Current EDI Module and D-Chamber Thicknesses

Dilute Chamber	*Thickness*
Thin cell	3.0-4.0 mm
Thick cell	8.0-9.1 mm

attraction to the anode. Concentrate and electrode flush water exits the EDI module and is most often sent directly to drain since this is typically only 5% to 10% of the feedwater but could be higher for high scaling or fouling potential. Some EDI devices have a separate electrode flush stream. EDI waste water is typical high quality and can be recovered by the RO inlet by sending it to a ventilated RO feedwater storage tank.

Resin regeneration. The third process that occurs as the ions are removed and migrate to the concentrate chamber is resin regeneration. EDI does not require acid to regenerate the cation exchange resin, nor does it require caustic to regenerate the anion resin. Instead, it takes advantage of the electrical current that is applied across the EDI module. In the presence of the electrical field, a phenomena known as "water splitting" occurs. As illustrated in Equation 1, the electricity causes a small percentage of water molecules to split into hydrogen and hydroxide ions which continuously regenerate the resin bed:

$$H_2O \rightarrow H^+ + OH^- \qquad \textit{Eq. 1}$$

Therefore, EDI operation is continuous. The ions are continuously removed, and the resin is continuously regenerated and without chemicals. This provides a significant advantage to high-purity water users over either onsite or offsite chemically regenerated IX. The operation of the EDI system is as simple as operating an RO system and the results of EDI are more reliable.

Manufacturers of EDI

There are many manufacturers of EDI around the world. There are many manufacturers of EDI around the world[A]. The most common devices are Ionpure (United States), GE E-Cell (Canada), Dow EDI (China), Qua (India), and ElectroPure by SnowPure LLC (United States). The nations in the parentheses reflect where the products are manufactured.

Ionpure manufactures plate-and-frame style EDI devices with "all-filled" concentrate chambers and co-current flow path. Flows range from 0.01 gallons per minute (gpm) to 82.5 gpm per module. Devices are offered in both standard rectangular plate-and-frame, and round-disc variations. There are pharmaceutical-grade EDI modules available in both chemically sanitizable and instantaneous hot water sanitizable variations. Standard modules have a limit of 1 part per million (ppm) hardness and high-hardness modules have limits of 2 ppm (VNX-HH) and 4 ppm (VNX-CDIT). Standard modules can tolerate as high as 40 microsiemens per centimeter (µS/cm) feed conductivity equivalent (FCE) and VNX-CDIT can tolerate as high as 100 µS/cm FCE.

E-Cell manufactures plate-and-frame style EDI devices with "all-filled" concentrate chambers and a counter-current flow path. Flows range from 2.5 gpm to 28 gpm per module. Devices are offered in standard rectangular plate-and-frame design. There are pharmaceutical-grade EDI modules available that are both chemically and hot water sanitizable. Standard modules have a limit of 1 ppm hardness and high-hardness modules are no longer available. Standard modules can tolerate as high as 41 µS/cm FCE, or 25 ppm total exchangeable anions (TEA), or 55 ppm TEA with low-flow and warm feedwater.

Dow Water manufactures spiral-wound style EDI devices with conductive media concentrate chambers and a cross-flow path. Modules have a built in sample port. Flows range from 6.6 gpm to 10 gpm per module. There are no pharmaceutical-grade EDI modules available. Dow EDI modules have a limit of 0.5 ppm hardness and can tolerate as high as 40 µS/cm FCE (25 ppm TEA) with a 5-megohm-cm product quality or 8 ppm TEA with 15 megohm-cm. Double-pass RO is the preferred pretreatment for Dow EDI, but softened single-pass RO can be used in some cases.

Qua manufactures plate-and-frame style "fractional" EDI devices with unfilled concentrate chambers and a co-current flow path. Flows range from 2.2 gpm to 44 gpm per module. Devices are offered in standard rectangular plate-and-frame design with either single- or dual-voltage options. There are hot water sanitizable variations available. Standard modules have a limit of 0.2- or 1-ppm hardness. High hardness modules with dual voltage and split concentrate flow are available for 2-ppm (FEDI-2) or 3-ppm limits (FEDI-1). Qua EDI modules can tolerate as high as 40 µS/cm FCE with less than 20 µS/cm FCE required for high-purity water modules (FEDI-2HF).

SnowPure manufactures Electropure plate-and-frame style EDI devices with co-current flow path. Flows range from 0.04 gpm to 39.6 gpm per module. Devices are offered in standard rectangular plate-and-frame design. There are pharmaceutical-grade EDI modules available in both chemically sanitizable and hot water sanitizable variations. Standard modules have a limit of 1 ppm hardness and can tolerate as high as 33 µS/cm FCE, while < 9 µS/cm FCE is recommended for optimal performance.

EDI Module Designs

Most EDI modules are plate-and-frame design. The plate-and-frame normally consists of rectangular dilute and concentrate chambers separated by IX membranes and sandwiched between two electrodes. The components are held in place by tie rods or bolts. Because of the uneven pressure distributions as well as the materials of construction and methods of sealing, some plate-and-frames are prone to leaking. This can be prevented in most cases by following the manufacturer's torqueing procedures. While some modules do not require any torqueing, others require torqueing bolts once prior to start up, and others require torqueing as part of a regular maintenance schedule. The benefit of plate-and-frame designs are that electrical resistance is consistent and current is evenly distributed throughout the device.

Spiral-wound EDI modules are manufactured by winding the flat-sheet spacers and membranes into a spiral wound element similar to how RO elements are manufactured. Dow spiral-wound EDI modules connect the center concentrate stainless steel pipe to the DC power source, while the titanium anode lines the inner fiber reinforced plastic (FRP) pressure vessel housing. The benefit to this design is that there are no bolts to torque. The spiral-wound EDI is limited by the uneven flow and current distribution.

Ionpure MX and VNX modules use a "round disc" plate-and-frame design. The plate-and-frame design provides even current distribution. The round plate-and-frame EDI modules are housed inside a round FRP pressure vessel, eliminating any need for bolt torqueing.

Dilute Chamber Construction

Prior to 1996, all EDI modules used "thin-cell" dilute chambers. Dilute chambers contained mixed-bed IX resin in 3-millimeter (mm) compartments. The cost of manufacturing such a design was prohibitive for many potential EDI applications, so mixed beds were the standard polishing technology.

In 1997, Glegg Water Conditioning Inc.'s (now part of GE Water) E-Cell introduced the first "thick cell" EDI device that arranged resin in "clusters" of anion and cation resin. This development significantly reduced the cost of manufacturing EDI by reducing the amount of membranes and standardizing the size of modules.

Ionpure introduced the thick-cell LX module in 1999. This device used a "layered-bed" design where resin is arranged in cation- and anion-resin layers.

Both cluster beds and layered beds have a limited number of cation-anion interaction points and require water splitting for all ion removal. Therefore thick cells operate at low-current efficiency. Current efficiency is defined in Equation 2:

Eq. 2

% Current efficiency = (Theoretical Current/Applied Current) x 100

Where:

Theoretical Current is calculated using Faraday's Law, based on the concentration of ions removed and the flow per cell.

E-Cell offered a similar idea by the reciprocal of current efficiency, called E-Factor (Equation 3).

Eq. 3

E-Factor = Applied Current/Theoretical Current

For example, a typical EDI system may be designed for 10% to 20% current efficiency, or an E-Factor of 5 to 10.

SnowPure's Electropure dilute chamber is considered thin cell by comparison to thick cell design with a 4-mm thickness.

Qua's fractional electrodeionization (FEDI) is a device that splits its dilute stream into two passes. The first pass is operated at lower current with less water splitting to reduce hardness. The second pass is operated at a higher current to increase water splitting and remove weakly ionized species.

Recent research and product development resulted in a thin-cell innovation called the VNX-CDIT. This design benefits from an all-filled thin-cell configuration minimizing problems with concentration polarization. The resulting device is an EDI that can handle much higher concentrations of hardness, silica, carbon dioxide (CO_2), and ions.

The VNX-EP is a specially configured resin configuration for the power industry that provides low-sodium and low-silica product water.

Table A differentiates current EDI module D-Chamber thicknesses. Thin cell devices operate at lower current efficiencies, while thick cells use less membrane area. Low current efficiency does not necessarily result in low power consumption unless concentrate chambers have low electrical resistance.

Concentrate Chamber

Early versions of EDI modules include a mesh concentrate spacer. The mesh provides support to the membranes. The mesh is typically a nonconductive polymer that results in high electrical resistance, voltage, and power consumption. The early method of reducing the resistance was by recirculating a large portion of concentrate outlet to the inlet, increasing concentrate conductivity. Concentrate recirculation is not desirable as the scaling and fouling contaminants being removed are recirculated in higher concentrations than in the feedwater.

Another method to increase conductivity is injecting a food-grade salt into the concentrate chamber to further reduce electrical resistance. Consistent conductivity is difficult to maintain with brine injection and this approach results in salt in unattractive locations. Mesh has also been shown to be problematic with biofouling. The concentrate chamber is prone to hardness scaling, especially in systems operated with low-current efficiency, so a design with maximum durability is desired for optimal performance.

Ionpure introduced a patented "All Filled" design in 1996 that includes resin in both the dilute chamber and concentrate chambers. The resin is a conductive media and allows efficient and even current passage with lower voltage and power consumption. While previous generations E-Cell MK-1 and MK-2 required concentrate recirculation and sometimes brine injection, GE introduced an all-filled design with the current MK-3 module in 2007, followed by the larger E-Cell-3X module in 2011.

Dow uses a concentrate screen that has been treated to provide IX properties, thus becoming ionically conductive. This eliminates the previously required concentrate recirculation and brine injection.

SnowPure reports that the Electropure modules use a thin concentrate spacer approximately 0.7-mm thick with woven fiber mesh. Concentrate flows through in a once through path. This design requires that concentrate conductivity be maintained between 10 to 100 µS/cm. Single-pass permeate is sometimes used

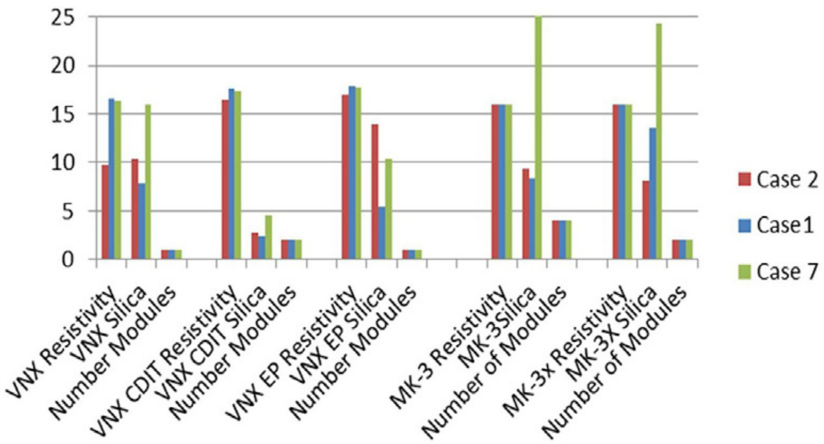

Figure 3. Unsoftened single-pass RO data from Cases 1, 2, and 7 in Table B.

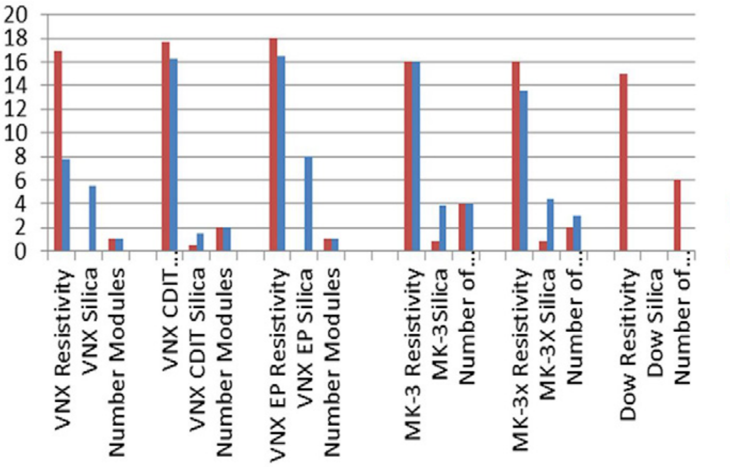

Figure 4. Two-pass RO and softened single pass data from Cases 3 and 4 in Table B.

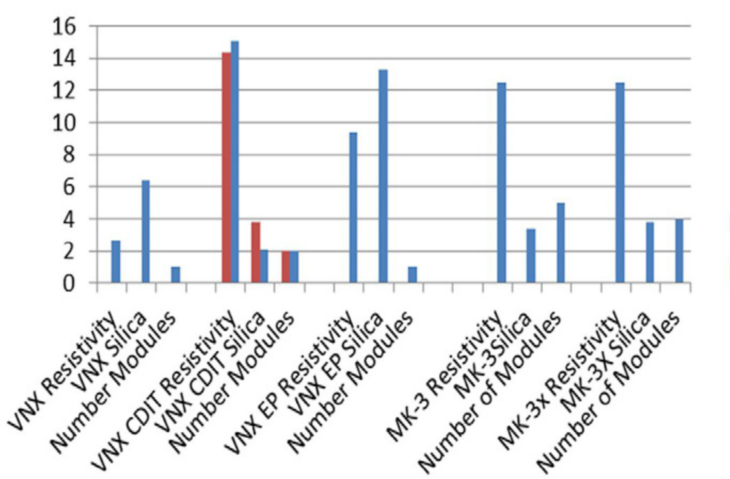

Figure 5. High CO_2 and hardness single pass data from Cases 5 and 6 in Table B.

as EDI concentrate feed with two-pass RO feed to increase concentrate conductivity. Alternatively, brine injection can be used in those cases.

The Qua EDI uses a once-through concentrate flow, but brine injection is required in some cases.

E-Cell is the only device that provides a "counter flow" concentrate design. In this design, concentrate enters next to the dilute outlet end exits adjacent to the concentrate inlet. Therefore, hardness does not pass all the way through the concentrate stream. In this design, higher feed pressure is required to maintain lower dilute pressure than concentrate pressure. Co-current flow is possible with hardness less than 0.1 ppm as calcium carbonate ($CaCO_3$).

Single- or Two-Pass RO Pretreatment

The pretreatment design and membrane selection is critical to a successful EDI installation. The EDI modules selected along with the knowledge and experience of the process design engineer will determine whether the RO can be single pass or double pass.

Single-pass RO systems have higher concentrations of scaling and fouling contaminants such as hardness, silica, and organics. Additionally, the performance can be affected by conductivity, scaling or fouling, and higher CO_2. Sodium hydroxide injection prior to the RO membranes is a low-cost method of controlling CO_2. By raising the pH, the RO membranes become more prone to scaling because of higher Langlier Saturation Index (LSI). Double-pass RO with caustic injection prior to second pass or membrane degasification provides the lowest stress to an EDI unit; however, this approach has the highest capital cost and is not always needed.

Some EDI suppliers are working to reduce the overall system cost by eliminating the need for a second-pass RO. Other EDI suppliers prefer two-pass RO. Dow offers an extended warranty for systems with two-pass RO feed.

There as many successful installations of EDI with single-pass RO around the world. One provided by one supplier[B] in 2006 has single pass RO feed treating 900 to 1,200 µS/cm and more than 300 ppm hardness as CaO_3. In 2014, the EDI system with a standard module is producing 17 megohm-cm.

Performance

All EDI manufacturers market a product water of up to 18 megohm-cm, but such a product quality will greatly depend on the EDI feedwater. Different EDI modules will produce different product qualities even with the same feedwater. Little research has been done to compare the performance of different EDI modules or standardize testing for comparative evaluation.

During the preparation of this article, each EDI manufacturer was requested to provide guaranteed product quality of various feedwaters. Feedwater sources outlined in Table B were selected from actual EDI projects (Case Studies 1 through 7) with a variety of combinations, single-pass or double-pass RO, softened or unsoftened, caustic injection or no caustic injection. Ion concentrations are listed in ppm as ion. Ionpure, GE, and Dow provided their product quality if an EDI module was available to treat the feedwater. For standard comparison, 50 gpm product flow and 60°F feedwater was used. Figures 3 through 5 present data from Cases 1 through 7 in graphs.

Figure 3 shows the performance of various EDI modules with unsoftened single pass RO feed described in Cases 1, 2 and 7. Hardness in these cases are less than 1 ppm as $CaCO_3$.

Figure 4 shows the performance of various EDI modules with typical two-pass RO feed (Case 3) and feedwater treated with softened single-pass RO feedwater (Case 4).

Figure 5 shows the performance of various EDI modules with high hardness (Case 5) and high CO_2 (Case 6).

TABLE B
Results of Water Quality from EDI Treatment

Case:	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Ca	0.2	0.21	0.00	0	0.5	0.03	0.06
Mg	0.06	0.06	0.00	0	0.12	0.01	0.05
Na	0.56	0.43	0.18	0.82	1.01	2	0.76
K	0.00	0.09	0.01	0.01	0.06	0.06	0.05
NH_4	0	0	0	0	0	0	0
Ba	0	0	0	0	0	0	0
Sr	0.00	0.00	0	0	0.01	0.01	0
CO_3	0.00	0	0	0	0	0	0
HCO_3	2.09	1.80	0.44	0.73	3.63	3.63	0.92
SO_4	0.02	0.02	0.01	0.02	0.07	0.07	0.04
Cl	0.15	0.14	0.04	0.36	0.89	0.89	0.95
F	0.00	0.00	0.00	0	0	0	0
NO_3	0	0	0.00	0.85	0.30	0.30	0.07
SiO_2	0.24	0.23	0.05	0.12	0.12	0.11	0.46
CO_2	0.31	8.07	0.2	13.8	16.8	16.8	1.24
pH	7.09	5.6	6.61	4.95	5.59	5.59	6.13
TEA	3.8	13.5	0.82	20.9	39.2	39.2	4.41
FCE	5.29	26.9	1.49	31.	56.9	56.9	9.15
Hardness	0.731	0.771	0.01	0	1.76	0.12	0.4

Note: Data in Table B is based on studies by EDI manufacturers mentioned in article text.

Conclusions

EDI is a reliable and cost effective technology for the production of high-purity water. There are many available EDI modules on the market and the selection of the optimal EDI module depends on the performance required, feedwater source, and available budget. Double pass RO is not always required, depending on the modules selected.

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Endnotes

[A]The companies that make these EDI products mentioned in the text are as follows: Ionpure, Evoqua Water Technologies, LLC, Warrendale, PA; GE E-Cell, GE Power and Water, Trevose, PA; Dow EDI, Dow Water and Process Solutions, Midland, MI; Qua, Qua Group LLC, Canonsburg, PA; and ElectroPure, SnowPure LLC, San Clemente, CA.

[B]Agape Water Solutions Inc. of Harleysville, PA, is the supplier referenced in the text that developed a single-pass RO feed for treating 900 to 1,200 µS/cm and more than 300 ppm hardness (as CaO_3). producing 17 megohm-cm.

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