

DEIONIZATION

PART 2: A COMPARISON BETWEEN SPIRAL-WOUND AND PLATE-AND-FRAME EDI TECHNOLOGIES

Part 1 of this series compared spiral-wound electrodeionization (EDI) with more traditional plate-and-frame EDI. The plate-and-frame design is similar in construction to a plate heat exchanger with multiple fluid chambers sandwiched between a set of endplates (and electrodes). Within there are a series of cation and anion ion-exchange (IX) membranes. The spiral-wound design uses a pressure vessel more similar to reverse osmosis membranes.

This article examines the serviceability and EDI module life of the spiral-wound design. IX resin, feedwater requirements, power consumption, module pairing, and performance are among other topics that will be addressed.

Serviceability and Module Life

The spiral-wound EDI module offers the only serviceable EDI system in the market as the replacement of resins and/or membranes is possible at anytime while reusing the housings, end caps, and titanium anode without difficulty resealing. This unique feature dramatically reduces the operating cost by extending the useful life of the spiral-wound EDI modules. Therefore, reducing the high replacement cost for the conventional EDI modules can lower operating costs. The fact that resin replacement can be done in place of module replacement for about 1/10th of the cost of

plate-and-frame stacks offers a reduction of operating costs over the life of the spiral-wound EDI module.

The influence of EDI module life is far greater on the overall operating cost than the influence of power consumption by the EDI module and associated electrical equipment in the EDI system. Previous EDI discussions show that the main contributor to EDI system operating cost is module replacement (1, 2). As these spiral-wound EDI modules are serviceable on-site or locally, it is not necessary to send the modules back to the manufacturing facility. On the contrary, manufacturers of plate-and-frame EDI devices do not sanction field rebuilding of modules (3). This is largely because of the requirement of high closing torque (in the vicinity of 20 foot-pounds) to assemble the plate-and-frame modules as well as the massive size and the difficult alignment of "cell packs". New plate-and-frame "stacks" are torqued at proper levels at the factory before shipping. Too much torque will result in deformation of the stack, while too little torque will result in internal and external leaks.

In the spiral-wound EDI modules, replacement of resins and/or membranes does not entail application of such torque to prevent leakage. Consequently, the task of membrane and/or resin replacement can be done in much shorter periods of time, usually about 20 to 30 minutes. The weight of one individual

spiral-wound EDI module is approximately 60 to 70 pounds and can be easily removed from the system for service while the remaining modules in the system continue to operate. One should realize that plate-and-frame devices characteristically suffer from leaks because of the difficulty of sealing rectangular pressure vessels. Most of the plate-and-frame "stacks" depend on either the gasket of the concentrate spacer or O-rings in the dilute spacers to prevent leakage. In comparison, spiral-wound EDI devices employ a fiber-reinforced plastic (FRP) pressure vessel where re-building merely involves opening and closing of threaded end-caps. The spiral-wound EDI design ensures the EDI module is easily assembled again with reliable sealing.

Ion Exchange Resin

IX resin acts as a path for ion transfer and also serves as an increased conductivity bridge between the membranes for the movement of ions. Customized cation and anion resins can be used in the spiral-wound EDI modules to maximize their performance for a given feedwater quality. Specially graded resins are used in the spiral-wound EDI modules. The resin beads are flushed out in less than 10 minutes with water under a voltage gradient between the cathode and the anode in order to remove extractable ions from the resin beads.

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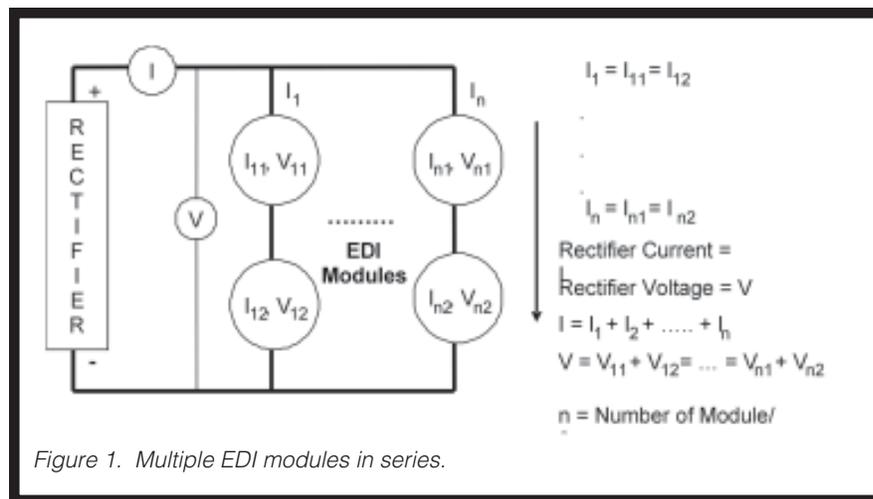


Figure 1. Multiple EDI modules in series.

As stated earlier in reference to the spiral-wound EDI modules, the only serviceable EDI technique in the market allows the replacement of resin at any time. Replacement of mixed resins in the spiral-wound EDI modules is accomplished by various proprietary methods.

Feedwater requirements. Appropriate pretreatment of the water is a basic prerequisite for optimum performance of the EDI process. The pretreatment should remove hardness, particulate matter, and chlorine. A major limitation of this process is the tendency of the membranes to become fouled by hard water constituents. Because of their requirements for softened pretreated water, EDI devices are always coupled with upstream RO units (4). Chlorine will attack IX resins and cause de-crosslinking, which results in reduced capacity. Particulate matter, organics, and colloids can cause the plugging and fouling of membrane and resin beds.

Since carbon dioxide (CO₂) is typically present in significant concentrations in the RO permeate water and is removed by a combination of anionic bicarbonate and carbonate forms, the total exchangeable anion (TEA) load is usually greater than the cation load (total exchangeable cation [TEC]) and determines the required EDI operating conditions (5). If free carbon dioxide is present in the EDI feed, as it generally is, it will also be present in the concentrate, and since it is not ionic, it will diffuse without restraint through the cation membrane back to the diluting chamber. It cannot diffuse through the anion membrane because most of the anion membrane is alkaline and the carbon dioxide would be converted into bicarbonate in the membrane and forced back into the concentrating chamber by the voltage gradient.

Bicarbonate or carbonate ions are forced by the voltage gradient within the concentrating chamber towards the cation membrane. The boundary layer next to this membrane is acidic, as is the membrane itself. This converts both bicarbonate and carbonate into carbon dioxide, which can diffuse without restraint into the diluting chamber through the cation membrane (6). Consequently, the occurrence of carbon dioxide and alkalinity at more than the recommended values can account for the degradation of EDI product water quality. The feedwater requirements for the

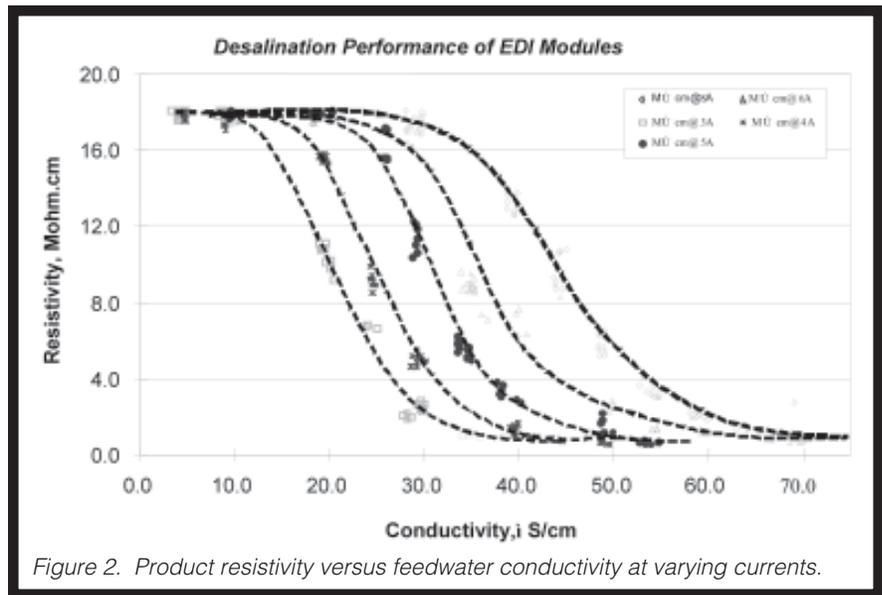


Figure 2. Product resistivity versus feedwater conductivity at varying currents.

spiral-wound EDI modules are as follows:

- TEA ≤ 25 ppm as calcium carbonate (CaCO₃)
- pH 5.0 to 9.0
- Hardness ≤ 2 parts per million (ppm) as CaCO₃
- Dissolved silica ≤ 1 ppm as SiO₂
- Total organic carbon (TOC) ≤ 500 parts per billion (ppb)
- Free chlorine ≤ 0.05 ppm
- Iron (Fe), Manganese (Mn) ≤ 0.01 ppm
- Carbon dioxide ≤ 10 ppm
- Alkalinity ≤ 20 ppm as CaCO₃
- Temperature 10 to 38°C

At this point it is important to realize that feedwater conductivity does not show a complete picture of the total ionic load in a water system. Conductivity measurement devices do not detect the full amount of weakly ionized species like CO₂, silica, and boron (7). Consequently, total ionic load is more accurately described by TEA and feedwater conductivity equivalent (FCE). Equation 1 illustrates TEA and Equation 2 illustrates FCE. (Editor's note: All equations for the article appear in a single Equations Table.)

All the EDI units have an upper operating temperature limit of approximately 38°C. The spacer material, the membrane material, and the anion-exchange resin present in the diluting chamber establish this limit. As the feedwater temperature decreases, reaction kinetics and diffusion rates decelerate and EDI module electrical resistance increases, causing a decline in perfor-

mance.

Power Consumption

The main consumable in EDI is electricity. The applied DC current, not the voltage, is the main parameter for the design of EDI units. The amount of current used by an EDI module is a function of the flowrate and the amount of salt being removed. Faraday's Law states that 96,500 amperes of electric current is required for 1 second to move one mole of ionic charge between electrodes. This is same as 26.8 amperes for one hour. One can also write 1 Faraday of charge is required to transfer 1-gram equivalent of salt. This is shown in Equation 3 where 1 Faraday = 96,500 ampere-seconds = 26.8 ampere-hours.

Equation 3 indicates that higher impurity concentrations and higher flowrate will entail a higher applied DC current in order to achieve the desired product water quality. Current efficiency is defined as the ratio of the current that transfers salt to the total amount of current applied. At this stage, it is imperative to realize that applied current level primarily determines the resistivity, silica, and boron concentration in the product stream.

The current is supplied by a power source capable of automatically increasing or decreasing voltage in response to a change in the electrical impedance of the EDI module to maintain constant current. Over time, the electrical impedance of all the modules increases, resulting in a gradual decrease in current at a given voltage level. All EDI manu-

TABLE A
Field Installation with 1 ppm as CaCO₃ or higher of Spiral-Wound EDI Feedwater Hardness

| <i>Plant</i> | <i>Start-up Date</i> | <i>Feedwater Conductivity (μS/cm)</i> | <i>Feedwater Hardness (ppm as CaCO₃)</i> | <i>Product Resistivity (megohm-cm)</i> | <i>Product Flowrate (gpm)</i> | <i>Cleaning Frequency (No. times/year)</i> |
|--------------|----------------------|---------------------------------------|---|--|-------------------------------|--|
| A | 2001 | 12.7 | 1.62 | 12.5 | 350 | 2 |
| B | 2001 | 11 | 1.76 | 6.0 | 260 | 2 |
| C | 2002 | 8.9 | 1.0 | 14.0 | 215 | 1 |

facturers limit the maximum DC rectifier voltage to 350 to 600 VDC, in order to elude the need for the more expensive wiring construction that is necessary for higher voltages.

Rectifiers used with the spiral-wound EDI modules require 350 VDC for 40 gallons per minute (gpm) systems and larger, even though the modules are limited to 160 VDC because of the patent-pending design of wiring multiple modules in series (Figure 1). This design reduces the current required by 50%, but doubles the voltage requirement. Although the rectifier is sized for a 175 VDC/module, the actual voltage requirement to achieve a desired current is normally in the vicinity of 75 to 110 VDC/module. Therefore, a standard 350-VDC rectifier may be used, a fraction of the 600 VDC typically required with plate-and-frame devices. Actual power consumption can be computed by using Equation 4.

Ohm's law indicates that the current flowing through an EDI module is directly proportional to the voltage applied, and inversely proportional to the overall resistance of the module (Equation 5).

Ammeters have extremely small internal resistances and are connected in series with the modules through which one wishes to measure the current (Figure 1). Voltmeters have extremely high internal resistances and are connected in parallel with the modules across which one wishes to measure a voltage drop (Figure 1). Equation 5 indicates that lower overall EDI module resistance will entail a lower voltage in order to pass a fixed amount of current through the module. The overall resistance is equal to the sum of the individual resistances, just as is the case in the flow of electric current through a series of resistances. The overall resistance of an EDI module is equal to the sum of that offered by individual membranes, resins, concentrate stream, anolyte, and catholyte at a given feedwater temperature and ionic

composition. For a given feedwater composition, electrical power necessary to attain a desired product water quality increases with the decrease in the water temperature for both plate-and-frame and spiral-wound EDI configurations because of increases in the overall module resistance.

The structural design of the spiral-wound EDI modules reduces the distance between anode and cathode, resulting in less overall module resistance when compared to conventional plate-and-frame modules. It is interesting to note that the distance between anode and cathode in the spiral-wound EDI modules is smaller than its radius while the overall length of the module in the conventional plate-and-frame configuration separates anode and cathode. Lower overall module resistance in spiral-wound EDI configuration leads to significant reduction of necessary voltage when compared to conventional plate-and-frame counterpart to obtain a given current through the module. However, the current density at the outside is lower compared to that near the center in the spiral-wound EDI modules.

To compensate for such uneven current density, sufficient current should be applied to achieve the desired desalination performance near the outer wall of these modules. Impact of the lower necessary voltage outweighs the higher current demand in determining the overall power consumption by the spiral-wound EDI modules. Consequently, reduction in power consumption by 20% to 25% is expected in spiral-wound EDI configurations when compared to conventional plate-and-frame modules. Moreover, paired wiring of modules in the spiral-wound EDI systems further lessens the power consumption. The steep escalation of energy costs in recent years has forced many companies to minimize the power consumption of various unit operations in high-purity water systems. As a re-

sult, power consumption has become a critical plant design and operation consideration. The use of EDI devices in the spiral-wound configuration can provide a significant contribution towards the needed conservation effort.

Pairing of Spiral-Wound Modules

Variance is a measure of heterogeneity of EDI module resistance. Variance will occur based on the electrochemical characteristics of each module, such as internal resistance and flow variance from module to module. As explained earlier, paired wiring sequence of the modules is employed in the spiral-wound EDI systems. Pairing of EDI modules creates homogeneous groups and reduces variation in passage of current through different modules. The resistance of each module can be slightly different but the same amount of current will flow through each in a group. The total resistance of a pair of modules connected in series is the sum of the resistances of the individual modules.

The variance is a measure of how spread out the current distribution is. It is computed as the average squared deviation (SD) of each number from its mean. A commonly used measure of dispersion is the standard deviation, which is simply the square root of the variance. Because the differences are squared, the units of variance are not the same as the units of the data. Therefore, the SD is reported as the square root of the variance and the units then correspond to those of the data set. Standard deviation is also useful when comparing the spread of two separate data sets that have approximately the same mean. Standard deviation is the measure of spread most commonly used in statistical practice when the mean is used to calculate central tendency. The SD for current drawn by N different group or individual EDI modules is defined in Equation 6. The bias can be corrected by using (N - 1) in the denom-

inator instead of just N, in which case sample SD becomes an unbiased estimator of the population SD. This is illustrated in Equations 6 and 7.

SD would always be larger if all the individual EDI modules are connected in parallel when compared to wiring of paired modules in series. The voltage is the same across all the individual modules in parallel connections. In this situation the amount of current passing through each module depends on the individual module resistance. Pairing of EDI modules reduces variation in the group resistances of the EDI circuits and lowers the dispersion in current flow through the modules.

In absence of paired wiring of EDI modules, one needs to apply sufficient voltage across the modules to achieve the minimum desired current through the module with the highest resistance. Homogenization of group resistance by using paired wiring leads to achievement of the same minimum desired current through the module with the highest resistance at a significantly lower applied voltage when it is coupled with a module that offers below average module resistance. Consequently, wiring a pair of EDI modules in series entails a lower applied voltage to achieve a given current level through the individual modules. Consequently, the design of wiring paired modules in series will significantly reduce the power consumption of the system without compromising on the quality of the product water for a given feedwater quality.

Performance Data

A full-size spiral-wound EDI system was operated on varying feedwater quality. Module desalination performance was evaluated by constructing a desalination performance curve as shown in Figure 2 (8). Desalination performance of the spiral-wound EDI modules was evaluated at various applied DC currents and feedwater conductivities. The dilute flowrate was kept constant at 2.0 cubic meters per hour (m³/h) per EDI module. The curves all have the same characteristic shape that in the beginning show a high resistivity plateau. Eventually that gives way to deterioration in product resistivity at higher feed conductivity values. The rudimentary requirement is to provide sufficient current to attain the desired product water quality for a given feedwater conductivity.

The spiral-wound EDI system at the Aquila Lake Road Power Plant in Missouri was producing product water where silica levels in the EDI product water were below the detection limit of 1 ppb. The spiral-wound EDI capacity was set at 125 gpm. The primary motivation of the customer for selecting EDI was to eliminate the chemicals needed for regeneration of conventional mixed-bed deionizers. This skid-mounted spiral-wound EDI system operated at 95% recovery. Conductivity of the concentrate stream was maintained at 215 to 275 microsiemens per centimeter ($\mu\text{S}/\text{cm}$) at 25°C. The spiral-wound EDI performance, measured as product resistivity, has remained consistently high at 14 to 16 megohm-cm at 25°C.

Table A contains data from three field installations that had 1 ppm as CaCO₃ or more of feedwater total hardness. The systems have been successfully operating for more than 2 years (Table A). The supplier of the spiral-wound EDI modules offers two different kinds of modules^a. One is designed to generate 5-megohm-cm resistivity and the second will generate 15-megohm-cm product water resistivity. This feature provides a low-cost option for EDI users who do not require high-purity quality water. Note that the 5-megohm-cm unit employed in the Plant B is producing 6-megohm-cm quality when 5-megohm-cm would have been expected.

Summary

The article series has compared two types of EDI—the conventional plate-and-frame design, and the newer spiral-wound design. Part 1 examined topics such as the design and operation of both EDI approaches, water recovery and scaling, and cross-flow designs. Part 2 reviewed EDI module life., feedwater requirements, power consumption, pairing of spiral-wound EDI modules, and performance data. ■

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Endnotes

^aEDI-210, which is designed to generate 5-megohm-cm resistivity and EDI-210U, which is designed to generate 15-megohm-cm product water resistivity. Omexell Inc. offers both models.

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Key words: CALCIUM CARBONATE, CARBON DIOXIDE, DEIONIZATION, EDI, HARDNESS, ION EXCHANGE, REVERSE OSMOSIS, SILICA

EQUATIONS TABLE

$$\begin{aligned} TEA \text{ (ppm as CaCO}_3\text{)} &= CO_3^{2-} \text{ as ppm CaCO}_3 + 1.7 \times HCO_3^- \text{ as ppm CaCO}_3 \\ &+ 50000 \times 10^{(pH-10)} + (SO_4^{2-} + F^- + Cl^- + NO_3^-) \text{ as CaCO}_3 + 0.83 \times SiO_2 \text{ as ion} \\ &+ \frac{1.7 \times 50}{44} \times CO_2 \text{ as ion} \end{aligned} \tag{Eq. 1}$$

$$FCE \text{ (}\mu\text{S/cm)} = \text{Feedwater Conductivity (}\mu\text{S/cm)} + \text{ppm CO}_2 \times 2.66 + \text{ppm SiO}_2 \times 1.94 \tag{Eq. 2}$$

$$I = \frac{F \times Q_p \times \Delta N \times 1000}{E \times N_{cp}} \tag{Eq. 3}$$

Where:

I = Applied Direct current (amperes)

F = Faraday's constant (ampere-hours/g-equivalent)

Q_p = Flowrate through dilute chambers (m³/hour)

ΔN = Change in normality of dilute stream between inlet and outlet (g-equivalent/liter)

E = Current efficiency in fraction (dimensionless)

N_{cp} = Number of cell pairs (dimensionless)

$$\text{Power Consumption} = \frac{I \times V}{1000 \times \eta_R \times Q_p} \frac{kW - h}{m^3 \text{ Water}} \tag{Eq. 4}$$

Where,

V = Applied voltage (amperes)

η_R = Rectifier Efficiency (fraction)

$$I = \frac{V}{R} \tag{Eq. 5}$$

Where:

R = the overall resistance of the EDI module.

$$SD = \sqrt{\frac{\sum_{j=1}^N (I_j - \bar{I})^2}{N-1}} \tag{Eq. 6}$$

$$\bar{I} = \frac{1}{N} \times \sum_{j=1}^N I_j \tag{Eq. 7}$$

Where:

I_j = Current drawn by jth group or individual EDI module (amperes)

\bar{I} = Mean current (amperes)

SD = Standard deviation of current drawn by N different group or individual EDI modules (amperes)