Cost Effective Modular Electrodeionization(EDI)

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COST-EFFECTIVE MODULAR ELECTRODEIONIZATION (EDI)

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ABSTRACT

Electrochemical deionization (EDI) offers continuous demineralization at higher water recovery rates (>90%), compared with mixed bed ion exchange, and without the use of chemical regenerants and the associated production of saline waste water. Although EDI technology has been used in some power generation applications, its wider application requires the satisfactory resolution of outstanding capital cost and performance issues. This paper reports on the field evaluation of a new cost-effective EDI technology in a power generation application. The E-Cell System™, which became commercially available in the fourth quarter of 1996, consists of a rugged, modular system, based on a new high-performance EDI stack.

Starting in May 1996, a 100 gpm modular EDI pilot system, rated for operation at 100 psi, was evaluated at the TVA Brown's Ferry Nuclear Plant. The feed consisted of Reverse Osmosis (RO) permeate with a conductivity of 4-7 μS/cm. The pilot system reliably produced 17.8-18.0 MΩ.cm water under design operating conditions, independent. Silica levels were reduced from ca. 50 ppb to 4 ppb, while TOC levels were reduced from ca. 120 ppb to 30 ppb.

INTRODUCTION

The production of high purity water to met the growing needs of the semiconductor, power generation and petrochemical industries has undergone major structural, competitive and technological changes over the last two decades. Driven by cost, environmental and quality factors, the water systems in use have undergone major technical changes during this period. In particular, there has been a definite trend to reduced dependence on ion exchange (IX) processes in order to minimize the use of regenerant chemicals and improve the yield of product water. A good example of this trend is the popularity reverse osmosis (RO) membrane technology has gained as a pretreatment for ion exchange demineralization, resulting in reduced capital and operating costs of the subsequent ion exchange processes. This substantial shift to RO membrane technology, which is particularly well advanced in Asia and the Americas, has taken place in just the last ten years.

Electrodeionization (EDI), in which the ion exchange media is continuously regenerated electrochemically using ion-exchange membranes, has the potential to bring similar benefits of reduced chemical usage and improved recoveries in replacing post-RO ion exchange (MB or C/A/MB) in high flow rate water systems in power generation applications. However, in order to realize this potential, EDI technology must achieve high reliability and consistently high product quality, while being cost competitive with current ion exchange technology.

This paper describes the development and introduction of the recently introduced E-Cell™ EDI technology and reports on pilot experience at the 200 gpm water plant operated at the TVA Brown's Ferry Nuclear Station. The E-Cell System™ is a high performance, cost-effective and flexible modular EDI technology developed jointly by Glegg Water Conditioning, Inc. and the Asahi Glass Company.

ION EXCHANGE vs MEMBRANE PROCESSES

The remarkable market penetration of RO membrane technology in the front end of water systems provides an instructive recent example of the widespread replacement of ion exchange unit operations by more efficient, continuous membrane processes. Early attempts to introduce RO membrane technology for industrial use met with reliability and performance problems, mainly associated with the high pressures required to achieve reasonable fluxes, limited membrane life, poor pretreatment selection and the lack of operating experience and guidelines.

Following this rather problematic initial introduction, viable RO technology, based on a new generation of membranes and a better understanding of operating requirements, was eventually introduced in the 1980's. The commercial introduction of RO then proceeded rapidly, so that today in Asia and in the Americas, most new and many retrofit water systems employ RO instead of the traditional IX systems. Furthermore, by using specific newly-developed membranes, RO technology has been successfully applied in other areas, including in large scale desalination. Thus, when technical performance and cost issues related to RO were satisfactorily resolved, its widespread introduction took place in a remarkably short time. Currently, many industries are applying membrane water purification technologies in recycling waste streams, such as rinse waters in semiconductor fabrication plants.

A problem still existed downstream of the RO in that additional ion exchange processes such as mixed bed (MB) or cation/anion/MB IX are required to meet the higher water purity demanded by industrial users. As efficient as RO technology is (typically 75% recovery), it cannot effectively remove ions to produce water with resistivities above 1 MΩ.cm, even in double pass applications.

EDI holds considerable potential for replacing IX processes in deionization by providing consistently high levels of deionization and removing contaminants such as silica and TOC, at attractive recoveries (ca. 90%+). Widespread adoption of EDI requires that this performance be delivered reliably in robust industrial equipment, cost-competitive with that of mixed bed ion exchange units and their ancillary equipment. The current EDI technology commercialized in 1986 appears to have been developed for small systems (ca. lab scale to 40 gpm) and is not cost-effectively scaled up to larger systems in the 100-2,000 gpm range. This latter result is partly due to the high cost and large area of membrane used. A recently introduced spiral EDI technology shows excellent performance[1], however, the cost is substantially higher due also to the intricate manufacturing technique.

E-CELL™ EDI TECHNOLOGY

To address the above opportunity, a modular EDI system was developed jointly by Glegg Water Conditioning, Inc. and the Asahi Glass Company. This joint development effort combined the experience of Glegg Water Conditioning in high purity water and systems integration, with that of Asahi Glass in membranes and electrochemical membrane processes. The goal of this development was to create a reliable, cost effective, robust alternative to conventional mixed bed technology for use initially in primary deionization in high flow rate systems (100-2,000 gpm). In 1996, we achieved that goal in the development of the E-Cell™ modular EDI system. The E-Cell System™ has undergone rigorous testing both under lab conditions and, more importantly, in field trials. Active commercialization and patent application are currently underway.

Modular nature of the E-Cell™ technology

In addition to illustrating well the trend towards membrane processes in water purification, modern RO technology also demonstrates the benefits of a modular system based on standardized components. Specifically, current RO technology offer flexibility in tailoring system capacity and performance to particular needs, while benefitting from the economies of scale associated with mass production of the standard RO elements and pressure housings. Therefore, a particular RO system is made up of an appropriate number of standard RO pressure housings containing standard RO elements.

For these reasons, a modular approach was taken in the development of the E-Cell™ product. This design feature was an important focus of the product development effort and a key to its success. The modular EDI system is built up from one or more E-Cell Racks™, just as an RO system consists of RO pressure housings. Each E-Cell Rack™ consists of several E-Cell Stacks™, analogous to the RO elements in each RO housing. A photo of an E-Cell System™ is shown in Figure 1.

In addition to the benefits noted above, such modular systems allow for convenient isolation of a particular RO pressure housing or E-Cell Rack™, and for the quick diagnosis and replacement of a faulty RO element or E-Cell Stack™. This increases system throughput and reduces system down time, compared, e.g., with an equivalent monolithic system configuration.

In summary, the E-Cell System™ hierarchy consists of a System composed of Racks, each comprising any number of EDI Stacks.

E-Cell System™ and E-Cell™ Rack

The E-Cell Rack™ is the building block of an E-Cell System™ and is made up of E-Cell Stacks™. In view of the range of system sizes required (100-2,000 gpm) a nominal rack capacity of 100 gpm was chosen. The E-Cell Rack™ was designed to be vertically stackable, 3 high, with a footprint of 4 feet x 5 feet.

Standard E-Cell Systems™ or trains were designed with nominal flow rates of 50, 100, 300 and 600 gpm. Each of these trains includes appropriately-sized standard subsystems, mounted at ground level below the stackable racks, providing the necessary pumping, water distribution and electric power rectification. These standard E-Cell Systems™ can then be combined flexibly to yield the desired system capacity. Intermediate flow rates can be achieved using the same standard building blocks by selecting the appropriate number of E-Cell Racks™ or E-Cell Stacks™.

The 50 gpm E-Cell System™ was developed primarily for pilot application and is available with an optional stand-alone control package.

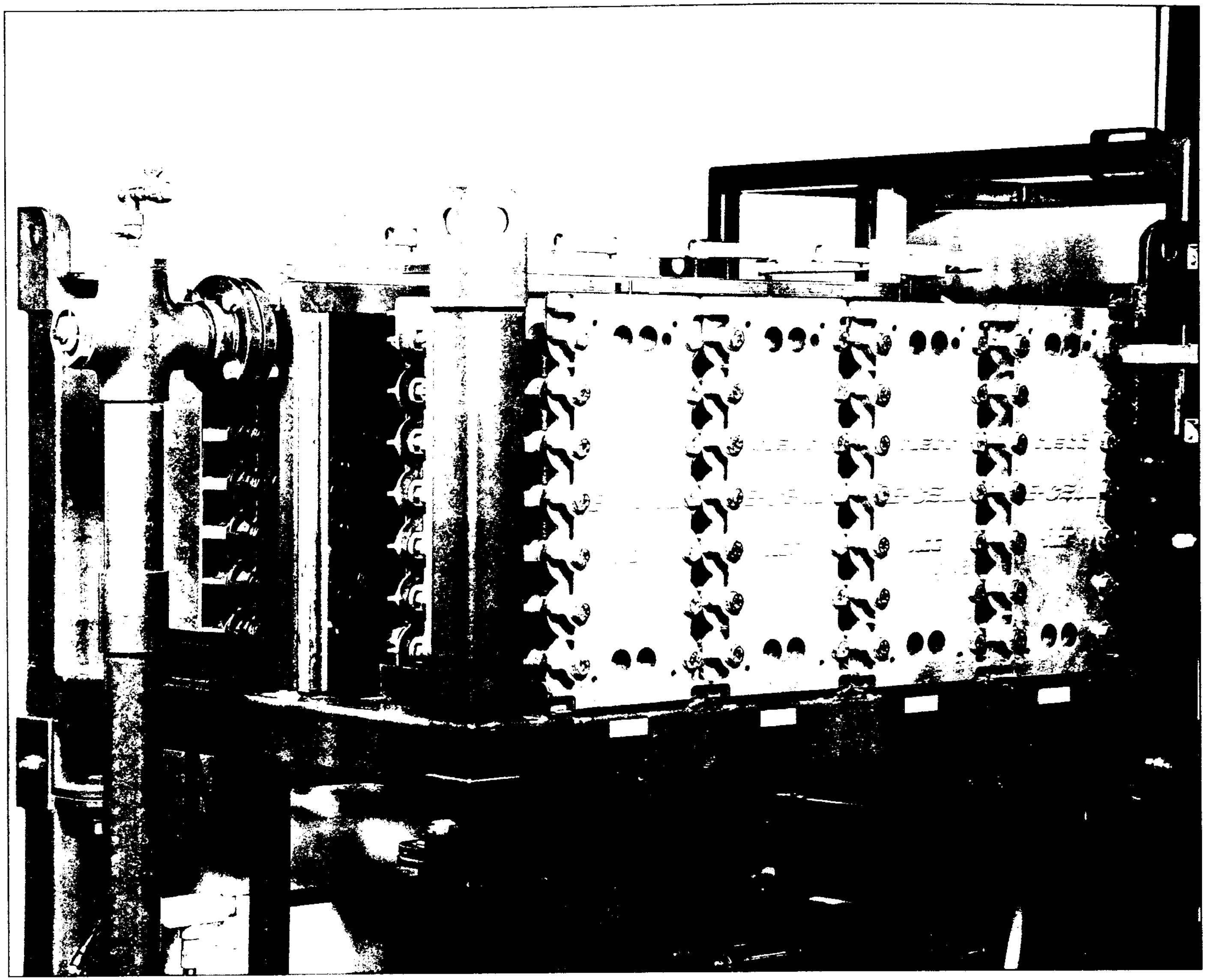


Figure 1 Photo of an E-Cell System™ showing an E-Cell Rack™ and E-Cell Stacks™.

E-Cell Stack™

The present modular EDI technology depends on a basic building block, the E-Cell Stack™ for its performance and for much of its cost effectiveness compared with mixed bed IX technology. Analysis of the existing literature on EDI indicated that, despite the presence of IX material in the diluting chambers, EDI has been viewed primarily as a membrane technology. Large amounts of ion exchange membranes per unit capacity were typically used, which resulted in higher equipment costs. This situation was reminiscent of the early introduction of RO technology, where low specific water permeation fluxes necessitated the use of large membrane areas and/or large pressure drops. Potential EDI users also required a robust technology, compatible with the other reliable unit operations found in modern water purification systems.

Based on this study, the key approaches of the joint Glegg Water Conditioning and Asahi Glass E-Cell™ development effort were:

(i) to develop a low cost membrane, tailored for the specific requirements of advanced EDI
(ii) to exploit the ion exchange aspect of EDI to significantly improve product quality (to >16 MΩ.cm) and consistency, while significantly reducing the area of membrane required.
(iii) to design and build a simple robust EDI stack, with fewer components whose cost would benefit from economies of mass production

In light of the considerable interest in the benefits of an advanced EDI technology, the program was carried out at an accelerated pace, with design and engineering being carried out concurrently with extensive research, development and innovation on new EDI membranes, novel EDI concepts and mechanistic modelling. The use of the parametric solids modelling software, Pro/ENGINEER, and the associated finite element analysis tool, Pro/MECHANICA (Parametric Technologies Corporation) proved valuable in this accelerated design process, particularly in meeting the goal of a robust stack, capable of continuous operation at pressures up to 100 psi and ASME pressure testing to 150 psi.

An advanced proprietary EDI Stack was developed, which met or exceeded the development goals. The resulting E-Cell Stack™ has a nominal flow rate of 12.5 gpm, a value derived primarily from low-cost manufacturability, including choice of fabrication methods (casting, moulding, extrusion) and of overall E-Cell System™ flexibility.

E-Cell™ performance characteristics

The performance characteristics of the E-Cell Stack™ are summarized in **Table 1**. Provided the proper combination of flow rate and applied current are used, the resistivity of the EDI product water is in the range 16-18 MΩ.cm, and is rather insensitive to changes in the conductivity of the feed water. This can be seen in **Figure 2a** and **Figure 2b** where the product resistivity is shown for feed conductivities of 5 and 10 μS/cm. Long term steady-state measurements confirm that the product resistivity is insensitive to the feed conductivity in this range. As with conventional ion exchange, the removal of neutral species such as carbon dioxide can be accomplished, within certain limits on concentration and flow rate analogous to those for ionic impurities. On a more practical level, the concurrently-designed and produced components yielded stacks with no external leaks at 100 psi. This is achieved, in part, by moulding meshed concentrate spacers in a patent pending design.

Although the modular nature of the E-Cell System™ allows the basic E-Cell Stack™ to be integrated quickly into a full sized rack or system, it was important to evaluate system control and performance issues at full rack scale (8 stacks) in the field. Based on the very promising laboratory findings for full-sized single E-Cell Stacks™ (12.5 gpm nominal), two full size 100 gpm beta test E-Cell Racks™ were built according to designs developed.

Figure 2a Single E-Cell Stack™ performance with 5 μS/cm feed at 12.5 gpm.

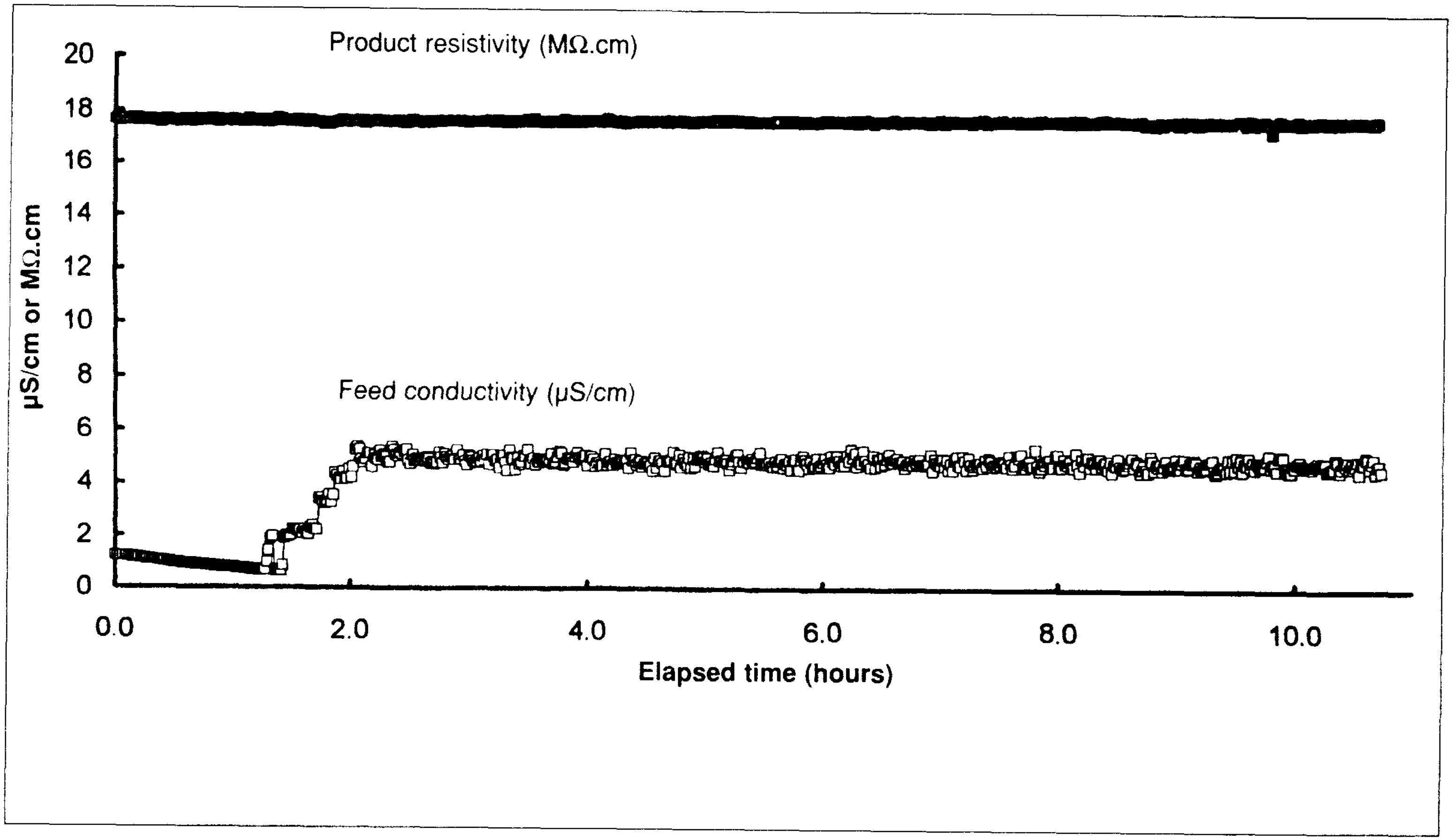
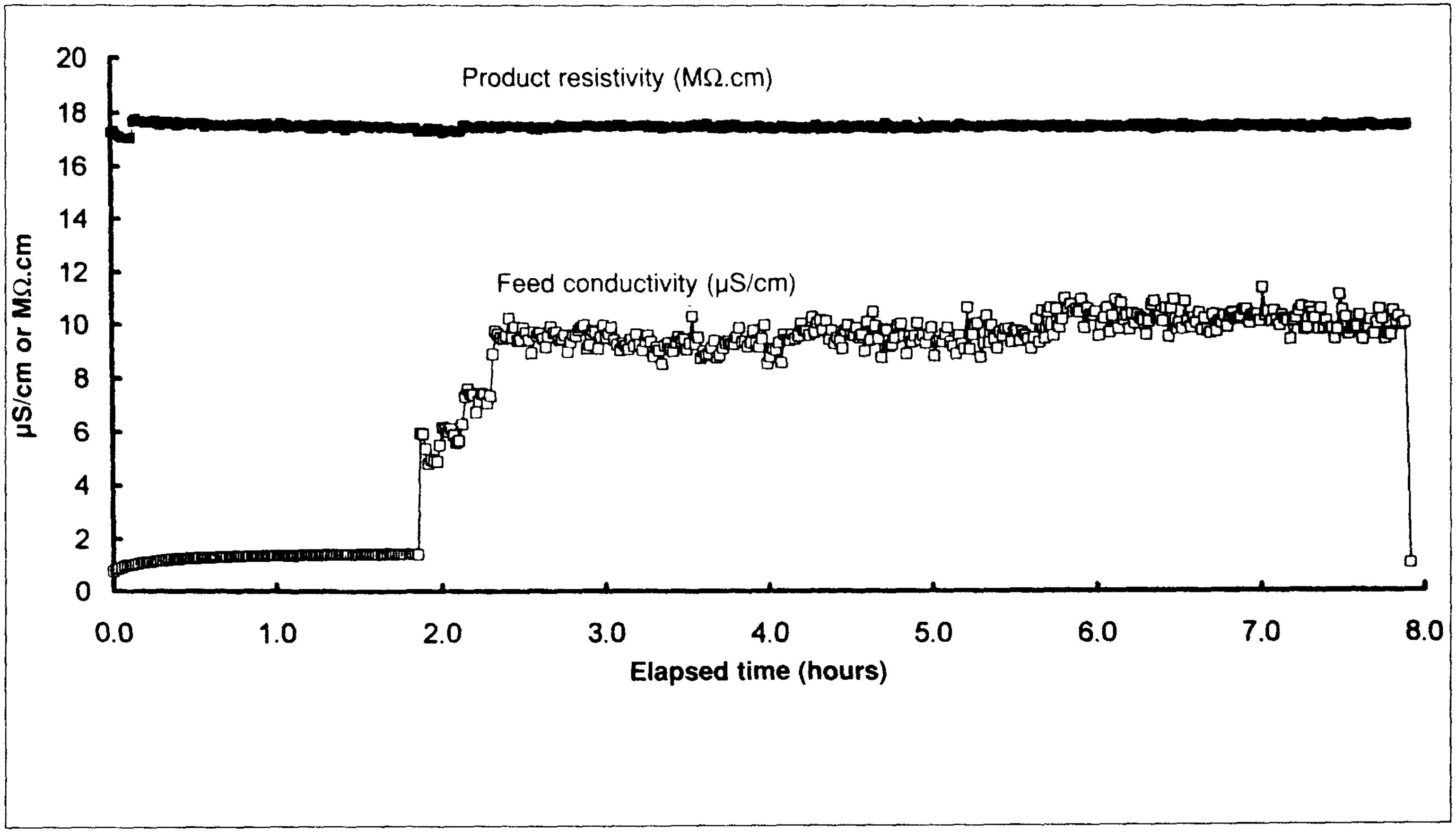


Figure 2b Single E-Cell Stack™ performance with 10 µS/cm feed at 12.5 gpm.



The first of these E-Cell Racks™ has been in operation at TVA Brown's Ferry Nuclear Station since May 1996. The second is under evaluation at a major semiconductor manufacturing location on the west coast.

Table 1 Characteristics of the E-Cell System™.

Parameter	Operational Range
Product resistivity	15-18 MΩ.cm
Feed conductivity	< 10 μS/cm
Nominal recovery	90-98%
Feed hardness	< 1.0 ppm $CaCO_3$
E-Cell Stack™	12.5 gpm (nominal)
Standard E-Cell Rack™	100 gpm
Standard E-Cell System™	50,100,300,600 gpm
Inlet pressure	15-100 psi
Electric power consumption	2.5 kWh/kgal

E-CELL™ EVALUATION AT TVA BROWN'S FERRY

Existing water system

Ecolochem Inc. operates a make-up water purification system in a building adjacent to the TVA Brown's Ferry Nuclear Plant, near Decatur, Alabama. The water system is run approximately 5 days per week for 8 hours per day to maintain a target level range in a storage tank, where it is pumped, as needed, for use in the power plant The system takes feed water from the Tennessee river, and processes it as follows:

media filter / softening / A.C. filter / RO / [cation IX / anion IX / mixed bed IX]

The ion exchange vessels, [cation IX / anion IX / mixed bed IX], are contained in a mobile trailer which is replaced periodically upon exhaustion. Regeneration is carried out off-site at an Ecolochem regional service center. There is considerable interest in a reliable robust EDI process to enhance capabilities and reduce reliance on conventional IX technology for transportation and chemical handling reasons. The TVA site provided a suitable test site for the E-Cell System™ since it was easily accessible, included a dedicated skilled operator to monitor the system and had softening/RO pretreatment.

A typical analysis of the RO feed and permeate water samples is given in **Table 2**. Due to fluctuations in the feed river water, the CO_2 levels in the RO permeate can vary from 6-15 ppm. At the higher levels, this additional load, beyond that of the ionic species reflected in the conductivity of the RO permeate, places a considerable extra load on the anion IX vessel or EDI unit.

Table 2 Typical analysis of RO feed and permeate water at TVA Browns' Ferry Nuclear Plant (ppm $CaCO_3$).

	RO feed	RO permeate
Sodium (ppm)	81.	1.9
Bicarbonate (ppm)	46.	3.0
Chloride (ppm)	14.	0.1
Nitrate (ppm)	0.2	<0.1
Sulfate (ppm)	17.	0.1
Dissolved silica (ppm)	3.0	0.041
Carbon dioxide (ppm)	4.6	6.0
TOC (ppm as C)	1.1	0.064
pH	7.4	6.0

Integration of beta test E-Cell Rack™ in Ecolochem/TVA system

The beta test E-Cell Rack™ installed in the Ecolochem system at TVA consisted of 8 x 12.5 gpm E-Cell Stacks™ for a nominal flow of 100 gpm, along with ancillary pump, rectifier and water distribution and recirculation manifolds. Additional instrumentation (flow rate, global and stack-by-stack conductivity/resistivity) and data logging/transmitting capability was included. EDI feed and product water samples were analyzed off-line at the site (grab sample) for silica with a Hach Analyzer, while TOC analyses were done online with a Sievers instrument. The performance was compared with the TVA plant specifications.

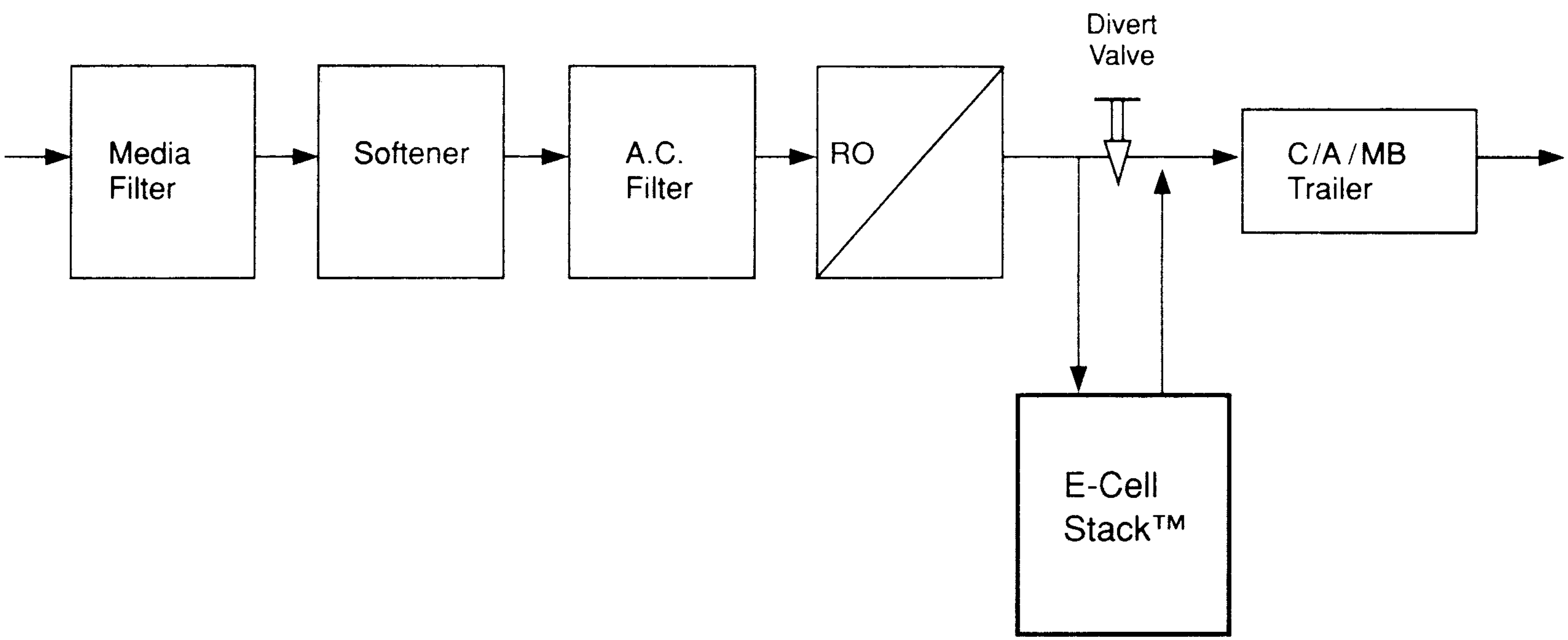
As shown in **Figure 3**, part of the RO permeate water flow was diverted to the E-Cell Rack™ at a feed pressure of ca. 70 psi, and the EDI product water was then recombined with the original flow and passed through the C/A/MB trailer. This arrangement allowed the performance limits of the E-Cell Rack™ to be explored, without compromising the ultimate water quality during the test period.

General operating features

The E-Cell Rack™ as a whole proved convenient to operate, with respect to establishing appropriate flows and relative pressure drops in the diluting (product) and concentrating streams. The equipment was insensitive to occasional pressure transients or non-standard manipulation of flow control valves on the various streams, and, as in the lab tests, the stacks did not show any external leaks. Following an initial start-up and experimental period (ca. 6 weeks), the E-Cell Rack™ was operated and monitored by the resident Ecolochem technical representative, with occasional intensive experimental campaigns also involving staff from Glegg Water Conditioning and Asahi Glass.

Although the stacks contained some intentional differences in the IX material in the diluting chambers, after start-up, stack-to-stack differences in product resistivity were generally very minor, reflecting the asymptotically high resistivities obtained with all stacks under normal operating conditions.

Figure 3 Layout of make-up water system and position of E-Cell pilot unit



Initial E-Cell™ performance

In the initial test period, the E-Cell Rack™ was run with 4-6 μS/cm feed water (RO permeate) with the elevated load of CO_2 indicated above. This net load is well above the designed nominal capacity of the present unit (< 10 μS/cm equivalent NaCl feed). Nonetheless, product water in the 14-16 MΩ.cm range was obtained. Based on analysis of the EDI feed water and parallel experiments in the laboratory, it was clearly demonstrated that the difference in performance in the field compared with laboratory tests was indeed due to the high CO_2 levels in the RO permeate. As indicated above, this places a considerable additional load on the anion IX vessels in the trailer. Nonetheless, over the first period of operation of the EDI system at 50% of its rated flow, IX trailer capacity was extended by 36%. In the initial test period, the additional pressure drop required to explore performance at flow rates significantly above design values was not available.

Although at full flow, product water in this resistivity range can extend by many times the duration of the service cycle of a C/A/MB IX train which would otherwise receive 4-6 μS/cm RO permeate as feed, it was decided to modify the operation of the RO to produce permeate (i.e., EDI feed) conforming to the E-Cell Stack™ design specifications and achieve the target EDI product resistivities in the range 16-18 MΩ.cm.

E-Cell Rack™ operation with nominal feed water

For beta testing, the pH of the RO feed was raised to 8.1-8.2 by injection of sodium hydroxide in order to convert virtually all of the molecular carbon dioxide present into the bicarbonate form[2]. Since the RO feed water is softened, extremely precise pH control and scaling of the RO membranes are not issues here. It is well-known that the bicarbonate ion is well rejected by the RO membranes, while molecular carbon dioxide is not. The effect of caustic injection ahead of the RO is shown in **Table** 3. As expected, the concentration of CO_2 in the permeate is significantly reduced. While the levels of reactive silica are unaffected by increasing the pH, it is interesting that the TOC levels are significantly reduced. This observation suggests that the organic compounds present are ionized at ph=8 and hence are better rejected by the RO membrane. In any case, the EDI unit is effective in further reducing the TOC levels. Under these operating conditions, the resulting RO permeate was found to have a conductivity in the range 4-8 μS/cm and contained less than 1.25 ppm of molecular carbon dioxide.

Carbon dioxide levels must be taken into account in designing the anion IX resin capacity needed in conventional IX systems. In instances where high carbon dioxide levels exist, it is often economical to employ a forced draft decarbonator prior to the IX train. Similarly, in designing a particular water system containing EDI units, a range of carbon dioxide levels can be accommodated by adjusting details of the stack design and operating parameters. From an overall system point of view, prior stripping of carbon dioxide will sometimes be the most cost effective approach.

Table 3 Effect of Pre-RO injection of NaOH (to pH=8.1) on the levels of carbon dioxide, silica and TOC in the RO permeate which served as feed to the EDI unit.

	NaOH injection	RO permeate	EDI product
CO_2	no	8-10 ppm	. . .(1)
	yes	< 1.25 ppm	. . .(2)
TOC	no	850 ppb	22 ppb
	yes	110 ppb	14 ppb
SiO_2	no	55 ppb	. . .
	yes	51 ppb	4.5 ppb

(1) Resistivity ca. 14.0 MOhm.cm
(2) Resistivity ca. 17.8 MOhm.cm

EDI product resistivity: The water system with the E-Cell Rack™ has been operating on a daily basis. The EDI feed conductivity and product resistivity during typical operation are shown in **Figure 4**. The product resistivity is seen to approach 18 MΩ.cm which exceeds the TVA specification of 16.7 MΩ.cm. Furthermore, the product resistivity is insensitive to variations in feed conductivity, from the raw water to the RO permeate.

EDI Silica and TOC levels: The silica and TOC content of the EDI feed and product water streams are given in **Table 4**. For comparison, the target specifications are also shown. It is evident that the performance of the E-Cell Rack™ with respect to both silica and TOC removal exceeds TVA's specifications for these impurities. Detailed experiments on the effectiveness of the E-Cell Rack™ in treating water with silica and TOC at higher levels are underway, and will be reported shortly. Systematic work on the removal of specific homologous series of organic species is scheduled.

EDI recovery: For the particular data presented in **Figure 4**, the feed flow rate to the seven EDI stacks operating was 87.7 gpm (=12.5 gpm/stack) while the effluent product flow rate was 85.6 gpm, for a recovery rate in excess of 90%. The recovery rate appropriate for a particular situation will depend on factors associated with operation of the concentrating compartment loop and the feed water chemistry.

Figure 4 E-Cell Rack™ feed conductivity and product resistivity for a typical day at the make-up water system operated by Ecolochem at TVA Browns' Ferry Nuclear Plant.

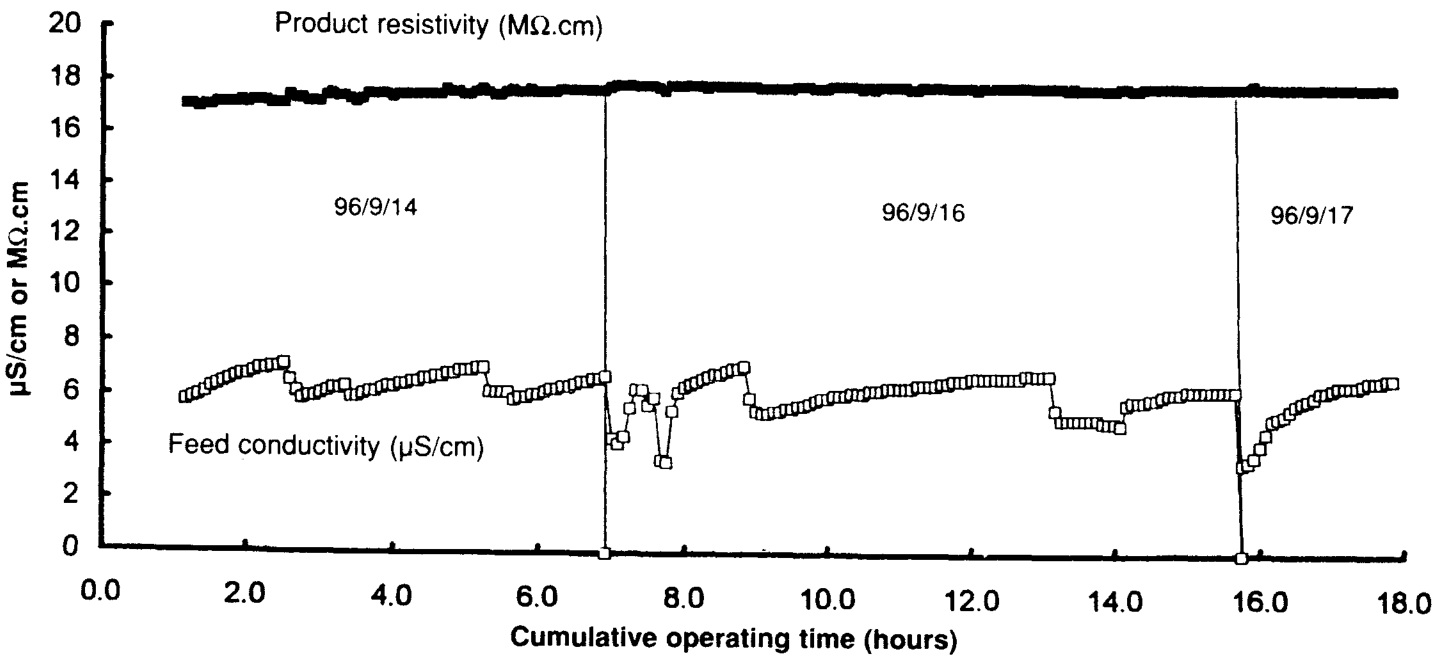


Table 4 E-Cell™ feed and product water characteristics in relation to specifications at the make-up water system operated by Ecolochem at TVA Browns' Ferry Nuclear Plant.

	E-Cell™ Feed	E-Cell™ Product	TVA specification
Resistivity (MΩ.cm)	. . .	17.8-18.0	>16.7
Conductivity (μS/cm)	$\approx$ 6.0	0.056	<0.06
SiO_2 (ppb)	55.0	4.06	<5.0
TOC (ppb)	110-120	30-32	<50
CO_2 (ppm)	$<$ 1.25	. . .	. . .

CONCLUSIONS

A robust, high performance EDI technology was developed which provides a cost effective and environmentally desirable alternative to conventional ion exchange processes. Traditional limits on EDI technology were overcome by the development of a new membrane tailored for EDI and by the application of basic electrochemical mechanistic approaches.

A nominal 100 gpm E-Cell Rack™ was operated over a period of 6 months in a make-up water purification plant at the TVA Brown's Ferry Nuclear Plant and produced 17.8-18.0 MΩ.cm water from a 4-6 μS/cm feed. The product resistivity was found to be insensitive to feed conductivity within nominal operating specifications. Silica and TOC removal was found to consistently exceeded the customer's product water specifications.

ACKNOWLEDGEMENTS

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