LOW ENERGY SYSTEM AND METHOD OF DESALINATING SEAWATER

Cross Reference to Related Application and Priority Claim

This application claims the benefit under 35 U.S.C. § 119(e) of copending U.S. Provisional Application Serial No. 61/042040 entitled HIGH CROSS LINKED ION EXCHANGE RESIN SOFTENING OF SEA WATER filed on April 3, 2008, which is hereby incorporated by reference in its entirety.

Field of the Invention

This invention relates to systems and methods desalinating seawater and, in particular, to low energy consuming systems and methods of desalinating seawater involving staged electrodialysis devices and electrodeionization devices having concentration-based potential half-cell pairs and including ion exchange in several alternative configurations. Other water sources may be desalinated by the systems and methods described herein.

Background of the Invention

Reverse osmosis (RO) and thermal methods (distillation) dominate the production of fresh water from seawater. A recent study has somewhat more than half of seawater desalination is done by RO. The use of energy recovery devices in reverse osmosis systems has further reduced the energy consumption. However, reverse osmosis technology typically require at least about 2.5 kWh/m^3. Thermal processes will continue to be high in power consumption due to phase change needed for desalination. If waste heat is available then processes such as membrane distillation may be used with power requirements of as low 1.5 kWh/ m^3.

Electrodialysis(ED) is generally considered suitable for brackish water and waste water desalination, but too expensive for seawater use. Some research indicates that ED has potential for seawater applications under carefully controlled conditions. However, ED has not been reduced to an economical method for seawater desalination.

Electrodialysis desalinates water by transferring ions and some charged organics through ion-selective membranes under the motive force of a direct current voltage. An ED apparatus consists of anion transfer membrane and cation transfer membranes arranged in cells. Each cell is bounded by a anion and a cation transfer membrane and combined into cell pairs, two adjacent cells. The membranes are electrically conductive and water impermeable. Membrane stacks consist of many, sometime hundreds of cell

pairs, and an ED systems consists of many stacks. Each membrane stack has a DC electrode at each end of the stack, a cathode and an anode. Under a DC voltage, ions move to the electrode of opposite charge. There are two types of cells, diluting cells and concentrating cells. In a diluting cell, cations will pass through the cation transfer membrane facing the anode, but be stopped by the paired membrane of the adjacent cell in that direction which is an anode transfer membrane in the adjacent cell facing the cathode. Similarly, anions pass through the anion transfer membrane facing the cathode, but will be stopped by the cation transfer membrane facing the anode. In this manner, the salt in diluting cell will be removed and in the concentrating adjacent cells cations will be entering from one direction and anions from the opposite direction. Flow in the stack is arranged so that the dilute and concentrated flows are kept separate, and in this manner, a desalinated water stream is produced.

In the ED process, material commonly builds up at the membrane surface in the direction of the electric field, which can, and usually does reduce process efficiency. To combat this effect, Electrodialysis reversal (EDR) was developed and is the primary method of use presently. In EDR, the electrodes are reversed in polarity on a regular basis, for example, every fifteen minutes. The flows are simultaneously switched as well, the concentrate becoming the dilute flow and vice versa. In this way fouling deposits are removed and flushed out.

With specific univalent membranes, sodium chloride can be concentrated from seawater by ED. Table salt can be produce by this process using, for example, Neosepta membranes ACS and CIMS (Astom Corporation, Tokyo, Japan).

Once the concentration in the dilution cells falls to lower than about 200 milligrams/liter (mg/l), electrical resistance is at a level that power demand becomes increasing expensive. To overcome this, and to be able to produce high quality water, electrodeionization (EDI), sometimes called continuous electrodeionization (CEDI) was developed. In this method the cells are filled with ion exchange media, usually ion exchange beads. The ion exchange media is orders of magnitude more conductive than the solution. The ions are transported by the beads to the membrane surface for transfer to the concentration cells. EDI is capable of producing purer water then ED at less power, when the feed concentration is reduced sufficiently.

ED processes for water desalination have advantages over RO. Since they do not use pressure to move solution and solute through the membrane,and therefore are less

prone to scale or other build-up on the membrane surface, they require less pretreatment which will reduce operating costs. They will have higher product water recovery and a higher brine concentration, i.e., less brine to dispose. In some cases, a product such as table salt may be produced.

The process designer and operator faces the problem when using ED/EDI of reducing capital and operating costs, including materials. Desizing equipment is a method of reducing capital costs, and when efficiency is gained, of operating costs. In order to take employ the advantages of ED and EDI for seawater desalination, an innovative system and method was developed which reduces certain process equipment size, particularly, ion exchange softener size..

SUMMARY OF THE INVENTION

Described herein is a low energy consuming system and process for the desalination of seawater.

In an embodiment, the system comprises an electrodialysis device and a second electrodialysis device containing monoselective membranes to partially desalinate the seawater being treated. The dilute stream from both are sent to an ion exchange softener where calcium and other scaling ions are removed or reduced in concentration. The effluent from the softener is sent to an electrodeionization device to produce final water product. The ion exchange softener having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream. The concentrate from the second electrodialysis may be used to regenerate the softener.

In an embodiment, the system comprises an electrodialysis device containing monoselective membranes to partially desalinate the seawater being treated. The dilute stream from both are sent to an ion exchange softener where calcium and other scaling ions are removed or reduced in concentration. The effluent from the softener is sent to an electrodeionization device to produce final water product. The ion exchange softener having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream. The concentrate from the electrodialysis may be used to regenerate the softener.

In embodiments described herein, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than 0.02.

In embodiments described herein, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than 0.01.

In embodiments described herein, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than 0.05.

In aspects of this description, the electrodeionization device comprises a first depleting compartment fluidly connected to a source of water having dissolved solids therein, the depleting compartment defined at least partially by a cationic selective membrane and a first anionic selective membrane; a first concentrating compartment fluidly connected downstream from a source of a first aqueous liquid having a first dissolved solids concentration, and in ionic communication with the first depleting compartment through the cationic selective membrane; and a second depleting compartment fluidly connected downstream from a source of a second aqueous liquid having a second dissolved solids concentration that is greater than the first dissolved solid concentration, and in ionic communication with the first concentrating compartment through a second anionic selective membrane.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing.

In the drawings:

FIG. 1 is a schematic flow diagram of a system in accordance with one or more embodiments of the invention;

FIG. 2 is a schematic flow diagram of a system in accordance with one or more further embodiments of the invention;

FIG. 3 is a schematic flow diagram of a seawater desalination system in accordance with one or more embodiments of the invention;

FIG. 4 is a schematic representation of a portion of an electrodeionization device which can be utilized in one or more systems in accordance with one or more aspects of the invention;

FIG. 5 is a schematic representation of a portion of an electrodeionization device in accordance with one or more aspects of the invention;

FIGS. 6A and 6B are schematic representations of portions of electrodeless continuous deionization devices in accordance with one or more aspects of the invention;

FIG. 7 is a graph illustrating the predicted energy requirements in accordance with one or more aspects of the invention;

FIG. 8 is a schematic representation of a Donnan-enhanced electrodeionization (EDI) module in accordance with one or more aspects of the invention;

FIGS. 9A and 9B are schematic representations of a system in accordance with one or more aspects of the invention;

FIGS. 10A and 10B are schematic representations of electrodialysis trains that can be utilized in accordance with one or more aspects of the invention.

FIGS. 11A and 11B are graphs showing the energy required in treating synthetic saltwater ("NaCl solution") and seawater relative to target product total dissolved solids concentration, utilizing electrodialysis devices with standard ion selective membranes (FIG. 11A) and monoselective membranes (FIG. 11B) in accordance with one or more aspects of the invention; and

FIGS. 12A and 12B are graphs showing the fractions of cations (FIG. 12A) and anions (FIG. 12B) during treatment of seawater relative to electrodialysis stages utilizing monoselective membranes, in accordance with one or more aspects of the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed to a treatment system, which in some aspects, embodiments, or configurations, can be a water treatment system. Some particularly advantageous aspects of the invention can be directed to seawater treatment systems or desalination systems and techniques involving seawater treatment or desalination. The systems and techniques of the invention can advantageously provide treated water by utilizing differences in concentrations to create potential or motive conditions that facilitate transport of one or more migratable dissolved solids in the water to be treated. Further

aspects of the invention can be directed to systems and techniques that provide potable water from seawater or brackish water.

One or more aspects of the invention can provide potable drinking water that meets or exceeds World Health Organization guidelines, that can be produced from typical seawater feed with a total energy consumption of below 1.5 kWh/m^3 of water produced. Other aspects of the invention can be directed to a combined electrodialysis and continuous electrodeionization system and device and novel continuous electrodeionization configuration that utilize concentration differences to facilitate ion separation.

Some embodiments of the invention can involve multiple step processes utilizing electrodialysis (ED) devices to desalinate seawater to a total dissolved solids (TDS) concentration, or salt concentration, in a range of about 3,500 to about 5500 ppm, followed by ion exchange (IX) softening, and final desalination to a TDS level of less than about 1,000 ppm salt content by a novel version of continuous electrodeionization (CEDI).

Our systems and processes of the present invention can involve a unique combination of existing and novel technologies, wherein each component thereof utilized for reducing, or even minimizing, overall energy consumption by advantageous use synergies between the different components and unit operations that aggregately overcomes respective limitations of current ED and CEDI devices. For example, because the energy efficiency of ED devices typically decreases as the product TDS level is reduced below 5500 ppm, typically because of concentration polarization and water splitting phenomena, CEDI devices can be used instead to further desalt water containing such low TDS levels, less than 5500 ppm, at higher comparative efficiency because the latter device utilize ion exchange resin. To address scaling concerns, a softener removes or reduces the concentration of non-monolalent, scale-forming species. A novel aspect of some embodiments described herein is the use of a softener that selectively removes calcium ions in a higher proportion compared magnesium when compared to the ratio of these ions at the inlet to the softener. The use of monovalent selective membranes in, for example, a second, parallel electrodialysis train, can be used to generate a regenerating stream for the softening stage, which typically has a high concentration of monovalent species, thereby at least reducing, if not eliminating any need for external salt stream storage. Further advantages can include improved water recovery.

Some further aspects of the invention can involve ED and CEDI devices that can be operated at sufficiently low current densities so that concentration polarization and water splitting are limited, which reduces power demand.

The seawater desalination system, for example, can comprise a first treatment stage that preferably reduces a concentration of dissolved species such as one or more dissolved solids. Some particular aspects of the present invention will be described with reference to seawater. The invention, however, is not limited to treating or desalinating seawater and one or more principles thereof can be utilized to treat a liquid having target species to be removed therefrom.

One or more aspects of the invention can be directed to an electrodeionization device comprising a first depleting compartment fluidly connected to a source of water having dissolved solids therein, the depleting compartment defined at least partially by a cationic selective membrane and a first anionic selective membrane; a first concentrating compartment fluidly connected downstream from a source of a first aqueous liquid having a first dissolved solids concentration, and in ionic communication with the first depleting compartment through the cationic selective membrane; and a second depleting compartment fluidly connected downstream from a source of a second aqueous liquid having a second dissolved solids concentration that is greater than the first dissolved solid concentration, and in ionic communication with the first concentrating compartment through a second anionic selective membrane.

In some embodiments of the invention, the first aqueous liquid is seawater, typically having a first dissolved solids concentration of less than about 4 wt%, typically about 3.3 wt% to 3.7 wt% and, in some cases, the second aqueous liquid is brine having a second dissolved solids concentration of at least about 10 wt%. In one or more further particular embodiments, the first depleting compartment is fluidly connected to a source of water having a dissolved solids concentration of less than about 2,500 ppm, or a ratio of the second dissolved solids concentration to the first dissolved solids concentration is at least about 3.

One or more aspects of the invention can be directed to devices for treating water having dissolved ionic species therein. The device can comprise, in some embodiments, a first depleting compartment fluidly connected to a source of the water, and at least partially defined by a first anion selective membrane and a first cation selective membrane; a first concentrating compartment fluidly connected to a source of a first aqueous solution having a first concentration of dissolved solids, the first concentrating compartment in ionic communication with the first depleting compartment through one of the first anion selective membrane and the first cation selective membrane; and a second depleting compartment fluidly connected to a source of a second aqueous solution having a second concentration of

dissolved solids that is greater than the first concentration of dissolved solids, wherein the second depleting compartment is typically in ionic communication with the first concentrating compartment through one of a second cation selective membrane and a second anion selective membrane.

In some embodiments of the invention, the device can further comprise a second concentrating compartment fluidly connected at least one of a source of a third aqueous solution having a third concentration of dissolved solids that is less than the second concentration of dissolved solids and the source of the first aqueous solution, the second concentrating compartment in ionic communication with the second depleting compartment through one of the second anion selective membrane and the second cation selective membrane. The second concentrating compartment can, but not necessarily, be ionic communication with the first depleting compartment through the first cation selective membrane. In further configurations in accordance with some aspects of the invention, the device comprises one or more salt bridges that, for example, ionically connect the first depleting compartment and the second concentrating compartment. In other further embodiments of the invention, the device can further comprise a third depleting compartment fluidly connected to at least one of the source of the second aqueous solution and a source of a fourth aqueous solution having a fourth concentration of dissolved solids that is greater than the third concentration of dissolved solids, wherein the third depleting compartment is typically in ionic communication with the second concentrating compartment through a third cation selective membrane. The device can further comprise a third concentrating compartment fluidly connected to at least one of a source of the first aqueous solution, the source of the third aqueous solution, and a source of a fifth aqueous solution having a fifth concentration of dissolved solids that is less than any of the second concentration of dissolved solids and the fourth concentration of dissolved solids, the third concentrating compartment in ionic communication with the third depleting compartment through a third anion selective membrane. The third concentrating compartment can be in ionic communication with the first depleting compartment through the first cation selective membrane and, in some cases, the third concentrating compartment is in ionic communication with the first depleting compartment through a salt bridge. Thus, in some configurations, the device has no electrodes or structures that provides external electromotive potential through the compartments thereof.

In other configurations of the device, the first depleting compartment and the first concentrating compartment are fluidly connected downstream from the same source.

One or more aspects of the invention can be directed to a seawater desalination system. The desalination system can comprise at least one first electrodialysis device including at least one first depletion compartment having a first depletion compartment inlet fluidly connected to a source of seawater, and a first depletion compartment outlet, and at least one first concentration compartment having a first depletion compartment inlet and a first depletion compartment outlet; at least one second electrodialysis device including at least one second depletion compartment having a second depletion compartment inlet fluidly connected to the source of seawater, and a second depletion compartment outlet, and at least one second concentration compartment having a second concentration compartment inlet fluidly connected to the source of seawater, and a brine outlet; at least one ion exchanging unit having an ion exchanger inlet fluidly connected to at least one of the first depletion compartment outlet and the second depletion compartment outlet, and an ion exchanger outlet; and at least one electrodeionization device having a first depleting compartment fluidly connected to the ion exchanger outlet, the depleting compartment can be defined at least partially by a first cationic selective membrane and a first anionic selective membrane, a first concentrating compartment fluidly connected to the source of seawater, and in ionic communication with the first depleting compartment through the first cationic selective membrane, and a second depleting compartment fluidly connected downstream from the brine outlet, and in ionic communication with the first concentrating compartment through a second anionic selective membrane.

In one or more embodiments of the desalination system, at least one of the first concentrating compartment and the second depleting compartment does not contain ion exchange resin.

In other configurations of the desalination system, the at least one electrodeionization device further comprises a second concentrating compartment at least partially defined by the first anionic selective membrane, and having an inlet fluidly connected to the source of seawater, and a third depleting compartment in ionic communication with the second concentrating compartment through a second cationic selective membrane, and having an inlet fluidly connected to at least one of the brine outlet, an outlet of the first concentrating compartment, and an outlet of the second depleting compartment. In some cases, at least one of the first concentrating compartment, the second depleting compartment, the second

concentrating compartment, and the third depleting compartment does not contain ion exchange resin.

The seawater desalination system, in some advantageous configurations, can further comprise one or more brine storage tanks, one or more of which can be fluidly connected to at least one of an outlet of the first concentrating compartment and an outlet of the second depleting compartment. One or more of the brine storage tanks can respectively comprise an outlet, any one or more of which can be fluidly connected to or connectable to the at least one ion exchanging unit, exclusively or to other unit operations of the desalination system.

In other configurations, the seawater desalination system can further comprise a third electrodialysis device having a third depletion compartment fluidly connected downstream from the first depletion compartment and upstream of the ion exchanging unit. Further configurations can involve systems that comprise a fourth electrodialysis device having a fourth depletion compartment fluidly connected downstream from the second depletion compartment and upstream of the ion exchanging unit.

In some advantageous configurations of the system, the at least one first electrodialysis device comprises a monovalent selective membrane disposed between the at least one first depletion compartment and the at least one first depletion compartment. Further, the first depleting compartment of the electrodeionization device can contain a mixed bed of ion exchange media, such as ion exchange resin.

Some further aspects of the invention can involve pre-treating water, preferably seawater or brackish water. In one or more configurations of the invention, the desalination system can further comprise at least one pretreatment unit operation which can be fluidly connected downstream from the source of water to be treated, which can be seawater, or brackish water, and, preferably, be fluidly connected, or connectable, upstream of at least one of the at least one first electrodialysis device, the at least one second electrodialysis device, and the at least one electrodeionization device. The at least one pretreatment unit operation can comprise at least one subsystem selected from the group consisting of a filtration system, a chlorination system, and a dechlorination system. Before entering the treatment process train, a prefiltration step may used to protect the electrodialysis, softener or electrodeionization devices by removing particles, organic matter, bacteria, and other contaminants. Slow sand filtration may be used. A more preferred method is dual media sand filtration. This method uses a layer of anthracite over a layer of fine sand. Other

methods may be used singularly or in combination. These include, but are not limited to, mixed media filtration, non-woven fabric cartridge filtration, and membrane filtration.

In some cases, the pretreatment system can also comprise a pressure-driven system that selectively removes divalent species such as sulfate. For example, a nanofiltration system utilizing a FILMTEC™ membrane, from The Dow Chemical Company, Midland, Michigan, can be used to reduce the concentration of at least the sulfate species, which should further reduce the power consumption by one or more downstream unit operations, such as any of the electrodialysis devices, and the electrodeionization devices.

In still other configurations of one or more of the systems of the invention, the at least one of the at least one electrodeionization device comprises an anionic species collector, a cationic species collector, and a salt bridge in ionic communication with the anodic and the cathodic collectors. The ionic species collectors can be compartments at least partially defined by ion selective media. When advantageous, at least one of the at least one electrodeionization device, the at least one first electrodialysis device, and the at least one second electrodialysis device comprises an anode compartment fluidly connected downstream from a source of an aqueous solution having dissolved chloride species, the electrode compartment comprising one of a chlorine outlet and hypochlorite outlet. Further configurations can involve at least one of the at least one the electrodeionization device, the at least one first electrodialysis device, and the at least one second electrodialysis device comprising a second electrode compartment comprising a caustic stream outlet.

One or more aspects of the invention can involve a desalination system comprising a source of water which can at least partially have or be seawater; a means for selectively reducing a concentration of monoselective species in a first seawater stream to produce a first diluted stream; a means for increasing a dissolved solids concentration in a second seawater stream to produce a brine stream; a means for exchanging at least a portion of divalent species for monovalent species in the first diluted stream, wherein the means for exchanging can have a second diluted stream outlet; and an electrochemical separation device. The electrochemical separation device typically has a depleting compartment fluidly connected to the second diluted stream outlet, and a means for providing a concentration-induced electrical potential in ionic communication with the depleting compartment.

In some configurations of the desalination system, the means for increasing a dissolved solids concentration in the first seawater stream comprises an electrodialysis device having a depletion compartment fluidly connected to the source of seawater, and a

concentration compartment separated from the depletion compartment by a monovalent selective membrane. The means for increasing a dissolved solids concentration in the second seawater stream can comprise an electrodialysis device having a concentration compartment fluidly connected to the source of seawater, and a brine outlet providing the brine stream. The means for providing a concentration-induced electrical potential can comprise a first half-cell compartment fluidly connected to a source of a first half-cell feed stream having a first concentration of total dissolved solids, and a second half-cell compartment fluidly connected to a source of a second half-cell feed stream having a second concentration of total dissolved solids that is greater than the first concentration of total dissolved solids. The first half-cell compartment is typically fluidly connected to a source of seawater and the second half-cell compartment is fluidly connected to a source of brine.

One or more further aspects of the invention can be directed to an electrodeionization device comprising a depleting compartment fluidly connected to a source of water having dissolved solids therein, the depleting compartment defined at least partially by a cationic selective membrane and a first anionic selective membrane; and at least one concentration half-cell pairs in ionic communication with the depleting compartment. The concentration half-cell pair typically comprises a first half-cell compartment fluidly connected to a source of a first aqueous liquid having a first dissolved solids concentration, and in ionic communication with the depleting compartment through one of the cationic selective membrane and the first anionic selective membrane, and a second half-cell compartment fluidly connected downstream from a source of a second aqueous liquid having a second dissolved solids concentration that is greater than the first dissolved solid concentration, and in ionic communication with the first half-cell compartment through a second anionic selective membrane.

In some configurations of the electrodeionization device, the first aqueous liquid is seawater. The second aqueous liquid can be a brine stream having a second dissolved solids concentration of at least about 10 wt%. Thus, in some embodiments of the invention, the second dissolved solids concentration to the first dissolved solids concentration is in a concentration ratio that is at least about three.

One or more still further aspects of the invention can be directed to a method of desalinating seawater comprising reducing a concentration of monovalent species of seawater in a first desalting stage to produce partially desalted water; producing a brine solution from seawater, the brine solution having a total dissolved solids concentration that is at least twice

the concentration of total dissolved solids in seawater; introducing the partially desalted water into a depleting compartment of an electrically-driven separation device; and creating a concentration-induced electrical potential in a concentration cell pair of the electrically-driven separation device while promoting transport of at least a portion of dissolved species from the partially desalted water in the depleting compartment into a compartment of the concentration cell pair. The method can further comprise passing at least a portion of the seawater through a nanofiltration system before reducing the concentration of monovalent species of seawater in the first desalting stage.

The method can further comprise, in some approaches, replacing at least a portion of dissolved non-monovalent species in the partially desalted water with dissolved monovalent species. Reducing the concentration of the monovalent species of seawater can involve selectively reducing the concentration of dissolved monovalent species in an electrodialysis device. Producing the brine solution can involve promoting transport of at least a portion of dissolved species from the seawater into a second seawater stream flowing in a concentration compartment of an electrodialysis device. The method of desalinating water can further comprise electrolytically generating one of chlorine and a hypochlorite species in an electrode compartment, typically the anode compartment, of at least one of an electrolytic device, an electrodialysis device and the electrically-driven separation device, and electrolytically generating a caustic stream in one or more compartments of at least one of the electrolytic device, the electrodialysis device, and the electrically-driven separation device. Further, the desalination method can also comprise at least partially disinfecting at least a portion of the seawater with the generated chlorine, the generated hypochlorite species, or both.

Some particular aspects, embodiments, and configurations of the systems and techniques of the invention can involve treating water in a system 100 as exemplarily illustrated in FIG. 1.

The treatment system 100 can be fluidly connected or connectable to a source of a liquid to be treated 110. Typically, the liquid to be treated has mobile ionic species. For example, the liquid to be treated can be or comprise water having salts as dissolved solids therein. In particular applications of the invention, the liquid to be treated can be seawater, comprise seawater, or consist essentially of seawater. In other cases, the liquid to be treated can be brackish water, comprise brackish water, or consist essentially of brackish water.

The treatment system 100 can comprise a first treatment stage 120 fluidly connected to the source of liquid to be treated 110. The treatment system 100 can further comprise a second stage 130, and where advantageous, a third treatment stage 140 to produce treated product to a point of use 190.

The first treatment stage modifies at least one property or characteristic of the liquid to be treated. Preferably, the first treatment stage 120 reduces at least a portion of one or more target species in the liquid to be treated to provide an at least partially treated liquid. For example, the first treatment stage 120 can utilize one or more unit operations that remove at least a portion of dissolved species in seawater from source 110 to produce at least a partially treated water or water stream 121 having a salinity content less than seawater. Preferred configurations can provide at least partially treated water stream 121 that has at least 5 % less salinity that seawater from source 110. Other preferred configurations can provide the at least partially treated water that has at least 10 % less salinity that seawater. The first treatment stage 120 can utilize or be designed to provide a target change or difference in relative concentration or salinity between the liquid to be treated, e.g., seawater, and the at least partially treated liquid stream, e.g., at least partially treated water. The target difference in concentration provided by the first treatment stage 120 can be at least partially dependent on several factors or conditions including, but not limited to, any one or more of the capacity of one or more downstream unit operations, one or more requirements of one or more of the downstream unit operations, and, in some case, the overall water demand of the treatment system 100. For example, the change in concentration, e.g., change in salinity, provided by the first treatment stage 120 can be dependent on desalinating seawater to provide at least partially treated water that is conducive to treatment by an electrodeionization device, a nanofiltration device or both. Other factors that may affect the design approach of the first treatment stage 120 can be dictated, at least partially, by economic or operating considerations. For example, the first treatment stage 120 can be configured to provide at least partially treated water utilizing available electrical power at an existing facility.

Further configurations or alternatives of the first treatment stage 120 can involve one or more unit operations that selectively remove one or more target or predetermined species from the liquid to be treated. For example, the first treatment stage can comprise or utilize one or more unit operations that at least partially selectively remove from or reduce the concentration of dissolved monovalent species in the liquid to be treated. In other cases, the first treatment stage can comprise or utilize one or more unit operations that provide a

product stream having a concentration of one or more types of dissolved species therein that is greater than the concentration of the dissolved species in the liquid to be treated. In still other cases, the first treatment stage can provide a second product stream 123 having a concentration of dissolved solids therein that is greater than ancillary liquid stream, which can be a stream from a unit operation that is unassociated with a unit operation of treatment system 100. For example, the ancillary stream can be a downstream byproduct of one or more sources (not shown). In other cases, the change in concentration or salinity provided by the first treatment stage 120 in the at least partially treated stream 102 can be dependent on providing a second product stream 123 that would be utilizable in one or more downstream unit operations of treatment system 100. In still other cases, the first treatment stage 120 can provide a second product stream 123 having a salinity that is greater than the salinity of seawater, which has a typically salinity of about 3.5 %. Preferably, the salinity of second product stream 123 is at least about 5 % but some particular embodiments of the invention can involve a product stream 123 having a salinity of at least about 9 %. For example, the second product stream 123 can be a brine stream with a dissolved solids concentration of at least about 10 %, or at least about 99,000 ppm. In other exemplary embodiments, a ratio of the dissolved solids concentration in second product stream 123 to one or more other process streams of treatment system 100 can be at least about 3, preferably, at least about 5, and, in some advantageous cases which, for example, may require a concentration difference or gradient, at least about 10.

The second stage 130 can have at least one unit operation that further treats the at least partially treated product stream 121. In some embodiments of the invention, the second stage 130 can comprise one or more unit operation that adjusts one or more characteristics of the at least partially treated stream 121 from the first stage 120 to provide a second at least partially treated product stream or modified liquid 131. Preferably, the second stage 130 modifies at least two characteristics of the stream 121 to produce stream 131.

The third treatment stage 140 can modify one or more properties or characteristics of one or more inlet streams thereinto. In particularly advantageous configurations in accordance with one or more aspects of the invention, the third treatment stage 140 can comprise one or more unit operations that utilize at least one stream from at least one upstream unit operation to modify another stream from one or more upstream unit operations to provide a product stream to the point of use 190 with at least one desirable property or characteristic. Further particular configurations of the third treatment stage 140 can involve

one or more unit operations that create a potential difference that facilitates treatment of the at least partially treated stream 131 to produce a product stream 141. In still further preferred configurations the third treatment stage can produce another product stream 142 that can be utilize in one or more upstream unit operations of treatment system 100. For example, the another product stream 142 can be a byproduct or second product stream utilized by one or more unit operations of second stage 130 in, for example, a step or an operation thereof, as an inlet stream that at least partially facilitates conversion of the at least partially treated stream 121 to provide the product stream 131 with at least one desirable property or characteristic. Further preferred embodiments or configurations of third treatment stage 140 can involve unit operations that rely on a difference of a property or characteristic of the liquid to be treated relative to the property or characteristic the product stream from the unassociated unit operation or an upstream stage or unit operation of treatment system 100 to at least partially facilitate treatment to provide the product stream 141. For example, the third treatment stage 140 can utilize the difference in salinity of seawater from the source 110, as stream 111, relative to the salinity of stream 122 to at least partially facilitate reducing a concentration of one or more target species in stream 131 to produce a product water 141 having at least one desired characteristic, e.g., purity.

FIG. 2 illustrates an exemplary water treatment system 200 in accordance with one or more aspects of the invention. The treatment system 200 can comprise a first treatment stage including a first unit operation 220 and a second unit operation 222, each preferably, but not necessarily fluidly connected to the source 110 of water to be treated through respective inlets thereof. The treatment system 200 further comprises a second stage 230 fluidly connected to receive, typically at an inlet thereof, one or each product stream from the first unit operation 220 and the second unit operation 222, typically from respective outlets thereof. The treatment system 200 can further comprise a third treatment stage 240 having an inlet fluidly connected to at least one of an outlet of the second stage 230, an outlet of one or more unit operations of the first treatment stage, the source of water to be treated, and the unassociated unit operation, to provide a product water to, for example, the point of use or a storage 190.

As illustrated in the exemplary embodiment of FIG. 2, the first unit operation 220 can provide a first partially treated water stream and be combined with another at least partially treated water stream from unit operation 222 to produce an at partially treated product stream 221. The first water stream from an outlet of unit 220 can have one or more characteristics that differ from those of the second water stream from unit 222. The first and second unit

operations are preferably designed to provide the at least partially treated water stream 221 having at least one target property for further modification or treatment in second stage 230. The second unit operation 222 can provide a second product stream 223, which preferably has one or more particular or target characteristics. Thus, some configurations of the invention contemplate unit operations 220 and 222 that collectively provide an at least partially treated water stream 221 with one or more particular characteristics while further providing a second product aqueous stream 223 with one or more characteristics that typically differ from the characteristics of stream 221. The first treatment stage can utilize water treating unit operations, devices, or systems such as, but not limited to electrodialysis devices and electrodeionization devices.

Further particular embodiments of the invention can involve a first unit operation that is operated to have lower power consumption relative to the second unit operation. The first unit operation 220 can be operated to produce from seawater, an at least partially treated water product or stream having a total dissolved solids of about 2,500 ppm, with about 30 % water recovery. The second unit operation 222 can be operated to produce from seawater, an about 10 % brine solution having a dissolved solids concentration of greater than about 99,000 ppm.

In another embodiment (not shown), the second stage 130 can comprise two or more unit operations that separately receive streams from the first and second unit operations 220 and 222. One or more preferred configurations of the second stage 230 can involve one or more unit operations that alter at least one property of inlet stream 221 from at least one unit operation of the first treatment stage. The second stage can thus provide a third product stream 231, with one or more target characteristics, and which can be further treated in the third treatment stage 240.

Other embodiments of the invention can involve ion exchanging units comprising chloride-form anion exchanging resin that exchange at least a portion of sulfate species in favor of chloride species to further reduce power requirements of one or more downstream unit operations, and, in some cases, to further reduce the likelihood of scale formation in such downstream unit operations. Thus, the exchanging unit can involve cation exchanging resin that at least partially reduces the concentration of non-monovalent cationic species, such as Ca^{2+} and Mg^{2+}, in favor of monovalent cation species, such as Na^{+}, and, preferably, further comprises anion exchanging resin that at least partially reduces the concentration of non-monovalent anionic species, such as SO_4^{2-}, in favor of monovalent anionic species, such as

Cl^-, a which can reduce the treatment power requirement of one or more downstream unit operations. In a particularly preferred embodiment the ion exchanging units are capable of reducing calcium ion concentration to an essentially non-scaling level while adsorbing magnesium ions to a relatively lesser amount. This reduces the needed volume of ion exchange resin. Regeneration of any of the ion exchanging resin types can be performed with, for example, a waste brine stream having dissolve Na^+ and Cl^-.

The third treatment stage 240 can comprise one or more unit operations that utilize the second product water or aqueous stream 223 and another stream, such as a water stream 111 from source 110 to facilitate treatment of the third water product stream 231 and provide treated, product water to the point of use or storage 190. Further preferred configurations of the third treatment stage 240 can involve producing a byproduct water or aqueous stream 241, which can be used in one or more upstream or downstream stages of the treatment system 200. For example, the byproduct water stream can be used in one or more unit operations in the second stage 230 as an input or reactant during operation thereof. The third treatment stage can utilize one or more unit operations, devices, or systems such as, but not limited to electrodialysis and electrodeionization devices.

FIG. 3 illustrates a seawater desalination system 300 in accordance with one or more aspects of the invention. Desalination system 300 typically comprises a first train having at least one first electrodialysis device 321A and, preferably, at least one second electrodialysis device 322B. Desalination system 300 can further comprise a second train having at least one third electrodialysis device 323A and, preferably, a second electrodialysis device 324B. Desalination system 300 can also comprise at least one ion exchanging subsystem 330 with at least one ion exchanger inlet in fluid communication with an outlet of at least one of the upstream electrodialysis devices 321A, 322B, 323A, and 324B. Desalination system 300 can also comprise a third treatment stage 340 that can further treat the at least partially treated water 331 from at least one ion exchanger outlet of ion exchanging subsystem 330.

The first electrodialysis device 321A has at least one depletion compartment 321D1 having an inlet fluidly connected to a source 310 of seawater. The first electrodialysis device 321A also comprises at least one concentration compartment 321C1, preferably fluidly connected to the source 310 of seawater. The second electrodialysis device 322B of the first train typically comprises at least one depletion compartment 322D2 and at least one concentration compartment 322C2. An outlet of the first depletion compartment 321D1 is fluidly connected to at least one of an inlet of the at least one depletion compartment 322D2

and an inlet of the at least one concentration compartment 322C2 of the second electrodialysis device 322B. In some particular embodiments, the inlet of the at least one concentration compartment 322C2 of the second electrodialysis device 322B is fluidly connected to the source 310 of seawater. Preferred embodiments in accordance with some aspects of the invention involve a first train of devices that at least partially treats seawater to produce an at least partially treated water 321 having at least one target characteristic. For example, the first train of electrodialysis devices that partially desalinate water, preferably, selectively removes dissolved solids species from the seawater, to produce an at least partially treated product water stream 321 having any one or more of a dissolved solids concentration that is less than seawater, relatively higher ratio of dissolved non-monovalent dissolved solids species to dissolved monovalent species than the corresponding ratio of seawater, and a lower concentration of dissolved monovalent species concentration. In embodiments that seek to selectively remove dissolved monovalent species, one or more monovalent selective membranes can be used to define, at least partially the depletion compartments, and, preferably, at least partially define a concentration compartment. For example, the electrodialysis device 321A can have a first depletion compartment 321D1 at least partially defined by a monovalent anionic selective membrane 381 and a monovalent cationic selective membrane (not shown), and a first concentration compartment 321C1 in ionic communication with the first depletion compartment through the monovalent anionic selective membrane 381, and, optionally, a second concentration compartment (not shown) through the monovalent cationic selective membrane. The second electrodialysis device 322B can also be optionally configured to have one or more monovalent selective membranes that facilitate selective removal or depletion one or more monovalent species from the water stream introduced into the depletion compartments thereof and accumulated into the concentration compartments thereof.

During operation of the first and second electrodialysis devices, seawater can be used as a concentration stream, feeding into the concentration compartments 321C1 and 322C2, which collects the one or more removed species from the streams introduced into the depletion compartments. The concentration streams leaving compartments 321C1 and 322C2 and containing species removed from the depletion compartments can be discharged as a waste or reject stream or be utilized in other unassociated processes R.

The at least one third electrodialysis device 323A can be configured to provide a product stream that is useable in a downstream unit operation of desalination system 300. In

accordance with a particular embodiment, the third electrodialysis device 323A can have at least one depletion compartment 323D1 and at least one concentration compartment 323C1 in ionic communication with at least one of the depletion compartments 323D1 through a ion selective membrane 382. Preferably, an electric current applied through the third electrodialysis device 323A provide sufficient potential to provide a product water stream from the concentration compartment 323C1 having one or more predetermined or target characteristics. For example, electrodialysis device 323A can also be constructed with a monovalent selective membrane that separates but provides ionic communication between the depletion compartment 323D1 and the concentration compartment 323C1. The at least one fourth electrodialysis device 324B can comprise at least one depletion compartments 324D2, defined at least partially by anionic and cationic selective membranes, and at least one concentration compartment 324C2, typically in ionic communication with at least one of a depletion compartment 324D2. During operation of system 300, product water from the depletion compartment 323D1 can be introduced into the depletion compartment 324B to further treat seawater from source 310 and facilitate production of at least partially treated water 221. As exemplarily illustrated, the product water from the depletion compartment 324D2 can be combined with product water 321 from the depletion compartment 322D2 to produce the at least partially treated water 221 for further treatment.

The first train including the first and second electrodialysis devices 321A and 322B can be operated to produce water having a target total dissolved solids concentration, such as about 2,500 ppm, with an overall water recovery rate of about 30 %. The first and second electrodialysis devices 321A and 322B can utilize at least one of monovalent anion selective membrane and cation selective membrane and, preferably, at least the first electrodialysis device 321A utilizes monovalent anion selective membranes and monovalent selective cation selective membrane, which should at least reduce any scaling potential therein.

The second train including the third and fourth electrodialysis devices 323A and 324A can be operated to produce a brine stream having a target salinity content of at least about 10 % (NaCl) in a concentrate stream from one or more concentration compartments thereof. Preferably, the third electrodialysis device produces a sufficient amount of brine at at least the target salinity level while operating at a water recovery of about 70 %. The fourth electrodialysis device 324B can be operated to produce the at least partially treated water having a target dissolved solids content of about 2,500 ppm, and preferably with a recovery

rate of about 48 %. In some particular configurations of the invention, the overall recovery rate of the second train can be about 40 %.

The ion exchanging subsystem 330 can be configured to receive at least a portion of the at least partially treated water 221 and convert or modify at least one characteristic thereof. Some embodiments of one or more aspects of the invention involve selectively reducing a concentration of a target dissolved species of a water to be treated while at least partially retaining or inhibiting transport of at least a portion of non-target or other dissolved species, and then substituting at least a portion of the retained dissolved species with the target dissolved species. For example, water 221 can have a relative high concentration of non-monovalent dissolved species, such as calcium and magnesium, compared to seawater, and be treated to exchange at least a portion of the non-monovalent species for monovalent species, such as sodium. In a particularly preferred embodiment the ion exchanging units are capable of reducing calcium ion concentration to an essentially non-scaling level while adsorbing magnesium ions to a relatively lesser amount. This reduces the needed volume of ion exchange resin.

Some configurations of the exchanging subsystem 330 can involve at least two exchange trains (not shown) of softeners or beds of ion exchange media. The first ion exchange train can comprise a leading ion exchange bed followed by a lagging ion exchange bed, which can preferably substitute at least a portion of the non-monovalent dissolved species in the water, such as Ca^{2+} and Mg^{2+}, in favor of monovalent dissolved species such as Na^{+}. . In a particularly preferred embodiment the ion exchanging units are capable of reducing calcium ion concentration to an essentially non-scaling level while adsorbing magnesium ions to a relatively lesser amount. This reduces the needed volume of ion exchange resin. The second ion exchange train can similarly comprise serial leading and lagging ion exchange beds. During operation, the one of the first and second ion exchange trains can have an inlet fluidly connected to receive at least a portion of at least partially treated water 221 and produce an exchange water stream having less non-monovalent dissolved species concentration. Once the first ion exchange train becomes saturated with non-monovalent species as a result of the non-monovalent for monovalent ion exchanging process, the second ion exchange train can be utilized. The first train can then be regenerated by introducing an aqueous stream rich in monovalent dissolved species to replace at least a portion of non-monovalent species bound to the ion exchange media of the ion exchange beds. The ion exchange units can comprise a mixed bed of ion exchange resin such as those

commercially available as AMBERLITE™ and AMBERJET™ resin from Rohm and Haas, Philadelphia, Pennsylvania.

Regeneration of the ion exchange media can be performed by utilizing a brine solution 261 with sufficient salinity, such as about 10 %, from a brine storage tank 260. A discharge stream 332 from ion exchanging subsystem 330 can be discharged as a reject stream. Salinity sufficient to regenerate the ion exchange media can be at a level that surpasses the thermodynamic resistance associated with binding the non-monovalent species to the exchange matrix.

The third treatment stage 340 can comprise one or more electrodeionization device. In some embodiments of the invention, the third treatment stage can comprise at least one of a conventional electrodeionization device as illustrated in FIG. 4 and a modified electrodeionization device as illustrated in FIG. 5. In still other configurations in accordance with one or more aspects of the invention, the third treatment stage can comprise one or more electrodeless continuous deionization devices.

The electrodeionization device illustrated in FIG. 4 typically comprises at least one depleting compartment 411 and at least one concentrating compartment 412, disposed adjacent at least one of the depleting compartment 411. Each of the depleting and concentrating compartments are at least partially defined by any of an anion selective membrane AEM and a cation selective membrane CEM. In contrast to electrodialysis devices, the compartments of electrodeionization device contain cation exchange resin and anion exchange resin. During operation with an imposed electrical current, cationic species, such as Na^+, typically migrate to a cathode (-) of the device and anionic species, such Cl^-, typically migrate toward an anode (+) of the device 400. The anion selective membrane AEM and the cation selective membranes CEM trap the migrating or transporting dissolved species, Na^+ and Cl^-, in respective concentrating compartments 412 as reject streams R. The feed into one or more of the depleting compartments is typically the softened water stream 331 from the ion exchanging subsystem 330. The product water from the depleting compartments can then be stored or delivered to a point use. One or more power supplies (not shown) typically provides electrical energy or power to the electrodeionization device 400 that facilitates separation of the target dissolved species. In some cases, a portion of the electrical energy is utilized to dissociate water to H^+ and OH^- species. The power supply can be controlled to provide a desired or target current level, desired or target voltage or potential level, and current polarity.

FIG. 5 exemplarily illustrates a modified electrodeionization device 500 that can be utilized in the third treatment stage of the treatment system. The device 500 comprises at least one first depleting compartment 511, which is typically at least partially defined by a first cation selective membrane 521C and a first anion selective membrane 531A at least one first concentrating compartment 521, and at least one first concentrating compartment 541, which can be at least partially defined by a second anion selective membrane 532A, and in ionic communication the first depleting compartment 511 through at least a portion of the first cation selective membrane 521C. The device 500 can further comprise a second depleting compartment 512, which is defined at least partially by a second cation selective membrane 522C, and in ionic communication with the first concentrating compartment 541 through at least a portion of the second anion selective membrane 532A. The electrodeionization device 500 can further comprise a second concentrating compartment 542 defined at least partially by a third cation selective membrane 523C. The second concentrating compartment 542 is preferably at least partially in ionic communication with the first depleting compartment 511 through the first anion selective membrane 531A. The electrodeionization device 500 can further comprise a third depleting compartment 513 preferably defined by a third anion selective membrane 533A. The third depleting compartment 513 is preferably at least partially in ionic communication with the second concentrating compartment 542 through the third cation selective membrane 523C. The electrodeionization device 500 typically has an anode compartment 562 housing an anode, and a cathode compartment 564 housing a cathode.

In accordance with other aspects of the invention, the electrodeionization device 500 comprises a first depleting compartment 511 containing cation exchange media and anion exchange media such as cation exchange resin CX and anion exchange resin AX, and at least partially defined by the first cation selective membrane 521C and the first anion selective membrane. In some cases, only the first depleting compartment or only the compartments receiving or fluidly connected downstream from any of the depletion compartments of the electrodialysis devices and the ion exchange unit comprises electroactive media such as ion exchange resin, and the other compartments are free of ion exchange media. For example, in some configurations of the electrodeionization device 500, each of the one or more first depleting compartments comprises 511 a mixed bed of ion exchange resin, and each of the one or more first concentrating compartments 541, the one or more second depleting

compartments 512, the one or more second concentrating compartments 542, and the one or more third depleting compartments 513 do not contain ion exchange media.

In operation, power from a power supply (not shown) provides electrical energy for an electric field, which is typically created across the electrodeionization device 500 through the anode and the cathode. Water to be treated from, for example, an outlet of second stage ion exchanging unit 330 enters the depleting compartment 511 through an inlet thereof. The water to be treated has dissolved species that can migrate under the influence of the electric field in the electrodeionization device 500. Typically, the aqueous stream 331 contains a higher amount of target dissolved monovalent species, Na+ and Cl-, relative to dissolved non-monovalent species because of the ion exchanging process in unit operation 330. Thus, because the amount of energy associated with promoting transport of monovalent species can be relatively less than the associated amount of energy in promoting transport of non-monovalent species, additional capital and operating costs for second stage 330 can be reduced, if not eliminated. The monovalent species typically migrate to the corresponding attracting electrodes and further through the anion or cation selective membranes into one of the first concentrating compartment and the second concentrating compartment. For example, cationic Na^+ species can be drawn to the direction of the cathode and typically pass through the cation selective membrane 521C whereas the anionic Cl^- species can be drawn toward the anode and typically pass through the anion selective membrane 531A. The product stream from the outlet of the depleting compartment 331 will typically have a reduced concentration of the target dissolved solids species.

In some configurations of the invention, a stream having a first concentration of dissolved solids therein can be used a concentrating stream to collect the migrating target dissolved solids species. For example, a seawater stream 111 having a salinity of about 3.5 % can be used as the concentrating stream introduced into the first concentrating compartment 541. The stream leaving the first concentrating compartment 541 will thus be typically rich in the migrating cation or anion species. This stream can be discharged as waste or reject stream R. Also during operation, another feed stream is typically introduced into the second depleting compartment 512 and the third depleting compartment 513.

The electrodeionization device 500 can further comprise a first concentration cell pair 531 and, optionally, a second concentration cell pair 532, each of which is preferably in ionic communication with the first depleting compartment 511. The first concentration cell pair 531 can comprise a first half-cell compartment 541 fluidly connected to a source of a first

aqueous liquid having a first dissolved solids concentration, and in ionic communication with the depleting compartment 511 through the first cationic selective membrane 521C, and a second half-cell compartment 512. The second half-cell compartment is typically in ionic communication with the first half-cell compartment 541 through the anion selective membrane 532A. The optional second concentration cell pair 532 can comprise a third half-cell compartment 542 and a fourth half-cell compartment 513. The third half-cell compartment is typically in ionic communication with the depleting compartment 511 through the anion selective membrane 531A. The fourth half-cell 513 compartment is typically in ionic communication with the third half-cell compartment 542 through the cation selective membrane 523C.

Further advantageous features of the invention can involve establishing a concentration difference between adjacent cell by providing compositionally similar respective feed streams but with differing concentrations of dissolved constituents. The concentration difference generates a potential, e.g., an electromotive potential E (in V), that can be at least partially quantified by the Nernst equation,

$$E = \frac{RT \ln\left[\frac{(conc1)}{(conc2)}\right]}{nF}$$

where *conc1* is the concentration of dissolved solids in the stream 223 introduced into the second half cell 512, *conc2* is the concentration of dissolved solids in the stream 111 introduced into the first half-cell 541, R is the gas constant, 8.314 J/(K·mole), T is the temperature, typically 298 K, n is the number of electrons transferred in the cell reaction, $n = 1$ for seawater and brine, and F is the Faraday constant, 96,498 coulombs/mole. Thus, some preferred configurations in accordance with some aspects of the invention can involve utilizing a brine stream 223 having a dissolved solids concentration greater than the dissolved concentration of seawater stream 111 introduced into the first depleting compartment. The brine stream, typically having a salinity of at least about 8 %, preferably at least about 10 %, and more preferably, at least about 12 %, or a dissolved solids concentration of at least about 80,000 ppm, preferably, at least about 99,400 ppm, and more preferably, at least about 120,000 ppm can be used a feed stream 223 introduced into the second half-cell compartment 512, and preferably also into the fourth half-cell compartment 513. Each of the streams 341 leaving the second and fourth half-cell compartments 512 and 513 may still have a high brine content, relative to seawater, and can be directed to storage in a brine storage tank 260. The feed stream 111 introduced into the first half-cell compartment 541, and optionally also the

third half-cell compartment 542, can be seawater or an aqueous stream having a salinity of about 3.5 % or a dissolved solids concentration of less than about 36,000 ppm. The above-noted exemplary conditions can provide about 0.026 volts per concentration cell pair. Thus, the present invention can advantageously generate electrical potential that facilitates treatment or desalination of seawater. Example 1 below provides expected generated potentials based on exemplary conditions when utilizing a first stream and a second stream in a concentration cell pair, wherein the second stream has a concentration of dissolved solids greater the concentration of dissolved solids of the first stream.

In some cases, one or more devices of the third treatment stage comprises sufficient number of concentration cell pairs to provide substantially all the electrical potential required to desalinate the product stream 331 to a desired level. In such configuration, the device can comprise a salt bridge (not shown), typically having an electrolyte therein, such as potassium chloride or sodium chloride, that ionically connects the half-cell compartments of the device. For example, a first end of a salt bridge can ionically connect the second half-cell compartment 512 with any of depleting compartment 511 and the fourth half-cell compartment 513.

FIGS. 6A and 6B illustrate electrodeless continuous deionization devices 600 and 610 that may be characterized, in accordance with still some aspects of the invention, as being Donnan potential assisted or a Donnan-enhanced EDI device. The device 600 can comprise a circular cylindrical shell 601 housing at least one first depleting compartment 611, each having liquid to be treated 331 introduced thereinto. The device can further comprise at least one first concentrating compartment 621, each having a first feed stream 111 introduced thereinto, and at least one second depleting compartment 612, each having a second feed stream 223 introduced thereinto. The device 600 typically further comprises at least one second concentrating compartment 622, each having a third feed stream 112 introduced thereinto. The first depleting compartment 611 can be defined by an anion selective membrane 641A and a cation selective membrane 651C. The first concentrating compartment 621 can be defined by an anion selective membrane, such as membrane 641A, and a second cation selective membrane 652C. As exemplarily illustrated, the first depleting compartment is in ionic communication with the first depleting compartment through membrane 641A. The second depleting compartment 612 can be defined by a cation selective membrane and second anion selective membrane 642A. Preferably, the second depleting compartment 612 is in ionic communication with the first concentrating

compartment 621 through cation selective membrane 652C. The second concentrating compartment 622 can be defined by an anion selective membrane and a cation selective membrane. Preferably, the second concentrating compartment is in ionic communication with the second depleting compartment 612 through the second anion selective membrane 642A. Further preferred configurations can involve having the second concentrating compartment in ionic communication with the first depleting compartment 611 through one of a salt bridge and the first cation selective membrane 651C. Member 661 can provide ionic and electrical insulation as well as structural support for the compartments.

The second feed stream 223 typically has a concentration of dissolved solids therein that is greater than the concentration of dissolved solids in the first feed stream 111, and preferably, also greater than the concentration of dissolved solids in the third feed stream 112. The concentrations of dissolved solids of each of the first feed stream and the third feed stream can be the same or less than the concentration of dissolved solids in the liquid to be treated 331. As described above, the concentration differences between the paired half-cells 612 and 621, and 612 and 622, can create a potential that facilitates transport of Na^+ and Cl^- species from the depleting compartment 611, as illustrated, to produce the product stream.

Similar to the electrodeless device 600, the device 610 illustrated in FIG. 6B comprises a second cell pair including a depleting compartment 613 and concentrating compartment 623, respectively having feed streams 113 and 114. Feed stream 113 can be brine from, for example, electrodialysis device 323A, and feed stream 114 can be seawater from the source 310. A plurality of pairs of depleting and concentrating compartments utilizing seawater and brine streams to advantageously generate a potential sufficient to drive the treatment of at least partially treated water, having a dissolved solids concentration of, for example, about 2,500 ppm, to produce product water having a target dissolved solids concentration of, for example, about 500 ppm.

Other configurations can involve any one or more of the feed streams 111 and 114 at least partially comprising at least partially treated water 331, which can provide a greater concentration difference relative to brine stream 223.

Further notable differences include countercurrent flow directions of some of the streams through the compartments. As illustrated, the second stream 111 can be counter-currently introduced into the first concentrating compartment 621, relative to the direction of the stream introduced into the first depleting compartment 611 or, in some cases, relative to the third stream 223 introduced into the second depleting compartment. Concentration

differences between the second and third streams can create a potential driven by the half-cell reactions associated with migration of dissolved species, such as Na^+ and Cl^-.

Any of the membranes in devices 600 and 610 can be monovalent anion selective or monovalent cation selective.

In some configurations of the invention, an electrolytic device (not shown) can be used to generate an aqueous solution comprising a disinfecting species such as chlorine, chlorite, hypochlorite, and hypobromite. In other configurations, at least one of the electrodeionization device and any one or more of the electrodialysis devices can be utilized to generate any one or more of an acidic solution, a basic solution, and a disinfecting solution. For example, a relatively pure water stream can be introduced into the anode compartment (+) to collect and aggregate H^+ species to produce an acidic outlet stream having a pH of less than 7. A chloride containing solution can be introduced in a feed stream into the cathode compartment to facilitate generation of a disinfecting species such as chlorine and a hypochlorite species. Gaseous hydrogen byproduct may be vented or otherwise discharged.

Any of the various subsystems, stages, trains, and unit operations of the invention can utilize one or more controllers to facilitate, monitor, and/or regulate operation thereof. Preferably, a controller (not shown) monitors and, in some cases, controls each of the components of the systems of the invention.

The controller may be implemented using one or more computer systems. The computer system may be, for example, a general-purpose computer such as those based on an Intel PENTIUM®-type processor, a Motorola PowerPC® processor, a Sun UltraSPARC® processor, a Hewlett-Packard PA-RISC® processor, or any other type of processor or combinations thereof. Alternatively, the computer system may include specially programmed, special-purpose hardware, for example, an application-specific integrated circuit ASIC or controllers intended for analytical systems.

The computer system can include one or more processors typically connected to one or more memory devices, which can comprise, for example, any one or more of a disk drive memory, a flash memory device, a RAM memory device, or other device for storing data. The memory device is typically used for storing programs and data during operation of the treatment system and/or the computer system. For example, the memory device may be used for storing historical data relating to the parameters over a period of time, as well as operating data. Software, including programming code that implements embodiments of the invention, can be stored on a computer readable and/or writeable nonvolatile recording medium, and

then typically copied into the memory device wherein it can then be executed by the processor. Such programming code may be written in any of a plurality of programming languages, for example, Java, Visual Basic, C, C#, or C++, Fortran, Pascal, Eiffel, Basic, COBAL, or any of a variety of combinations thereof.

Components of the computer system may be coupled by an interconnection mechanism, which may include one or more busses, e.g., between components that are integrated within a same device and/or a network e.g., between components that reside on separate discrete devices. The interconnection mechanism typically enables communications e.g., data, instructions to be exchanged between components thereof.

The computer system can also include one or more input devices, for example, a keyboard, mouse, trackball, microphone, touch screen, valves, position indicators, fluid sensors, temperature sensors, conductivity sensors, pH sensors, and composition analyzers, and one or more output devices, for example, a printing device, display screen, or speaker, actuators, power supplies, and valves. In addition, the computer system may contain one or more interfaces not shown that can connect the computer system to a communication network in addition or as an alternative to the network that may be formed by one or more of the components of the system.

According to one or more embodiments of the invention, the one or more input devices may include sensors for measuring one or mo re parameters of the treatment system. Alternatively, the sensors, the metering valves and/or pumps, or all of these components may be connected to a communication network that is operatively coupled to the computer system. For example, sensors may be configured as input devices that are directly connected to the computer system, and metering valves and/or pumps may be configured as output devices that are connected to the computer system, and any one or more of the above may be coupled to another computer system or component so as to communicate with the computer system over a communication network. Such a configuration permits one sensor to be located at a significant distance from another sensor or allow any sensor to be located at a significant distance from any subsystem and/or the controller, while still providing data therebetween.

The controller can include one or more computer storage media such as readable and/or writeable nonvolatile recording medium in which signals can be stored that define a program to be executed by the one or more processors. The medium may, for example, be a disk or flash memory. In typical operation, the one or more processors can cause data, such as code that implements one or more embodiments of the invention, to be read from the

storage medium into a memory structure that allows for faster access to the information by the one or more processors than does the medium. The memory structure is typically a volatile, random access memory such as a dynamic random access memory DRAM or static memory SRAM or other suitable devices that facilitates information transfer to and from the processor.

Although the computer system is shown by way of example as one type of computer system upon which various aspects of the invention may be practiced, it should be appreciated that the invention is not limited to being implemented in software, or on the computer system as exemplarily shown. Indeed, rather than implemented on, for example, a general purpose computer system, the controller, or components or subsections thereof, may alternatively be implemented as a dedicated system or as a dedicated programmable logic controller PLC or in a distributed control system. Further, it should be appreciated that one or more features or aspects of the invention may be implemented in software, hardware or firmware, or any combination thereof. For example, one or more segments of an algorithm executable by the controller can be performed in separate computers, which in turn, can be communication through one or more networks.

Examples

The function and advantages of these and other embodiments of the invention can be further understood from the examples below, which illustrate the benefits and/or advantages of the one or more systems and techniques of the invention but do not exemplify the full scope of the invention.

Example 1

In this example, the expected potential that can be generated by utilizing concentration cell pairs in some configurations of the devices of the invention. Table 1 below provides calculated potentials based on concentrations of streams introduced into the half-cell compartments according to the Nernst equation at room temperature.

The table below shows that the ratio of concentrations of the feed streams is preferably as large a possible to increase the generated potentials. For example, the concentration ratios can be at least about 2, preferably at least about 3, more preferably at least about 5, and even more preferably at least about 10.

Table 1.

CONC1	CONC2	E (volts)	E (mV)
1	1	0	0
10	1	0.059	59.1
100	1	0.118	118.2
1,000	1	0.177	177.4
10,000	1	0.024	236.5
2	1	0.018	18.8
3	1	0.028	28.2
4	1	0.036	35.6
5	1	0.041	41.3
6	1	0.046	46.0
7	1	0.050	50
8	1	0.053	53.4
9	1	0.056	56.4
5.68	1	0.044	44.6
2.3	1	0.021	21.4

The following listing provides the ionic concentrations of typical seawater. The predominant cationic species in seawater are Na^+, K^+, Ca^{+2} and Mg^{+2}, and the predominant anionic species are Cl^- and SO_4^{2-}. The respective concentrations of the bicarbonate and carbonate species will depend on pH of the water.

Species	Concentration (ppm)
Chloride	19,353
Sodium	10,781
Sulfate	2,712
Magnesium	1,284
Potassium	399
Calcium	412
Carbonate/bicarbonate	126
Bromide	67
Strontium	7.9
Boron	4.5
Fluoride	1.28
Lithium	0.173
Iodide	0.06
Barium	less than 0.014
Iron	less than 0.001
Manganese	less than 0.001
Chromium	less than 0.001
Cobalt	less than 0.001
Copper	less than 0.001
Nickel	less than 0.001
Selenium	less than 0.001
Vanadium	less than 0.002
Zinc	less than 0.001
Molybdenum	less than 0.01
Aluminum	less than 0.001
Lead	less than 0.001
Arsenic	less than 0.002
Cadmium	less than 0.001
Nitrate	1.8
Phosphate	0.2

Example 2

This example provides exemplarily electrodialysis trains that can be utilized in accordance with some aspects of the invention.

FIG. 10A exemplarily illustrates train of electrodialysis devices that can be used in the first train 220 of the first treatment stage. Train 220 can comprise multiple stages, each

operating at optimum voltage and current density to minimize energy use. As illustrated, the train 220 can have four stages of electrodialysis devices.

In the first train, the depletion compartment can be serially connected and dilution streams are in series, with the product from one stage serving as a feed to downstream depletion compartments. Fresh seawater is used as feed to each of the associated concentrate compartments in each stage to minimize any concentration difference between the dilute and concentrate compartments in each stage.

Each stage can also have a number of ED modules operating in parallel.

The second train 222 can also comprise multiple stages of electrodialysis devices, having serially connected depletion compartments. The respective depletion compartments can also be serially connected to increase the aggregate NaCl concentration in the brine stream therefrom to a salt content of about 10%. As illustrated in FIG. 10B, the second train 222 can have four electrodialysis stages, each of which preferably utilizes monovalent selective membranes.

The third train (not show) can also involve a plurality of electrodialysis stages to facilitate reducing the dissolved solids concentration of the water stream to be in a range of about 3,500 ppm to about 5,500 ppm.

Example 3

This example describes expected performance of a system utilizing the techniques of the invention as substantially represented in FIG. 3 with a device schematically illustrated in FIG. 4 for desalinating seawater at a rate of about 8,000 m^3/hr.

Two trains of electrodialysis (ED) device were simulated with finite element calculations with a softener and an electrodeionization (EDI) device. Several stages were used in the finite element simulation; stages 1-5 were designed to generate a brine stream with at least 10 % NaCl; and the final two stages were designed to reduce the dissolved solids concentration of the product stream by the softener and the electrodeionization device. Table 2 and 3A-3C below list the simulation parameters and calculated results. Table 4 summarizes the predicted energy requirement for the ED/EDI system.

FIG. 7 graphically illustrates the expected energy required in desalinating seawater to produce product water of various target characteristics.

The incoming sweater was assumed to have about 35,700 ppm total dissolved solids (TDS) after being pretreated with a 10 micron prefiltration (not shown) using commercially

available pretreatment equipment. It is noted that extensive pretreatment, such as pretreatment typically associated with reverse osmosis systems is unnecessary for ED/CEDI process of the present invention because the water is not forced through the membrane in these processes.

The feed water is split into ED train 1, ED train 2 and a concentrate stream (brine) from ED train 2 is configured to feed to the CEDI train.

ED train 1 is passed through two stages to optimize the power utilization for each stage. Train 1 produces 2,500 ppm TDS quality product at about a 30% recovery. Standard electrodialysis modules are expected to be used in this train. The use of monovalent selective ion exchange membrane in stage 1 of this train should minimize the potential of scaling in the concentrate compartment.

ED train 2, stage 1 is designed to produce 10% NaCl (brine) solution in the concentrate stream. The brine will be used to regenerate the softener downstream and as one of the concentrating stream in the CEDI module. This Electrodialysis stage would utilize monovalent selective ion exchange membranes to produce 10% NaCl solution in the concentrating compartment. Stage 1 in ED train 2 would operate at about 70% recovery to produce the brine solution. ED Stage 2 has an estimated recovery of 48%. The overall recovery of ED train 2 is about 40%.

The at least partially treated product water has a TDS of about 2,500 ppm with high content of calcium, magnesium ions from the two trains. The at least partially treated water stream would be softened the softener or ion exchanging unit to exchange calcium and magnesium ions therein for sodium ions. The softened feed from the softener to the downstream CEDI train should not have a tendency to form scale during desalination to the target drinking water quality. The softener is periodically regenerated by the 10% brine solution supplied by ED train 2, stage 1.

The electrodeionization device provides transport of Na^+ and Cl^- ions from the brine stream (10% NaCl) into a reject stream. Transport of counter-ions from the diluting stream into the reject stream should maintain electroneutrality. The net thermodynamic voltage across the streams is reduced because at least a portion of the DC voltage is generated by the half-cell pairs. Although not illustrated, any of the EDI reject streams can be recycled to the feed into the ED devices.

The effluent from the brine compartments can be discharged to a storage tank for use as a softener regenerant.

Some of the simulation parameters (TDS concentration and flow rates) include (with reference to FIGS. 2 and 3):

- Inlet

Seawater inlet:	35,700 ppm 25,277 m^3/hr

- First Treatment Stage

First ED Train 220, First ED Device 321A and Second ED Device 322B

Inlet seawater to depletion compartment 321D1:	3,100 m^3/hr
Inlet seawater to concentration compartment 321C1:	5,167 m^3/hr
Reject from compartment 321C1:	49,929 ppm
Inlet to depletion compartment 322D2:	10,000 ppm 3,100 m^3/hr
Inlet seawater to concentration compartment 322C2:	2,067 m^3/hr
Reject from compartment 322C2:	49,929 ppm
Product water 321 from compartment 322D2:	2,500 ppm
Brine from ED train 222:	99,500 ppm

Second ED Train 222, Third ED Device 323A and Fourth ED Device 324B

Inlet seawater to depletion compartment 323D1:	4,900 m^3/hr
Inlet seawater to concentration compartment 323C1:	2,100 m^3/hr
Outlet Brine from compartment 323C1:	99,467 ppm (10 % salinity)
Inlet to depletion compartment 324D2:	10,000 ppm
Inlet seawater to concentration compartment 324C2:	5,277 m^3/hr
Reject from compartment 324C2:	42,664 ppm
Outlet from compartment 324D2:	2,500 ppm

- Second Stage

Inlet to softener 330:	2,500 ppm

- Third Treatment Stage

Electrodeionization device 340

Inlet to depleting compartment 511:	8,000 m^3/hr
Inlet seawater to first concentrating compartment 541:	2,667 m^3/hr
Inlet to compartment 512 (brine):	2,100 m^3/hr (10 % salinity)
Outlet brine from compartment 512:	91,848 ppm

- Product

Outlet from compartment 511:	500 ppm

Table 2.

	ED overall	ED/EDI overall
TDS in feed to product stream	35,700 ppm	35,700 ppm
TDS in feed to reject stream	35,700 ppm	35,700 ppm
Recovery	39.9 %	32.9 %
Flow rate per membrane area (flux)	1.79 gfd 0.0030 m/hr	1.60 gfd 0.0027 m/hr
Product TDS	2,500 ppm	500 ppm
Reject TDS – Stage 1 thru Stage 5	99,467 ppm	
Reject TDS – Stage 6 thru Stage 7	42,664 ppm	
Total power	1,706 kW	1,799 kW
Total energy required per unit product	1.39 kWh/m^3 5.27 kWh/Kgal	1.47 kWh/m^3 5.56 kWh/Kgal
Membrane area per flow rate	0.560 ft^2/gpd 329.9 m^2/(m^3/hr)	0.627 ft^2/gpd 369.1 m^2/(m^3/hr)
Product flow rate	1,225 m^3/hr	1,225 m^3/hr
Reject flow rate Stage 1 thru 5	525 m^3/hr	
Reject flow rate Stage 6 and 7	1,319 m^3/hr	
Reject flow rate, ED total	1,844 m^3/hr	
Reject flow rate, ED/EDI total		2,504 m^3/hr
Total projected membrane area	404,068 m^2	452,171 m^2

Table 3A.

	Stage		
	1	2	3
TDS in feed to product stream	35700 ppm	30000 ppm	25000 ppm
TDS in feed to reject stream	35700 ppm	52800 ppm	64467 ppm
Total voltage drop per cell pair	0.0584 Volt	0.0632 Volt	0.0744 Volt
Recovery	75.0 %	70.0 %	70.0 %
Flow rate per membrane area (flux)	25.0 gfd 0.0174 gpm/ft^2 0.0424 m/hr	25.0 gfd 0.0174 gpm/ft^2 0.0424 m/hr	25.0 gfd 0.0174 gpm/ft^2 0.0424 m/hr
Product TDS	30000 ppm	25000 ppm	20000 ppm
Reject TDS	52800 ppm	64467 ppm	76133 ppm
Total power	196.7 kW	186.8 kW	220.1 kW
Total energy required per unit product	0.161 kWh/m^3 0.61 kWh/Kgal	0.153 kWh/m^3 0.58 kWh/Kgal	0.180 kWh/m^3 0.68 kWh/Kgal
Membrane area per flow rate	0.04 ft^2/gpd 23.56 m^2/(m^3/hr)	0.04 ft^2/gpd 23.56 m^2/(m^3/hr)	0.04 ft^2/gpd 23.56 m^2/(m^3/hr)
Product flow rate	1225 m^3/hr	1225 m^3/hr	1225 m^3/hr
Reject flow rate	408 m^3/hr	525 m^3/hr	525 m^3/hr
Total projected cation membrane area	28862 m^2	28862 m^2	28862 m^2
Total projected anion membrane area	28862 m^2	28862 m^2	28862 m^2
Total projected membrane area	57724 m^2	57724 m^2	57724 m^2

Table 3B.

	Stage		
	4	5	6
TDS in feed to product stream	20000 ppm	15000 ppm	10000 ppm
TDS in feed to reject stream	76133 ppm	87800 ppm	35700 ppm
Total voltage drop per cell pair	0.0892 Volt	0.1110 Volt	0.1160 Volt
Recovery	70.0 %	70.0 %	65.0 %
Flow rate per membrane area (flux)	25.0 gfd 0.0174 gpm/ft^2 0.0424 m/hr	25.0 gfd 0.0174 gpm/ft^2 0.0424 m/hr	25.0 gfd 0.0174 gpm/ft^2 0.0424 m/hr
Product TDS	15000 ppm	10000 ppm	5000 ppm
Reject TDS	87800 ppm	99467 ppm	44986 ppm
Total power	263.8 kW	328.2 kW	342.9 kW
Total energy required per unit product	0.215 kWh/m^3 0.82 kWh/Kgal	0.268 kWh/m^3 1.01 kWh/Kgal	0.280 kWh/m^3 1.06 kWh/Kgal
Membrane area per flow rate	0.04 ft^2/gpd 23.56 $m^2/(m^3/hr)$	0.04 ft^2/gpd 23.56 $m^2/(m^3/hr)$	0.04 ft^2/gpd 23.56 $m^2/(m^3/hr)$
Product flow rate	1225 m^3/hr	1225 m^3/hr	1225 m^3/hr
Reject flow rate	525 m^3/hr	525 m^3/hr	660 m^3/hr
Total projected cation membrane area	28862 m^2	28862 m^2	28862 m^2
Total projected anion membrane area	28862 m^2	28862 m^2	28862 m^2
Total projected membrane area	57724 m^2	57724 m^2	57724 m^2

Table 3C.

	Stage 7	EDI
TDS in feed to product stream	5000 ppm	2500 ppm
TDS in feed to reject stream	35700 ppm	35700 ppm
Total voltage drop per cell pair	0.1133 Volt	0.0788 Volt
Recovery	65.0 %	70.0 %
Flow rate per membrane area (flux)	25.0 gfd 0.0174 gpm/ft^2 0.0424 m/hr	60.0 gfd 0.0417 gpm/ft^2 0.1019 m/hr
Product TDS	2500 ppm	500 ppm
Reject TDS	40343 ppm	40367 ppm
Total power	167.5 kW	93.2 kW
Total energy required per unit product	0.137 kWh/m^3 0.52 kWh/Kgal	0.076 kWh/m^3 0.29 kWh/Kgal
Membrane area per flow rate	0.04 ft^2/gpd 23.56 m^2/(m^3/hr)	0.02 ft^2/gpd 9.82 m^2/(m^3/hr)
Product flow rate	1225 m^3/hr	1225 m^3/hr
Reject flow rate	660 m^3/hr	525 m^3/hr
Total projected cation membrane area	28862 m^2	24052 m^2
Total projected anion membrane area	28862 m^2	24052 m^2
Total projected membrane area	57724 m^2	48103 m^2

Table 4.

	ED Train 1	ED Train 2	Combined ED Stages	EDI Stage	Combined ED and EDI
Product Flowrate, m^3/hr					8,000
Power Requirement, kW	3,938	6,824	10,762	628	11,390
Energy Requirement per cubic meter of product, kW/m^3	0.492	0.853	1.345	0.079	1.424

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Example 4

This example describes a Donnan-enhanced EDI device in accordance with one or more aspects of the invention. FIG. 8 shows a schematic of the Donnan-enhanced EDI process, with four cells identified as the "repeating unit" in a module.

In the absence of an applied electric field, anions in the brine stream B1 are transferred towards the concentrating stream C1B on the right across the separating anion exchange membrane due to concentration difference between the brine and concentrating streams. To maintain electroneutrality, an equivalent amount of cationic species, on a charge basis, would typically migrate from the diluting stream D1 into the concentrating stream C1B, across the cation selective membrane CM. Similarly, cationic species typically migrate from the brine stream B1 into the concentrating stream C1A across another cation selective membrane CM. To maintain electroneutrality, anionic species typically migrate from the diluting stream D2 into the concentrating stream C1A, across the anion selective membrane AM. In effect, transfer of ions from a brine stream into the adjacent concentrating streams due to concentration difference can be considered as promoting migration of ionic species from the diluting streams to the concentrating streams to maintain electroneutrality. The diluting streams are therefore deionized.

If a direct current DC electric field is applied, the ionic transfer due to the electric field can be augmented by the ionic migration phenomena due to the concentration difference between the brine and adjacent concentrating streams in a process referred to as Donnan-enhanced EDI, which is based on the Donnan potential that arises as a result of a concentration difference of ions across an ion exchange membrane permeable to those ions.

Example 5

This example describes alternative configurations of the treatment system and techniques of the invention, utilizing ED devices, with softening and EDI devices to desalinate brackish and seawater.

FIGS. 9 and 9B show further embodiments of the treatment system in accordance with one or more aspects of the invention. In contrast to the system illustrated in FIG. 2, the treatment system 905 further utilizes a third train electrodialysis units ED TRAIN 3 disposed to receive the at least partially treated water and further treat the water stream by removing at least a portion of target species before ion exchange and further treatment in the third treatment stage which can be a Donnan-enhanced electrodeionization device (DE-EDI).

FIG. 9B shows another exemplary treatment system 910 that also utilizes a third train electrodialysis units ED TRAIN 3, which is also disposed to receive the at least partially treated water and further treat the water stream, but instead utilizes a conventional EDI without a brine stream, or an EDI with polarity and flow reversal (EDIR), rather than an DE-EDI device.

The EDI R device is disposed downstream from the IX softener and may tolerate higher hardness feed streams which can allow lower softener hardness removal, or higher hardness breakthrough before regeneration. Higher breakthrough conditions would increase the time between IX softener unit regenerations and may also reduce the size and capital and operating cost of the softeners.

Further variation or modifications of the systems of FIGS. 9A and 9B may involve, for example, disposing the IX softener before ED TRAIN 3.

Figure 9A illustrates a further version of the process of Figure 2 using ED, ion exchange and EDI. Seawater, pretreated as necessary, is fed to two parallel ED trains. Train 1is usually a standard ED train, but can be equipped with monovalent specific membranes. ED train 2 is preferably equipped monovalent selective membranes in order to produce a brine of high sodium chloride content. The dilute streams of 1 and 2 are combined and fed to optional ED train 3 for treatment to further reduce ion content. If train 3 is used, the dilute stream from 3 is fed to a softener capable of reducing calcium ion concentration to an essentially non-scaling level while adsorbing magnesium ions to a relatively lesser amount. This reduces the needed volume of ion exchange resin. The low scaling output stream is fed to an electrodeionization device which produces the final product water and a concentrate which in this embodiment is combined with the concentrate stream of ED train 2. This can be stored for later use as regenerating brine for the softener, or used directly, or disposed of as waste.

Figure 9B illustrates a similar process as that of Figure 9A, except that the brine stream from ED train 2, is stored for later use as regenerating brine for the softener, or used directly for regeneration, or disposed of as waste.

Such systems may be utilized to desalinate seawater as well as brackish water from estuaries, rivers and/or even groundwater.

Example 6

In this example, desalination experiments were performed using electrodialysis modules which had either standard or monovalent selective membranes. The initial feed solution was either an about 35,000 ppm NaCl solution or synthetic seawater with about 35,000 ppm total dissolved solids (TDS).

FIGS. 11A and 11B show the calculated energy required per m^3 of ED product as the target concentration in the product stream was reduced from about 35,000 ppm to about 500 ppm, using standard ion selective membranes (FIG. 11A) and monovalent selective membranes (FIG. 11A). The monovalent selective membranes used were the CMS cation selective membrane and the AMS anion selective membrane from Tokuyama Soda Co., Tokyo, Japan. FIGS. 12A and 12B shows the fractions cationic species (FIG. 12A) and anionic species (FIG. 12B) remaining relative to electrodialysis stages utilizing monovalent selective membranes.

For both types of ED modules, the energy consumption is higher when the feed is synthetic seawater. The ratio of energy consumption for seawater compared to the synthetic NaCl solution range from 17% - 32% for an ED module with standard membranes and 21 % for an ED module with monovalent selective membranes.

The energy consumption is much higher for an ED module with monovalent membranes, almost twice that of an ED module with standard membranes.

The energy consumption increased steeply as the target product TDS was reduced below about 5,000 ppm.

Seawater contains divalent ions such as Ca^{+2}, Mg^{+2}, and SO_4^{-2} in addition to NaCl, as shown listed above in Example 1, which can affect the divalent ions energy consumption, as illustrated with the data between seawater vs. and synthetic NaCl solution.

Because monovalent selective membranes preferentially allow passage of monovalent ions relative to divalent ions, it is believed that the that the ratio of concentrations of divalent to monovalent ions in the diluting compartments would increase as seawater is desalinated in a series of ED modules. FIGS. 12A and 12B show the fraction of ions remaining in an experiment with ED modules with monovalent selective membranes. The data show that the membranes retard passage of divalent ions relative to monovalent ions. The selectivity of the anion membrane is almost 100%, which is consistent with published data on the Tokuyama Soda monovalent selective anion membranes. A perfectly selective anion membrane would

result in no transfer of SO_4 ions and therefore the amount of SO_4 ions remaining would remain at 100 %. It is believed that the increase in SO_4 concentration is due to a electroosmosis phenomena, whereby water is also transported through the membranes.

Based on FIGS. 12A and 12B, it is believed that the higher energy consumption in ED modules with monovalent selective membranes is due to the increase in ratio of concentrations of divalent to monovalent ions. It is also expected that removal of divalent ions in the feed water, particularly SO_4, would reduce the energy consumption in both ED and EDI modules. Removal of divalent ions as part of the pretreatment to the ED step by nanofiltration (NF), for example, would reduce the energy consumption of both ED and the EDI step. The NF product would therefore contain primarily NaCl and KCl at a lower concentration than the starting seawater and would require less energy to desalinate to 500 ppm. Thus, in some configurations of the invention, NF operations as a pressure driven process can be utilized to facilitate recovery, and the energy spent and remaining in the NF reject would further reduce the system energy consumption. Energy recovery devices, originally developed for reverse osmosis (RO), are believed to be applicable also to NF unit operations.

Alternatively, a salt regenerated anion exchange step ahead of the ED devices or between the ED and the EDI devices would also reduce the overall energy consumption.

Studies on Ion Exchange (IEX)

In the discussion that follows, certain terms and terminology are used with specific meanings directed to the descriptions and explanations herein.

Electrodialysis (ED) and electrodialysis reversal (EDR) will be described generically as electrodialysis except where either is specifically meant.

Univalent selective or monovalent selective membranes or equivalently ion exchange membranes are membranes which primarily transfer monovalent ions. Monovalent selective cation transfer membranes primarily transfer sodium, potassium, etc. likewise, monovalent selective anion membranes transfer ions such as chloride, bromide, etc.

Dilute stream refers to the ion depleted stream resulting from an electrodialysis or electrodeionization process. The concentrate stream is the stream containing the transferred ions.

As used herein, an electrodialysis step means the use of electrodialysis or electrodialysis reversal. This can be a done by a system of one stack or many stacks of membranes operated in a manner understood by those skilled in the art of water purification

or water desalination. Similarly, an electrodeionization step means the use of one or more electrodeionization stacks of any size needed for the particular use.

Resins used were Lewatit (Sybron Birmingham, NJ), Amberlite (Rohm & Haas, Philadelphia, PA), Purolite (Blal Cynwyd, PA), Diaion (Mitsubishi Tokyo Japan).

Fluidly connected refers to the liquid of a process step or piece of equipment being transferred to another step or piece of equipment. This can be accomplished by piping and any associated valves and control equipment, or could be done in a semi-batch mode where the fluid is held in a tank or other storage after a process step until pumped or otherwise transported to a next process step or piece of equipment.

Breakthrough of 2 mg/l calcium in the softener is used as a figure of merit to describe softener column effectiveness. At breakthrough, the calcium ion content is at or above approximately 2 mg/l and the calcium content in the effluent starts to increase rapidly. At this stage regeneration may be considered by the process operator.

Monovalent or univalent ED is used to produce a brine with approximately 10% sodium chloride content, which has been found capable of regenerating the softener of the present process. However, the brine so produced will contain divalent cations. These will be in a lower proportion than in the fed seawater, but still able to interfere to some extent in the column regeneration.

The use of selective ion exchange softeners to selectively reduce calcium content of a water stream will be useful in many applications. While much discussion herein has been directed to selective ion exchange softener use prior to EDI, other uses are available. Reducing calcium content in the water fed to reverse osmosis membranes would help maintain productivity. In processes requiring purified magnesium salts, this technology may provide purer magnesium starting materials or even final products. For example, magnesium sulfate is used in pregnancy to prevent premature contractions and seizures, and to treat heart attack and asthma. Magnesium hydroxide is a flame retardant, and oil product additive. Therefore, the technology has general use.

Seawater has about a 6:1 ratio of magnesium to calcium ions which enhances the benefits of using calcium selective ion exchange softener. By using a selective ion exchange softener, a possible 6 fold reduction in ion exchange softener size is possible. This design can be used worldwide, as differences in the ratio geographically should not greatly affect operation. Other waters, such as acid mine drainage, have varying ratios and may not be as amenable to this approach.

It is well known that multivalent cations have a detrimental effect on EDI. Surprisingly, it has been found that removal of the major portion of calcium ions was sufficient to prevent EDI deterioration without the need to remove a high percentage of magnesium ions. In a typical seawater, calcium is approximately 1/6 of total hardness. Since magnesium ions are very soluble, they should pose less of a problem in the EDI device and step than calcium as long as the pH does not get too high. Therefore designing and operating the softeners to selectively remove calcium while allowing magnesium to pass will reduce softener size and operating costs, as well as reduce the amount of 10% brine that will have to be used in regeneration.

Reducing the brine needed will also allow a higher proportion the feed flow to go to the ED train with standard membranes instead of the train with monoselective membranes. Standard membranes are more efficient and will remove more divalent ions, reducing the load on the softener.

The practitioner will operate the process described herein to reduce energy use. One aspect of this is to control the amount of flow to the monovalent selective ED. This is due to the higher energy draw of the selective membranes. A practitioner may use a very highly selective membrane to maximize sodium chloride percentage in the brine and minimize interfering divalent ions. An added benefit may be reduced flow through the selective ED process , if the higher sodium chloride purity allows lower flows.

An alternative operating method is to , the practitioner will have to accept increased divalent, particularly calcium ion, leakage into the brine being produced by the selective membranes. Increased leakage occurs with higher ion permeable membranes, which operate at lower energy requirements.

Experimental studies done in conjunction with this work has shown an optimum dilute stream flow strategy of 84% from Train 1, with standard ED membranes and 16% from train 2, having monoselective membrane or membranes, giving a ratio of regular to monoselective flows of about 5.25 to about 1.0. This ratio will be affected by changes in feed water ionic concentrations and also by the degree of selectivity of the monovalent selective membrane. For example, an ion exchange membrane that is more selective than the experimental membranes would result in an increase in the ratio of standard ED to monovalent selective ED. To optimize flows, the ratio of percentages of dilute streams that make up the total dilute stream between the at least first regular ED step and the monovalent selective second step should be about 9.0 to about 1.0, more preferably between about 6.0 to

about 1.0 and most preferably between 5.25 to about 1.0. Other acceptable ratios include between about 4.0 to about 1.0 and about 3.0 to about 1.0.

The primary findings of the present work are that by proper choice of ion exchange media and operating conditions, calcium removal and the ration of calcium to magnesium ions can be optimized with a minimum of media. This will reduce operating and capital costs of the ion exchanger softener step.

Variables that affect selective calcium ion removal by cation exchangers are media type, media percent crosslinking, method of regeneration, particularly regenerant concentration, adsorption and desorption process variables, such as flow rates and degree of regeneration.

Cation exchanger media generally comprise beads of crosslinked polymer with negatively charged groups. A very common polymeric structurefor cation exchangers is sulfonated polystyrene crosslinked with divinylbenzene. Increasing the percentage of crosslinks in the structure gives a bead with less porosity and lower capacity. However, higher crosslink content will give increased selectivity, i.e., larger differences in affinity for different ions. The practitioner has to balance higher selectivity, in this case increasing the calcium to magnesium adsorption ratio, with reduced capacity, the latter effect will require either larger columns or more frequent regeneration.

The volume of solution used for regeneration is controlled to optimize efficiency. Volume is measured in number of bed volumes of regenerant solution that is used. Bed volumes refers to the regenerating solution or brine volume used in terms of the number of equivalent volumes of packed column. It is essentially the total volume of solution used divided by the column volume. Too few bed volumes of regenerating solution will incompletely regenerate the column, requiring more frequent regenerations and added costs. Using excess bed volumes reduces the concentration of the salts in the effluent, which will add more difficulty and costs to waste disposal. Added to this is the added cost of producing extra regenerating solution.

Other regeneration variables that affect process performance are the concentration of sodium chloride in the regeneration solution, and the amount of divalent cations, primarily calcium and magnesium in the regeneration brine. Higher sodium chloride content will reduce regeneration time and brine volume needed. However, producing higher brine concentrations requires more energy and will add more divalent ions to the brine.

The process designer may choose to use a combination of cation and anion removal softener columns to optimize ion removal prior to the EDI step. This will remove sulfate ions among others that could poison the positively charged media in the flow space on the EDI modules.

The use of selective anion membranes provides added benefits to the systems and processes described herein. Selective anion membranes would be especially useful for sulfate ion removal. Sulfate removal is important in various application. In electrodialysis, it is well known that sulfate ions increase the resistivity of the anion transfer membranes and cause unwanted increased energy use. Calcium sulfate scaling on reverse osmosis membranes can dramatically reduce productivity. FILMTEC™ SR90 nanofiltration(NF) membrane is an example of a membrane specifically developed to remove sulfate and for example, prevent sulfate scale precipitation in off-shore oil wells where seawater is injected.

Nanofiltration also has the general property of having high rejection capability for multivalent ions, while having lower rejection for monovalent ions. Processes can be envisioned where the proper NF membrane will greatly reduce the divalent content of seawater being fed the ED or ion exchange softener steps, reducing energy use by reducing the higher energy requirements of electrodialyzing divalent ions.

Other means for reducing scaling divalent cations, particularly calcium, may be used to reduce to burden on the electrodialysis devices and process steps. An ion exchange softener may be used as part of the pretreatment for the seawater, or may be used on the feed to the selective membrane ED device. Reducing the calcium and magnesium that contacts these devices, particularly the selective devices, will reduce energy requirements.

A person skilled in the art of water, particularly seawater desalination by electrodialysis will recognize that the choices involved in designing and operating a plant as outline above will depend on many variables specific to each plant. These variables may include plant output volume, feed water type and ionic concentrations, plant footprint and its effect on process design, and cost of the various ion exchange media available. He skilled person will adapt the teachings herein to accommodate the particular plant of interest.

Example 7 shows the effects of different cation exchange media, which also have different percentage of crosslinking (XL). Table 14 summarizes the amount adsorbed and desorbed as well as the bed volumes of regenerating brine required. The K2629(18%XL) and he SK116 (16%XL) in their initial trial have high bed volume in their initial trial, which

is presumably due to being in the acid form as received. The second trial of each is more representative of regular long term use.

These second trials and the trial for the S100 resin show that the SK116 resin operates longer, BV=106 (number of bed volumes at which the effluent calcium concentration reaches approximately 2 milligrams per liter (mg/l) and adsorbs the largest quantity of calcium. It does not have the highest crosslink percentage.

Comparing the effluent concentration of calcium and magnesium at the approximate 2mg/l calcium effluent concentration, the table below shows that SK116 has a high selectivity as the amount of magnesium ion passing is the highest of the three media.

Resin	Ca (mg/l)	Mg (mg/l) in same sample
S100	1.9	5.5
K2629	2.44	19.3
SK116	1.83	108.5

The skilled person will realize that one cannot rely only on the rated crosslink percentage, but must evaluate media in the process of interest.

Example 8 gives the results of a trial comparing three resins tested in three sequential trials. The results of the third trial are recorded in Tables 18 through IEX 25. The summary in the Table 15 shown below shows the initial high bed volumes seen for new media for the Purolite and Lewatit resins. The results also show inconsistent results between the second and third trials which indicate to a person skilled in ion exchange that sufficient trials have to be run to gain sufficient knowledge to choose an operating resin.

Resin/trial	Bed volumes at ~2mg/l Ca breakthrough	Ca in combined regenerate (mg/l)	Mg in combined regenerate (mg/l)
Purolite C100/1	25	2400	3300
Purolite C100/2	~37	1600	3100
Purolite C100/3	<76	2100	3200
Amberlite IR1200/1	>169	1500	2900
Amberlite IR1200/2	~37	1200	1900
Amberlite IR1200/3	<80	2500	3900
Lewatit S100/1	>157	1600	2800
Lewatit S100/2	~82	1400	2000
Lewatit S100/3	<77	2600	4200

Example 9 compares concurrent and countercurrent regeneration modes of operation. The results in Table18 indicate that the countercurrent mode gives higher desorption amount

and requires less bed volumes of brine. The Diaion SK116 resin also had a high ratio of calcium to magnesium adsorption as was also seen in the results of Table 12. At the approximate 2 mg/l Ca breakthrough, the data from this testing was 1.83 mg/l Ca and 108.5 mg/l Mg in the effluent sample for the exhaustion cycle prior to the countercurrent regeneration and 2.18 Ca to 46 Mg for the exhaustion cycle prior to the concurrent regeneration. The shows the potential to operate at reduce resin volumes by proper choice of resin type.

Example 10 was conducted with synthetic seawater made up by dissolving local sea salts to a concentration of about 3.5%. The data (Table 26) for this resin show high calcium and magnesium ion removal early in the trial with a sharp magnesium ion breakthrough and a slower calcium breakthrough.

Example 1 1compares three levels of brine concentration in the regeneration step. Table IEX 33 below summarizes the results.

Table 38 Regeneration of Lewatit S100 with 4%-6%-8% solutions

Regenerant	Calcium adsorbed (mg)	Calcium desorbed (mg)	Regeneration efficiency (%)	Bed volumes of solution required for regeneration
8%	1063	777	73	4.4
8%	1150	940	82	4.7
6%	1375	1108	81	6.9
6%	1371	1242	91	7.0
4%	1228	881	72	10.6
4%	1150	940	82	10.6

The results show these data indicate the best results are from the intermediate 6% brine in terms of amount adsorbed and desorbed and efficiency.

Tables 35 and 36 give the results of two trials in which multi-stage ED was run with a cation selective membrane. Average passage of ions was calculated as 1 minus the concentration in the dilute stage.

The results from these trials are shown in the Table below.

Trial Name	1-(Ca ion in dilute stream)	1-(Na ion in dilute stream)	Ratio Na/Ca passage
Tropic Marin	0.125	0.605	4.8
Instant Ocean	0..36	0.721	2.0

These results indicate the range of passage ratios available with this selective membrane to the process design engineer too use to optimize energy requirements as described above. Other membranes, including membranes of future development may give other ranges of use.

Table 37 gives the reject(i.e., concentrate stream) concentrations using the monoselective cation membranes. In this trial, calcium content of the reject stream peaks at about 500 mg/l. This is illustrative of a typical trial, but should not be considered limiting.

EXAMPLES

Example 7

Comparison of ion exchange resins having different crosslink percentages

Test solutions of the following composition were made up and run through different IEX resins in columns of the same approximate dimensions. The tabulated results show the reduction of specific ions as a function of operating time during the exhaustion cycle, and the time course of specific ion regeneration.

Table 5

Concentration of chemicals used (g/l) in exhaustion cycle				
NaCl	$MgCl_2.6H_2O$	Na_2SO_4	KCl	$CaCl_2$
3.3	0.9	0.8	0.03	0.2

Table 6 Exhaustion cycle operating conditions and resins used

Resin type	Resin volume, ml	Column diameter, mm	Column height, mm	Measured flowrate, ml/min	% Cross link
Lewatit S100	218	26	410	54.71	8
Lewatit K2629	223	26	420	58.00	18
Diaion SK116	220	26	415	56.00	16

Table 7

Weight of chemicals used (g/l) for regeneration cycle 8% Regenerant				
NaCl	$MgCl_2.6H_2O$	Na_2SO_4	KCl	$CaCl_2$
67.6	9.7	2.7	2.3	1.8

Regeneration samples were taken at ten minute intervals after an initial ten minute run. Approximate residence time for regenerant in column was 50 minutes. After regeneration deionized water was flushed through at the same rate for 15-25 minutes and then at twice that rate for 20-25minutes.

Samples were taken at the time indicated and analyzed for the specific ions

Table 8

Ion concentrations during exhaustion cycle Lewatit S100

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	Bed volumes	code	Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	59	100	1,500	17	2700	440
30	1.641	7.538	L#28	2.1	7.1	1800			
60	3.282	15.077	L#29						
90	4.924	22.615	L#30						
120	6.565	30.154	L#31						
150	8.206	37.692	L#32	1.9	4.7	1,900			
180	9.847	45.230	L#33						
210	11.488	52.769	L#34	1.9	4.6	1900			
240	13.129	60.307	L#35						
270	14.771	67.846	L#36	1.8	4.4	1900			
300	16.412	75.384	L#37						
330	18.053	82.922	L#38	1.9	5.5	1900			
360	19.694	90.461	L#39						
390	21.335	97.999	L#40	3.8	33	1800			
420	22.976	105.537	L#41						
450	24.618	113.076	L#42						
480	26.259	120.614	L#43	9.9	140	1,600			
510	27.900	128.153	L#44						
540	29.541	135.691	L#45						
570	31.182	143.229	L#46						

Table 9 Regeneration of Lewatit S100 resin

Duration (min)	Throughput (liters)	Throughput bed volumes	Sample code	Laboratory analysis for specific ions, mg.l Ca	Mg	Na	K	Cl	SO4
0	0	0	Fresh regenerant	470	1,100	27,000	1,200	49,000	1,600
10	0.15	0.69	L#47	2,200	3,700	18,000			
20	0.3	1.38	L#48	2,000	3,000	22,000			
30	0.45	2.07	L#49	1,300	1,800	25,000			
40	0.6	2.76	L#50	1,100	1,600	25,000			
50	0.75	3.44	L#51	950	1,400	26,000			
combined	0.95	4.36	L#53	1,400	2,000	24,000			

Table 10 Exhaustion using Lewatit K2629

Duration (min)	Throughput (liters)	Throughput Bed volumes	Sample code	Laboratory analysis for specific ions, mg/l Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	60.6	137.65	1,759	31.85	2485.9	520
60	3.480	15.604	L#254	0.84	17.67	1278	5.08	2604.3	560
120	6.960	31.208	L#255						
180	10.440	46.812	L#256						
240	13.920	62.416	L#257	0.36	2.56	1703.5	18.46	2485.9	560
300	17.400	78.020	L#258	0.305	22.075	1,695	23.685	2485.9	560
360	20.880	93.624	L#259	0.255	90.85	1,641	23.185	2485.9	540
420	24.360	109.228	L#260	0.195	130.45	1,375	17.71	5073.3	550
480	27.840	124.832	L#261	0.3	143.75	1,347	17.12	5073.3	550
540	31.320	140.436	L#262	0.585	146.85	1,382	17.775	5073.3	550
600	34.800	156.040	L#263	0.79	150.25	1,384	17.615	5073.3	550

Table 11 Regeneration of Lewatit K2629

Duration (min)	Throughput (liters)	Throughput bed volumes	Sample code	Laboratory analysis for specific ions, mg/l Ca	Mg	Na	K	Cl	SO4
				477	1160	27400	1200	47600	1780
0	0	0	Fresh regenerant	456	1,353	25,695	1,369	46,877	1,900
10	0.065	0.2914548	L#264	79	183	1,666	21	2,841	600
20	0.225	1.0088819	L#265	2,415	5,005	9,845	131	34,803	1,200
30	0.385	1.7263091	L#267	2,410	4,339	18,645	232	46,877	1,380
40	0.545	2.4437362	L#268	1,682	2,749	22,565	416	46,877	1,400
50	0.705	3.1611634	L#269	1,297	1,973	24,570	754	46,167	2,000
60	0.865	3.8785905	L#270	1,005	1,630	25,375	1,065	46,877	1,950
70	1.025	4.5960177	L#271	867	1,535	26,550	1,304	46,522	1,950

drain	missed	missed	missed	867	1,535				1,950
combined	included	included	combined	1,534	2,602	22,710	733	47,943	1,900

Table 12 Exhaustion using Diaion SK116

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	Bed volumes	code	Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	59.05	136.45	1,709	29.335	2485.9	520
60	3.360	15.247	L#286						
120	6.720	30.495	L#287	0.495	0.33	1748	2.605	2485.9	550
180	10.080	45.742	L#288						
240	13.440	60.990	L#289						
300	16.800	76.237	L#290						
360	20.160	91.485	L#291						
420	23.520	106.732	L#292						
480	26.880	121.980	L#293	0.52	13.94	1,764	25.23	2485.9	550
540	30.240	137.227	L#294	0.265	44.25	1,723	24.735	2485.9	550
600	33.600	152.475	L#295	0.005	85.45	1,489	20.015	2485.9	
660	36.960	167.722	L#296	<0.1	118.2	1,436	18.68	2485.9	

Table 13 Regeneration cycle for Diaion SK 116

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	bed volumes	code	Ca	Mg	Na	K	Cl	SO4
				477	1160	27400	1200	47600	1780
0	0	0	Fresh regenerant	456	1,353	25,695	1,369	46,877	1,900
10	0.064	0.2904283	L#297	230	574	2,185	27	4,972	650
20	0.224	1.0164992	L#298	2,540	5,670	14,475	177	46,167	1,850
30	0.384	1.74257	L#299	1,640	3,895	19,580	233	46,167	1,950
40	0.544	2.4686409	L#300	1,241	3,122	21,425	332	46,167	1,900
50	0.704	3.1947117	L#301	1,085	2,719	23,355	517	47,943	1,900
60	0.864	3.9207826	L#302	929	2,433	23,875	692	47,943	1,850
70	1.024	4.6468534	L#303	828	2,207	24,250	869	47,943	1,850
drain	included	included	L#304	422	1,687	25,675	1,387	46,167	1,850
combined	included	included	L#305	1,264	2,924	23,185	593	46,167	1,850

Table 14 Summary of resins and % Crosslink comparison

Resin/%XL	Test	Amount adsorbed (mg)	Amount desorbed (mg)	Regeneration Efficiency (%)	Bed volumes to Ca breakthrough (2%)
Lewatit S100/8		1482	777	52	82
Lewatit K2629/18	initial	2081	931	45	>156
Lewatit K2629/18	second	1111	931	84	45
Diaion SK166/16	initial	2178	764	35	>167
Diaion SK116/16	second	1765	1145	65	106

Example 8

In another set of trials, three resins were each operated as described in Example 1. Each resin was tested in three sequential trials. The results are summarized in Table 15 below.

Resin/trial	Bed volumes at ~2mg/l Ca breakthrough	Ca in combined regenerate (mg/l)	Mg in combined regenerate (mg/l)
Purolite C100/1	25	2400	3300
Purolite C100/2	~37	1600	3100
Purolite C100/3	<76	2100	3200
Amberlite IR1200/1	>169	1500	2900
Amberlite IR1200/2	~37	1200	1900
Amberlite IR1200/3	<80	2500	3900
Lewatit S100/1	>157	1600	2800
Lewatit S100/2	~82	1400	2000
Lewatit S100/3	<77	2600	4200

In Example 9 below, Diaion SK116 was exhaustion tested as before and regenerated in concurrent and current modes. Table 16 gives exhaustion operating data, and Table 17 the regeneration operating data.

Table 16

Column code	Resin type	Resin volume, ml	Column diameter, mm	Column height, mm	Measured flowrate, ml/min
Counter	Diaion SK116	220	26	415	56.00
Cocurrent	Diaion SK116	220	26	415	56.00

Table 17

	Regenerant "IN" & slow rinse (top down i.e. co-current)		Fast rinse (top down)	
Cocurrent	Pump setting	Measured flowrate, ml/min	Pump setting	Measured flowrate, ml/min
	14	16	24	26
	Regenerant "IN" & slow rinse (bottom up)		Fast rinse (top down)	
Countercurrent	Pump setting	Measured flowrate, ml/min	Pump setting	Measured flowrate, ml/min
	14	16	24	27

Table 18

Desorption of calcium ion in co- and countercurrent modes

Minutes	Calcium desorption in concurrent mode (mg/l)	Calcium desorption in countercurrent mode (mg/l)
10	709	225
20	2969	1063
30	2179	1647
40	1794	1655
50	1441	1550
60	1258	1430
70	1120	1319
Combined	1581	1148
Milligrams Ca adsorbed in exhaustion cycle	1298	1766
Milligrams Ca desorbed in regeneration cycle	857	1145
Regeneration efficiency (%)	66	65
Bed volumes	5.4	4.6

Example 10

Comparison of Purolite C100, Amberlite IR1200, and Lewatit S100. Average of three run conditions.

Table 19 Operating conditions for resin comparison

S/N	Description	Unit of measure	IEX resins		
			Purolite C100	Amberlite IR1200	Lewatit S100
1	IEX column configuration				
1.1	Diameter of column	mm	26	26	26
1.2	Bed depth	mm	405	407	410
1.3	Volume of IEX resins used	ml	215	216	218
3	Exhaustion cycle (top to bottom)				
3.1	Feed flowrate	ml/min	52.49	54.48	53.36
		gpm/ft3	1.82	1.88	1.83
		BV/h	14.65	15.13	14.69
4	Counter-current regeneration				
4.1	Regeneration level	lb/ft3	18.49	19.75	19.03
		g/l	297.17	317.43	305.82
4.2	Regenerant "IN"				
4.2.1	Flowrate	ml/min	14.92	15.83	15.24
4.2.2	Duration	min	57	57	57
4.2.3	Total volume of regenerant used	BV	3.93	4.15	3.96
4.3	Slow rinse				
4.3.1	Flowrate	ml/min	14.92	15.83	15.24
4.3.2	Duration	min	15	15	15
4.3.3	Total volume of rinse water used	BV	1.04	1.10	1.05
4.4	Fast rinse				
4.4.1	Flowrate	ml/min	29.83	31.67	30.48
4.4.2	Duration	min	20	20	20
4.4.3	Total volume of rinse water used	BV	2.78	2.93	2.80

Table 20 Exhaustion of Purolite C100 Trial 3

Duration (min)	Throughput (liters)	Throughput Bed volumes	Sample code	Laboratory analysis for specific ions, mg/l Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	58	100	1,400	15	2700	400
30	1.530	7.116	P#54	3	9	1800			
60	3.060	14.233	P#55						
90	4.590	21.349	P#56						
120	6.120	28.465	P#57						
150	7.650	35.581	P#58						
180	9.180	42.698	P#59						
210	10.710	49.814	P#60						
240	12.240	56.930	P#61						
270	13.770	64.047	P#62						
300	15.300	71.163	P#63						
330	16.830	78.279	P#64	3.7	22	1600			
360	18.360	85.395	P#65						
390	19.890	92.512	P#66	5.5	38	1700			
420	21.420	99.628	P#67						
450	22.950	106.744	P#68	7.6	67	1,600			
480	24.480	113.860	P#69						
510	26.010	120.977	P#70	11	92	1,700			
540	27.540	128.093	P#71	13	120	1,700			
570	29.070	135.209	P#72	15	130	1,600			

Table 21 Regeneration of Purlolite C100 Trial 3

Duration (min)	Throughput (liters)	Throughput bed volumes	Sample code	Laboratory analysis for specific ions, mg.l Ca	Mg	Na	K	Cl	SO4
0	0	0	Fresh regenerant	490	1,100	27,000	1,200	49,000	1,500
10	0.1575	0.73	P#73	1,700	3,100	6,300			
20	0.315	1.47	P#74	3,500	6,100	14,000			
30	0.4725	2.20	P#75	2,700	4,300	19,000			
40	0.63	2.93	P#76	2,100	3,100	22,000			
50	0.7875	3.66	P#77	1,400	2,000	25,000			
60	0.945	4.40	P#78	1,200	1,700	26,000			
combined	0.8425	3.92	P#79	2,100	3,200	21,000			

Table 22 Exhaustion of Amberlite IR1200 Trial 3

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	Bed volumes	code	Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	58	100	1,400	15	2700	400
30	1.575	7.292	A#54	2.7	8.4	1800			
60	3.150	14.583	A#55						
90	4.725	21.875	A#56						
120	6.300	29.167	A#57						
150	7.875	36.458	A#58						
180	9.450	43.750	A#59						
210	11.025	51.042	A#60						
240	12.600	58.333	A#61						
270	14.175	65.625	A#62						
300	15.750	72.917	A#63						
330	17.325	80.208	A#64	3	15	1800			
360	18.900	87.500	A#65						
390	20.475	94.792	A#66	5	36	1800			
420	22.050	102.083	A#67						
450	23.625	109.375	A#68	8.5	86	1,700			
480	25.200	116.667	A#69						
510	26.775	123.958	A#70	13	130	1,600			
540	28.350	131.250	A#71	14	130	1,500			
570	29.925	138.542	A#72	14	140	1,600			

Table 23 Regeneration of Amberlite IR1200 Trial 3

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg.l					
(min)	(liters)	bed volumes	code	Ca	Mg	Na	K	Cl	SO4
0	0	0	Fresh regenerant	490	1,100	27,000	1,200	49,000	1,500
10	0.165	0.76	A#73	320	570	2,500			
20	0.33	1.53	A#74	3,500	6,400	12,000			
30	0.495	2.29	A#75	2,700	4,200	19,000			
40	0.66	3.06	A#76	2,000	2,600	22,000			
50	0.825	3.82	A#77	1,700	2,300	24,000			
60	0.99	4.58	A#78	1,200	1,700	25,000			
combined	0.9	4.17	A#79	2,500	3,900	20,000			

Table 24 Exhaustion of Lewatit S100 Trial 3

Duration (min)	Throughput (liters)	Throughput Bed volumes	Sample code	Laboratory analysis for specific ions, mg/l Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	58	100	1,400	15	2700	400
30	1.530	7.018	L#54	2.6	8.4	1800			
60	3.060	14.037	L#55						
90	4.590	21.055	L#56						
120	6.120	28.073	L#57						
150	7.650	35.092	L#58						
180	9.180	42.110	L#59						
210	10.710	49.128	L#60						
240	12.240	56.147	L#61						
270	13.770	63.165	L#62						
300	15.300	70.183	L#63						
330	16.830	77.202	L#64	2.2	6.5	1800			
360	18.360	84.220	L#65						
390	19.890	91.239	L#66	2.2	7.4	1800			
420	21.420	98.257	L#67						
450	22.950	105.275	L#68	5	44	1,800			
480	24.480	112.294	L#69						
510	26.010	119.312	L#70	11	130	1,600			
540	27.540	126.330	L#71	11	140	1,600			
570	29.070	133.349	L#72	11	130	1,600			

Table 25 Regeneration of Lewatit S100 Trial 3

Duration (min)	Throughput (liters)	Throughput bed volumes	Sample code	Laboratory analysis for specific ions, mg.l Ca	Mg	Na	K	Cl	SO4
0	0	0	Fresh regenerant	490	1,100	27,000	1,200	49,000	1,500
10	0.157143	0.72	L#73	910	1,600	4,000			
20	0.314286	1.44	L#74	3,400	7,300	1,500			
30	0.471429	2.16	L#75	2,900	4,500	19,000			
40	0.628571	2.88	L#76	2,000	2,800	23,000			
50	0.785714	3.60	L#77	1,500	2,000	24,000			
60	0.942857	4.33	L#78	1,200	1,600	26,000			
combined	0.850714	3.90	L#79	2,600	4,200	18,000			

Example 10

Tests done with 3.5% (w/w) seawater made from local (Singapore) seawater salts

Table 26 Operating conditions

Resin type	Resin volume, ml	Column diameter, mm	Column height, mm	Measured flowrate, ml/min
Lewatit TP208	191	26	360	15.00

Table 27 Exhaustion cycle Lewatit TP 208 with synthetic seawater

Duration	**Throughput**		**Sample**	**Laboratory analysis for specific ions, mg/l**					
(min)	**(liters)**	**Bed volumes**	**code**	Ca	Mg	Na	K	Cl	SO_4
0	0	0	nil	379	1200	9,800		17700	2520
30	0.450	2.354	L#98	<0.5	<0.5	12270	345.4	17700	2100
60	0.900	4.708	L#99	<0.5	<0.5	13030	463.1	17700	2300
90	1.350	7.062	L#100	<0.5	<0.5	12490	444.3	17700	2200
120	1.800	9.416	L#101	<0.5	9.45	11970	428.4	17700	2100
150	2.250	11.770	L#102	<0.5	159.05	11,810	428.8	17700	2200
180	2.700	14.124	L#103	7.266	714.68	10640	409.2	17700	2200
210	3.150	16.478	L#104	26.6	1085.92	9,802	390.5	17700	2100
240	3.600	18.832	L#105	50.46	1213.74	9,756	393.6	17700	2200

Example 11

Testing the effect of different regeneration solutions

Table 28 Resins and operating conditions

Resin type	Resin volume, ml	Column diameter, mm	Column height, mm	Measured flowrate, ml/min	Regenerant Concentration
Lewatit S100	218	26	410	44.00	8%
Lewatit S100	218	26	410	44.00	6%
Lewatit S100	218	26	410	44.00	4%

Table 29

Weight of chemicals used (g/l) For regeneration					
%regen	NaCl	$MgCl_2.6H_2O$	Na_2SO_4	KCl	$CaCl_2$
8%	67.4	9.7	2.7	2.3	1.8
6%	40.8	7.5	2.33	1.5	0.9
4%	33.6	9.5	3.1	1.3	0.9

Table 30 Exhaustion cycle for 8% Regeneration

Duration (min)	Throughput (liters)	Throughput Bed volumes	Sample code	Laboratory analysis for specific ions, mg/l Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	59	100	1,500	17	2700	440
30	1.641	7.538	L#28	2.1	7.1	1800			
60	3.282	15.077	L#29						
90	4.924	22.615	L#30						
120	6.565	30.154	L#31						
150	8.206	37.692	L#32	1.9	4.7	1,900			
180	9.847	45.230	L#33						
210	11.488	52.769	L#34	1.9	4.6	1900			
240	13.129	60.307	L#35						
270	14.771	67.846	L#36	1.8	4.4	1900			
300	16.412	75.384	L#37						
330	18.053	82.922	L#38	1.9	5.5	1900			
360	19.694	90.461	L#39						
390	21.335	97.999	L#40	3.8	33	1800			
420	22.976	105.537	L#41						
450	24.618	113.076	L#42						
480	26.259	120.614	L#43	9.9	140	1,600			
510	27.900	128.153	L#44						
540	29.541	135.691	L#45						
570	31.182	143.229	L#46						

Table IEX 28 Regeneration with 8% solution

Duration (min)	Throughput (liters)	Throughput bed volumes	Sample code	Laboratory analysis for specific ions, mg.l Ca	Mg	Na	K	Cl	SO4
0	0	0	Fresh regenerant	470	1,100	27,000	1,200	49,000	1,600
10	0.15	0.69	L#47	2,200	3,700	18,000			
20	0.3	1.38	L#48	2,000	3,000	22,000			
30	0.45	2.07	L#49	1,300	1,800	25,000			
40	0.6	2.76	L#50	1,100	1,600	25,000			
50	0.75	3.44	L#51	950	1,400	26,000			
combined	0.95	4.36	L#53	1,400	2,000	24,000			

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Table 31 cycle for 6% Regeneration

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	Bed volumes	code	Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	59.8	119.7	1,403	14.22	2433	520
60	2.640	12.126	L#163	2.64	8.34	1523	61.2	2499	580
120	5.280	24.253	L#164						
180	7.920	36.379	L#165						
240	10.560	48.505	L#166						
300	13.200	60.631	L#167						
360	15.840	72.758	L#168	1.94	8.05	1,557	18.52	2429	580
420	18.480	84.884	L#169	2.73	21.64	1,491	17.64	2429	500
480	21.120	97.010	L#170	6.06	75.5	1,441	16.14	2360	500
540	23.760	109.136	L#171	10.64	142.4	1,339	13.77	2433	500
548	24.112	110.753		10.64	142.4				

Table 32 Regeneration with 6% solution

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	bed volumes	code	Ca	Mg	Na	K	Cl	SO4
				391	1120	19800	970	35800	1900
0	0	0	Fresh regenerant	316	1,136	18,738	907	35,447	1,900
10	0.065	0.2985634	L#172	496	939	3,001	32	8,549	800
20	0.225	1.0334888	L#173	2,779	4,886	10,245	112	34,404	1,850
30	0.385	1.7684142	L#174	2,038	3,306	11,070	106	36,142	1,950
40	0.545	2.5033395	L#175	1,567	2,566	13,614	152	36,142	1,900
50	0.705	3.2382649	L#176	1,215	1,675	15,790	321	35,447	1,950
60	0.865	3.9731903	L#177	932	1,391	16,610	552	36,142	1,850
70	1.025	4.7081157	L#178	767	1,239	17,640	752	35,447	1,900
80	1.185	5.443041	L#179	631	1,115	17,390	812	36,142	1,900
90	1.345	6.1779664	L#180	520	1,049	17,560	854	36,142	1,900
100	1.505	6.9128918	L#181	456	1,013	17,980	882	36,142	1,950
drain	included	included	L#182	247	961	17,910	889	35,447	1,900
combined	included	included	L#183/184	996	1,568	15,730	566	35,447	1,950

Table 33 Exhaustion cycle for 4% Regeneration

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	Bed volumes	code	Ca	Mg	Na	K	Cl	SO_4
0	0	0	Feed	60.2	17.37	108	1594	2433	530
60	2.640	12.126	L#206	3.24	15.99	1782	75.92	2363	500
120	5.280	24.253	L#207						
180	7.920	36.379	L#208						
240	10.560	48.505	L#209						
300	13.200	60.631	L#210	1.93	9.73	1,746	22.56	2294	500
360	15.840	72.758	L#211	1.78	9.03	1,687	21.18	2328	550
420	18.480	84.884	L#212	2.39	14.97	1,790	22.28	2328	500
480	21.120	97.010	L#213	7.3	92.02	1,613	18.86	2363	500

Table 34 Regeneration with 4% solution

Duration	Throughput		Sample	Laboratory analysis for specific ions, mg/l					
(min)	(liters)	bed volumes	code	Ca	Mg	Na	K	Cl	SO4
				323	1130	13900	660	24800	2070
0	0	0	Fresh regenerant	266	1,256	14,085	721	24,674	990
10	0.066	0.3031567	L#214	319	596	2,796	30	5,526	750
20	0.226	1.0380821	L#215	1,696	2,528	7,154	81	23,631	2,050
30	0.386	1.7730075	L#216	1,595	2,794	8,410	87	25,021	2,100
40	0.546	2.5079328	L#217	1,290	2,768	9,952	90	24,674	2,100
50	0.706	3.2428582	L#218	929	2,114	10,090	99	25,021	2,050
60	0.866	3.9777836	L#219	839	1,862	11,910	180	24,674	2,050
70	1.026	4.7127089	L#220	670	1,674	12,278	294	24,326	2,050
80	1.186	5.4476343	L#221	595	1,536	13,318	440	24,326	2,050
90	1.346	6.1825597	L#222	501	1,488	13,382	532	25,021	2,050
100	1.506	6.9174851	L#223	439	1,474	13,792	598	31,972	2,000
110	1.666	7.6524104	L#224	386	1,452	13,862	626	24,674	2,050
120	1.826	8.3873358	L#225	318	1,320	12,772	587	25,021	2,100
130	1.986	9.1222612	L#226	287	1,312	12,698	587	24,674	2,000
140	2.146	9.8571865	L#227	273	1,370	13,094	608	25,021	2,000
150	2.306	10.592112	L#228	258	1,360	13,140	617	24,674	2,050
drain	included	included	L#229	227	1,325	13,138	611	24,326	2,000
combined	included	included	combined	784	1,923	12,505	456	25,214	2,100

Table 35 SAMPLES FROM ED EXPERIMENT WITH Tokuyama Soda CMS Monovalent Selective Cation Membrane FEED SOLUTION "Tropic Marin"

Stage No	Sample ID	Fraction Remaining in Dilute Stream						
		B	Ca	K	Mg	Na	Cl	SO4
0	ED2-Feed	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	ED2-1P	0.929	0.956	0.875	0.965	0.912	0.923	1.049
2	ED2-2P	0.953	0.957	0.785	0.992	0.868	0.885	1.049
3	ED2-3P	1.053	0.978	0.713	1.016	0.837	0.846	1.024
4	ED2-4P	1.009	0.931	0.610	0.978	0.752	0.788	1.024
5	ED2-5P	0.979	0.966	0.559	1.051	0.727	0.712	0.976
6	ED2-6P	1.015	0.889	0.451	0.975	0.620	0.654	1.049
7	ED2-7P	1.050	0.873	0.383	0.978	0.560	0.615	1.049
8	ED2-8P	1.033	0.886	0.334	1.009	0.512	0.538	1.073
9	ED2-9P	1.050	0.918	0.283	1.032	0.460	0.500	1.049
10	ED2-10P	1.035	0.875	0.229	1.002	0.395	0.428	1.049
11	ED2-11P	0.999	0.919	0.193	1.067	0.354	0.404	1.049
12	ED2-12P	1.065	0.867	0.141	1.022	0.275	0.346	1.024
13	ED2-13P	1.082	0.818	0.096	0.988	0.203	0.288	1.024
14	ED2-14P	1.062	0.843	0.065	1.026	0.152	0.250	1.024
15	ED2-15P	1.076	0.879	0.033	1.008	0.092	0.192	1.024
16	ED2-16P	0.794	0.807	0.017	0.912	0.050	0.139	1.098
17	ED2-17P	1.074	0.551	0.004	0.825	0.015	0.101	0.951
18	ED2-18P	1.029	0.467	0.001	0.649	0.006	0.067	0.878
19	ED2-19P	0.997	0.219	0.001	0.470	0.001	0.032	0.707
20	ED2-20P	1.032	0.141	0.001	0.264	0.002	0.013	0.463
21	ED2-21P	1.012	0.028	0.001	0.100	0.000	0.004	0.171

Table 36

Tokuyama Soda CMS Monovalent Selective Cation MembraneS

FEED SOLUTION "INSTANT OCEAN"

Stage No	Sample ID	Fraction Remaining in Dilute Stream						
		Na	K	Mg	Ca	Cl	SO4	HCO3
0	ED2-Feed	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	ED2-1P	0.909	0.833	1.019	0.941	0.946	1.010	1.027
2	ED2-2P	0.850	0.722	1.000	0.901	0.875	1.015	1.203
3	ED2-3P	0.788	0.694	0.963	0.941	0.821	1.054	1.334
4	ED2-4P	0.699	0.583	0.926	0.801	0.738	1.030	1.301
5	ED2-5P	0.629	0.417	0.944	0.816	0.679	1.034	1.285
6	ED2-6P	0.575	0.361	0.953	0.779	0.607	1.044	1.273
7	ED2-7P	0.498	0.306	0.931	0.757	0.546	1.049	1.288
8	ED2-8P	0.441	0.256	1.000	0.757	0.479	1.039	1.301
9	ED2-9P	0.352	0.189	0.935	0.710	0.415	1.084	1.193
10	ED2-10P	0.279	0.142	0.917	0.640	0.349	1.039	1.252
11	ED2-11P	0.195	0.100	0.862	0.702	0.279	1.030	1.201
12	ED2-12P	0.147	0.056	0.864	0.669	0.213	1.074	1.141
13	ED2-13P	0.089	0.036	0.764	0.643	0.170	1.064	1.180

Table 37 Reject concentrations from

Tokuyama Soda CMS Monovalent Selective Cation MembraneS

FEED SOLUTION "INSTANT OCEAN"

Sample ID	(mg/L)	Reject	Conc.				
	Na	K	Mg	Ca	Cl	SO4	HCO3
	9110	360	1070	272	16800	2030	62.2
ED2-1R	11600	530	1060	286	21400	2060	25.2
ED2-2R	13900	660	1130	323	24800	2070	21.9
ED2-3R	15300	730	1100	333	27600	2020	1.17
ED2-4R	16600	730	1100	342	29900	2000	<0.5
ED2-5R	18500	900	1130	362	32600	1900	<0.5
ED2-6R	19800	970	1120	391	35800	1900	<0.5
ED2-7R	21400	1100	1160	417	38200	1850	<0.5
ED2-8R	25700	1100	1260	437	40700	1830	<0.5
ED2-9R	26700	1100	1210	434	43100	1860	<0.5

ED2-10R	28000	1200	1280	459	45300	1780	<0.5
ED2-11R	27400	1200	1160	477	47600	1780	<0.5
ED2-12R	29500	1100	1160	499	49100	1850	<0.5
ED2-13R	29600	1100	1450	531	47900	1970	<0.5

Table 39 below and the associated Figure shows that the results from the ST label trials. In the 15th stage the percent sodium in the dilute stream has fallen to about 10% of the feed, and the Mg percent remaining in the dilute stream is starting to decline precipitously from that point. The corresponding concentrate concentration has increased 87% over the feedconcentration. At about 30% decline in dilute stream sodium concentration, the magnesium concentration in the concentrate is increased 63%

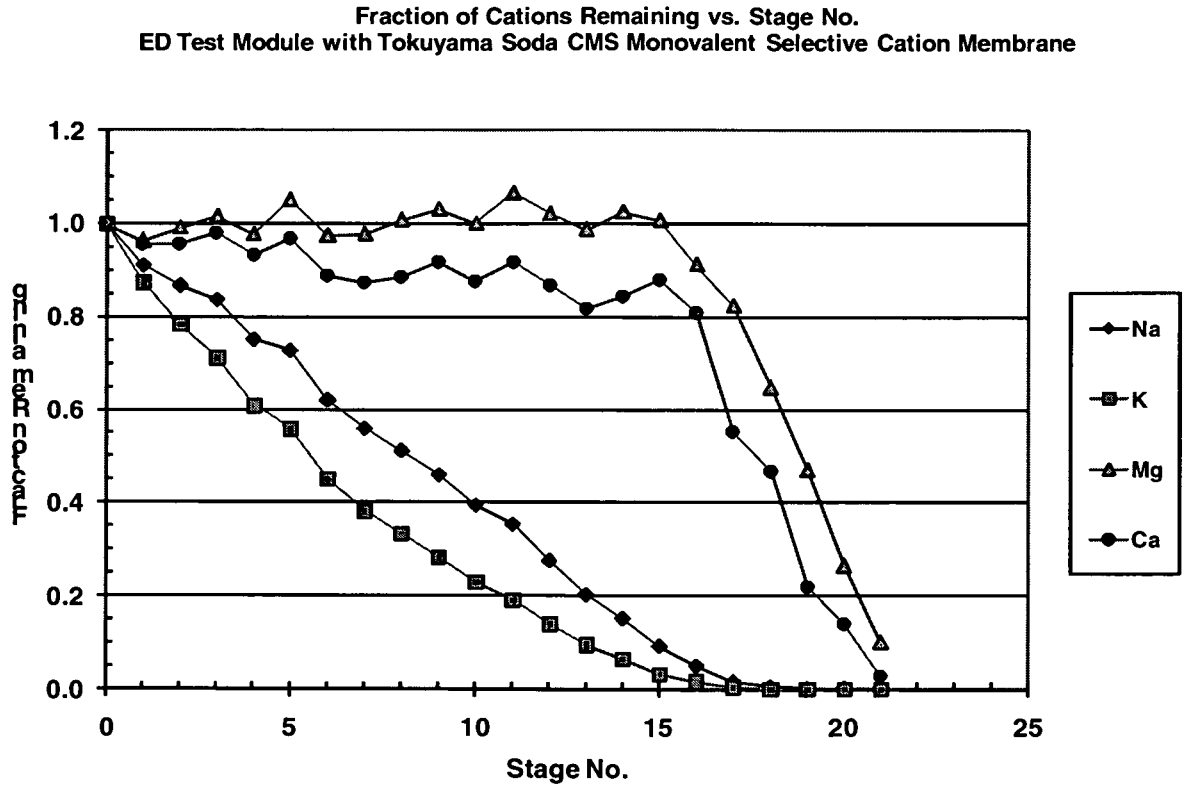
Table 39

Channel width	in	1.25	
	cm	3.18	
Channel length	in	14	
	cm	35.56	
Channel area	in^2	17.5	
	cm^2	112.9	
	m^2	0.0113	A
Number of cell pairs per module		16	NCP
Number of membranes per module		34	
Number of modules		1	NMOD
Total membrane area per module	m^2	0.3839	
	cm2	3838.7	
	ft2	4.13	
Total membrane area	m^2	0.3839	AT
	cm2	3838.7	
	ft2	4.13	

	Manufacturer	Type	Country of origin
Cation membrane	ASTOM	CMX	Japan
Anion membrane	ASTOM	AMX	Japan

Sample	Ca ion in concentrate mg/l	Na ion in concentrate mg/l	Sample	Ca ion in dilute mg/l	Na ion in dilute mg/l
Conc Feed	366.7	10395.0	Dilute Feed	363.3	10175.0
Conc ST-1	393.3	12570.0	Dilute ST-1	347.2	9280.0
Conc ST-2	447.4	16030.0	Dilute ST-2	347.7	8830.0
Conc ST-3	436.0	16755.0	Dilute ST-3	355.4	8520.0
Conc ST-4	435.4	18565.0	Dilute ST-4	338.4	7650.0
Conc ST-5	470.5	21760.0	Dilute ST-5	351.1	7400.0
Conc ST-6	499.1	22660.0	Dilute ST-6	322.9	6310.0
Conc ST-7	511.0	25610.0	Dilute ST-7	317.1	5695.0
Conc ST-8	645.0	29475.0	Dilute ST-8	321.8	5205.0
Conc ST-9	588.5	32115.0	Dilute ST-9	333.6	4676.5
Conc ST-10	641.0	35910.0	Dilute ST-10	317.9	4024.0
Conc ST-11	725.5	38205.0	Dilute ST-11	333.9	3598.5
Conc ST-12	596.5	36390.0	Dilute ST-12	315.1	2796.5
Conc ST-13	682.5	42420.0	Dilute ST-13	297.1	2068.0
Conc ST-14	653.0	42115.0	Dilute ST-14	306.2	1546.5

Conc ST-15	683.5	44835.0	Dilute ST-15	319.5	938.0
Conc ST-16	608.5	39435.0	Dilute ST-16	293.3	505.0
Conc ST-17	902.5	42975.0	Dilute ST-17	200.2	153.8
Conc ST-18	1201.0	42695.0	Dilute ST-18	169.8	57.4
Conc ST-19	1337.0	37730.0	Dilute ST-19	79.7	10.8
Conc ST-20	1491.0	38790.0	Dilute ST20	51.1	17.6
Conc ST-21	1499.5	35565.0	Dilute ST-21	10.0	3.4



Some aspects of the present invention provide systems and techniques of seawater desalination through electrically driven processes. Transfer of ions facilitated by an electrical potential is described as a relatively efficient process because the resistance to ion movement is limited by the membranes that are used to separate purified water from the waste/concentrated water. Additional features and aspects of the invention can pretreatment operation as described herein.

Having now described some illustrative embodiments of the invention, it should be apparent to those skilled in the art that the foregoing is merely illustrative and not limiting, having been presented by way of example only. Indeed, some exemplary configurations of the device, systems, and techniques of the invention and particular components implemented in such configurations are considered a part of the present disclosure. For example, each of the unit operations when described herein as being connectable or being connected, such as fluidly connected, involve respective inlet and outlet ports that provide such connectivity. Non-limiting examples of connecting structures include pipes and threaded or welded flanges secured by bolts and nuts, and typically sealed with gaskets. Numerous modifications and other embodiments are within the scope of one of ordinary skill in the art and are contemplated as falling within the scope of the invention. In particular, although many of the examples presented herein involve specific combinations of method acts or system elements, it should be understood that those acts and those elements may be combined in other ways to accomplish the same objectives.

Those skilled in the art should appreciate that the parameters and configurations described herein are exemplary and that actual parameters and/or configurations will depend on the specific application in which the systems and techniques of the invention are used. Those skilled in the art should also recognize or be able to ascertain, using no more than routine experimentation, equivalents to the specific embodiments of the invention. It is therefore to be understood that the embodiments described herein are presented by way of example only and that, within the scope of the appended claims and equivalents thereto; the invention may be practiced otherwise than as specifically described.

Moreover, it should also be appreciated that the invention is directed to each feature, system, subsystem, or technique described herein and any combination of two or more features, systems, subsystems, or techniques described herein and any combination of two or more features, systems, subsystems, and/or methods, if such features, systems, subsystems, and techniques are not mutually inconsistent, is considered to be within the scope of the

invention as embodied in the claims. Further, acts, elements, and features discussed only in connection with one embodiment are not intended to be excluded from a similar role in other embodiments.

As used herein, the term "plurality" refers to two or more items or components. The terms "comprising," "including," "carrying," "having," "containing," and "involving," whether in the written description or the claims and the like, are open-ended terms, i.e., to mean "including but not limited to." Thus, the use of such terms is meant to encompass the items listed thereafter, and equivalents thereof, as well as additional items. Only the transitional phrases "consisting of" and "consisting essentially of," are closed or semi-closed transitional phrases, respectively, with respect to the claims. Use of ordinal terms such as "first," "second," "third," and the like in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name but for use of the ordinal term to distinguish the claim elements.

What is claimed is:

1. A seawater desalination process comprising,
    a. providing a source of pretreated seawater fluidly connected to an electrodialysis step,
    b. said electrodialysis step comprising at least a cation transfer membrane and an anion transfer membrane, further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane to produce a dilute stream and a concentrate stream from said seawater, wherein
    c. the dilute stream is fluidly connected an ion exchange softener step capable of removing at least calcium,
    d. said ion exchange softener step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream, and,
    e. providing an ion exchange softener effluent stream having reduced calcium ion content.

2. The process of Claim 1 wherein the cation transfer membrane is a monoselective cation transfer membrane.

3. The process of Claim 1 wherein the anion transfer membrane is a monoselective cation transfer membrane.

4. The process of Claim 1 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

5. The process of Claim 1 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

6. The process of Claim 1 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.9 to about 5.0.

7. The process of Claim 1 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.2.

8. The process of Claim 1 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.1.

9. The process of Claim 1 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.05.

10. The process of Claim 1 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 90%.

11. The process of Claim 1 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 70%.

12. The process of Claim 1 wherein the concentrate from the electrodialysis step is used to regenerate the ion exchange softener.

13. The process of Claim 12 wherein the regenerating brine contains less than about 1000 mg/l calcium ion.

14. The process of Claim 12 wherein the regenerating brine contains less than about 500mg/l calcium ion.

15. The process of Claim 1 wherein at least a nanofiltration membrane process step is used to provide the pretreated seawater.

16. The process of Claim 1 wherein at least an ion exchange softener process step is used to provide the pretreated seawater.

17. The process of Claim 1 wherein a nanofiltration membrane process step filters the dilute stream provided to the ion exchange softener.

18. A water desalination process comprising,

a. providing a source of pretreated seawater fluidly connected to,

b. at least a first electrodialysis step an electrodialysis step comprising at least a cation transfer membrane and at least an anion transfer membrane to produce first dilute stream and a first concentrate stream from said seawater, and,

c. said water source fluidly connected to a second electrodialysis step,

d. said second electrodialysis step comprising at least a cation transfer membrane and at least an anion transfer membrane further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane to produce a second dilute stream and a second concentrate stream from said seawater,

e. wherein the dilute streams are fluidly connected an ion exchange softener step capable of removing at least calcium,

f. said ion exchange step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream, and,

g. providing an ion exchange softener effluent stream having reduced calcium ion content.

19. The process of Claim 18 wherein the cation transfer membrane of the second electrodialysis step is a monoselective cation transfer membrane.

20. The process of Claim 18 wherein the anion transfer membrane of the second electrodialysis step is a monoselective anion membrane.

21. The process of Claim 18 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

22. The process of Claim 18 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

23. The process of Claim 18 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.9 to about 5.0.

24. The process of Claim 18 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.2.

25. The process of Claim 18 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.1.

26. The process of Claim 18 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.05.

27. The process of Claim 18 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 90%.

28. The process of Claim 18 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 70%.

29. The process of Claim 18 wherein the concentrate from the second electrodialysis step is used to regenerate the ion exchange softener.

30. The process of Claim 29 wherein the regenerating brine contains less than about 1000 mg/l calcium ion.

31. The process of Claim 29 wherein the regenerating brine contains less than about 500 mg/l calcium ion.

32. The process of Claim 18 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 5.25 to about 1.0.

33. The process of Claim 18 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 6.0 to about 1.0.

34. The process of Claim 18 wherein at least a nanofiltration membrane process step is used to provide the pretreated seawater.

35. The process of Claim 18 wherein at least an ion exchange softener process step is used to provide the pretreated seawater to the second electrodialysis step.

36. The process of Claim 18 wherein a calcium reduction process step is used to provide the pretreated seawater to the second electrodialysis step.

37. The process of Claim 18 wherein a nanofiltration membrane process step filters the dilute stream provided to the ion exchange softener.

38. A seawater desalination process comprising,

a. providing a source of pretreated seawater fluidly connected to,
b. an electrodialysis step comprising at least a cation transfer membrane and an anion transfer membrane, further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane, to produce a dilute stream and a concentrate stream from said seawater, wherein
c. the dilute stream is fluidly connected an ion exchange softener step capable of removing at least calcium,
d. said ion exchange softener step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream, and,
e. the ion exchange effluent fluidly connected to an electrodeionization step to produce final product water.

39. The process of Claim 38 wherein the cation transfer membrane is a monoselective cation transfer membrane.

40. The process of Claim 38 wherein the anion transfer membrane is a monoselective cation transfer membrane.

41. The process of Claim 38 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

42. The process of Claim 38 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

43. The process of Claim 38 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion from about 1.9 to about 5.0.

44. The process of Claim 38 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.2.

45. The process of Claim 38 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.1.

46. The process of Claim 38 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.05

47. The process of Claim 38 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 90%.

48. The process of Claim 38 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 70%.

49. The process of Claim 38 wherein the concentrate from the electrodialysis step is used to regenerate the ion exchange softener.

50. The process of Claim 49 wherein the regenerating brine contains less than about 1000 mg/l calcium ion.

51. The process of Claim 49 wherein the regenerating brine contains less than about 500mg/l calcium ion.

52. The process of Claim 38 wherein at least a nanofiltration membrane process step is used to provide the pretreated seawater.

53. The process of Claim 38 wherein at least an ion exchange softener process step is used to provide the pretreated seawater..

54. The process of Claim 38 wherein a nanofiltration membrane process step reduces calcium content of the stream provided to the ion exchange softener

55. The process of Claim 38 wherein the electrodeionization step comprises a process step using;

an electrodeionization device comprising:

a first depleting compartment, the depleting compartment defined at least partially by a cationic selective membrane and a first anionic selective membrane;

a first concentrating compartment fluidly connected downstream from a source of a first aqueous liquid having a first dissolved solids concentration, and in ionic communication with the first depleting compartment through the cationic selective membrane; and

a second depleting compartment fluidly connected downstream from a source of a second aqueous liquid having a second dissolved solids concentration that is greater than the first dissolved solid concentration, and in ionic communication with the first concentrating compartment through a second anionic selective membrane.

56. A water desalination process comprising,

a. providing a source of pretreated seawater fluidly connected to a first electrodialysis step,
b. said first electrodialysis step an electrodialysis step comprising at least a cation transfer membrane and at least an anion transfer membrane to produce first dilute stream and a first concentrate stream from said seawater, and,
c. said water source fluidly connected to a second electrodialysis step,
d. said second electrodialysis step comprising at least a cation transfer membrane and at least an anion transfer membrane further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane to produce a second dilute stream and a second concentrate stream from said seawater,
e. wherein the dilute streams are fluidly connected an ion exchange softener step capable of removing at least calcium, and,
f. said ion exchange step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream, and,
g. the ion exchange effluent fluidly connected to an electrodeionization step to produce final product water.

57. The process of Claim 56 wherein the cation transfer membrane is a monoselective cation transfer membrane.

58. The process of Claim 56 wherein the anion transfer membrane is a monoselective cation transfer membrane.

59. The process of Claim 56 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

60. The process of Claim 56 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

61. The process of Claim 56 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.9 to about 5.0.

62. The process of Claim 56 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.2.

63. The process of Claim 56 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.1.

64. The process of Claim 56 wherein the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than about 0.05

65. The process of Claim 56 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 90%.

66. The process of Claim 56 wherein the increase in calcium ion concentration in the concentrate stream is less than about 100% based on the feed concentration when the sodium depletion in the dilute stream is about 70%.

67. The process of Claim 56 wherein the concentrate from the electrodialysis step is used to regenerate the ion exchange softener.

68. The process of Claim 67 wherein the regenerating brine contains less than about 1000 mg/l calcium ion.

69. The process of Claim 67 wherein the regenerating brine contains less than about 500 mg/l calcium ion.

70. The process of Claim 56 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 5.25 to about 1.0.

71. The process of Claim 56 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 6.0 to about 1.0.

72. The process of Claim 56 wherein at least a nanofiltration membrane process step is used to provide the pretreated seawater.

73. The process of Claim 56 wherein at least an ion exchange softener process step is used to provide the pretreated seawater to the second electrodialysis step.

74. The process of Claim 56 wherein a calcium reduction process step is used to provide the pretreated seawater to the second electrodialysis step.

75. The process of Claim 56 wherein a nanofiltration membrane process step reduces calcium content of the stream provided to the ion exchange softener.

76. The process of Claim 50 wherein the electrodeionization step comprises a process step using;

an electrodeionization device comprising:

a first depleting compartment, the depleting compartment defined at least partially by a cationic selective membrane and a first anionic selective membrane;

a first concentrating compartment fluidly connected downstream from a source of a first aqueous liquid having a first dissolved solids concentration, and in ionic communication with the first depleting compartment through the cationic selective membrane; and

a second depleting compartment fluidly connected downstream from a source of a second aqueous liquid having a second dissolved solids concentration that is greater than the first dissolved solid concentration, and in ionic communication with the first concentrating compartment through a second anionic selective membrane.

77. A seawater desalination system comprising,

f. an electrodialysis device fluidly connected to a source of pretreated seawater to produce a dilute stream and a concentrate stream from said seawater comprising,

g. at least a cation transfer membrane and an anion transfer membrane, further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane, wherein,

h. the dilute stream of the electrodialysis step is fluidly connected an ion exchange softener step, and,

i. said ion exchange softener step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream.

78. The system of Claim 77 wherein the cation transfer membrane is a monoselective cation transfer membrane.

79. The system of Claim 77 wherein the anion transfer membrane is a monoselective cation transfer membrane.

80. The system of Claim 77 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

81. The system of Claim 77 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

82. The system of Claim 77 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.9 to about 5.0.

83. The system of Claim 77 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.2.

84. The system of Claim 77 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.1.

85. The system of Claim 77 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.05

86. The system of Claim 77 wherein the concentrate from the electrodialysis step is fluidly connected to the ion exchange softener in order to regenerate the ion exchange softener.

87. The system of Claim 86 wherein the electrodialysis device produces a brine regenerating solution containing less than about 1000 mg/l calcium ion.

88. The system of Claim 86 wherein the electrodialysis device produces a brine regenerating solution containing less than about 500 mg/l calcium ion.

89. The system of Claim 77 wherein at least a nanofiltration membrane process step is used to provide the pretreated seawater.

90. The system of Claim 77 wherein at least a ion exchange softener process step is used to provide the pretreated seawater.

91. The system of Claim 77 wherein a nanofiltration membrane process step filters the dilute stream provided to the ion exchange softener.

92. A water desalination system comprising,

a. A first electrodialysis device fluidly connected to a source of pretreated seawater to produce a first dilute stream and a first concentrate stream from said seawater comprising, at least a cation transfer membrane and an anion transfer membrane, and,

b. a second electrodialysis device fluidly connected to said source of pretreated seawater to produce a second dilute stream and a second concentrate stream from said seawater comprising, at least a cation transfer membrane and an anion transfer membrane, further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane, wherein

c. the dilute stream of the electrodialysis step is fluidly connected an ion exchange softener step, and,

d. said ion exchange softener step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream.

93. The system of Claim 92 wherein the cation transfer membrane of the second electrodialysis step is a monoselective cation transfer membrane.

94. The system of Claim 92 wherein the anion transfer membrane of the second electrodialysis step is a monoselective anion membrane.

95. The system of Claim 92 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

96. The system of Claim 92 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

97. The system of Claim 92 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.9 to about 5.0.

98. The system of Claim 92 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.2.

99. The system of Claim 92 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.1.

100. The system of Claim 92 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.05.

101. The system of Claim 92 wherein the concentrate from the second electrodialysis step is fluidly connected to the ion exchange softener in order to regenerate the ion exchange softener.

102. The system of Claim 25 wherein the electrodialysis device produces a brine regenerating solution containing less than about 1000 mg/l calcium ion.

103. The system of Claim 25 wherein the electrodialysis device produces a brine regenerating solution containing less than about 500 mg/l calcium ion.

104. The system of Claim 92 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 0.70 to about 1.0.

105. The system of Claim 92 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 0.75 to about 0.85.

106. The system of Claim having at least a nanofiltration seawater pretreatment device fluidly attached to either or both of the electrodialysis devices.

107. The system of Claim 92 having at least an ion exchange softener seawater pretreatment device fluidly attached to either or both of the electrodialysis devices.

108. The system of Claim 92 having at least a calcium reduction seawater pretreatment device fluidly attached to either or both of the electrodialysis devices.

109. The system of Claim 92 having a nanofiltration membrane dilute stream filter fluidly attached to the ion exchange softener.

110. A seawater desalination system comprising,

a. an electrodialysis device fluidly connected to a source of pretreated seawater to produce a dilute stream and a concentrate stream from said seawater comprising,

b. at least a cation transfer membrane and an anion transfer membrane, further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane, wherein,

c. the dilute stream of the electrodialysis step is fluidly connected an ion exchange softener step, and,

d. said ion exchange softener step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream, and,

e. the ion exchange effluent fluidly connected to an electrodeionization step to produce final product water

111. The system of Claim 110 wherein the cation transfer membrane is a monoselective cation transfer membrane.

112. The system of Claim 110 wherein the anion transfer membrane is a monoselective cation transfer membrane.

113. The system of Claim 110 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

114. The system of Claim 110 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

115. The system of Claim 110 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.9 to about 5.0.

116. The system of Claim 110 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.2.

117. The system of Claim 110 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.1.

118. The system of Claim 110 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.05.

119. The system of Claim 110 wherein the concentrate from the second electrodialysis step is fluidly connected to the ion exchange softener in order to regenerate the ion exchange softener.

120. The system of Claim 119 wherein the electrodialysis device produces a brine regenerating solution containing less than about 1000 mg/l calcium ion.

121. The system of Claim 119 wherein the electrodialysis device produces a brine regenerating solution containing less than about 500 mg/l calcium ion.

122. The system of Claim 110 wherein at least a nanofiltration membrane process step is used to provide the pretreated seawater.

123. The system of Claim 110 wherein at least a ion exchange softener process step is used to provide the pretreated seawater.

124. The system of Claim 110 wherein a nanofiltration membrane process step filters the dilute stream provided to the ion exchange softener.

125. The system of Claim 107 wherein the electrodeionization device comprises,

a first depleting compartment, the depleting compartment defined at least partially by a cationic selective membrane and a first anionic selective membrane;

a first concentrating compartment fluidly connected downstream from a source of a first aqueous liquid having a first dissolved solids concentration, and in ionic communication with the first depleting compartment through the cationic selective membrane; and

a second depleting compartment fluidly connected downstream from a source of a second aqueous liquid having a second dissolved solids concentration that is greater than the first dissolved solid concentration, and in ionic communication with the first concentrating compartment through a second anionic selective membrane.

126. A water desalination system comprising,

a. A first electrodialysis device fluidly connected to a source of pretreated seawater to produce a first dilute stream and a first concentrate stream from said seawater comprising, at least a cation transfer membrane and an anion transfer membrane, and,

b. a second electrodialysis device fluidly connected to said source of pretreated seawater to produce a second dilute stream and a second concentrate stream from said seawater comprising, at least a cation transfer membrane and an anion transfer membrane, further comprising that at least one of said cation transfer membrane and anion transfer membrane is a monoselective ion transfer membrane, wherein

c. the dilute stream of the electrodialysis step is fluidly connected an ion exchange softener step, and,

d. said ion exchange softener step having the property that at a breakthrough concentration of 2 milligram per liter of calcium ion, the ratio of calcium ion to magnesium ion in the ion exchange effluent is less than the ratio of calcium ion to magnesium ion in the inflowing dilute stream, and,

e. the ion exchange effluent fluidly connected to an electrodeionization step to produce final product water.

127. The system of Claim 126 wherein the cation transfer membrane is a monoselective cation transfer membrane.

128. The system of Claim 126 wherein the anion transfer membrane is a monoselective cation transfer membrane.

129. The system of Claim 126 wherein the cation transfer membrane and the anion transfer membrane are a monoselective cation transfer membrane and a monoselective anion membrane respectively.

130. The system of Claim 126 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.5 to about 8.0.

131. The system of Claim 126 wherein the cation transfer membrane is a monoselective cation transfer membrane having a selectivity ratio for sodium ion to calcium ion of from about 1.9 to about 5.0.

132. The system of Claim 126 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.2.

133. The system of Claim 126 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.1.

134. The system of Claim 126 wherein the ion exchange softener is designed to produce a ratio of calcium ion to magnesium ion in the ion exchange effluent of less than about 0.05.

135. The system of Claim 126 wherein the concentrate from the second electrodialysis step is fluidly connected to the ion exchange softener in order to regenerate the ion exchange softener.

136. The system of Claim 135 wherein the electrodialysis device produces a brine regenerating solution containing less than about 1000 mg/l calcium ion.

137. The system of Claim 135 wherein the electrodialysis device produces a brine regenerating solution containing less than about 500 mg/l calcium ion.

138. The system of Claim 126 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 0.70 to about 1.0.

139. The system of Claim 126 wherein the ratio of the flow rate of the dilute stream from the first electrodialysis step to that of the dilute flow rate of the second electrodialysis step is from about 0.75 to about 0.85.

140. The system of Claim having at least a nanofiltration seawater pretreatment device fluidly attached to either or both of the electrodialysis devices.

141. The system of Claim 126 having at least a ion exchange softener seawater pretreatment device fluidly attached to either or both of the electrodialysis devices.

142. The system of Claim 126 having at least a calcium reduction seawater pretreatment device fluidly attached to either or both of the electrodialysis devices.

143. The system of Claim 126 having a nanofiltration membrane dilute stream filter fluidly attached to the ion exchange softener.

144. The system of Claim 126 wherein the electrodeionization device comprises,

a first depleting compartment, the depleting compartment defined at least partially by a cationic selective membrane and a first anionic selective membrane;

a first concentrating compartment fluidly connected downstream from a source of a first aqueous liquid having a first dissolved solids concentration, and in ionic communication with the first depleting compartment through the cationic selective membrane; and

a second depleting compartment fluidly connected downstream from a source of a second aqueous liquid having a second dissolved solids concentration that is greater than the first dissolved solid concentration, and in ionic communication

with the first concentrating compartment through a second anionic selective membrane.