

ION EXCHANGE MEMBRANES AND METHODS OF MAKING THE SAME

FIELD OF THE TECHNOLOGY

Aspects relates generally to ion exchange membranes having enhanced properties and to improved processes of making ion exchange membranes having said properties.

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SUMMARY

In accordance with one or more aspects, an ion exchange membrane may comprise a polymeric microporous substrate, and a cross-linked ion transferring polymeric layer on the substrate, the cross-linked ion transferring polymeric layer comprising a polymerization product of at least a functional monomer and a low value r_2/r_s monomer.

In accordance with one or more aspects, an ion exchange membrane may comprise the polymerization product of a first monomer having a reactivity ratio r_1 and a second monomer having a reactivity ratio r_2 wherein the reactivity ratio product of the first monomer and the second monomer is less than about 0.6 or between about 0.7 to 1.3.

In accordance with one or more embodiments, a method of making an ion exchange membrane may comprise mixing a solution including at least a functional monomer and a low value r_2/r_s monomer, wherein at least two of the monomers have a reactivity ratio product of less than about 0.6 or between about 0.7 to 1.3, saturating a polymeric microporous substrate with the solution, and polymerizing the solution on the saturated substrate to form the ion exchange membrane.

Still other aspects, embodiments, and advantages of these exemplary aspects and embodiments, are discussed in detail below. Embodiments disclosed herein may be combined with other embodiments in any manner consistent with at least one of the principles disclosed herein, and references to “an embodiment,” “some embodiments,” “an alternate embodiment,” “various embodiments,” “one embodiment” or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described may be included in at least one embodiment. The appearances of such terms herein are not necessarily all referring to the same embodiment.

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BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide illustration and a further understanding of the various aspects and embodiments,

and are incorporated in and constitute a part of this specification, but are not intended as a definition of the limits of the invention. Where technical features in the figures, detailed description or any claim are followed by reference signs, the reference signs have been included for the sole purpose of increasing the intelligibility of the figures and description. In the figures, 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 figure. In the figures:

FIG. 1 presents an electrochemical test unit used; and

FIG. 2 presents the electrodes of the electrochemical test unit of FIG. 1

DETAILED DESCRIPTION

Devices for purifying fluids using electrical fields are commonly used to treat water and other liquids containing dissolved ionic species. Two types of devices that treat water in this way are electrodeionization and electrodialysis devices. Within these devices are concentrating and diluting compartments separated by ion exchange membranes. An electrodialysis device typically includes alternating electroactive semipermeable anion and cation exchange membranes. Spaces between the membranes are configured to create liquid flow compartments with inlets and outlets. An applied electric field imposed via electrodes causes dissolved ions, attracted to their respective counter-electrodes, to migrate through the anion and cation exchange membranes. This generally results in the liquid of the diluting compartment being depleted of ions, and the liquid in the concentrating compartment being enriched with the transferred ions.

Electrodeionization (EDI) is a process that removes, or at least reduces, one or more ionized or ionizable species from water using electrically active media and an electric potential to influence ion transport. The electrically active media typically serves to alternately collect and discharge ionic and/or ionizable species and, in some cases, to facilitate the transport of ions, which may be continuously, by ionic or electronic substitution mechanisms. EDI devices can comprise electrochemically active media of permanent or temporary charge, and may be operated batch-wise, intermittently, continuously, and/or even in reversing polarity modes. EDI devices may be operated to promote one or more electrochemical reactions specifically designed to achieve or enhance performance. Further,

such electrochemical devices may comprise electrically active membranes, such as semipermeable or selectively permeable ion exchange or bipolar membranes.

Continuous electrodeionization (CEDI) devices are EDI devices known to those skilled in the art that operate in a manner in which water purification can proceed continuously, while ion exchange material is continuously recharged. CEDI techniques can include processes such as continuous deionization, filled cell electrodialysis, or electrodiuresis. Under controlled voltage and salinity conditions, in CEDI systems, water molecules can be split to generate hydrogen or hydronium ions or species and hydroxide or hydroxyl ions or species that can regenerate ion exchange media in the device and thus facilitate the release of the trapped species therefrom. In this manner, a water stream to be treated can be continuously purified without requiring chemical recharging of ion exchange resin.

Electrodialysis (ED) devices operate on a similar principle as CEDI, except that ED devices typically do not contain electroactive media between the membranes. Because of the lack of electroactive media, the operation of ED may be hindered on feed waters of low salinity because of elevated electrical resistance. Also, because the operation of ED on high salinity feed waters can result in elevated electrical current consumption, ED apparatus have heretofore been most effectively used on source waters of intermediate salinity. In ED based systems, because there is no electroactive media, splitting water is inefficient and operating in such a regime is generally avoided.

In CEDI and ED devices, a plurality of adjacent cells or compartments are typically separated by selectively permeable membranes that allow the passage of either positively or negatively charged species, but typically not both. Dilution or depletion compartments are typically interspaced with concentrating or concentration compartments in such devices. In some embodiments, a cell pair may refer to a pair of adjacent concentrating and diluting compartments. As water flows through the depletion compartments, ionic and other charged species are typically drawn into concentrating compartments under the influence of an electric field, such as a DC field. Positively charged species are drawn toward a cathode, typically located at one end of a stack of multiple depletion and concentration compartments, and negatively charged species are likewise drawn toward an anode of such devices, typically located at the opposite end of the stack of compartments. The electrodes are typically housed in electrolyte compartments that are usually partially isolated from fluid communication with the depletion and/ or concentration compartments. Once in a concentration compartment,

charged species are typically trapped by a barrier of selectively permeable membrane at least partially defining the concentration compartment. For example, anions are typically prevented from migrating further toward the cathode, out of the concentration compartment, by a cation selective membrane. Once captured in the concentrating compartment, trapped
5 charged species can be removed in a concentrate stream.

In CEDI and ED devices, the DC field is typically applied to the cells from a source of voltage and electric current applied to the electrodes (anode or positive electrode, and cathode or negative electrode). The voltage and current source (collectively “power supply”) can be itself powered by a variety of means such as an AC power source, or for example, a
10 power source derived from solar, wind, or wave power. At the electrode/liquid interfaces, electrochemical half cell reactions occur that initiate and/ or facilitate the transfer of ions through the membranes and compartments. The specific electrochemical reactions that occur at the electrode/ interfaces can be controlled to some extent by the concentration of salts in the specialized compartments that house the electrode assemblies. For example, a feed to the
15 anode electrolyte compartments that is high in sodium chloride will tend to generate chlorine gas and hydrogen ion, while such a feed to the cathode electrolyte compartment will tend to generate hydrogen gas and hydroxide ion. Generally, the hydrogen ion generated at the anode compartment will associate with a free anion, such as chloride ion, to preserve charge neutrality and create hydrochloric acid solution, and analogously, the hydroxide ion
20 generated at the cathode compartment will associate with a free cation, such as sodium, to preserve charge neutrality and create sodium hydroxide solution. The reaction products of the electrode compartments, such as generated chlorine gas and sodium hydroxide, can be utilized in the process as needed for disinfection purposes, for membrane cleaning and defouling purposes, and for pH adjustment purposes.

25 Plate-and-frame and spiral wound designs have been used for various types of electrochemical deionization devices including but not limited to electrodialysis (ED) and electrodeionization (EDI) devices. Commercially available ED devices are typically of plate-and-frame design, While EDI devices are available in both plate and frame and spiral configurations.

30 One or more embodiments relate to the composition of ion exchange membranes that may be used in devices that purify fluids electrically, as well as methods of manufacture and use thereof.

Electrochemical separation systems are used to create ultrapure water for the pharmaceutical and semiconductor industries, are used as power generating sources in reverse electro dialysis, as separators in fuel cells, are used in the recovery of metal ions in the electroplating and metal finishing industries, are in various other applications including the food and beverage industry. Among the most important applications of ion exchange membranes, however, is the desalination of seawater by electrochemical methods.

Seawater is traditionally desalinated by pressure driven methods, and is most commonly accomplished by reverse osmosis. Seawater reverse osmosis however requires extensive pre-treatment of the feed and is an energy-intensive process. Electrochemical desalination has advantages over reverse osmosis in that less pretreatment is required. Though electrochemical methods are often used to treat brackish and waste water, electrochemical methods are still often considered too expensive for seawater desalination.

Seawater has a total dissolved solids content of about 35,000 parts per million (ppm). The majority of the dissolved solids in seawater is sodium chloride, and thus treating seawater predominantly involves removing monovalent ions. Reverse osmosis membranes, however, generally, preferentially remove divalent ions and thus are less efficient at treating seawater than membranes that selectively remove monovalent ions. Electrochemical desalination may have advantages over reverse osmosis desalination because monovalent selective membranes can be used to treat seawater.

Ion exchange membranes can be fabricated to be ion selective. For example, a membrane can be fabricated from a specific precursor such that the resulting membrane preferentially removes a certain ion from a treatment water. Certain industries require water with a particularly low concentration of a specific ion. For example, water flooding used in the oil refinery business must have very low sulfate values, and the semiconductor and pharmaceutical industries require ultra pure water having very low concentrations of boron and silica. The fabrication of ion-selective membranes is thus highly desirable because of their ability to efficiently remove species of interest contained in a treatment water for use in a specific application.

The design of a successful and economical electrochemical separation system, including an electrochemical system for desalinating seawater, is affected by a number of parameters, including the ion selectivity of the membranes, but most importantly, the voltage drop across a pair of ion exchange membranes and the electric power consumed in the desalting process. The properties of the ion exchange membranes used in such systems

impact the system efficiency. The development of ion exchange membranes requires an optimization of properties in order to overcome competing effects. Ion exchange membranes for seawater desalination generally must meet four main characteristics to be considered successful. The membranes must have low electrical resistance, high permselectivity, high
5 chemical stability, and good mechanical strength. Of these parameters, low electrical resistance and high permselectivity are of the most importance because they directly affect the energy consumption of an electrochemical separation process.

The electrical resistivity of an ion exchange membrane is an expression of how strongly the membrane resists the flow of electric current. When resistivity is high, more current, and thus more energy, must be applied to the electrochemical cell to facilitate ion transfer across the membrane to perform electrochemical separation. Thus generally, the lower the resistivity of the ion exchange membrane, the more efficient the membrane, and system having said membrane, can perform electrochemical separations. Membrane resistivity is generally expressed in units of resistance by area, for example, ohm-square centimeters, $\Omega \cdot \text{cm}^2$. In at least some embodiments, an ion exchange membrane may have a resistivity of less than about 1.5 Ohm-cm².

The permselectivity measures the degree to which a membrane is permeable to counter-ions and impermeable to co-ions. When an electric current is applied to an
10 electrochemical cell having an anion exchange membrane and a cation exchange membrane, specifically referring to the cation exchange membrane for explanative purposes, counter-ions (cations) in solution will cross the cation membrane and theoretically, co-ions (anions) will be rejected by the membrane. In practice however, some anions will cross the cation exchange membrane. The passage of these co-ions across the membrane reduces the overall
15 process efficiency. Thus membranes that have a high permselectivity, that is, are highly permeable to counter-ions and highly impermeable to co-ions, are more efficient than membranes having lower permselectivity.

Seawater desalination generally causes membranes to foul. Ion exchange membranes used in seawater desalination must be able to withstand cleaning by oxidative chemicals, and
20 therefore must also be able to withstand pHs in a range of from about 0 to about 14, for example, a pH in the range of about 2 to about 12. The membranes must also be able to withstand the stress of being handled while being manufactured into modules or other processing devices. The membrane must also have good dimensional stability in operation.

Seawater feed can vary in temperature and concentration and the membrane should not swell or shrink excessively when the properties of fluid contacting the membrane change.

In order to be competitive with seawater reverse osmosis desalination, an electrochemical apparatus, such as an ED or EDR, must have membranes with a resistance of
5 less than about 1 ohm-cm² preferably less than 0.8 ohm-cm², and most preferably, less than about 0.5 ohm-cm². Further, the ion permselectivity must be greater than about 90%, more preferably greater than about 95%, and most preferably, greater than about 98%.

The membrane must also have a long service life, be physically strong and chemically durable, and it must be capable of fabrication at low cost. Though thinner membranes will
10 have lower resistance and allow for more membrane area per unit volume of a device, thinner membranes are more susceptible to dimension changes from environmental effects, such as changes in the temperature and concentration of the solution contacting the membrane. Moreover, the development and production of defect-free thinner membranes is more difficult than when a relatively greater thickness is allowed because production of thinner
15 membranes reduces the available margin of error during membrane production.

Ion exchange membranes comprise polymeric materials that facilitate the transport of either positive or negative ions across the membrane. Ion exchange membrane properties, including resistivity and permselectivity, are controlled, in part, by the amount, type, and distribution of fixed ionic groups in the membrane. For example, strong base anion exchange
20 membranes generally comprise quaternary ammonium salts, where as weak base anion exchange membranes generally comprise tertiary amines. The ammonium ylides have fixed positive charges that allow anionic species to permeate across the membrane.

Commercially available ion exchange membranes are generally heterogeneous membranes. Heterogeneous membranes comprise a polymeric layer coated on top of a film
25 and are fabricated by a multi-step process that involves calendaring neutral polymers, a binder, and a plasticizer onto a reinforcing monofilament, such as a woven fabric, at a high temperature and pressure. The calendared monofilament film is then functionalized in a batch process. The polymer coated on the film undergoes a reaction that creates fixed charges in the resulting membrane. For the fabrication of cation exchange membranes, the
30 coated films undergo a batch process to sulfonate the polymer coating. For the fabrication of anion exchange members, the coated film undergoes a process that chloromethylates the polymer coating.

The functionalization step is time consuming, and may take longer than a day, longer than two days, or longer than three days to complete. After functionalization is complete, the membranes are thoroughly washed and rinsed of excess sulfonating, in the case of cation exchange, and chlormethylation in the case of anion exchange, agents. The solvents used to wash the membranes are costly and may be carcinogenic or otherwise hazardous and therefore the rinsing process requires both good ventilation and a solvent recovery process.

Other classes of commercially available ion exchange membranes involve disposing an ion exchange functionalized thermoplastic polymer solution on a releasing surface with, or without, reinforced supporting substrates. The functionalization of ion exchange thermoplastics, such as polysulfone, poly(ether-ether ketone), poly(phenylene oxide), and fluorinated polymers requires multiple steps, is tedious, can result in low yields. Membranes made with this technique generally have low permselectivity and are expensive. Further, because the polymer is not crosslinked, the membranes experience a greater degree of dimensional change when exposed to high salinity gradients during separation processes.

Commercially available membranes are therefore expensive, and the installation of commercially available membranes may be cost-prohibitive and inefficient for large scale commercial desalination installations.

Membranes fabricated by these multi-step processes often have a thickness of about 150 μm to about 200 μm , depending on the type of membrane fabricated. Thicker membranes may be fabricated by using powdered ion exchange resin beads in a hot blending process with a polyethylene binder. The blended polymeric compound is extruded onto a film. Membranes fabricated by coating a film by extrusion have a typical thickness of about 300 μm to about 500 μm . These membranes are also expensive, and their thickness is undesirable for the installation of large scale desalination processes.

In accordance with aspects and embodiments, a homogenous ion exchange membrane and process of fabricating a homogenous ion exchange membrane is disclosed. The fabrication process of the present invention may be a one step process. The process may enable ion exchange membranes to be produced in large quantities, in shorter time periods, and at lower cost.

In accordance with embodiments, reactive monomers may be used to fill the pores of a polymeric microporous substrate. The pore-filling process may be a one step process and may produce membranes having enhanced electrical properties as compared to commercially available membranes. The membranes of the present invention may have a lower area

resistivity, and higher permselectivity than commercially available membranes.

Heterogeneous membranes generally suffer from variations and inconsistencies in electrochemical properties. The process and membranes of the present disclosure may have a more uniform microstructure and may thus provide a higher degree of consistency in the electrochemical properties of like-fabricated membranes. The membranes of the present disclosure may have a permselectivity of greater than about 95% and an area resistivity of less than about $1.5 \Omega \cdot \text{cm}^2$.

Commercially available membranes are not generally weldable and typically must be kept wet at all times, which makes installation of the ion exchange membranes in an electrochemical device and operation of the device difficult. In accordance with aspects and embodiments, a thermally weldable membrane is provided that can be dried out, re-wet, and re-used. The membranes of the present disclosure may also be thinner than commercially available membranes and may, for example, have a thickness of less than about $255 \mu\text{m}$, less than about $155 \mu\text{m}$, less than about $55 \mu\text{m}$, and in some embodiments, the membrane may have a thickness of about $20 \mu\text{m}$. Thus, the membranes disclosed may allow packing of a larger effective membrane area in a smaller space than would be achievable by commercially available membranes. The membranes of the present disclosure may thus be used to design electrochemical devices having increased productivity. The membranes of the present invention may allow for more versatile product design.

In accordance with aspects and embodiments, a homogenous ion exchange membrane is produced having improved electrochemical properties. The homogenous ion exchange membrane may be produced by the polymerization of monomers. A polymeric microporous substrate may be soaked in a monomer mixture. Typically, when a polymeric microporous substrate is used to fabricate an ion exchange membrane, a polymer mixture coats the substrate. The pores of the substrate may not be filled by the polymers in the mix because the polymers in the mixture have a size much greater than the size of the substrate pores. In accordance with aspects and embodiments, the pores of a polymeric microporous support may be filled by reactive monomers and the pore-filled substrate may be used to produce an ion exchange membrane. Anion exchange membranes may, for example, be fabricated from a substrate filled with a vinylimidazole monomer, such that when the monomer filling the pores is polymerized to form a membrane, the polymerized product comprises fixed charge quaternary amine groups that function as active sites for anion exchange. Cation exchange membranes, may, for example, be fabricated from a substrate filled with a sulfoethyl

methacrylate monomer, such that when the monomer filling the pores is polymerized to form a cation exchange membrane, the polymerization product comprises fixed sulfonic acid groups that provide active sites for cation exchange.

5 The monomers, however, that polymerize to polymers containing fixed charges are generally hydrophilic. Thus, if a monomeric precursor containing quarternary ammonium salt was homo-polymerized to produce an anion exchange membrane, the ammonium ylide groups that facilitate the exchange of anions, would ultimately leach out of the membrane during membrane conditioning or when exposed to treatment solutions. If the polymers having active sites leach out of the membrane, the electrochemical performance of the
10 membrane declines. When preparing ion exchange membranes from monomers, it is thus necessary to polymerize the functional monomer with a cross-linking agent that renders the polymerized product of the functional monomer less hydrophilic. As used herein, a functional monomer is a monomer that can be polymerized to have a fixed charge suitable to function as an active site in an ion exchange membrane. As used herein, a cross-linking
15 agent, or cross-linking monomer, is any monomer capable of copolymerizing with the functional monomer to render the polymerization product less hydrophilic.

In accordance with aspects and embodiments, ion exchange membranes may thus be prepared by the free radical polymerization of two monomers, the functional monomer and the cross-linking monomer. Free radical reactions are difficult to control, however, and often
20 result in inconsistent products. For example, when preparing ion exchange membranes, the hydrophilic and hydrophobic ingredients may separate over time or in response to temperature changes, the mix may turn cloudy, or may prematurely set. Further, run-away reactions may occur, which can lead to safety hazards and loss of time and material.

Other problems associated with controlling free radical polymerization reactions
25 include the homo-polymerization of the water soluble functional monomer, the homo-polymerization of the cross-linking monomer, and low conversion of copolymerization. Low conversion of polymerization leaves a portion of incompletely polymerized monomers, dimers, and oligomers. The homo-polymerized functional monomers and incompletely polymerized monomers, dimers, and oligomers may leach out during the ion exchange
30 membrane conditioning process and may negatively impact the electrochemical performance of the membranes. Area-resistivity may increase and permselectivity may decrease.

In accordance with aspects of the present disclosure, monomers for the fabrication of ion exchange membranes may be selected based on their reactivity ratios. Selecting

monomers based on their reactivity ratios may facilitate controlling polymerization reactions and the process of selecting monomers based on their reactivity ratios may enable the fabrication of membranes having enhanced electrochemical properties.

The efficiency of a free radical polymerization of copolymers can be calculated by the mole ratios of the starting monomers to determine their theoretical ion exchange capacities as compared to the experimentally measured properties of a fabricated ion exchange membrane. The measured efficiencies of copolymerization reactions can be used to modify reaction mixtures and fabricate membranes with improved properties.

The properties of fabricated membranes can be measured by ion exchange capacity tests and by spectroscopic analytical methods, such as FTIR, FT-UV, FT-Raman, or NMR spectroscopy. Monomer sequence distributions in a copolymer can often be determined and classified by spectroscopic methods.

The reactivity ratio of two polymers can be determined by comparing the composition of the initially formed copolymer and the initial mixture of monomers. The reactivity ratio of a vinyl monomer copolymerizing with a second monomer is defined by:

$$m_1/m_2 = [M_1(r_1M_1 + M_2)]/[M_2(r_2M_2 + M_1)]$$

where m_1 = the mole of monomer 1 entering the copolymer, m_2 = the mole of monomer 2 entering the copolymer; M_1 = the mole of monomer 1 in the monomer mix, M_2 = the mole of monomer 2 in the monomer mix, and r_1 and r_2 are the monomer reactivity ratios.

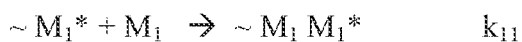
The behavior of monomers in copolymerization reactions is especially useful for analyzing the effect of chemical structure on reactivity. Copolymerization reactions facilitate the fabrication of polymer products with specifically desired properties. Homopolymerization of single monomers cannot produce a wide range of products. Copolymerization, however, provides for the synthesis of a near unlimited number of different products. By varying the nature and relative amounts of two monomer units, a wide variety of copolymers can be produced from a binary monomer combination.

Copolymerization reactions can produce four distinct types of polymers; random, block, alternative, and graft. Spectroscopic analysis can be used to identify the copolymer that results from a copolymerization reaction.

Random ~AABABBBABABBAABABBAAB~
 Block ~AAAAAAAAAAAAABBBBBBBBBBB~
 Alternative ~ABABABABABABABABABABAB~
 Graft ~A-A-A-A-A-A-A-A-A-A~



The Mayo-Lewis copolymerization equations shown below for a two monomer system leads to two types of propagating species—one with M_1 at the propagating end and the other with M_2 at the propagating end. These can be represented by M_1^* and M_2^* , where the asterisk represents the radical as the propagating species.



20 The monomer reactivity ratios, r_1 and r_2 , for any monomer pair are the ratios of the rate constants of the different propagation reactions:

$$r_1 = k_{11} / k_{12}$$

25

$$r_2 = k_{22} / k_{21}$$

From these equations, several limiting cases can be derived:

- $r_1 = r_2 \gg 1$: both reactivity ratios very high, the two monomers have no inclination to react to each other except with themselves leading to a mixture of two homo-polymers.

- $r_1 = r_2 > 1$: both ratios larger than 1, homo-polymerization of component M₁ is favored but in the event of a cross polymerization by M₂ the chain-end will continue as such giving rise to block copolymer.
- $r_1 = r_2 \approx 1$: both ratios around 1, monomer 1 will react as fast with another monomer 1 or monomer 2 and a random copolymer results.
- $r_1 = r_2 \approx 0$: both values approaching 0 the monomers are unable to react in homo-polymerization and the result is an alternating polymer.
- $r_1 \gg r_2 \gg 1$: In the initial stage of the copolymerization monomer 1 is incorporated faster and the copolymer is rich in monomer 1. When this monomer gets depleted, more monomer 2 segments are added. This is called composition drift.

Table 1. Reactivity Ratio of copolymers from binary monomer system.(Excerpt from Polymer Handbook, 3rd Ed. pages 153-226)

Monomer	Monomer 2	r_1	r_2
2-Sulfoethyl methacrylate	Styrene	0.60	0.37
2-Sulfoethyl methacrylate	Ethyl methacrylate	2.0	1.0
2-Sulfoethyl methacrylate	Ethyl acrylate	3.2	0.3
Methyl acrylate	Sodium (2-Sulfoethyl methacrylate)	0.78	1.20
Styrene	Acrylic acid	0.253	0.136
Styrene	methyl methacrylate	0.49	0.48
Styrene	1-vinylimidazole	9.94	0.071
Styrene	2-Sulfoethyl methacrylate	0.37	0.60
Styrene	2-Hydroxyethylmethacrylate	0.44	0.54

Styrene	Ethyleneglycol dimethacrylate	0.28	0.98
Styrene	p-Divinyl benzene	0.26	1.18
Styrene	m-Divinyl benzene	0.65	0.60
styrene	Glycidyl methacrylate	0.54	0.16
Styrene	N-vinylcarbazole	6.0	0
Styrene	p-chloromethylstyrene	0.62	1.12
Styrene	N-Methyl-3-vinylcabazole	0.735	1.404
Styrene	2-vinylpyridine	0.46	0.75
Styrene	4-vinylpyridine	0	1.04
2-Hydroxyethylmethacrylate	2-acrylamido-2-methylpropanesulfonic acid	0.86	0.90
2-Hydroxyethylmethacrylate	2-vinylpyridine	0.56	0.64
2-Hydroxyethylmethacrylate	3-vinylpyridine	0.69	0.73
2-Hydroxyethylmethacrylate	4-vinylpyridine	0.62	0.90
2-Hydroxyethylmethacrylate	Methylmethacrylate	0.63	0.83
Methylmethacrylate	4-vinylpyridine	0.54	0.99
Methylmethacrylate	Ethyleneglycol dimethacrylate	1.8635	0.6993
Sodium styrenesulfonate	Acrolein	0.047	0.260
Sodium styrenesulfonate	α -chloro-acrylate, sodium salt	1.44	0.27
Vinylidene dichloride	N-vinylcarbazole	0	3.6

Vinylidene dichloride	2-Sulfoethylmethacrylate	0.22	3.6
Vinylidene dichloride	Methacrylic acid	0.154	3.368
Butyl acrylate	Styrene, p-octylamine sulfonate	0.30	2.30
Butyl acrylate	2-vinylpyridine	0.11	2.59
Butyl acrylate	4-vinylpyridine	0.23	4.30
Methacrylic Acid	Diethylaminoethylmethacrylate	0.63	2.34
2-acrylamido-2-methylpropanesulfonic acid	N,N-dimethyl acrylamide	0.590	1.108
Sodium, 2-acrylamido-2-methylpropanesulfonate	Vinyl acetate	11.60	0.05
Sodium, 2-acrylamido-2-methylpropanesulfonate	2-Hydroxypropyl methacrylate	1.03	0.89
Ethyl acrylate	N-vinylcarbazole	1.10	0.27
Ethyl acrylate	1,3-divinylimidazolid-2-one	0.41	0
Ethyl acrylate	1-ethyl-3-vinyl imidazolid-2-one	0.47	0.01
Ethyl acrylate	2-Sulfoethyl methacrylate	0.30	3.20
Ethyl acrylate	2-Vinylpyridine	0.21	2.25
Ethyl acrylate	4-Vinylpyridine	0.29	2.58
Methyl acrylate	N-Vinylcarbazole	0.530	0.049
Methyl acrylate	1-Vinyl-2-methylimidazole	1.280	0.050

Methyl acrylate	Vinyl butyl sulfonate	4.14	0
Methyl acrylate	p-N,N-dimethylamino-styrene	0.06	0.38
Acrylonitrile	N-Vinylcarbazole	0.390	0.090
Acrylonitrile	Maleic anhydride	6.0	0
Acrylonitrile	N,N-divinyl aniline	0.246	-0.006*
Methacrylic Acid	Na, 2-sulfoethylmethacrylate	0.78	1.20
Methacrylic Acid	Styrene	0.550	0.210
Methacrylic Acid	Diethylaminoethylmethacrylate	0.63	2.34
Methacrylic Acid	Sulfolanylmethacrylate	0.810	0.810
Methacrylic Acid	Glycidylmethacrylate	0.98	1.20
Methacrylic Acid	Vinyl diethyl phosphonate	1.90	0.15
Methacrylic Acid	2-Vinylpyridine	0.58	1.69
Methacrylic Acid	o-Chlorostyrene	0.622	0.101
N-Vinylpyrrolidone	1-vinylimidazole	0.160	0.960

* Artifact negative value considered the r value is approaching zero.

Table 1 lists the reactivity ratio values determined for some common monomers. Table 1, however, is incomplete and does not include all monomers of interest. Without experimental data, which is time consuming and difficult to collect, it is difficult to determine how two monomers will co-polymerize. There may, however, be data on how monomers of interest react with other monomers having known properties.

In accordance with aspects and embodiments, data from a single monomer may be used to produce derivative reactivity ratios of monomers of interest where reactivity data is otherwise unavailable. The derivative reactivity ratios obtained may be used to assist in the

selection of monomers for the fabrication of ion exchange membranes having enhanced electrochemical properties. A derivative reactivity ratio of a monomer can be created by normalizing published reactivity data with a polymer having known properties and comparing the normalized value to the published value. For example, styrene is a very hydrophilic monomer and can be used to produce a normalized reactivity ratio that may gauge how a functional monomer or neutral monomer may react with a hydrophobic monomer, such as a cross-linking agent. Table 2 presents the styrene-normalized reactivity ratios of monomers of interest for membrane fabrication.

10 **Table 2**

Monomer S	Monomer 2		r_s	r_2	r_2/r_s
Styrene	p-Divinyl benzene	p-DVB	0.26	1.18	4.54
Styrene	m-Divinyl benzene	m-DVB	0.65	0.60	0.92
Styrene	2-Hydroxyethylmethacrylate	HOEMA	0.44	0.54	1.23
Styrene	2-Sulfoethyl methacrylate	2-SEM	0.37	0.60	1.62
Styrene	1-vinylimidazole	VI	9.94	0.071	0.0007
Styrene	N-vinylcarbazole	NVK	6.0	0	0
Styrene	p-chloromethylstyrene	VBC	0.62	1.12	1.81
Styrene	Acrylic Acid	AA	0.253	0.136	0.54
Styrene	methylmethacrylate	MMA	0.49	0.48	0.98
Styrene	glycidylmethacrylate	GMA	0.54	0.16	0.30
Styrene	Ethyleneglycol dimethacrylate	EGDM	0.28	0.98	3.50

By comparing the styrene-normalized reactivity ratios (r_s) to r_2 of functional, cross-linking, and neutral polymers, conclusions can be drawn regarding the reactivity of the monomers. For example, if the styrene-normalized derivative reactivity ratio (r_2/r_s) is greater

than about one, monomer 2 may have an equal tendency of reacting to another monomer and itself. If, for example, the ratio is much greater than 1, the monomer may have a much greater tendency to react with itself than with another monomer. If the ratio is less than about one, less than about 0.5, or even less than about 0.2, monomer 2 may have a greater tendency to copolymerize with another monomer than itself. Generally, the r_2/r_s value of a monomer is considered a low r_2/r_s value if the ratio is less than about 1.3, less than about 1.0, and more preferably, less than about 0.6.

In accordance with aspects and embodiments, a styrene-normalized derivative reactivity ratio may be used to select monomers to copolymerize for the fabrication of an ion exchange membrane and the styrene-normalized derivative reactivity ratio may further assist in optimizing the composition of the selected monomer mix.

When fabricating an ion exchange membrane with a cross-linking agent having a styrene normalized reactivity ratio higher than one, which indicates that the cross-linking agent is likely to homo-polymerize, it is important that the reaction be altered to limit homo-polymerization. By limiting or eliminating homo-polymerization, the electrochemical performance of the produced membranes may be enhanced.

Homo-polymerization may be controlled by adding additional monomers to the functional monomer-cross-linking agent mix. A monomer having an r_2/r_s value of less than about one may be added to the mix to start the copolymerization of the polymer chain.

Adding an additional monomer with a low r_2/r_s value may facilitate the formation of alternative or random copolymers and thereby limit or eliminate homo-polymerization.

For example, 2-SEM may be used to fabricate a cation exchange membrane having sulfonic acid active sites for cation exchange. The r_2/r_s value of 2-SEM is greater than one and therefore indicates a likelihood for 2-SEM to homo-polymerize. The homo-polymerized polymerization product of 2-SEM will be hydrophilic. A cross-linking monomer must be copolymerized with the 2-SEM to render the resulting membrane hydrophobic to ensure the sulfonic acid groups do not leach out of the fabricated membrane.

p-DVB and m-DVB are cross-linking agents. Though m-DVB has an r_2/r_s value of less than one, which is considered a "low" r_2/r_s value as the term is used herein, m-DVB is commercially only available in a mixture of m-DVB and p-DVB, and the high purity grade DVB commercially available generally comprises about 70% m-DVB and 30% p-DVB. Thus when using DVB as a cross-linking agent, DVB may have an r_2/r_s value that is greater than, or much greater than one. This indicates that DVB has a high tendency to homo-

polymerize and therefore less DVB should be used in the monomer mix. Some amount of DVB must be used to co-polymerize the 2-SEM, however, additional monomers, for example, neutral monomers can be added to the mix. Neutral monomers are defined herein as monomers with a styrene-normalized derivative reactivity ratio of less than about 1.3, less than about 1.0, less than about 0.5, or even less than about 0.20. The addition of a neutral monomer may facilitate the production of a more random copolymer product. Thus, by adding for example, acrylic acid (AA), which has an r_2/r_s value of 0.54, the resulting cation exchange membrane fabricated from 2-SEM, DVB, and AA may have enhanced electrochemical properties as compared to a cation exchange membrane fabricated from 2-SEM and DVB in the absence of a neutral monomer.

The same principles can be applied to the fabrication of anion exchange membranes. For example, 1-vinylamidazole (VI) may be used to fabricate an anion exchange membrane having tertiary or quaternary amine groups that function as active sites for anion exchange. Based on the near zero r_2/r_s value, VI is more likely to polymerize with a different monomer rather than with itself. By further selecting a cross-linking monomer with a low r_2/r_s value, an anion exchange membrane with excellent electrochemical properties can be achieved.

When, for example, VI is copolymerized with a cross-linking agent having an r_2/r_s value that is greater than 1, such as VBC, a neutral monomer, such as HOEMA, glycidyl methacrylate, or methyl methacrylate, can be added to the monomer mix to fabricate an anion exchange membrane with superior electrochemical properties than an anion exchange membrane fabricated from VI and VBC, alone.

In the event that a high r_2 or a high r_2/r_s crosslinking agent is selected, an additional monomer having a low r_2 or low r_2/r_s value can be added to help achieve a higher degree of co-polymerization. In some non-limiting embodiments, monomers that may improve the resulting properties of the membrane may include hydroxyethylmethacrylate, glycidyl methacrylate, methyl methacrylate, ethyl methacrylate, butyl methacrylate, hydroxyethylacrylate, glycidyl acrylate, methyl acrylate, ethyl acrylate, butyl acrylate, acrylic acid, methacrylic acid.

In accordance with embodiments, the product of the reactivity ratio of two monomers, or the product of the styrene-normalized derivative reactivity ratio of two monomers, can be used to determine desirable membrane compositions. A product of reactivity ratios of about 1 indicates that the copolymer will be a random copolymer. A product of reactivity ratios of about 0 indicates that the resulting copolymer will be an alternative copolymer. The same

principle can be applied to the product of the styrene normalized derivative reactivity ratios, $[r_2/r_s]_1$, of a first monomer and $[r_2/r_s]_2$ for a second monomer. Thus, it is most desirable to have the product of the reactivity ratios of the two monomers to be near 1 or near zero, such as less than about 0.6 or in the range of between about 0.7 to about 1.3. In accordance with
5 some embodiments, the product of the reactivity ratio of the two monomers may be less than about 0.3 or in the range of between about 0.9 to 1.1.

Other factors in addition to the reactivity ratios of monomers will affect the outcome of a copolymerization reaction. The type of initiator used, the polarity of solvents, temperature, relative humidity, the viscosity of the monomer mixture, the method of stirring
10 during polymerization, the electron withdrawing or electron releasing nature of the pendant functional groups of the final monomer, and polarity all may affect polymerization reactions. In accordance with aspects and embodiments, polymeric microporous substrates may be used to produce ion exchange membranes from monomer mixes. The monomer mix is selected, in part, based on the reactivity ratios, the styrene-normalized reactivity ratios, and the styrene-normalized derivative reactivity ratios of monomers. The microporous substrate may
15 comprise polypropylene, high molecular weight polyethylene, ultrahigh molecular weight polyethylene, or polyvinylidene fluoride in some non-limiting embodiments.

The selected monomers are mixed, and in some embodiments, mixed in a solvent system. The substrate may then be wet with the monomer mix. The monomer mix may be
20 allowed to fill the pores of the substrate, and the wet or saturated substrate may then be cast into an ion exchange membrane. The casting process used to fabricate membranes may include application of a vacuum, application of a positive pressure, application of ultraviolet radiation, heat, or any other process sufficient to solidify the mix on and in the substrate.

In accordance with one or more embodiments, a polymeric microporous substrate
25 may comprise at least one of polypropylene, high molecular weight polyethylene, ultrahigh molecular weight polyethylene, polyvinyl chloride, polyvinylidene difluoride, and polytetrafluoroethylene. A thickness of the polymeric microporous substrate may be between about 20 microns and about 255 microns. In some embodiments, it may be less than about 155 microns. In other embodiments, it may be less than about 55 microns. The resulting
30 membrane may have a thickness that is substantially the same as the polymeric substrate.

The electrochemical characteristics of the ion exchange membranes fabricated in accordance with aspects and embodiments may be easily measured by using an electrochemical cell. The performance of ion exchange membranes, including the resistivity

and permselectivity may be measured and compared using a small piece of sample in a bench top electrochemical test unit.

For example and referring to FIG. 1, electrochemical test unit 100 has electrode pair 110. Electrodes 110 may be platinum disks. One electrode functions as a cathode and the other functions as an anode. Electrochemical test unit 100 has a pair of reference electrodes 120. Referring also to FIG. 2, reference electrodes 120 may comprise a silver wire 10 with a silver chloride coating 20. Wire 10 with coating 20 is disposed in glass tubing 30. Glass tubing 30 has porous tip 35 that allows electrode solution 40 to flow out of tubing 30 very slowly.

To take measurements, the cell is filled with a test solution and a current is applied to the cell. The conductivity of the test solution is calculated from the measured voltage drop between the two reference electrodes at the applied current.

A sample of an ion exchange membrane of interest is then placed between the reference electrode and the voltage drop across the membrane is measured by the reference electrodes at the applied current. The resistance of the membrane is calculated as a function of the total resistance less the solution resistance. The permselectivity is calculated as a function of the measured voltage drop, solution temperature, and concentration of the test solution on the two sides of the membrane in the cell.

Existing electrochemical water treatment systems may be retrofitted by providing and implementing the membranes discussed herein fabricated in accordance with one or more embodiments. For example, an existing water treatment system comprising an electrochemical separation device may be retrofitted with one or more of the membrane enhancements and modifications discussed herein. The modifications and enhancements to the process of making ion exchange membranes may be used individually, or in combination.

The improved membranes and processes of the present disclosure may be able to treat water more efficiently and with total lower capital cost than traditional water treatment systems providing and implementing the modifications discussed herein in accordance with one or more embodiments.

The function and advantages of these and other embodiments can be further understood from the examples below, which illustrate the benefits and/or advantages of the one or more systems, methods, and techniques but do not exemplify the full scope of the invention. The standard operating procedures used to fabricate ion exchange membranes and

the standard operating procedures used to collect data on the resulting membranes are detailed below.

STANDARD OPERATING PROCEDURES

Standard Ion Exchange Membrane Fabrication Procedures

Ion exchange membranes were fabricated by polymerizing various monomer solutions on polymeric microporous substrates. The microporous substrates used to fabricate the membranes of the present invention were polyethylene (PE) films, high density polyethylene (HDPE) films, ultrahigh molecular weight polyethylene (UHMWPE) films, and polypropylene (PP) films.

The substrates had a porous structure having pores in a size of from about 100 nm to about 10,000 nm and about 20% to about 90% porosity. Sandwiched polymer substrates with differently structured layers were investigated to accommodate different solution penetrations. Monofilament and multifilament yarns, staple yarns, woven fabrics, wet-laid, and melt spun bonded and non-bonded, non-woven fabric sheets ranging from about 100 micrometers to about 1 mm were also investigated and found to be suitable substrates. A list of preferred substrates and their properties are listed in Table 3 below.

Table 3: Specification of Preferred Substrates

Abbreviation	Trade name	Manufacturer	Material	Rated pore size	Thickness microns	Porosity %
AP H6A	APorous lots: H6A or NS7	Aporous Billerica, MA	HDPE	0.1	52	68
TK20	Teklon HPIP20	Entek Lebanon,OR	UHMWPE		20	48
TK32(Bi)	Teklon HPIP32Bi	Entek Lebanon,OR	UHMWPE		32	48
TK32	Teklon HPIP32	Entek Lebanon,OR	UHMWPE		32	48

S16P05A	Solupor 16P05A	Lydall Filtration Rochester NH	UHMWPE	0.5	60 & 115	83 & 85
S16P10A	Solupor 16P10A	Lydall Filtration Rochester NH	UHMWPE	0.9	120	85
EK2045	Celgard	Celgard	UHMWPE	0.097	20	45
EZ2590	Celgard	Celgard	PP	0.1	26	66

Polymeric microporous substrates were die-cut into discs having a diameter of about 4.3 cm. Clear polyester (PET) films having a 3 mm thickness were die cut into discs having a size of about 5 cm to about 10 cm and were used as dividers between substrates to insulate the substrates from contacting air and to prevent the different substrate materials from adhering to each other during thermoset curing operations. An aluminum weighting boat having a diameter of about 10.5 cm was used to facilitate the fabrication of the membranes.

Specific monomer mixtures of interest were poured into the aluminum boat. A PET disc was placed in the boat and a piece of substrate was layered on top of the PET disc. Sufficient time was allowed for the monomer solution to wet the substrate. Air bubbles were smoothed out from the substrate completely before a second layer of PET film was placed on top of the wetted substrate.

This procedure provided for more than 10 layers of substrate sandwiched between layers of PET to be wetted in about 8 gram of monomer mixture. Alternatively, the substrates were pre-wetted in a separate container by first soaking the substrate in the monomer solution. A vacuum and mild heating at less than about 40°C were used to degas the wetted substrates, and were used independently and in conjunction with one another with efficacy.

Polymerization of the monomer solution on the substrate was then initiated by the application of pressure and heat to form ion exchange membranes. The PET-wetted substrate layers were placed in an air-tight container and the container was filled with nitrogen gas to provide a positive pressure. Heat was then applied to the container by placing it in an oven pre-set at 80°C. The PET-substrate layers were heated for about 10 to about 30 minutes.

Alternatively, polymerization was also initiated by exposure to ultraviolet light with a wavelength of about 100 nm to about 400 nm.

The monomer solution was exposed to conditions sufficient to cause the solution to solidify. After the solution was observed to have solidified, the PET-substrate layers were
5 disassembled and the fabricated ion exchange membranes were placed in a 0.5 NaCl solution for conditioning at about 40°C to about 50°C for about 30 minutes to about 12 hours before their area resistivity and permselectivity were tested.

Standard Procedures for Measuring Membrane Area Resistivity and Apparent Permselectivity

10 After membranes were fabricated in accordance with aspects and embodiments, their electrochemical properties were measured. A Solartron 1280 electrochemical measurement unit, offered by Solartron Analytics, was used to measure the apparent permselectivity and resistivity of the fabricated membranes. These values were then compared to standard, commercially available membranes.

15 The Solartron 1280 has the configuration of electrochemical test unit 100 shown in FIG. 1. The cylindrical path of the Solartron 1280 cell had a controlled cross sectional area of 7.0 cm². Reference electrodes 120 were platinum electrodes and were used to apply current across the cell. Reference electrodes 120 were fabricated in the lab by creating an electrochemical cell comprising a platinum wire cathode and a silver wire anode 10 filled
20 with a 0.1 HCL solution. Current was supplied to the cell by a power supply and an ammeter. After about 10 minutes at a current of about 2-3 milliamps (Ma), silver wire 10 began to turn black, indicating the formation of silver chloride layer 20 on the surface of silver wire 10. Reference electrodes 120 were newly fabricated for each experiment.

The fabricated silver/silver chloride wire was disposed in glass tubing 30 having
25 porous tip 35. Glass tubing 30 had a diameter of about ¼ inches and was filled with 1.0 KCL electrode solution. Electrode solution was added about every 20 minutes to the electrodes to compensate for electrode solution 40 that leaked through porous tips 30 of electrodes 120.

Prior to taking measurements, the reference electrode horizontal positions were set by a pair of screws to ensure precise dimensional control between the two reference electrodes.
30 Precise dimensional control is essential in accurately calculating resistance measurements and also ensures that the electrode tips do not damage the membrane samples. To set up the reference electrode positions, a rigid plastic disk was used in place of a membrane. The

reference electrodes were positioned such that the electrode tip touched the plastic disk. Once proper placement was achieved, the reference electrodes were fixed by a pair of screws adjusted to touch against the wall of the sample slider.

The plastic disc was then removed and test solution measurements were taken in the absence of a membrane sample. The test solution was generally 0.50 NaCl. The voltage drop between and current density between the two reference electrodes was recorded at an applied current of about 10 Ma to about 50 Ma and a distance of about 1.00 cm. From these measurements, the conductivity of the solution was obtained. The solution conductivity was compared to the measurement taken by a conductivity meter to ensure accuracy.

The conductivity, C , of the solutions in the cell can be expressed as

$$C = \frac{1}{\rho} = \frac{L}{RA} = \frac{L}{\frac{U}{I} \times A}$$

Where L is the distance between reference electrodes, U is the voltage measured between the electrodes at distance L , I is the current being drawn, and A is the cross-sectional area of the cell.

For example, for a 0.500M NaCl solution when 10.00mA of current was being drawn and a voltage drop of 33.1 mV was measured across membranes, spaced 1.0 cm apart, the conductivity of the solution was:

$$C = \frac{1}{\rho} = \frac{L}{RA} = \frac{L}{\frac{U}{I} \times A} = \frac{1.00cm}{\frac{33.1mV}{10.0mA} \times 7.00cm^2} = 0.0432S/cm$$

After solution conductivity was measured, a sample of membrane was placed in the Solartron 1280 and the voltage and current density were again measured. The resistance of the membrane is the total resistance measured less the solution resistance measured in the absence of a membrane sample. The area resistivity, R , can thus be expressed as:

$$R = \frac{(Tr - Sr)}{I} \times A$$

Where R equals area resistivity, T_r is the total measured resistivity, S_r is the measured resistivity of solution, I is the measured current being drawn between the reference electrodes, and A is the area of the membrane.

For example, a standard commercially available cation exchange membrane (CXM) offered by Astom Corporation of Japan was placed in the Solartron 1280 cell and a potential of 38.0Mv was measured across the membrane. The Solartron 1280 cross-sectional area and thus the cross sectional area of the CXM was 7.0 cm². The solution absent a membrane

sample had a resistivity of 33.1 mV and a current of 10.00 mA. The CXM thus has an area resistivity of:

$$R = \frac{(38.1 - 33.1)mV}{10.0mA} \times 7.00cm^2 = 3.42\Omega \cdot cm^2$$

The permselectivity of a cation (+) or anion (-) membrane, $T_{\pm}$ is obtained by:

$$V = (2T_{\pm} - 1) \frac{RT}{F} \ln \frac{a_L}{a_R}$$

Where V is the measured voltage by the reference electrodes, R is the gas constant (8.314 Joule•K⁻¹•mole⁻¹), where T is the Kelvin temperature of solution, F is Faraday's constant (96480 coulomb/mole) and a_R and a_L are the activities of solution on the right and left sides of the membrane, respectively. Activity, a , is a function of concentration, C:

$$a = \gamma(C);$$

Where γ is the activity coefficient of solution. The activity coefficient of the solution can be calculated using known models, such as the Debye-Hückel Equation, the Extended Debye-Hückel Equation, and the Davies Equation.

The area-resistance and apparent permselectivity of the polymeric microporous substrates were measured and compared before being used to fabricate ion exchange membranes. Polymeric microporous substrates were obtained from lithium ion battery suppliers. Teklon HPIP substrates manufactured by Entek of Lebanon OR, Aporous substrates manufactured by Aporous Inc. of Billerica, MA, Celgard substrates manufactured by Celgard, LLC of Charlotte, NC, and Solupur 16P10A substrates manufactured by Lydall Filtration of Rochester, NH were pre-washed using isopropanol-ethanol and deionized water each for five minutes, respectively. The substrates were then rinsed by 0.5N NaCl (aq.) four times. Discs of substrate were die cut and the area resistivity and apparent permselectivity of each substrate was measured in accordance with Solartron 1280 operating procedures above. The data recorded is presented in Table 3.

Table 3: Resistivity and Permselectivity of Substrates

Substrate	R(ohm cm ²)	Apparent Permselectivity %
Teklon HPIP	0.593	57.24

Solupor 16P10A	2.192	57.38
Celgard EZ-2590 PP	0.788	57.54
Celgard EZ-2090 PP	1.159	57.38

EXAMPLES

CATION MEMBRANE FABRICATION

Cation exchange membranes were fabricated in accordance with aspects and
embodiments to test the improvement in electrochemical properties of cation exchange
membranes fabricated from processes disclosed herein. Solutions having different monomer
mixes were cast on microporous polymeric substrates and allowed to fill the pores of the
substrate. As used herein, monomer mix and monomer solution are used interchangeably.
An ion exchange membrane comprising a cation transferring polymeric layer was then
formed from the wet, pore-filled, substrate. The area-resistivity and apparent permselectivity
of resulting cation exchange membranes were then measured and the values were compared
to the measured area resistivity and apparent permselectivity of a commercially available
cation exchange membrane (CMX) offered by the Astom Corporation of Japan. The CMX
membrane had a thickness of about 170 μm .

EXAMPLE 1: CEM fabrication based on 2-SEM/DVB/EGDM/AA

The effect of monomer composition on resulting membranes was investigated by
adding a monomer having a low r_2/r_s value to a system having a cation functional monomer
and cross-linking agents having r_2/r_s values greater than one. A nine ounce jar immersed in
an ice water bath at about 5°C was charged with a solvent system of 30.0 g NMP and 21 gm
of 1-butanol. 135.1 gm of 2-SEM, 9 gm of DVB (80% m-DVB, 20% p-DVB), 36.5 gm of
EGDM and 3.0 gm of AA were added to the solvent system and stirred to get a homogenous
dark red, wine colored, clear solution. 1.54 gm of 2,2'-dimethyl-2,2'-azodipropionitrile
(Vazo® 64 produced by DuPont™) was added to the mix to initiate free radical
polymerization. The Vazo® 64 was stirred until dissolved.

Three 32 μm Teklon HPIP discs and three 32 μm Teklon HPIP discs were soaked in
the monomer mix solution for 80 minutes. The bilayer comprised two layers of substrate

calendared together. The discs were sandwiched between polyester (Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight container, filled with nitrogen gas, and placed in a 90°C oven for 2 hours. The fabricated membranes were then removed from the assembly and conditioned in 0.5 N NaCl (aq). The area resistance and permselectivity of the fabricated membranes is presented in Table 4.

Table 4: Data of CEM based on 2-SEM/DVB/EGDM/AA

Description	R(ohm cm ²)	Apparent Permselectivity (%)
Astom CMX	2.94	106
Teklon HPIP 32 µm	1.67	105
Teklon HPIP 32 µm bilayer	0.84	104

The resulting membranes had improved apparent permselectivity, were thinner, and had a lower area resistance than the Astom CMX. The addition of acrylic acid (AA) significantly reduced the area resistivity of the resulting membranes. As indicated by the improved electrochemical properties of the resulting membranes, the addition of acrylic acid, which has an r_2/r_3 of 0.54, to the monomer mix enhanced the reactivity of 2-SEM, which resulted in a more fully copolymerized product.

EXAMPLE 2: CEM fabrication based on 2-SEM/DVB/AA

The impact of monomer composition was then investigated by fabricating a cation exchange membrane with DVB and AA. A six ounce jar immersed in an ice water bath at about 10°C was charged with a solvent system of 7.0 g NMP. 15.8 gm of 2-SEM, 9 gm of DVB (80% m-DVB, 20% p-DVB), and 2.0 gm of AA were added to the system and stirred to get a homogenous dark red, wine colored, clear solution. 0.34 gm of Vazo® 64 was added and stirred until dissolved.

Ten 20 µm Teklon HPIP discs, ten 115 µm Solupor 10P05A discs, and 4 120 µm Solupor 16P10A discs were soaked in the solution monomer mix solution for 120 minutes. The discs were sandwiched between polyester (Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight container, filled with nitrogen gas, and placed in an 80°C oven for 40 minutes. The fabricated membranes were

then removed from the assembly and conditioned in 0.5 N NaCl (aq). The area resistance and permselectivity of the fabricated membranes is presented in Table 5.

Table 5: Data of CEM based on 2-SEM/DVB/AA

Description	R (ohm cm ²)	Apparent Permselectivity %
CMX	3.3	106
Solupor 16P10A	2.6	105
Solupor 16P10A	3.1	104
Teklon HPIP 20 μ m	5.8	105
Teklon HPIP 20	3.3	105
Solupor 16P05A _1	3.6	104
Solupor 16P05A _2	3.7	105

5

The resulting membranes had improved apparent permselectivity, were thinner, and had and lower area resistance than the Astom CMX. p-DVB has a high r_2/r_s value, however, the addition of acrylic acid (AA) significantly reduced the area resistivity of the resulting membranes. As indicated by the improved electrochemical properties of the resulting membranes, the addition of acrylic, which has an r_2/r_s value of 0.54, to the monomer mix enhanced the reactivity of 2-SEM, which resulted in a more fully copolymerized product.

10

EXAMPLE 3: CEM fabrication based on 2-SEM/Sty/DVB/HOEMA

The impact of monomer composition was further investigated by fabricating a cation exchange membrane with DVB, styrene (Sty), and HOEMA. A six ounce jar immersed in an ice water bath at about 16°C was charged with 7.6 g NMP solvent. 18.0 gm of 2-SEM, 5.7 gm of DVB (80% m-DVB, 20% p-DVB), 1.8 gm of styrene, and 2.7 gm of HOEMA were added to the NMP and stirred to get a homogenous dark red, wine colored, clear solution. 0.198 gm of Vazo® 64 was added and stirred until dissolved.

20

Seventeen 120 μ m Solupor 10P10A discs were soaked in the monomer mix solution solution for 19 hours in a refrigerator. The discs were then sandwiched between polyester

(Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight container, filled with nitrogen gas, and placed in an 80°C oven for two hours. The fabricated membranes were then removed from the assembly and conditioned in 0.5 N NaCl (aq). The area resistance and permselectivity of the fabricated membranes is presented in Table 6.

Table 6: Data of CEM based on 2-SEM/Sty/DVB/HOEMA

Description	R (ohm cm ²)	Apparent Permselectivity %
CMX	3.0	105.3
Solupor 16P10A #1	1.9	102.8
Solupor 16P10A #2	1.8	103.5
Solupor 16P10A #3	2.4	103.8
Solupor 16P10A #4	2.4	104.0

The resulting membranes had improved apparent permselectivity, were thinner, and had and lower area resistance than the Astom CMX, however the the area resistivity and permselectivity of the resulting membranes were not as desirable as membranes fabricated with AA. The addition of HOEMA, which has an r_2/r_s value of 1.23 and the absence of AA, which has an r_2/r_s of 0.54, negatively impacted the electrochemical properties of the resulting membrane.

ANION MEMBRANE FABRICATION

Anion exchange membranes were fabricated in accordance with aspects and embodiments to test the improvement in electrochemical properties of anion exchange membranes fabricated from processes disclosed herein. Solutions having different monomer mixes were cast on microporous polymeric substrates and allowed to fill the pores of the substrate. An ion exchange membranes comprising an anion transferring polymeric layer was then formed from the wet, pore-filled, substrate. The area-resistivity and apparent permselectivity of resulting anion exchange membranes were then measured and the values were compared to the measured area resistivity and apparent permselectivity of a commercially

available anion exchange membrane (AMX) offered by the Astom Corporation of Japan. The AMX membrane had a thickness of about 140 μm .

The functional monomers used to produce the anion exchange membranes were quaternary amine monomers. The quaternary amine monomers were produced in a unique, two step process. The process comprised quaternizing a tertiary amine monomer by a chloro-alkylating agent or chloro-acylating agent and allowing the reaction to go to completion. The intermediate Quat product was then subsequently used to fabricate anion exchange membranes.

EXAMPLE 4: AEM fabrication based on VI/BC/VBC

A quaternized monomer was produced in a 100 ml beaker charged with 29.2221 gm of clear and light yellow color 1-vinylimidazole and 38.1466 gm of clear, colorless benzyl chloride. The solution was stirred at room temperature for 17 hours. After stirring, the mix was very viscose and had a clear orange color. The resulting quaternized monomer solution was then mixed with 7.05 gm of VBC, 13.10 gm of dipropylene glycol (DPG), and 0.88 gm of Vazo® 64, and stirred. A clear solution was obtained immediately after stirring. An additional 4.01 gm DPG was added to the solution.

One 20 μm Teklon HPIP disc and one 20 μm Celgard EK2045 discs were wet instantaneously and allowed to stay in the solution for 25 minutes. The discs were sandwiched between polyester (Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight container, filled with nitrogen gas, and placed in an 80 °C oven for 2 hours. The fabricated membranes were then removed from the assembly and conditioned in 0.5 N NaCl (aq). The area resistance and permselectivity of the fabricated membranes is presented in Table 7.

Table 7: Data of AEM based on VI/BC/VBC

Description	R(ohm cm^2)	Apparent Permselectivity %
Astom AMX	2.87	94.1
Teklon HPIP	1.48	96.2
Celgard EK-2045	1.31	95.6

The monomer formulation was very stable at room temperature and could be stirred continuously, in part, due to the reactive properties of 1-vinylimidazole. Vinylimidazole does not have a tendency to homo-polymerize, as indicated by its low r_2/r_s value of 0.0007. The resulting anion exchange membranes fabricated from the monomer solution had improved apparent permselectivity, were thinner, and had a lower area resistance than the Astom AMX. The membranes also had good uniform topology and were completely transparent, which indicated that the copolymer had a uniform microstructure.

EXAMPLE 5: AEM fabrication based on VI/BC/VBC

The quaternized monomer solution of example 5 was further investigated. An additional 4.17 grams of DPG were added to 76.07 gm of the mix made and described in Example 5. One 20 μm Teklon HPIP disc and one 20 μm Celgard EK2045 disc were wet instantaneously and allowed to stay in the solution for 90 minutes. The discs were sandwiched between polyester (Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight container, filled with nitrogen gas, and placed in an 80°C oven for 65 minutes. The fabricated membranes were then removed from the assembly and conditioned in 0.5 N NaCl (aq). The area resistance and permselectivity of the fabricated membranes is presented in Table 8.

Table 8: Data of AEM based on VI/BC/VBC

Description	R(ohm cm^2)	Apparent Permselectivity %
Astom AMX	2.81	94.9
Teklon HPIP	1.41	95.1
Celgard EK-2045	1.13	95.1

The resulting anion exchange membranes fabricated from the monomer solution had improved apparent permselectivity, were thinner, and had a lower area resistance than the Astom AMX. The membranes also had good uniform topology and were completely transparent. As in Example 4, the monomer mix was very stable and thus the process could easily be scaled up to produce larger membranes having uniform properties.

EXAMPLE 6

Different cross-linking agents were then investigated to determine their effect on the properties of the resulting membranes. Each membrane was made from a 20 μm Teklon HPIP substrate and the substrate was coated with quaternized 1-vinylimidazole produced from the same batch of quaternized 1-vinylimidazole solution.

A quaternized 1-vinylimidazole (QVI) solution was prepared by mixing 15.6823 gm of 1-vinylimidazole, 21.1925 gm of benzyl chloride, and 6.2581 gm of N-methylpyrrolidone (NMP) in a 250 ml beaker. The solution was stirred at room temperature of 5 hours, and then mixed for an addition hour at a gradually increasing temperature. The temperature after the 6th hour was 58°C. The mixture was then removed from heat and stirred at room temperature for an additional 18 hours. The mixture turned a clear golden color. 10 gms of NMP were added.

Example 6A: AEM fabrication from VI/BC/NMP/VBC on 20 μm Teklon HPIP substrate

The QVI solution was first mixed with vinylbenzyl chloride. 13.0580 gm of QVI were mixed with 2.5427 gm of vinylbenzyl chloride (VBC) and stirred to homogenize the mixture. Teklon HPIP discs having a thickness of 20 μm were wet instantaneously and allowed to soak in the mixture for 1 hour. The discs were sandwiched between polyester (Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight container, filled with nitrogen gas, and placed in an 80 °C oven for 70 minutes. The fabricated membranes were then removed from the assembly and conditioned in 0.5 N NaCl (aq).

Example 6B: AEM fabrication from VI/BC/NMP/DVB/HEOMA on 20 μm Teklon HPIP substrate

The QVI solution was then mixed with divinylbenzene (DVB) and hydroxyethylmethacrylate (HOEMA). 15.2864 gm of QVI were mixed with 3.7745 gm of DVB (80%) and 2.8966 gm of HEOMA and stirred to homogenize the mixture. Teklon HPIP discs having a thickness of 20 μm were wet instantaneously and allowed to soak in the mixture for 1 hour. The discs were sandwiched between polyester (Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight

container, filled with nitrogen gas, and placed in an 80°C oven for 80 minutes. The fabricated membranes were then removed from the assembly and conditioned in 0.5 N NaCl (aq).

Example 6C: AEM fabrication from VI/BC/NMP/EGDM/HEOMA on 20 µm

5 Teklon HPIP substrate

The QVI solution was then mixed with ethyleneglycol dimethacrylate (EGDM) and HOEMA. 15.2864 gm of QVI were mixed with 2.5707 gm EGDM, 1.4550 gm HOEMA, and 1.0784 gm 1-propanol. Teklon HPIP discs having a thickness of 20 µm were wet instantaneously and allowed to soak in the mixture for 1 hour. The discs were sandwiched between polyester (Mylar) discs and air bubbles were removed from the soaked substrates. The assembly was placed in an airtight container, filled with nitrogen gas, and placed in an 80°C oven for 50 minutes. The fabricated membranes were then removed from the assembly and conditioned in 0.5 N NaCl (aq). The data from Examples 6A-6C is presented in Table 9.

Table 9: AEM fabrication from VI/BC/NMP and Different Cross-Linking Agents

Cross-linking agent(s)	R(ohm cm ²)	Apparent Permselectivity %
Example 6A: (VBC)	2.62	95.2
Example 6B: (DVB, HEOMA)	28.97	95.0
Example 6C: (EGDM, HEOMA)	3.57	95.0

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All cross-linking agents tested produced comparable apparent permselectivity values and all were higher than the apparent permselectivity of the Astom AMX. When DVB and HOEMA were used as cross-linking agents, the area-resistivity was very high, which correlated directly to the high r_2/r_s values of the cross-linking agents used. When EGDM and HOEMA were used as cross-linking agents, the area resistivity was lower, but still not as low as when VBC was used, which had the lowest r_2/r_s value of the cross-linking monomer combinations used. The data indicated that when fabricated anion exchange membranes,

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electrochemical properties are enhanced when a cross-linking agent with a low r_2/r_s value is used.

Casting a monomer mix on a microporous substrate to prepare ion exchange membranes in accordance with the one-step methods disclosed herein provides for the fabrication of improved ion exchange membranes. The method enables the fabrication of membranes using at least one functional monomer and at least one cross-linking agent on thermal weldable, microporous, polyolefin substrates. The membranes described herein may be made in large quantities and may be made continuously. The membranes may be fabricated in a machine having a saturation tank that allows the pores of a substrate to be completely filled by a monomer mix. The wet substrates may then pass through a heated or UV curing zone to polymerize and solidify the mix on the substrate into a finished membrane. The membranes can be dried, re-wet, and reused, and may be thinner, and fabricated at costs lower than commercially available membranes. Further, membranes in accordance with aspects and embodiments may have improved electrochemical properties, such as lower area resistance and higher permselectivity. The membranes of the present invention may reduce the energy consumption of an electrochemical separation process, increase water recovery, increase the effective membrane area capable of being packed in the same volume of membrane module, and may enhance the overall efficiency of electrochemical separation processes.

The phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. Any references to embodiments or elements or acts of the apparatus and methods herein referred to in the singular may also embrace embodiments including a plurality of these elements, and any references in plural to any embodiment or element or act herein may also embrace embodiments including only a single element. The use herein of “including,” “comprising,” “having,” “containing,” “involving,” and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Any references to positional or spatial orientation are intended for convenience of description, not to limit the present apparatus and methods or their components.

Having described above several aspects of at least one embodiment, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be

part of this disclosure and are intended to be within the scope of the invention. Accordingly, the foregoing description and drawings are by way of example only.

CLAIMS

1. An ion exchange membrane, comprising:
a polymeric microporous substrate; and
a cross-linked ion transferring polymeric layer on the substrate, the cross-linked ion transferring polymeric layer comprising a polymerization product of at least a functional monomer and a low value r_2/r_s monomer.
2. The ion exchange membrane of claim 1, wherein the low value r_2/r_s monomer is a cross-linking monomer.
3. The ion exchange membrane of claim 1, wherein the cross-linked ion transferring polymeric layer comprises the polymerization product of at least the functional monomer, a cross-linking monomer, and the low value r_2/r_s monomer.
4. The ion exchange membrane of claim 1, wherein the thickness of the polymeric microporous substrate is between about 20 microns and about 255 microns.
5. The ion exchange membrane of claim 1, wherein the cross-linked ion transferring polymeric layer comprises a cross-linked cation transferring polymer.
6. The ion exchange membrane of claim 5, wherein the cross-linked cation transferring polymer is formed by the polymerization of 2-sulfoethylmacrylate and a cross-linking monomer.
7. The ion exchange membrane of claim 6, wherein the cross-linking monomer is selected from the group consisting of ethyleneglycol-dimethacrylate, m-divinylbenzene, p-divinylbenzene and mixtures thereof.
8. The ion exchange membrane of claim 5, wherein the cross-linked cation transferring polymer is formed by the polymerization of 2-sulfoethylmacrylate, a low value r_2/r_s monomer and a cross-linking monomer.
9. The ion exchange membrane of claim 8, wherein the low value r_2/r_s monomer has an r_2/r_s value of less than about 1.3.

10. The ion exchange membrane of claim 8, wherein the low r_2/r_1 monomer is selected from the group consisting of acrylic acid and methacrylic acid, glycidylmethacrylate, and methylmethacrylate.
11. The ion exchange membrane of claim 8, wherein the cross-linking monomer comprises at least one of ethyleneglycol- dimethacrylate, m-divinylbenzene, and a mixture of m-divinylbenzene and p-divinylbenzene.
12. The ion exchange membrane of claim 1, wherein the polymeric microporous substrate comprises polypropylene, high molecular weight polyethylene, ultrahigh molecular weight polyethylene, polyvinyl chloride, or polyvinylidene fluoride.
13. The ion exchange membrane of claim 5, wherein the membrane has an apparent permselectivity of at least about 95%.
14. The ion exchange membrane of claim 5, wherein the membrane resistivity is less than about 1.5 Ohm-cm².
15. The ion exchange membrane of claim 5, wherein the ion transferring polymeric layer comprises a cross-linked anion transferring polymer.
16. The ion exchange membrane of claim 15, wherein the cross-linked anion transferring polymer comprises the polymerization product of:
 - at least one of 1-vinylimidazole, 2-methyl-1-vinylimidazole, N-vinylcarbazole, 2-vinylpyridine, or 3-vinylpyridine;
 - a cross-linking monomer comprising at least one of m-divinylbenzene, p-divinylbenzene, or chloromethyl styrene (vinylbenzyl chloride); and
 - a quaternization agent comprising at least one of benzyl chloride, benzyl bromide, methyl iodide, or butyl chloride.
17. The ion exchange membrane of claim 16, wherein the cross-linked anion transferring polymer is the polymerization product of 1-vinylimidazole, vinylbenzyl chloride and/or divinylbenzene.

18. The ion exchange membrane of claim 16, wherein the quaternization agent is benzyl chloride.
19. The ion exchange membrane of claim 16, wherein the membrane has a permselectivity of at least about 88%.
20. The ion exchange membrane of claim 15, wherein the membrane has a resistivity less than about 1.5 Ohm-cm^2 .
21. An ion exchange membrane, comprising the polymerization product of a first monomer having a reactivity ratio r_1 and a second monomer having a reactivity ratio r_2 wherein the reactivity ratio product of the first monomer and the second monomer is less than about 0.3 or between about 0.9 and 1.1.
22. A water treatment system, comprising:
an electrochemical separation device including at least one ion exchange membrane of claim 1.
23. A method of making an ion exchange membrane, comprising:
mixing a solution including at least a functional monomer and a low value r_2/r_s monomer, wherein at least two of the monomers have a styrene-normalized reactivity ratio product $[(r_2/r_s)_1 \times (r_2/r_s)_2]$ of less than about 0.6 or between about 0.7 to 1.3;
saturating a polymeric microporous substrate with the solution; and
polymerizing the solution on the saturated substrate to form the ion exchange membrane.