

Anion Exchange Membranes and Process for Making

This application claims the benefits of US provisional application 61/393715 filed on October 15, 2010.

Field

Embodiments of the present invention provide for anion exchange membranes and processes for their manufacture.

Background

Anion exchange membranes transport anions under an electrical or chemical potential. Anion exchange membranes will have fixed positive charges and mobile negatively charged anions. Ion exchange membrane properties are controlled by the amount, type and distribution of the fixed ionic groups. Quaternary and tertiary amines respectively produce the fixed positive charged groups in strong and weak base anion exchange membranes.

Among the most important applications of ion exchange membranes are desalination of water by electrodialysis (ED), as a power generating sources in reverse electrodialysis and as separators in fuels cells. Other applications include recovery of metal ions in the electroplating and metal finishing industries and various applications in the food and beverage industry.

Electrodialysis desalinates water by transferring ions and some charged organics through paired cation and anion selective membranes under the motive force of a direct current voltage. An ED apparatus consists of electrically conductive and substantially water impermeable cation selective and anion selective membranes arranged as opposing walls of a cell. Adjacent cells form a cell pair. Membrane stacks consist of many, sometime hundreds of cell pairs, and an ED systems may consist of many stacks. Each membrane stack has a DC (direct current) anode at one end of the stack and a DC cathode at the other end. Under a DC voltage, ions move to the electrode of opposite charge.

A cell pair consists of two types of cells, a diluting cell and a concentrating cell. As an illustrative example, consider a cell pair with a common cation exchange membrane wall and two anion exchange membrane walls forming the two cells. That is, a first anion exchange membrane and the cation exchange membrane form the dilute cell and the cation exchange membrane and a second anion membrane form the concentrating cell. In the diluting cell, cations will pass through the

cation exchange membrane facing the anode, but be stopped by the paired anion exchange membrane of the concentrating cell in that direction facing the cathode. Similarly, anions pass through the anion exchange membrane of the diluting cell facing the cathode, but will be stopped by the cation exchange membrane of the adjacent pair facing the anode. In this manner, salt in a diluting cell will be removed and in the adjacent concentrating 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 a desalinated water stream is produced from the dilute flow.

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 to sixty minutes. The dilute and concentrate 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.

Once the concentration in the dilution cells falls to lower than about 2000 milligrams/liter (mg/l), electrical resistance is at a level that power demand becomes increasingly 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 resin 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 concentrate cells. EDI is capable of producing purer water than ED at less power when the feed concentration is reduced sufficiently.

ED processes for water desalination have advantages over RO. They require less pretreatment which will reduce operating costs. They will have higher product water recovery and a higher brine concentration, i.e., there is less brine to dispose.

Univalent selective or monovalent selective membranes primarily transfer monovalent ions. Monovalent selective cation exchange membranes primarily transfer sodium, potassium, etc. Likewise, monovalent selective anion membranes transfer ions such as chloride, bromide, nitrate etc.

Reverse osmosis (RO) dominates the production of fresh water from seawater by membrane processes. While electrodialysis (ED) is used for brackish water and waste water desalination, it is generally considered too expensive for seawater use. In order to be competitive with RO, ED and EDR will require membrane resistance of less than 1 ohm-cm², preferably less than 0.8 ohm-cm², and most preferably less than 0.5 ohm-cm². Ion permselectivity of greater than 90%, more preferably greater than 95%, and most preferably greater than 98% is desired. The membrane has to have long service life, and be physically strong and chemically durable and be low cost.

Reverse electrodialysis (RED) converts the free energy generated by mixing the two aqueous solutions of different salinities into electrical power. The greater the difference in salinity, the greater the potential for power generation. For example, researchers have studied RED using Dead Sea water and fresh or seawater. Researchers in Holland have mixed river water entering the sea and seawater. RED membranes preferably will have a low electrical resistance and a high co-ion selectivity and long service life time, acceptable strength and dimensional stability and, importantly, low cost.

The polymer electrolyte membrane (PEM) is a type of ion exchange membrane that serves both as the electrolyte and as a separator to prevent direct physical mixing of the hydrogen from the anode and oxygen supplied to the cathode. A PEM contains positively charged groups, usually sulfonic acid groups, attached or as part of the polymer making up the PEM. Protons migrate through the membrane by jumping from one fixed positive charge to another to permeate the membrane. PEM's requirements include chemical, thermal and electrochemical stability, and adequate mechanical stability and strength when swollen and under mechanical stress. Other requirements include low resistance, low or preferably no methanol transport in direct methanol fuel cells (DMFC), and low cost.

Bipolar membranes are made of a cation exchange and an anion exchange membrane laminated or bound together, sometimes with a thin neutral layer between. Under an electric field water is split into H⁺ and OH⁻ ions. The hydroxyl ions are transported through the anion exchange membrane and the H⁺ ions through the cation exchange layer and will form base and acid in the respective cells. Organic acids are also made using bipolar membranes.

Development of ion exchange membranes requires an optimization of properties in order to overcome competing effects. Ion exchange membranes for water desalination traditionally have had to meet four main characteristics to be considered successful. These are:

Low electrical resistance to reduce potential drop during operation and to increase energy efficiency

High permselectivity – that is, high permeability to counter-ions but approximately impermeable to co-ions

High chemical stability – ability to withstand pH from 0 to 14 and oxidizing chemicals

Mechanical strength – The membrane must be able to withstand the stresses of being handled while being manufactured into a module or other processing device. The membrane must also have good dimensional stability in operation and not swell or shrink excessively when the fluid contacting it changes concentration or temperature.

Membrane developers have recognized that for a given chemistry used to make an ion exchange membrane, a thinner membrane would give a lower resistance and also allow more membrane area per unit volume of device. However, thinner membranes are more susceptible to dimensional change from environmental effects, such as changes in ionic concentration of the fluids contacting them or operating temperature changes. Moreover, to develop and produce defect-free membranes is more difficult for the case of thinner membranes because there is less margin of error during membrane production as there is for thicker membranes where the membrane thickness covers over defects that may occur in membrane formation.

Detailed Description

International Application # PCT/US 10/46777 describes a method of making ion exchange membranes produced by polymerizing one or more monofunctional ionogenic monomers with at least one multifunctional monomer in the pores of a porous substrate.

As described herein the inventor has found that by using functional monomers having a tertiary amine group with a quaternizing chemical, anion exchange membranes of low resistance high permeability and good chemical resistance can

be made. The quaternary ammonium functional groups are strongly basic and ionized to act over the pH range of 0 to 13 allowing a broad operational range. Of particular utility are vinyl compounds having nitrogen containing rings.

Preferred tertiary amine monomers are vinylimidazole and vinylcarbazole.

The tertiary amine containing monomer is polymerized with at least one crosslinking monomer and at least one quaternizing agent and one or more polymerization initiators to form the ionogenic polymer in the pores of the porous substrate.

The tertiary amine containing monomer may be copolymerized with at least one secondary functional monomer such as but not limited to;

vinylbenzyltrimethylammonium chloride, trimethylammonium ethylmethacrylic chloride, methacrylamidopropyltrimethylammonium chloride,

(3-acrylamidopropyl)trimethylammonium chloride, 2-vinylpyridine, and 4-vinylpyridine, at least one crosslinking monomer and at least one quaternizing agent, and one or more polymerization initiators.

Furthermore, either of these methods may be done with at least one added non-functional secondary monomer such as but not limited to; styrene, vinyl toluene, 4-methylstyrene, t-butyl styrene, alpha-methylstyrene, methacrylic anhydride, methacrylic acid, n-vinyl-2-pyrrolidone, vinyltrimethoxysilane, vinyltriethoxysilane, vinyl-tris-(2-methoxyethoxy)silane, vinylidene chloride, vinylidene fluoride, vinylmethyldimethoxysilane, 2,2,2,-trifluoroethyl methacrylate allyamine, vinylpyridine, maleic anhydride, glycidyl methacrylate, hydroxyethylmethacrylate, methylmethacrylate, or ethylmethacrylate.

The at least one crosslinker is preferably divinylbenzene or ethylene glycol dimethacrylate.

Optionally, at least one crosslinker may be chosen from propylene glycol dimethacrylate, isobutylene glycol dimethacrylate, Octa-vinyl POSS® (OL1160) ($C_{16}H_{24}O_{12}Si_8$), Octavinyl dimethylsilyl POSS® (OL1163) ($C_{32}H_{72}O_{20}Si_{16}$), Vinyl POSS® Mixture (OL1170) $((CH_2CH)_n(SiO_{1.5})_n$ wherein $n=8, 10, \text{ or } 12$), Trisilabolethyl POSS® (S01444) ($C_{14}H_{38}O_{12}Si_7$), Trisilanolisobutyl POSS® (S01450) ($C_{28}H_{66}O_{12}Si_7$), Trisilanolisooctyl POSS® (S01455) ($C_{56}H_{122}O_{12}Si_7$), Octasilane POSS® (SH1310) ($C_{16}H_{56}O_{20}Si_{16}$), Octahydro POSS® (SH1311) ($H_8O_{12}Si_8$), epoxycyclohexyl-POSS® cage mixture (EP0408) $((C_6H_{13}O)_n(SiO_{1.5})_n$ wherein $n=8, 10, 12$), glycidyl-POSS®

cage Mixture (EP0409) $((C_6H_{11}O_2)_n(SiO_{1.5})_n$ wherein $n= 8, 10, \text{ or } 12$), methacryl POSS® Cage Mixture (MA0735) $((C_7H_{11}O_2)_n(SiO_{1.5})_n$ wherein $n= 8, 10, \text{ or } 12$), or Acrylo POSS® Cage Mixture (MA0736) $((C_6H_9O_2)_n(SiO_{1.5})_n$ wherein $n= 8, 10, \text{ or } 12$).

Solvents found useful are N-propanol and dipropylene glycol. Similar hydroxy containing solvents, such as alcohols, for example isopropanol, butanol; diols such as various glycols, or polyols, such as glycerine may be useful in some cases. Additionally aprotic solvents such as N-methylpyrrolidone and dimethylacetamide may be used. These are given as examples, not to be limiting to a practitioner. Dipropylene glycol is a preferred solvent.

Free radical initiators useful for the present invention include, but are not limited to; benzoyl peroxide (BPO), ammonium persulfate, 2,2'-azobisisobutyronitrile (AIBN), 2,2'-azobis(2-methylpropionamidine)dihydrochloride, 2,2'-Azobis[2-(2-imidazolin-2-yl)propane]dihydrochloride, 2,2'-Azobis[2-(2-imidazolin-2-yl)propane] and dimethyl 2,2'-azobis(2-methylpropionate).

A person skilled in the art of membrane development and manufacturing will realize that this convenient laboratory method can be adapted to other laboratory scaled methods and may be scaled up to continuous manufacturing.

For example, the substrate pore filling or saturation may be done at a slightly elevated temperature ($>40^{\circ}\text{C}$) to reduce air solubility, or this step could be done after a mild vacuum treatment of the substrate sample submerged in the formulation solution. Substrate samples may be presoaked and then placed on the polyester or similar sheet and covered with a covering sheet and smoothed out to remove air bubbles. Several presoaked pieces may be layered and then placed on the polyester or similar sheet and covered with a covering sheet and smoothed out to remove air bubbles.

Rather than heating in an oven, the saturated substrate sandwich may be placed on a heated surface at a temperature sufficient and for a time necessary to initiate and complete polymerization. Alternate methods for initiation of the polymerization reaction may be used. Ultraviolet light or ionizing radiation, such as gamma radiation or electron beam radiation may be used to initiate the polymerization reaction.

Low resistance reduces the electrical energy required to desalinate and lowers operating cost. Specific membrane resistance is measured in Ohm-centimeters ($\Omega \text{ cm}$). A more convenient engineering measure is area resistance, Ohm-cm^2 ($\Omega \text{ cm}^2$).

Area resistance may be measured by using a cell having two electrodes of known area, platinum or black graphite are typically used, with the membrane sample of known area between them in an electrolyte solution. The electrodes do not touch the membrane. Membrane resistance is estimated by subtracting the electrolyte resistance without the membrane from the test result with the membrane in place. The resistance may also be measured by determining a voltage vs. current curve in a cell having two well stirred chambers separated by the membrane. A calomel electrode measures the potential drop across the membrane. The slope of the potential drop vs. current curves, which may be obtained by varying voltage and measuring current. Electrochemical impedance may also be used. In this method, alternating current is applied across the membrane. Measurement at a single frequency gives data relating to electrochemical properties of the membrane. By using frequency and amplitude variations, detailed structural information may be obtained. Herein, resistance will be defined by the methods described in the Experimental section.

Permselectivity refers to the relative transport of counterions to co-ions during electrodialysis. For an ideal cation exchange membrane only positively charged ions would pass the membrane, giving a permselectivity of 1.0. Permselectivity is found by measuring the potential across the membrane while it separates monovalent salt solutions of different concentrations. The method and calculations used herein are described in the Experimental section.

To meet these initial goals the inventors developed a type of composite ion exchange membrane in which a cross-linked polymer having charged ionic groups attached is contained in the pores of a microporous membrane substrate. The porous membrane substrate is preferably less than about approximately 155 microns thick, more preferably less than about approximately 55 microns thick.

Substrate membranes having porosity greater than about 45% are preferred, with those having porosities greater than about 60% more preferred. In the most preferred embodiments, the substrate membranes have porosities greater than about 70 %. Preferred substrate membranes have a rated pore size of from about approximately 0.05 microns to about approximately 10 microns, with a more preferred range of from about approximately 0.1 microns to about approximately 1.0 microns. Most preferred porous substrates have a rated pore size of from about approximately 0.1 microns to about approximately 0.2 microns.

Microporous membrane supports may be manufactured from polyolefins, polyolefin blends, polyvinylidene fluoride, or other polymers. A class of preferred substrates comprises thin polyolefin membranes manufactured primarily for use as battery separators. A more preferred substrate class are thin battery separators manufactured from ultrahigh molecular weight polyethylene (UHMWPE).

To produce the desired ion exchange membranes, the inventors developed a method of placing the crosslinked charged polymer in the pores of the substrate by polymerizing the crosslinked polymer in these pores. The method involved saturating the porous substrate with a solution of charged monomer, multifunctional monomer, (e.g., a crosslinking agent) and polymerization initiator. Herein we use the term ionogenic monomer to mean a monomer species having at least one charged group covalently attached. The charged group can be positively charged or negatively charged. In an embodiment, the crosslinked polymer was produced by polymerizing a multifunctional charged monomer. The Polymerization was initiated by heat or by UV light, preferably with a polymerization initiator such as a free radical initiator. Monofunctional monomers are monomers which have a single site for carrying forward the polymerization reaction. Multifunctional monomers have more than one polymerization reaction site and so can form networked or crosslinked polymers.

The following laboratory method was used to investigate formulation and process effects by producing small coupons for resistivity and permselectivity testing. Porous membrane substrate 43mm diameter coupons were die cut. Somewhat larger discs (50mm or 100mm diameter) of transparent polyester sheets were also die cut. A 105mm aluminum weighing boat was typically used to hold a set of coupons. The coupons were sandwiched between two polyester film discs. First, substrate coupons were thoroughly wetted with a monomer solution to make up a test sample. This was done by adding the formulated solution to the aluminum boat, and immersing a polyester film disc with a substrate coupon layered on it into the solution so that the porous support is saturated. The saturated support was then removed from the monomer solution and placed on a piece of polyester film. Air bubbles were removed from the coupon by, for example, smoothing or squeezing the coupon with a convenient tool, such as a small glass rod, or by hand. A second polyester disc was then layered on top of the first coupon and smoothed to have complete surface contact between the coupon and the lower and upper polyester film layers. A second porous substrate was then layered on the upper polyester

film and the saturation, smoothing and addition of a over layer of polyester film repeated to give a multilayer sandwich of two coupons and three protective polyester film layers. A typical experimental run would have a multilayered sandwich of 10 or more saturated substrate coupon layers. The rim of the aluminum boat can be crimped down to hold the disc/coupon assembly if required.

The boat and assembly were then placed in a sealable bag, typically a zip-lock polyethylene bag and a low positive pressure of inert gas, usually nitrogen, added before sealing the bag. The bag containing the boat and coupon assembly is placed into a oven at 80°C for up to about 60 minutes. The bag is then removed and cooled, and the now reacted ion exchange membrane coupons are placed in 0.5N NaCl solution at 40°C-50°C for at least 30 minutes, with a soak in NaCl solution of up to 18 hours being found satisfactory.

Experimental examples

The following examples are meant to illustrate the extent of effort expended in developing the subject membranes. The finding resulted in showing that ion exchange membranes having the desired properties could be made and that improvements are possible with further experimentation. These results are meant to be illustrative and to indicate developmental directions to those skilled in the art of membrane development and associated arts and not to be limiting as to the extent of the matter disclosed herein.

Properties and suppliers of the supports used are given in Table 1 below.

Table 1:Substrates Used

Porous Substrates					
Trade name	Manufacturer	Material	Rated pore Size	Thickness microns	Porosity %
APorous H6A	APorous Billerica MA	HDPE	0.1	52	68
APorous S14		HDPE	0.1	84	77
Ahlstrom (Hollytex)	Wall Township, New Jersey	polyester		200	
Teklon HPIP32	Entek Lebanon,OR	UHMWPE		32	48
Delpore 6002	Delstar Middleton DE	meltblown			
Delstar Stratex 3.6SL-G	Delstar Middleton DE				
Novatexx 2413	Freudenberg Hopkinsville, KY	Spunlace polyester		558	
Celgard EZ2090	CELGARD Charlotte NC	pp			
Celgard EZ2590	CELGARD Charlotte NC	pp		32	45
Solupor 16P5A	Lydall Filtration Rochester NH	UHMWPE	0.5	115	83%
Solupor 16P10A	Lydall Filtration Rochester NH	UHMWPE	0.9	120	85%

Representative porous substrates were tested for baseline permselectivity and resistance. They are pre-washed using isopropanol-ethanol and D.I. water each for 5 minutes, then they were rinsed by 0.5 N NaCl (aq) 3 times testing

Table 2 below shows the results of area resistance in Ohm cm^2 of

AEM thus made and their apparent permselectivity %:

Table 2

Characteristics of selected substrates		
Description	R(ohm cm ²)	Apparent Permselectivity %
Teklon HPIP	0.593	57.24
Solupor 16P10A	2.192	57.38
Aporous H6A	0.152	57.54
Celgard EZ-2590	0.788	57.54
Celgard EZ-2090	1.159	57.38

EXAMPLE 1. In a 4 oz jar with 17.08 g of 1-vinylimidazole, 9.14 g of vinylbenzyl chloride, 5.39 g of divinylbenzene (80%), 16.61 g of benzyl chloride, 20.65 g of dipropylglycol (DPG) and 0.40 g Vazo-64 were combined with stirring. A clear brown solution formed immediately. Substrates Solupor 16P10A, 16P05A, Teklon, Aporous S14, Celgard EZ2090, EZ2590, Novatexx 2431ND, Delstar 6SLG, Ahlstrom 3329, Delpore DP3924-80PNAT, Delpore 6002-20PNAT were soaked the solution for 1 hour to assure complete pore filling. Then they were sandwiched between Mylar disks, air bubbles between Mylar disks removed by pressure and the sandwiched substrates placed in an aluminum weighting dish. The dish was loaded into a Ziploc® bag, the bag pressurized with nitrogen gas and placed in an 80°C oven for 1 hour. The membrane coupon thus made was placed in 0.5 N NaCl(aq) for conditioning. Table 3 below shows the results of area resistance in Ohm cm² of AEM thus made and their apparent permselectivity%:

TABLE 3

Substrates		R(ohm cm ²)	Apparent Perms%
Ahsltrom 3329	200micron thick	31.75	92.62
Aporous S14		2.145	93.11
Celgard X021 (EZ2590)	32micron thick	2.68	92.78
Teklon HPIP	32micron thick	5.00	94.26
Solupor 16P05A	115micron thick	2.55	92.95
Solupor 16P10A	200micron thick	3.55	92.62
Delpore6002-20PNAT nonwoven		3.64	89.01
Novatexx 2431ND		7.51	73.03
Delstar 6SLG nonwoven		12.62	87.70
Celgard EZL2090		3.29	90.52
Delpore6002-20PNAT nonwoven	2nd coupon	2.35	89.86

EXAMPLE 2

In a 4 oz jar with 15.71 g of 1-vinylimidazole, 25.47 g of vinylbenzyl chloride, 13.25 g of DPG and 0.42 g Vazo-64 were combined with stirring. A clear brown solution formed immediately. Substrates Solupor 16P10A, 16P05A and Teklon HPIP, were soaked the solution for 1 hour to assure complete pore filling.

Then they were sandwiched between Mylar disks, air bubbles between Mylar disks removed by pressure and the sandwiched substrates placed in an aluminum weighting dish. The dish was loaded into a Ziploc bag, the bag pressurized with nitrogen gas and placed in an 80°C oven for 1 hour. The membrane coupon thus made was placed in 0.5 N NaCl(aq) for conditioning. Table 4 below shows the results of area resistance in Ohm cm² of AEM thus made and their apparent permselectivity%.

Also shown are commercially available ion exchange membranes AMX and CMX from Astom-Japan. Both are 125 microns thick.

TABLE 4

Description	R(ohm cm ²)	Apparent Permselectivity %
Teklon HPIP 32micron thick	6.55	91.64
Solupor 16P10A 120micron thick	3.54	92.62
Astom AMX (anion exchange membrane)	3.13	96.07
Astom CMX (cation exchange membrane)	2.37	106.50

The results in tables 3 and 4 show that membranes made by the inventive method has approximately equivalent properties to much thicker membranes. Thinner membranes allow for increased number of membranes per module or housing volume and therefore more productivity per unit volume.

EXAMPLE 3

In a 4 oz jar with 17.12 g of 1-vinylimidazole, 20.00 g of vinylbenzyl chloride, 16.00 g of benzyl chloride, 11.02 g of DPG and 0.51 g Vazo-64 were combined with stirring. A clear brown solution formed immediately. Substrates Solupor 16P10A, and Teklon (HPIP, 32 micron, single layer) were soaked in the solution for 1.5 hour to assure complete pore filling.

Then they were sandwiched between Mylar disks, air bubbles between Mylar disks removed by pressure and the sandwiched substrates placed in an aluminum weighting dish. The dish was loaded into a Ziploc® bag, the bag pressurized with nitrogen gas and placed in an 80°C oven for 40 minutes. The membrane coupon thus made was placed in 0.5 N NaCl (aq) for conditioning. Table 5 below shows the results of area resistance in Ohm cm² of AEM thus made and their apparent permselectivity%.

Also shown is a commercially available ion exchange membranes AMX from Astom-Japan. Its thickness is 125 micron.

TABLE 5

Description	R(Ω cm ²)	Apparent
Teklon HPIP 32 micron	2.33	95.09
Solupor 16P10A 120 micron	2.17	95.57
Astom AMX (anion exchange membrane)	2.73	94.55

EXAMPLE 4

In a 4 oz jar with 8.55 g of 1-vinylimidazole, 10.01 g of vinylbenzyl chloride, 1.02 g of divinyl benzene (80%), 12.01 g of benzyl chloride, 5.61 g of DPG and 0.31 g Vazo-64 were combined with stirring. A clear brown solution formed immediately. Substrates Solupor 16P10A, and Teklon HPIP (single layer), Aporous H6A and Celgard EZ2590, were soaked in the solution for 75 minutes to assure complete pore filling.

Then they were sandwiched between Mylar disks, air bubbles between Mylar disks removed by pressure and the sandwiched substrates placed in an aluminum weighting dish. The dish was loaded into a Ziploc® bag, the bag pressurized with nitrogen gas and placed in an 80°C oven for 47 minutes. The membrane coupon thus made was placed in 0.5 N NaCl (aq) for conditioning. Table 6 below shows the results of area resistance in Ω cm² of AEM thus made and their apparent permselectivity%.

Also shown is a commercially available ion exchange membranes AMX from Astom-Japan. Its thickness is 125 micron.

TABLE 6

Description	R(Ohm cm ²)	Apparent Permselectivity %
Teklon HPIP 32 micron	4.24	95.21
Solupor 16P10A, 120 micron	2.62	94.71
Aporous H6A, 52 micron	2.55	95.04
Celgard EZ2590, 27 micron	1.98	94.55
Astom AMX (anion exchange membrane)	2.73	94.55

EXAMPLE 5

In an 8 oz jar with 30.7 g of 1-vinylimidazole, 17.2 g of vinylbenzyl chloride, 42.5 g of benzyl chloride, 11.8 g Divinylbenzene (80%), 27.0 g of DPG and 0.41 g Vazo-64 were combined with stirring. A clear brown solution formed immediately. Coupons of substrates Solupor 16P05A were soaked in the solution for 2 hour to assure complete pore filling.

Then they were sandwiched between Mylar disks, air bubbles between Mylar disks removed by pressure and the sandwiched substrates placed in an aluminum weighting dish. The dish was loaded into a Ziploc® bag, the bag pressurized with nitrogen gas and placed in an 80°C oven for 1 hour. The membrane coupon thus made was placed in 0.5 N NaCl (aq) for conditioning. Table 7 below shows the results of area resistance in $\Omega \text{ cm}^2$ of AEM thus made and their apparent permselectivity %.

Also shown is a commercially available ion exchange membranes AMX from Astom-Japan. Its thickness is 125 micron.

TABLE 7

Description	R(Ohm cm^2)	Apparent Permselectivity% %
Solupor 16P05A , 115 micron	2.60	95.00
Astom AMX (anion exchange membrane)	3.10	95.08

EXAMPLE 6

In a 20 ml vial with 3.43 g of 1-vinylimidazole, 3.0 of vinylbenzyl chloride, 1.0 gm EP0409 (Hybrid Plastics, glycidyl-POSS® cage mixture CAS # 68611-45-0), 3.2 g of benzyl chloride, 2.20 g of DPG and 0.10 g Vazo-64 were combined with stirring. A clear brown solution formed immediately. Coupons of substrate Solupor 16P10A were soaked in the solution for 0.5 hour to assure complete pore filling.

Then they were sandwiched between Mylar disks, air bubbles between Mylar disks removed by pressure and the sandwiched substrates placed in an aluminum weighting dish. The dish was loaded into a Ziploc® bag, the bag pressurized with nitrogen gas and placed in an

90°C oven for 1 hour. The membrane coupon thus made was placed in 0.5 N NaCl (aq) for conditioning. Table 8 below shows the result of area resistance in Ohm cm² of AEM thus made and their apparent permselectivity%.

Also shown is a commercially available ion exchange membranes AMX from Astom-Japan having a thickness is 125 micron.

TABLE 8

Description	R(Ohm cm ²)	Apparent Permselectivity% %
Solupor 16P10A , 120 micron	2.59	93.92
Astom AMX (anion exchange membrane)	2.42	93.59

Experiment Procedures for Membrane Area Resistivity and Apparent Permselectivity Characterization

The membrane resistance and counter ion transport number (permselectivity) can be measured using an electrochemical cell. This bench top experiment provides us with a very effective and quick experiment using a small piece of sample. The equipment and procedure are described here.

Experiment preparation

(1) Solartron 1280 electrochemical measurement unit

The Solartron 1280 electrochemical measurement unit enables us to apply a current between the two platinum electrodes on the two sides of the cell and to measure the voltage drop across membrane. It has 4 connectors: work electrode (WE), counter electrode (CE), Reference electrodes (RE1 and RE2). The CE and WE are used to apply current and RE1 and RE2 to measure the voltage drop.

(2) Reference electrodes

Reference electrodes (see the insert in figure 1) used for membrane characterization are made in R&D lab. ¼" glass tubing is softened, then bent and drawn to the form shown. A porous plug is inserted in the tip to control solution flow to a low rate.

Silver/silver chloride wire is freshly made for each day's testing. A current of 2-3 mA was supplied and controlled by a power supplier and an ampere meter to a

platinum wire cathode and silver wire anode immersed in a 0.1N HCl solution. After several minutes, the silver wire starts to turn black, indicating the formation of AgCl layer on the surface. The solution used inside the reference electrode tubing is 1.0M KCl solution. Since the solution will leak through the porous tip, constant addition of KCl is a necessary (~every 20 min) during experiment.

(3) Membrane test cell

Figure 1 shows the detailed electrochemical testing cell construction used for the experiment to measure resistance and counter ion permselectivity of the membrane. The membranes are cut into disc using a die cutter. The reference electrodes are used to monitor the voltage drop across the testing membrane and the 2 platinum discs are used to provide a current through the membrane. The cylindrical path of the cell has a cross section area of 7.0 cm²

(4) Solutions

All the solutions need to be prepared with quantitative level as indicated by their significant figures. These includes 0.500N NaCl, 1.0N HCl and 1.0N NaOH (caustic, using plastic container or volumetric flask). The 0.5N Na₂SO₄ is used to feed the electrode compartments without evolution of chlorine gas.

3-III. Measurement procedures

(1) Resistance measurement

Resistance here refers to area resistance $\Omega\text{-cm}^2$. The measurement contains 3 steps.

- (a) Set up electrode positions: Prior to a measurement, the reference electrode horizontal positions are set. To set reference electrode position, a rigid plastic disc is used as a stand-in for the membrane. Each reference electrode is adjusted to just touch the plastic disc and their position fixed by two set screws.
- (b) Measure the solution conductivity: The plastic disc was then removed and the two reference electrodes moved to 1.0 cm apart by removing the two 0.50 mm plastic blocks. The voltage drop between the two reference

electrodes is recorded at an applied a current (~10-50 mA) by the Solartron 1280. The distance of the 2 reference electrodes(1.00 cm here), the current density (10.00 mA) and voltage (to 0.1 mV precision) used to obtain the conductivity of the solution (0.50 N NaCl typically).

- (c) Measuring membrane resistance: The membrane sample is then placed by the sample slider and the voltage and current measured again. The resistance of membrane is the total resistance less the solution resistance measured in procedure (b)

(2) Counter ion Permselectivity (Transport number)

The measurement procedures are:

- (a) Reference electrode position is set as described by part(a) of Resistance measurement. The reference electrodes position may be approximate since the voltage measured in this test is theoretically independent of the distance, but it is recommended that the position be located as reproducibly as possible.
- (b) Solutions: After emplacing the sample membrane with the slider, pour 0.500N NaCl solution in the right part of the cell separated by the testing membrane and 0.250N NaCl on the left side of the cell.
- (c) Measuring the voltage: the voltage was measured (without applying current) using a voltage meter attached to the platinum electrodes and data were entered the spreadsheet to obtain counter ion permselectivity.

3-IV. Sample calculations:

C = conductivity (siemens/cm)

ρ = resistance (ohms/cm)

R = resistivity (ohm-cm² or $\Omega \cdot \text{cm}^2$)

A = area (cm²)

U, V = measured voltage (mV)

I = measured current (mA)

L = distance between reference electrodes

- (1) Conductivity of the 0.500 M NaCl at 10.00 mA current and 33.1 mV measured for a reference electrode distance of 1.00 cm, the conductivity of solution:

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

- (2) Area resistance of the membrane calculation needs to subtract the solution resistance. For a CMX membrane with a measured potential of 38.0mV, the area resistance is:

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

- (3) Permselectivity (transport number) of anion(+) or anion(-) membrane $T_{\pm}$ is obtained by:

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

Which rearranges to;

$$2T_{\pm} = 1 + VF/RT \left(\ln \frac{a_R}{a_L} \right)$$

Where V is measured voltage by the reference electrodes, R is gas constant (8.314 Joule•K⁻¹•mole⁻¹) T is Kelvin temperature of solution, F is Faraday constant (96480 coulomb/mole) and a_R and a_L are concentration (activity format) of the solution on the two sides of the membrane in the cell.

CLAIMS

1. An anion exchange membrane comprising:
a microporous membrane support wherein the thickness of the microporous support is greater than 20 microns and less than 55 microns, said microporous support having a porous first side, a porous second side, and a continuous porous structure extending from said first side to said second side; and a crosslinked ion transferring polymer completely filling said porous structure, said polymer formed in the continuous porous structure and comprising:
the polymerization product of a monomeric solution having at least one functional monomer comprising a tertiary amine, at least one crosslinking monomer and at least one quaternizing agent, and at least one polymerization initiator; wherein the at least one functional monomer is selected from the group consisting of vinylimidazole and vinylcarbazole.
2. The anion exchange membrane of claim 1, wherein the at least one crosslinking monomer is selected from the group consisting of divinylbenzene, ethylene glycol dimethacrylate, vinylbenzyl chloride, dichloroethane, propylene glycol dimethacrylate, isobutylene glycol dimethacrylate, Octa-vinyl POSS®(OL1160) ($C_{16}H_{24}O_{12}Si_8$), Octavinyl dimethylsilyl POSS® (OL1163) ($C_{32}H_{72}O_{20}Si_{16}$), Vinyl POSS® Mixture (OL1170) $((CH_2CH)_n(SiO_{1.5})_n$ wherein $n=8, 10, \text{ or } 12$), Trisilabolethyl POSS® (S01444) ($C_{14}H_{38}O_{12}Si_7$), Trisilanolisobutyl POSS® (S01450) ($C_{28}H_{66}O_{12}Si_7$), Trisilanolisooctyl POSS® (S01455) ($C_{56}H_{122}O_{12}Si_7$), Octasilane POSS® (SH1310) ($C_{16}H_{56}O_{20}Si_{16}$), Octahydro POSS® (SH1311) ($H_8O_{12}Si_8$), epoxycyclohexyl-POSS® cage mixture (EP0408) $((C_8H_{13}O)_n(SiO_{1.5})_n$ wherein $n=8, 10, 12$), glycidyl-POSS® cage Mixture (EP0409) $((C_6H_{11}O_2)_n(SiO_{1.5})_n$ wherein $n=8, 10, \text{ or } 12$), methacryl POSS® Cage Mixture (MA0735) $((C_7H_{11}O_2)_n(SiO_{1.5})_n$ wherein $n=8, 10, \text{ or } 12$), or Acrylo POSS® Cage Mixture (MA0736) $((C_6H_9O_2)_n(SiO_{1.5})_n$ wherein $n=8, 10, \text{ or } 12$).
3. The anion exchange membrane of claim 1, wherein the at least one quaternizing agent is selected from the group consisting of benzyl chloride, benzyl bromide, vinyl benzyl chloride, dichloroethane, or methyl iodide.

4. The anion exchange membrane of Claim 1, wherein the at least one polymerization initiator is selected from the group consisting of organic peroxides, 2,2' azobis[2,[2-imidazolin-2-yl]-propane] dihydrochloride, [alpha],[alpha]'-azoisobutyronitrile, 2,2'-azobis[2-methylpropioaminidine] dihydrochloride, 2,2'-azobis[2,[2-imidazolin-2-yl]-propane], or dimethyl2,2'-azobis[2-methylpropionate].
5. The anion exchange membrane of Claim 4 wherein the organic peroxide is benzoyl peroxide.
6. The anion exchange membrane of claim 1 wherein the monomeric solution further comprises at least one polymerization inhibitor.
7. The anion exchange membrane of claim 6, wherein the at least one polymerization inhibitor is selected from the group consisting of 4-methoxyphenol and 4-tert-butyl catechol.
8. The anion exchange membrane of claim 1 wherein the microporous support comprises polypropylene, high molecular weight polyethylene, ultrahigh molecular weight polyethylene or polyvinylidene fluoride.
9. A process for producing an ion exchange membrane comprising:
choosing a porous substrate having a porous first side, a porous second side, and a continuous porous structure extending from the first side to the second side;
saturating the porous substrate with a monomeric solution comprising at least one functional monomer comprising a tertiary amine, at least one crosslinking monomer, at least one quaternizing agent, and at least one polymerization initiator; wherein the at least one functional monomer is selected from the group consisting of vinylimidazole and vinylcarbazole;
removing excess solution from the substrate while leaving the continuous porous structure filled with solution, and
initiating polymerization to form a crosslinked anion exchange polymer in the continuous porous structure of the substrate wherein the thickness of the microporous porous support is greater than 20 microns and less than 55 microns.

10. The process of Claim 9, wherein the at least one crosslinking monomer is selected from the group consisting of divinylbenzene, vinylbenzyl chloride, dichloroethane, an octaglycidyl-polyhedral oligomeric silsesquioxane or ethylene glycol dimethacrylate.
11. The process of Claim 9, wherein the at least one quaternizing agent is selected from the group consisting of benzyl chloride, vinyl benzyl chloride, dichloroethane, or methyl iodide.
12. The process of Claim 9, wherein the at least one polymerization initiator is selected from the group consisting of organic peroxides, 2,2'-azobis[2,(2-imidazolin-2-yl)-propane] dihydrochloride, a,a'- azoisobutyronitrile, 2,2'-azobis (2-methylpropioaminidine) dihydrochloride, 2,2'-azobis[2,(2-imidazolin-2-yl)-propane], and dimethyl 2,2'-azobis (2-methylpropionate).
13. The process of Claim 12, wherein the organic peroxide is benzoyl peroxide.
14. The process of Claim 9, wherein the monomeric solution further comprises at least one polymerization inhibitor.
15. The process of Claim 14, wherein the at least one polymerization inhibitor is selected from the group consisting of 4-methoxyphenol and 4-tert-butyl catechol.
16. The process of Claim 9 wherein the microporous support comprises polypropylene, high molecular weight polyethylene, ultrahigh molecular weight polyethylene or polyvinylidene fluoride.