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(72) Inventeurs/Inventors:
FORMATO, RICHARD M., US;
KOVAR, ROBERT F., US;
OSENAR, PAUL, US;
LANDRAU, NELSON, US;
RUBIN, LESLIE S., US

(73) Propriétaire/Owner:
FOSTER-MILLER, INC., US

(74) Agent: RIDOUT & MAYBEE LLP

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(71) Applicant *(for all designated States except US)*: FOSTER–MILLER, INC. [US/US]; 350 Second Avenue, Waltham, MA 02154 (US).

(71)(72) Applicants and Inventors: FORMATO, Richard, M. [US/US]; 28B Svenson Road, Shresbury, MA 01545 (US). KOVAR, Robert, F. [US/US]; 203 Beach Street, Wrentham, MA 02093 (US). OSENAR, Paul [US/US]; 100 Waltham Street #9, Watertown, MA 02472 (US). LANDRAU, Nelson [US/US]; P.O. Box 625, Marlborough, MA 01752 (US).

(74) Agents: BRONSTEIN, Sewall, P. et al.; Dike, Bronstein, Roberts & Cushman, LLP, 130 Water Street, Boston, MA 02109 (US).

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(57) Abstract

The present invention relates to composite solid polymer electrolyte membranes (SPEMs) which include a porous polymer substrate interpenetrated with an ion–conducting material. The SPEMs are useful in electrochemical applications, including fuel cells and electrodialysis.

COMPOSITE SOLID POLYMER ELECTROLYTE MEMBRANES

STATEMENT OF GOVERNMENT RIGHTS

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FIELD OF THE INVENTION

This invention relates to novel composite solid polymer electrolyte membranes (SPEMs) for use in electrochemical applications. Methods for producing the composite membranes of the invention are also disclosed.

BACKGROUND OF THE INVENTION

There is a considerable need in both the military and commercial sectors for quiet, efficient and lightweight power sources that have improved power density. Military applications include, but are not limited to, submersibles, surface ships, portable/mobile field generating units, and low power units (i.e., battery replacements). For example, the military has a strong interest in developing low range power sources (a few watts to a few kilowatts) that can function as replacements for batteries. Commercial applications include transportation (i.e., automotive, bus, truck and railway), communications, on-site cogeneration and stationary power generation.

Other interest exists for household applications, such as radios, camcorders and laptop computers. Additional interests exist in higher power sources that can be used in operating clean, efficient vehicles. In general, there is a need for quiet, efficient, and lightweight power sources anywhere stationary power generation is needed.

Additionally, the use of gasoline-powered internal combustion engines has created several environmental, gas-related exhaust problems. One possible solution to these environmental problems is the use of fuel cells. Fuel cells are highly efficient electrochemical energy conversion

devices that directly convert the chemical energy derived from renewable fuel into electrical energy.

Significant research and development activity has focused on the development of proton-exchange membrane fuel cells. Proton-exchange membrane fuel cells have a polymer electrolyte membrane disposed between a positive electrode (cathode) and a negative electrode (anode). The polymer electrolyte membrane is composed of an ion-exchange polymer (i.e., ionomer). Its role is to provide a means for ionic transport and prevent mixing of the molecular forms of the fuel and the oxidant.

Solid polymer electrolyte fuel cells (SPEFCs) are an ideal source of quiet, efficient, and lightweight power. While batteries have reactants contained within their structure which eventually are used up, fuel cells use air and hydrogen. Their fuel efficiency is high (45 to 50 percent), they do not produce noise, operate over a wide power range (10 watts to several hundred kilowatts), and are relatively simple to design, manufacture and operate. Further, SPEFCs currently have the highest power density of all fuel cell types. In addition, SPEFCs do not produce any environmentally hazardous emissions such as NOx and SOx (combustion by-products).

The traditional SPEFC contains a solid polymer ion-exchange membrane that lies between two gas diffusion electrodes, an anode and a cathode, each commonly containing a metal catalyst supported by an electrically conductive material. The gas diffusion electrodes are exposed to the respective reactant gases, the reductant gas and the oxidant gas. An electrochemical reaction occurs at each of the two junctions (three phase boundaries) where one of the electrodes, electrolyte polymer membrane and reactant gas interface.

During fuel cell operation, hydrogen permeates through the anode and interacts with the metal catalyst, producing electrons and protons. The electrons are conducted via an electronic route through the electrically conductive material and the external circuit to the cathode, while the protons are simultaneously transferred via an ionic route through the polymer electrolyte membrane to the cathode. Oxygen permeates to the catalyst sites of the cathode, where it gains electrons and reacts with protons to form water. Consequently, the products of the SPEFC's reactions are water and electricity. In the SPEFC, current is conducted

simultaneously through ionic and electronic routes. Efficiency of the SPEFC is largely dependent on its ability to minimize both ionic and electronic resistivity to currents.

Ion exchange membranes play a vital role in SPEFCs. In SPEFCs, the ion-exchange membrane has two functions: (1) it acts as the electrolyte that provides ionic communication between the anode and cathode; and (2) it serves as a separator for the two reactant gases (e.g., O_2 and H_2). In other words, the ion-exchange membrane, while serving as a good proton transfer membrane, also must have low permeability for the reactant gases to avoid cross-over phenomena that reduce performance of the fuel cell. This is especially important in fuel cell applications in which the reactant gases are under pressure and the fuel cell is operated at elevated temperatures.

Fuel cell reactants are classified as oxidants and reductants on the basis of their electron acceptor or electron donor characteristics. Oxidants include pure oxygen, oxygen-containing gases (e.g., air) and halogens (e.g., chlorine). Reductants include hydrogen, carbon monoxide, natural gas, methane, ethane, formaldehyde and methanol.

Optimized proton and water transports of the membrane and proper water management are also crucial for efficient fuel cell application. Dehydration of the membrane reduces proton conductivity, and excess water can lead to swelling of the membranes and flooding of the electrodes. Both of these conditions lead to poor cell performance.

Despite their potential for many applications, SPEFCs have not yet been commercialized due to unresolved technical problems and high overall cost. One major deficiency impacting the commercialization of the SPEFC is the inherent limitations of today's leading membrane and electrode assemblies. To make the SPEFC commercially viable (especially in automotive applications), the membranes employed must operate at elevated/high temperatures (>120°C) so as to provide increased power density, and limit catalyst sensitivity to fuel impurities. This would also allow for applications such as on-site cogeneration (high quality waste heat). Current membranes also allow excessive methanol crossover in liquid feed direct methanol fuel cells (approximately 50 to 200 mÅ/cm² @ 0.5V). This crossover results in poor fuel efficiency as well as limited performance levels.

Several polymer electrolyte membranes have been developed over the years for application as solid polymer electrolytes in fuel cells. However, these membranes have significant limitations when applied to liquid-feed direct methanol fuel cells and to hydrogen fuel cells. The membranes in today's most advanced SPEFCs do not possess the required combination of ionic conductivity, mechanical strength, dehydration resistance, and chemical stability and fuel impermeability (e.g., methanol crossover) to operate at elevated temperatures.

DuPont developed a series of perfluorinated sulfonic acid membranes known as Nafion® membranes. The Nafion® membrane technology is well known in the art and is described e.g. in U.S. Patent Nos. 3,282,875 and 4,330,654. Unreinforced Nafion® membranes are used almost exclusively as the ion exchange membrane in present SPEFC applications. This membrane is fabricated from tetrafluoroethylene (TFE), also known as Teflon®, and a vinyl ether comonomer. The vinyl ether comonomer is copolymerized with TFE to form a melt-fabricable polymer. Once in the desired shape, the sulfonyl fluoride group is hydrolyzed into the ionic sulfonate form.

The fluorocarbon component and the ionic groups are incompatible (the former is hydrophobic, the latter is hydrophilic). This causes a phase separation, which leads to the formation of interconnected hydrated ionic "clusters". The properties of these clusters determine the electrochemical characteristics of the polymer, since protons are conducted through the membrane as they "hop" from one ionic cluster to another. To ensure proton flow, each acid group needs a minimum amount of water to surround it and form a cluster. If the acid group concentration is too low (or hydration is insufficient) proton transfer will not occur. At higher acid group concentrations (or increased hydration levels) proton conductivity is improved, but membrane mechanical characteristics are sacrificed.

As the membrane temperature is increased, the swelling forces (osmotic) become larger than the restraining forces (fluorocarbon chains). This allows the membrane to assume a more highly swollen state, but may eventually promote membrane dehydration. Peroxide radicals will form more quickly as the temperature is increased; these radicals can attack and degrade the membrane. At even higher temperatures (230°C), the

fluorocarbon phase melts and permits the ionic phase to "dissolve" (phase inversion of Nafion®).

There are several mechanisms that limit the performance of Nafion® membranes in fuel cell environments at temperatures above 100°C. In fact, these phenomenon may begin at temperatures above even 80°C. These mechanisms include membrane dehydration, reduction of ionic conductivity, decreased proton affinity for water, radical formation in the membrane (which can destroy the solid polymer electrolyte membrane chemically), loss of mechanical strength via softening of TFE, and increased parasitic losses through high fuel permeation.

Additional problems with Nafion® membranes have been observed in liquid feed direct methanol fuel cell applications, where excessive methanol transport (which reduces power density) occurs. Methanol-crossover not only lowers fuel utilization efficiency but also adversely affects the oxygen cathode performance, significantly lowering cell performance.

The Nafion® membrane/electrode is also very expensive to produce, and as a result it is not (yet) commercially viable. Reducing membrane cost is crucial to the commercialization of SPEFCs. It is estimated that membrane cost must be reduced by at least an order of magnitude from the Nafion® model for SPEFCs to become commercially attractive.

Another type of ion-conducting membrane, Gore-Select® (commercially available from W.L. Gore), is currently being developed for fuel cell applications. Gore-Select® membranes are further detailed in a series of U.S. Patents (U.S. 5,635,041, 5,547,551 and 5,599,614).

Gore discloses a composite membrane consisting of a Teflon® fluoropolymer film filled with a Nafion® ion-conducting solution. Although it has been reported to show high ionic conductivity and greater dimensional stability than Nafion® membranes, the Teflon® and Nafion® materials selected and employed by Gore as the film substrate and the ion-exchange material, respectively, may not be appropriate for operation in SPEFCs. Teflon® undergoes extensive creep at temperatures above 80°C, and Nafion® swells and softens above the same temperature. This can result in the widening of interconnected channels in the membrane and allow performance degradation, especially at elevated temperatures and pressures.

Further, Gore-Select®, as well as many other types of perfluorinated ion-conducting membranes, are just as costly as Nafion®, since these membranes also use a high percentage of Nafion® and Nafion®-like ionomers.

In an effort to reduce costs and move toward potential commercialization of SPEFCs, ion-exchange membranes that are less expensive to produce also have been investigated for use in polymer electrolyte membrane fuel cells.

Poly(trifluorostyrene) copolymers have been studied as membranes for use in polymer electrolyte membrane fuel cells. See e.g., U.S. Patent No. 5,422,411.

Sulfonated poly(aryl ether ketones) developed by Hoechst AG are described in European Patent No. 574,891,A2. These polymers can be cross-linked by primary and secondary amines. However, when used as membranes and tested in polymer electrolyte membrane fuel cells, only modest cell performance is observed. Sulfonated polyaromatic based systems, such as those described in U.S. Patent Nos. 3,528,858 and 3,226,361, also have been investigated as membrane materials for SPEFCs. However, these materials suffer from poor chemical resistance and mechanical properties that limit their use in SPEFC applications.

Solid polymer membranes comprising a sulfonated poly(phenylene oxide) alone or blended with poly(vinylidene fluoride) also have been investigated. These membranes are disclosed in WO 97/24777. However, these membranes are known to be especially vulnerable to degradation from peroxide radicals.

The inherent problems and limitations of using solid polymer electrolyte membranes in electrochemical applications, such as fuel cells, at elevated/high temperatures (>100°C) have not been solved by the polymer electrolyte membranes known in the art. Specifically, maintaining high ion conductivity and high mechanical strength, resisting dehydration and other forms of degradation remain problematic, especially at elevated operating temperatures. As a result, commercialization of SPEFCs has not been realized.

It would be highly desirable to develop an improved solid polymer electrolyte membrane with high resistance to dehydration, high mechanical

strength and stability to temperatures of at least about 100°C, more preferably to at least about 120°C.

It would also be highly desirable to develop a membrane with the afore-mentioned characteristics that would be suitable for use in a hydrogen or methanol fuel cell and that would provide an economical option to currently available membranes. The development of such a membrane would promote the use of SPEFCs in a variety of highly diverse military and commercial applications, and would be beneficial to industry and to the environment.

SUMMARY OF THE INVENTION

The present invention provides innovative solid polymer electrolyte membranes that are capable of operating at much higher temperatures and pressures than those known in the art. Methods for producing such membranes are also provided. The membrane manufacturing technologies developed emphasize improved performance at reduced cost.

A central object of the invention is to provide an improved solid polymer electrolyte membrane (SPEM) having the following characteristics: high ionic conductivity, high resistance to dehydration, high mechanical strength, chemical stability during oxidation and hydrolysis, low gas permeability to limit parasitic losses, and stability at elevated temperatures and pressures.

Another object of the invention is to provide an improved solid polymer electrolyte membrane with electronic conductivity approaching zero, dimensional stability, and a membrane that is non-brittle in both dry and wet forms.

Another object of the invention is to provide an improved solid polymer electrolyte membrane that is resistant to methanol cross-over when used in a direct methanol fuel cell.

Another object of the invention is to lower the overall cost of producing solid polymer electrolyte membranes to allow for commercialization of SPEFCs.

A further object of the invention is to provide methods that can be employed to produce these solid polymer electrolyte membranes.

Another object of this invention is to provide novel polymer substrates and ion-conducting materials and novel combinations thereof.

Yet another object of the present invention is to provide SPEMs that are substantially stable to temperatures of at least about 100°C, preferably to at least about 150°C, more preferably to at least about 175°C.

It has been discovered that a high performance SPEM, suitable for use in fuel cells, can be produced by interpenetrating a porous polymer substrate with an ion-conducting material to form a composite membrane. This composite ion-conducting membrane will exhibit the strength and thermal stability of the polymer substrate and the excellent ionic conductivity of the ion-conducting material.

The composite SPEM of the present invention comprises a porous polymer substrate that is interpenetrated with an ion-conducting material.

The present invention also provides novel substrates and novel substrate/ion-conducting material combinations. These materials can be tailored and combined to produce membranes useful over a range of operating conditions and/or applications.

Preferred polymer substrates are easily synthesized from commercially-available, low-cost starting polymers, into thin, substantially defect free polymeric films which have high strength even at low thickness (in preferred embodiments less than about 1 mil), outstanding crease/crack resistance and high tear strength. Preferred polymer substrates are substantially chemically resistant to acids, bases, free radicals and solvents (i.e., methanol) and are thermally and hydrolytically stable from temperatures of about 50°C to 300°C. Preferred polymer substrates possess exceptional mechanical properties (much greater than about 2,500 psi tensile, much less than about 100% elongation to break), dimensional stability, barrier properties (to methanol, water vapor, oxygen and hydrogen) even at elevated temperatures and pressures and exceptional gauge uniformity (+/- 0.2 mils preferable). In preferred embodiments, the polymer substrates are thermally and hydrolytically stable to temperatures of at least about 100°C.

Preferred polymer substrates have a pore size range of 10 Å to 2000 Å more preferably 500 Å to 1000 Å, and have a porosity range from about 40% to 90%.

In some preferred embodiments of the present invention, the polymer substrate of the SPEM comprises a lyotropic liquid crystalline polymer, such as a polybenzazole (PBZ) or polyaramid (PAR or Kevlar®) polymer. Preferred polybenzazole polymers include polybenzoxazole (PBO), polybenzothiazole (PBT) and polybenzimidazole (PBI) polymers. Preferred polyaramid polymers include polypara-phenylene terephthalimide (PPTA) polymers.

In other preferred embodiments, the polymer substrate of the SPEM comprises a thermoplastic or thermoset aromatic polymer. Preferred aromatic polymers include: polysulfone (PSU), polyimide (PI), polyphenylene oxide (PPO), polyphenylene sulfoxide (PPSO), polyphenylene sulfide (PPS), polyphenylene sulfide sulfone (PPS/SO_2), polyparaphenylene (PPP), polyphenylquinoxaline (PPQ), polyarylketone (PK) and polyetherketone (PEK) polymers.

Preferred polysulfone polymers include polyethersulfone (PES), polyetherethersulfone (PEES), polyarylsulfone, polyarylethersulfone (PAS), polyphenylsulfone (PPSU) and polyphenylenesulfone ($PPSO_2$) polymers. Preferred polyimide polymers include the polyetherimide polymers as well as fluorinated (5 membered ring) polyimides. Preferred polyetherketone polymers include polyetheretherketone (PEEK), polyetherketone-ketone (PEKK), polyetheretherketone-ketone (PEEKK) and polyetherketoneetherketone-ketone (PEKEKK) polymers.

Preferred ion-conducting materials for use in the fuel cells of the present invention are easily sulfonated or synthesized from commercially-available, low-cost starting polymers, and are swellable, but highly insoluble in boiling water (100°C) or aqueous methanol (>50%) over extended time periods.

Preferred ion-conducting materials have limited methanol permeability (limited methanol diffusivity and solubility) even at elevated temperatures and pressures, are substantially chemically stable to acids and free radicals, and thermally/hydrolytically stable to temperatures of at least about 100°C. Preferred ion-conducting materials have an ion-exchange capacity (IEC) of >1.0meq/g dry membrane (preferably, 1.5 to 2.0meq/g) and are highly ion-conducting (preferably, from about 0.01 to about 0.5S/cm, more preferably, to greater than about 0.1 S/cm or <10Ωcm resistivity).

Preferred ion-conducting materials are easily cast into films and/or imbibed into the polymer substrate. Such films are durable, substantially defect-free, and dimensionally stable (less than about 20% change in dimension wet to dry), preferably even above temperatures of at least about 100°C. Particularly preferred ion-conducting materials have the ability to survive operation in fuel cells (i.e., H_2/O_2, methanol) for at least about 5000 hours (automotive).

In one preferred embodiment of the present invention, the ion-conducting material of the SPEM comprises a sulfonated, phosphonated or carboxylated ion-conducting aromatic polymer or a perfluorinated ionomer. For example, it may comprise a sulfonated derivative of at least one of the above-listed thermoset or thermoplastic aromatic polymers. It may also comprise a sulfonated derivative of a polybenzazole or polyaramid polymer.

In an alternate embodiment, the ion-conducting material of the SPEM of the present invention comprises a non-aromatic polymer, such as a perfluorinated ionomer. Preferred ionomers include carboxyl-, phosphonyl- or sulfonyl-substituted perfluorinated vinyl ethers.

Other preferred ion-conducting materials for use in the present invention include polystyrene sulfonic acid (PSSA), polytrifluorostyrene sulfonic acid, polyvinyl phosphonic acid (PVPA), polyvinyl carboxylic acid (PVCA) and polyvinyl sulfonic acid (PVSA) polymers, and metal salts thereof.

Substrate and ion-conducting materials for use in the present invention may be substituted or unsubstituted and may be homopolymers or copolymers of the polymers listed above. Representative formulae of the unsubstituted monomers can be found in Tables 4 to 7 at the end of the Detailed Description of the Invention.

Following selection of a suitable polymer substrate and ion-conducting material in accordance with criteria set forth herein, one preferred method of fabricating a membrane of the present invention comprises the following steps: solubilizing the ion-conducting material, preparing a polymer substrate membrane, swelling the membrane with water, solvent exchanging the water swollen membrane, imbibing the solvent swollen substrate with the ion-conducting material via solution infiltration such that the microinfrastructure of the porous polymer substrate is substantially interpenetrated with the ion-conducting

material. Upon solvent evaporation and drying, the microporous substrate will collapse locking the ion-conductor within the microinfrastructure of the polymer substrate. Post imbibing steps may include tension drying, stretching and hot pressing of the composite membrane. The substrate provides mechanical and chemical stability, while the ion-conductor provides a high-flux proton path. The SPEMs of the present invention also act as a barrier against fuel (H_2, O_2 and methanol permeation) in fuel cell applications.

Another preferred method of producing the membranes of the present invention comprises the steps of preparing a mixture of the porous polymer substrate and the ion-conducting material in a common solvent and casting a composite membrane from the mixture. Preferred solvents for these methods include tetrahydrofuran (THF), dimethylacetamide (DMAc), dimethylformamide (DMF), dimethylsulfoxide (DMSO), N-Methyl-Z-pyrrolidinone (NMP), sulfuric acid, phosphoric acid, chlorosulfonic acid, polyphosphoric acid (PPA) and methanesulfonic acid (MSA). PPA/MSA are preferred solvents for a polymer substrate and ion-conducting material combination of PBO/PPSU.

Still another method of producing a membrane of the present invention comprises the steps of sulfonating the pores of the polymer substrate with a sulfonating agent.

Yet another method of producing a membrane of the present invention comprises the steps of preparing a mixture of a porous polymer substrate and an ion-conducting material and extruding a composite film directly from the mixture.

The membranes of the present invention are useful in a variety of electrochemical devices, including fuel cells, electronic devices, systems for membrane-based water electrolysis, chloralkali electrolysis, dialysis or electrodialysis, pervaporation or gas separation.

The foregoing and other objects, features and advantages of the invention will become better understood with reference to the following description and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic illustrating the preparation of a composite membrane of the present invention.

Fig. 2 shows a graph of % dry loading of ICP/PBO vs. initial ICP solution wt.% for Nafion®/PBO, Radel R®/PBO and Sulfide-Sulfone/PBO, in accordance with the present invention.

DETAILED DESCRIPTION

The composite membranes of the present invention are designed to address the present shortcomings of today's solid polymer electrolyte membranes, specifically Nafion® and other like membranes (e.g., Gore-Select®).

The present invention provides a relatively low cost, composite solid polymer electrolyte membrane (SPEM), with improved power density and reduced sensitivity to carbon monoxide in hydrogen fuel. It also alleviates water management problems which limit the efficiency of present Nafion® membrane-based fuel cells.

The composite membranes of the present invention may be employed in various applications, including but not limited to, polarity-based chemical separations; electrolysis; fuel cells and batteries; pervaporation; reverse osmosis - water purification, gas separation; dialysis separation; industrial electrochemistry, such as choralkali production and other electrochemical applications; water splitting and subsequent recovery of acids and bases from waste water solutions; use as a super acid catalyst; use as a medium in enzyme immobilization, for example; or use as an electrode separator in conventional batteries.

The composite SPEMs of the present invention comprise a porous polymer substrate interpenetrated with an ion-conducting material. The porous polymer substrate serves as a mechanically, thermally, chemically and oxidatively durable support for the ion-conducting material, e.g., polymer. Ion-conducting polymers (ICPs) with very high ion-exchange capacities (IEC>2.0 meq/g) can be used in SPEMs of the present invention, since the strength properties of the ICP are not needed for membrane mechanical integrity. These ion-exchange polymers with higher degrees of

sulfonation than typical Nafion® and Nafion®-like materials, will possess correspondingly higher values for ionic conductance.

The porous polymer substrate is characterized by a microinfrastructure of channels that have substantially uniform, unchanging dimensions (Tg is higher than use temperature). That is, the substrate material will not flow, since the operating temperature is less than the Tg of the substrate. The ion-conducting polymer substantially interpenetrates the microinfrastructure of the porous polymer substrate. This configuration, which can be made quite thin, promotes efficient proton transport across the membrane and minimizes water management problems. As a consequence, eventual membrane dehydration, parasitic losses and loss of ionic conductivity can be substantially prevented.

Preferably, thermally stable, wholly aromatic polymers are used in producing the composite membranes of the present invention, but any material(s) meeting the following requirements may generally be used: low cost, high ionic conductivity, electronically insulating, impermeable to fuel (H_2, O_2, methanol) permeation at elevated temperatures and pressures in fuel cell applications, chemically resistant to acids, bases and free radicals, Tg above fuel cell operating temperature (at least about 175°C is preferred), minimal water transport rate during operation, resistance to puncture or burst during operation at high temperatures and pressures, and maintenance of ionic conductivity at elevated/high operating temperatures.

The selection criteria for polymer substrates and ion-conducting materials suitable for SPEMs of the present invention are described below. Structures for preferred polymer substrates and ion-conducting polymers are indicated in Tables 4 to 7 which appear at the end of this section.

Preferred polymer substrates are easily synthesized from commercially-available, low-cost starting polymers, into thin, substantially defect free polymeric films which have high strength even at low thickness (preferably less than about 1 mil), outstanding crease/crack resistance and high tear strength. Preferred polymer substrates are substantially chemically resistant to acids, bases, free radicals and solvents (i.e., methanol) and are thermally and hydrolytically stable from temperatures of about 50°C to 300°C. Preferred polymer substrates possess exceptional mechanical properties (much greater than about 2,500 psi tensile, much

less than about 100% elongation to break), dimensional stability, barrier properties (to methanol, water vapor, oxygen and hydrogen) even at elevated temperatures and pressures and exceptional gauge uniformity (+/- 0.2 mils preferable). In preferred embodiments, the polymer substrates are thermally and hydrolytically stable to temperatures of at least about 100°C.

Preferred polymer substrates have a pore size range of 10 Å to 2000 Å more preferably 500 Å to 1000Å, and have a porosity range from about 40% to 90%.

In some preferred embodiments of the present invention, the porous polymer substrate of the SPEM comprises a lyotropic liquid crystalline polymer, such as a polybenzazole (PBZ) or polyaramid (PAR or Kevlar®) polymer. Preferred polybenzazole polymers include polybenzoxazole (PBO), polybenzothiazole (PBT) and polybenzimidazole (PBI) polymers. Preferred polyaramid polymers include polypara-phenylene terephthalamide (PPTA) polymers. Structures of the above-mentioned polymers are listed in Table 4.

In other preferred embodiments, the porous polymer substrate of the SPEM comprises a thermoplastic or thermoset aromatic polymer. Preferred groups of these aromatic polymers include the following: polysulfone (PSU), polyimide (PI), polyphenylene oxide (PPO), polyphenylene sulfoxide (PPSO), polyphenylene sulfide (PPS), polyphenylene sulfide sulfone (PPS/SO_2), polyparaphenylene (PPP), polyphenylquinoxaline (PPQ), polyarylketone (PK) and polyetherketone (PEK) polymers.

Preferred polysulfone polymers include polyethersulfone (PES), polyetherethersulfone (PEES), polyarylsulfone polyarylethersulfone (PAS), polyphenylsulfone (PPSU) and polyphenylenesulfone ($PPSO_2$) polymers. Preferred polyimide polymers include the polyetherimide polymers and fluorinated polyimides. Preferred polyetherketone polymers include polyetheretherketone (PEEK), polyetherketone-ketone (PEKK), polyetheretherketone-ketone (PEEKK) and polyetherketoneetherketone-ketone (PEKEKK) polymers. The structures of the above polymers are listed in Tables 5 and 6 below.

More preferably, the porous polymer substrate comprises a PBO or a PES polymer. Most preferably, the porous polymer substrate comprises a PBO polymer, such as a poly(benzo-bisoxazole).

The PBO polymer is a member of a relatively new class of polymeric materials collectively referred to as ordered polymers. As a result of its rigid-rod-like molecular structure, PBO forms liquid crystalline solutions from which extremely strong stiff fibers and films have been processed. Foster-Miller has pioneered the development of innovative methods for processing PBO into microporous high-strength high-modulus thermally-stable films that are useful for a multitude of high-performance applications, e.g., in advanced aircraft and spacecraft.

When the PBO polymer is in a dry (entirely collapsed) form, it has the following characteristics: high strength and dimensional stability, superior barrier (gaseous) properties, excellent crease/crack resistance, excellent tear strength, and superior thermal and hydrolytic temperature stability (>300°C).

Film-forming processes involve several operations in which a PBO polymer solution in polyphosphoric acid undergoes a succession of structural changes, leading to the final product form. One basic process for producing PBO products includes extrusion of the polymer substrate solution (polymer and acid solvent), coagulation to lock-in the molecular structure, washing to remove the acid solvent, and drying (at high temperatures) to remove the exchanged water and consolidate the polymer into the end product.

In one particularly preferred embodiment, the PBO film is extruded and multiaxially oriented using a blown process as disclosed, e.g., in U.S. Patent Nos. 4,939,235, 4,963,428 and 5,288,529. The degree of multiaxial orientation can be varied from $\pm\theta$ of 5° to 65°, though an orientation of 22° to 30° is preferred.

During composite membrane fabrication, the following problems may be encountered: substrate film delamination, imbibtion of an insufficient amount of ion-conducting material inside the porous substrate and/or inability to maintain, if desired, a smooth outer layer of ion-conducting polymer for proper bonding. These problems may be overcome by heating of the ion-conducting polymer solution during imbibtion into the substrate (which decreases the solution viscosity and swells the pores of the substrate) and using less oriented films (which allows more ion-conducting material into the substrate, decreased bubble point).

The polymer substrate processing system includes a hydrolic flask, extruder, pump, counter-rotating die (CRD), porous ring, water wash tank/collapse shed and film take-up system. In one embodiment, the take-up system includes a 3" porous sizing ring followed by a 6" diameter take-up roll along with a 4" diameter spooler. A number of CRDs and annular configurations may be used.

Information is collected and recorded for wet film thickness, dry film thickness, draw ratio, blow-up ratio, overall film quality (veins, thin spots, voids, cracks, etc.) and extrusion system settings.

Samples (wet and dry) of PBO film from each extrusion run are then tested for tensile strength and tensile modulus, bubble point, pore size distribution, total pore volume and mean pore size, gas vapor (H_2O, O_2) permeability, zinc metal level in polymer.

Interestingly, smaller die gaps have been shown to cause greater shearing during extrusion, which results in fewer veins (defects) in the PBO film. High blow-up ratios also have resulted in improved films. Additionally, smaller die gaps and larger blow-up ratios increase PBO fibril orientation without the drawback of additional shear from die rotation (although torsional stress increases slightly.)

In the coagulation stage, a liquid to solid phase transition is induced by diffusion of a non-solvent (water) into the PBO solution. During this phase transition cycle, the final structure of the solid is established. It is believed that the structure formed during the coagulation stage of PBO fiber and film is an interconnected network of highly oriented microfibrils of 80 Å to 100 Å diameter. Such films have been dried under tension in order to produce high tensile properties. During the drying process, the micropores present as spaces between microfibrils in PBO film undergo substantial shrinkage decreasing in dimensions from several thousand Angstroms (e.g., 2000 Å) in size to less than 10 Å in size for the dried heat-treated PBO film. The final pore size depends highly upon the heat treatment methods employed.

In forming a porous polymer substrate of the present invention, instead of drying the water from the network, the water is replaced by the desired ion-conducting material.

It has been discovered that a high performance PBO fuel cell membrane can be produced by interpenetrating the interior porosity of water-swollen PBO films with concentrated or dilute solutions of ion-conducting polymers, such as Nafion® or polyethersulfone polysulfonic acid. For example, after the coagulated PBO film has been infiltrated with a Nafion® solution, the Nafion® regions within the pores (and coating on the surface) of the film will form a highly ionically-conducting gelatinous Nafion® membrane supported by the porous PBO membrane substrate. Such SPEMs will exhibit the strength and thermal stability of PBO and the excellent ionic conductivity of water-swollen Nafion® copolymer.

The usual deficiencies of Nafion®, such as membrane weakness and softening at elevated temperatures, are negated by the PBO substrate to support against compression while simultaneously providing sufficient porosity to allow for adequate water content, thus enabling high proton transport. In preferred embodiments, the substrate will accommodate about 40 to about 90 volume percent, preferably about 70 to about 80 volume percent of ion-conducting polymer.

As noted above, a second preferred polymer substrate comprises a PES polymer. PES is a high use temperature amorphous thermoplastic that exhibits long-term stability at elevated temperature (>175°C). The microporous PES substrate represents a new class of high performance fuel cell membranes that can be used to solve the difficulties inherent in current Nafion® membranes as discussed above.

PES is readily available from Amoco Performance, Inc. in Alpharetta, Georgia, USA, in large quantity at low cost and exhibits the combination of desirable properties required for efficient function at much higher temperatures and pressures than are now possible (potentially greater than about 175°C temperature and greater than about 100 psi gas pressure).

Microporous PES films for use in the SPEMs of the present invention can be produced via standard film casting techniques or purchased directly from appropriate vendors. As with other suitable polymer substrates, in one preferred embodiment, PES is dissolved in an appropriate water-miscible solvent to a predetermined concentration. A wt.% solution of PES is selected to produce a film with minimized thickness (preferably less than about 1 mil). The PES solution is then cast onto glass plates to form a film,

e.g., about 0.5 mil thick. Immersion of the plates in water coagulates the polymer and leaches out the solvent forming the microporous substrate membrane in a water swollen state. The ion-conducting polymer can then be introduced into the microporous voids of the water swollen PES substrate membrane using solvent exchange processes to form the composite membrane. Alternatively, the membrane can be dried first and then infiltrated with the ion-conducting solution using vacuum to remove air bubbles and fill the pores with Nafion®. The membrane may also be produced by an extrusion process as described herein.

Preferred ion-conducting polymers for use in the present invention are easily sulfonated or synthesized from commercially-available, low-cost starting polymers, and are swellable, but highly insoluble in boiling water (100°C) or aqueous methanol (>50%) over extended time periods. Preferred ion-conducting polymers have limited methanol permeability (limited methanol diffusivity and solubility) even at elevated temperatures and pressures, are substantially chemically stable to acids and free radicals, and thermally/hydrolytically stable to temperatures of at least about 100°C. Preferred ion-conducting polymers have an ion-exchange capacity (IEC) of >1.0meq/g dry membrane (preferably, 1.5 to 2.0meq/g) and are highly ion-conducting (preferably, from about 0.01 to about 0.5S/cm, more preferably, to greater than about 0.1 S/cm or <10Ωcm resistivity). Preferred ion-conducting polymers are easily cast into films and/or imbibed into the polymer substrate. Such films are durable, substantially defect-free, and dimensionally stable (less than about 20% change in dimension wet to dry) even above temperatures of at least about 100°C. Preferred ion-conducting polymers have the ability to survive operation in fuel cells (i.e., H_2/O_2, methanol) for at least about 5000 hours (automotive).

Preferred ion-conducting polymers are substantially chemically stable to free radicals. Cross-linking methods or the use of additives can also provide or enhance peroxide stability.

The peroxide (H_2O_2) screening test serves as an accelerated fuel cell life test. The test simulates long term fuel cell operation by exposing the subject aqueous ion-conducting membrane to a peroxide/iron solution at 68°C for 8.0 hours. Under these conditions, aggressive hydroperoxide (HOO-) radicals are produced. It has been shown that these radicals are

formed during normal H_2/O_2 fuel cell operation, and are the prominent membrane degradation mechanism.

Polymer additives have also been evaluated that can be used as radical scavengers within the ion-conducting component of the SPEMs of the present invention. Examples of these include Irganox* 1135 (commercially available from Ciba Geigy) and DTTDP (commercially available from Hampshire). In addition, the ion-conducting component polymer can be cross-linked via heating to slow membrane degradation.

In one preferred embodiment of the present invention, the ion-conducting material of the SPEM comprises a sulfonated (SO_3H), phosphonated ($PO(OH)_2$) or carboxylated (COOH) aromatic polymer. For examples of phosphonates, see *Solid State Ionics*, 97 (1997), 177-186. For examples of carboxylated solid polymer electrolytes, see *Solid State Ionics*, 40:41 (1990), 624-627. For example, the ion-conducting material may comprise a sulfonated derivative of at least one of the above-listed thermoset or thermoplastic aromatic polymers. It may also comprise a sulfonated derivative of a polybenzazole or polyaramid polymer.

Though sulfonated polymers are not readily available in industry, the synthesis of such polymers is well known to the skilled artisan and can be found in various patents and publications. See for example, U.S. Patent Nos. 4,413,106, 5,013,765, 4,273,903 and 5,438,082, and Linkous, et al., *J. Polym. Sci.*, Vol. 86: 1197-1199 (1998).

In an alternate embodiment, the ion-conducting material of the SPEM of the present invention comprises a non-aromatic polymer, such as a perfluorinated ionomer. Preferred ionomers include carboxyl-, phosphonyl- or sulfonyl-substituted perfluorinated vinyl ethers.

Other preferred ion-conducting materials for use in the present invention include polystyrene sulfonic acid (PSSA), polytrifluorostyrene sulfonic acid, polyvinyl phosphonic acid (PVPA), polyvinyl carboxylic acid (PVCA) and polyvinyl sulfonic acid (PVSA) polymers, and metal salts thereof.

More preferably, the ion-conducting material comprises a sufonated derivative of a polyphenylsulfone (PPSU), polyethersulfone (PES), polyimide (PI), polyphenylene sulfoxide (PPSO) and polyphenylenesulfide-sulfone (PPS/SO_2). These polymers and additional preferred polymers are listed in Table 7.

* Trade-mark

In order to facilitate interpenetration of the ion-conducting polymer into the pores of the polymer substrate, surfactants or surface active agents having a hydrophobic portion and hydrophilic portion may be utilized in promoting the interpenetration of the ion-conducting polymer into the pores of the polymer substrate. These agents are well known in the art and include Triton*X-100 (commercially available from Rohm & Haas of Philadelphia, PA).

Compatibilizers may also be employed in producing composite membranes of the present invention. As used herein, "compatibilizers" refer to agents that aid in the blendability of two or more polymers that would otherwise be resistant to such blending. Examples include block copolymers containing connecting segments of each component. These include potential substrate and/or ion-conducting polymer components.

The SPEMs and methods of the present invention will be illustrated by specific combinations of polymer substrates and ion-conducting polymers. However, the present invention should not be construed as being limited in use to any particular polymer substrate or ion-conducting material. Rather, the present teachings are suitable for any polymer substrate and ion-conducting material meeting the criteria set forth herein.

Several different innovative methods have been developed for producing the solid polymer electrolyte membranes of the present invention by providing a polymer substrate interpenetrated with an ion-conducting polymer. Each method is lower in cost and higher in efficiency than current methods of producing Nafion® (or Nafion®-like) membranes. These methods include imbibing a porous substrate membrane with an ion-conducting material, casting a composite membrane from a common solvent, sulfonating the pores of a suitable polymer substrate to form a composite SPEM of the present invention, and extruding a composite film directly from the mixture of a polymer substrate and ion-conducting material.

The first method uses Nafion® as an example of a suitable ion-exchange material, in order to demonstrate the clear advantage of using the composite SPEM of the present invention.

Initially, a porous membrane having the desired pore size and pore content is made using a suitable polymer substrate, e.g., PES or PBO. Either casting or extrusion processes are utilized to produce these

* Trade-mark

membranes as described above. The pores of the porous polymer substrate membrane are then interpenetrated with an ICP, e.g., solubilized Nafion® ion-conducting polymer. The Nafion®-interpenetrated porous membrane is then immersed into a dilute acid releasing the insoluble free sulfonic acid form of Nafion® as a high ionically conducting gel within the micropores and as thin coatings on the surfaces of the membrane. The flexible, pressure-resistant, high Tg, porous substrate provides puncture and crush-resistance to the thin coating of ion conductor membrane and also to the Nafion®-filled micropores even at temperatures above 175°C (the Tg of PES is 220°C, PBO has no Tg).

Composite membrane porosity is controlled during the imbibtion processes by varying the %wt. of ion-conducting material in solution to produce a membrane with numerous pores (preferably microscopic) of substantially uniform dimensions (preferably $\leq$ about 1000 Å).

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A comparison of physical chemical properties of Nafion® 117 and SPEMs of the present invention follows in Table 1 below.

TABLE 1

PROPERTY	NAFION® 117	SPEMS OF THE PRESENT INVENTION
Thickness (mil) - wet	6 to 8	~0.1 to ~5.0, preferably <~0.1
H+ resistance (ohm-cm)	10.0	~5.0 to ~100.0, preferably <~10.0
Tensile (psi) at break	2500 to 2700	~2500 to ~50,000, preferably >~10,000
Elongation (%) at break	110 to 130	~5 to ~20, preferably <~15
% water content* (based on dry weight of membrane)	35 to 40	~20 to ~100, preferably <~50
Ion-exchange capacity (meq/g dry SPE)	0.8 to 1.0	~0.2 to ~2.0, preferably ~1.5 to ~2.0
Methanol permeability (cm^3-sec)	0.01	preferably << ~0.01
H_2 permeability (cm^3-mil/ft^2 hr-atm)	600	~60 to ~600, preferably ~600
O_2 permeability (cm^3-mil/ft^2 hr-atm)	330	~30 to ~330, preferably ~330
Hydrodynamic H_2O permeability (cm^3-mil/ft^2hr-atm)	50	~5 to ~50, preferably ~50
Electro-osmotic H_2O permability (cm^3-coulomb)	7.5×10^{-4}	----
Minimum temperature (°C) of thermal/hydrolytic stability	~100	~100 to ~175, preferably ~150
Dimensional stability: dry to wet expansion of membrane	<20%	0 to ~20%, preferably <~20%
Ionomer degradation: (accelerated life testing)	<10%	0 to ~20%, preferably <~10%
Chemical stability: oxidation and hydrolysis (useful life, hours)	20,000	~250 to ~5000
Crease/crack (ability to withstand five folds in hydrated or dry state)	Pass	Pass
Tear strength (ability to withstand tearing in hydrated or dry state)	Pass	Pass

*Membrane hydrated by soaking in 100°C H_2O for 1 hour

In one preferred embodiment, the polymer substrate is dissolved in an appropriate water-miscible solvent to a predetermined concentration. The wt.% solution of polymer substrate is selected to produce a film with minimized thickness (preferably <1mil). The polymer substrate solution is then cast onto glass plates to form ~0.5 mil thick film. Immersion of the plates in water coagulates the polymer and leaches out the solvent forming the microporous substrate membrane in a water swollen state. Nafion® (or other ion-conducting polymers) can then be introduced into the microporous voids of the water swollen substrate membrane using solvent exchange processes to form the composite membrane. Alternatively, the membrane can be dried first and then infiltrated with Nafion® solution using vacuum to remove air bubbles and fill the pores with Nafion®. The membrane may also be produced by an extrusion process as described herein.

In a second preferred embodiment of the invention, porous polymer substrate membranes containing an ion-conducting material can also be produced by casting the membranes from a common solution containing appropriate concentrations of the polymer substrate and ion-conducting material. Determination of %wt. ion conductor/%wt. substrate are based on the desired final thickness, % volume of ion-conducting polymer and the particular polymers employed. In some instances, this process may produce composite membranes in which the ion-conducting polymer domain sizes are smaller and more uniform than in composite membranes produced by imbibing pre-formed porous substrate membranes. In this process, pore size and content can be more easily controlled in the membrane by adjustment of individual component concentrations. The %wt. of the solution is adjusted to obtain the desired composite. In one embodiment, the ion-conducting polymer solution can be prepared by dissolving the ion-conducting polymer in sulfonate salt form in hot alcohol/water mixtures (e.g., Nafion 1100 EW solution, 5% from Dupont).

Preferred cosolvents include, but are not limited to, the following: tetrahydrofuran (THF), dimethylacetamide (DMAc), dimethylformamide (DMF), dimethylsulfoxide (DMSO), N-Methyl-Z-pyrrolidinone (NMP), sulfuric acid, phosphoric acid, chlorosulfonic acid, polyphosphoric acid (PPA) and

methanesulfonic acid (MSA). PPA/MSA are preferred solvents for a polymer-substrate and ion-conducting material combination of PBO/PPSU.

In a third preferred embodiment of this invention, a polymer substrate is chemically sulfonated to produce a sulfonated composite in situ. This concept draws on a number of technologies. A variety of methods exist for the fabrication of porous polymer films, most centered around dissolving a polymer within a water miscible solvent. A freshly cast film is then soaked in water causing the polymer to precipitate from solution. This phase separation of the solvent and the polymer causes the formation of the porous network as the solvent is leached into the water. One example would be the formation of the PBO polymer substrate, but this can be extended to a large number of polymers. One typical method for sulfonating polymers is direct exposure to concentrated sulfuric acid (esp. at elevated temperatures). Imbibing a sulfuric acid solution into the porous polymer network, followed by rapid heating to high temperatures (250-350°C) has been shown to sulfonate the polymer. If a dilute acid solution is used, the polymer will not dissolve in the sulfonating process. As a result, only the surface within the porous network will be sulfonated. The product is a composite structure of unsulfonated polymer with sulfonated polymer on the surface.

In a fourth preferred embodiment, a solid polymer electrolyte composite membrane of the present invention can be made by preparing a mixture of a polymer substrate and an ion-conducting polymer and extruding or casting a composite film directly from this mixture.

One way to realize the direct extrusion of a solid polymer electrolyte composite membrane without imbibing a porous polymer substrate with an ion-conducting polymer solution would be the fine dispersion of one component in a solution of the other. Provided the solvent used would only dissolve one of the components, a composite could be obtained by extruding or casting this physical mixture of the components followed by removal of the solvent.

Another possibility would be the dissolution of both components in a common solvent. A composite membrane would be formed with the phase separation of the components, either before or after the removal of the

solvent. Similarly, many polymers can be uniformly blended in the melt (e.g. without solvent). However, upon cooling the components may phase separate into the appropriate interpenetrating network (IPN)-type structure. This last method would also be useful from the standpoint that no solvent is required.

Examples of these methods include blending of sulfonated and unsulfonated versions of one polymer in the high temperature melt, followed by their phase separation on cooling. The typical solution of PBO in polyphosphoric acid would dissolve the ion-conducting polymer. Fibers of a suitable polymer substrate could be dispersed into a solution (or melt) of the ion-conducting polymer. Extrusion or casting of this mixture, followed by removal of the solvent would provide a typical fiber reinforced composite structure.

Optimal interpenetration of the polymer substrate by the ion-conducting polymer is estimated to be in the range of 40-90% volume. More preferably, interpenetration is in the range of 70-80% volume. Percent values can be determined by comparing the thickness of a membrane infiltrated with ion-conducting polymer with a control membrane with no infiltration. (For example, double thickness would indicate 50% interpenetration.) General microscopic techniques are employed in this determination. For example, in the case of PBO polymer substrates, this measurement was achieved by swelling a PBO membrane in water and replacing the water with the ion-conducting polymer.

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The following tables further illustrate SPEMs of the present invention.

TABLE 2
Comparative Data for Water and Methanol Transmission Experiments

SAMPLE: Material & Type	Film: 2 HR Water Uptake (%)	Film: 1 HR Boiling Water Uptake (%)	Avg. WVTR (25°C) g/(mil*100in² *24 hr)	Avg. WVTR (80°C) g/(mil*100in² *24 hr)	Avg. MeOHTR (25°C) g/(mil*100in² *24 hr)
Unsulfonated Udel PES	0.00	1.20	5.7	106.0	NT
50% Sulfonated Udel PES (FMI)	8.70	3.23	47.3	673.0	NT
75% Sulfonated Udel PES (FMI)	12.12	11.94	29.1	814.4	NT
85% Sulfonated Udel PES (FMI)	12.50	92.70	116.2	2850.0	NT
100% Sulfonated PES (FMI) in PBO	1074.68	462.25	109.30	3095.3	288.1
Nafion® 117 Control	16.88	35.34	1003.10	15200.4	2680.1
PBO Control	0.00	0.30	0.0	4.1	NT

NT = Not Tested

The following table shows comparative data for membrane properties for PBO/PES-PSA (75%) and PBO/PES-PSA (85%) and Nafion®.

TABLE 3
Comparative Data of Membrane Properties

	MEMBRANE		
Property	PBO/PES-PSA (75%)	PBO/PES-PSA (85%)	Nafion® 117
Thickness (mils)	1.5	1.5	7.0
Resistivity (ohm-cm)	14.7	11.38	9.5 - 10.0
Water content (%)	45	55	35 - 40
IEC_{drv} (meq/g)	0.55	0.96	0.91

TABLE 4

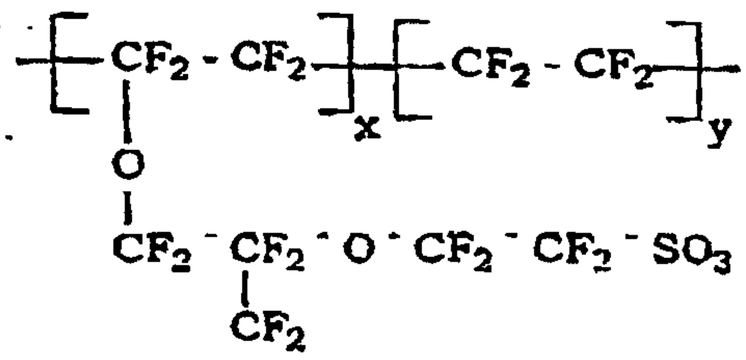
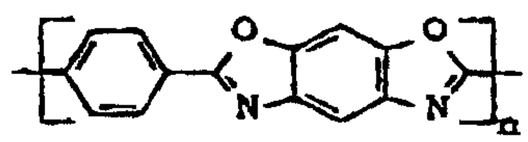
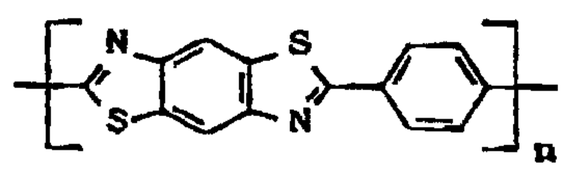
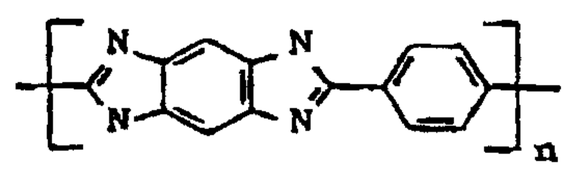
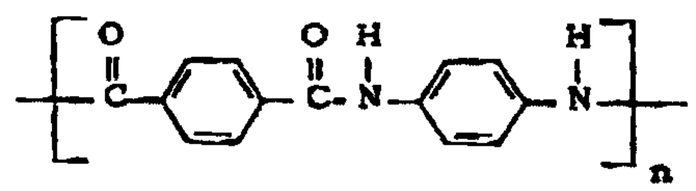
Nafion®	
PBO (poly(bisbenzoxazole))	
PBT (poly(benzo(bis-thiazole)-1,4-phenylene))	
PBI (poly(benzo(bis-diazole)-1,4-phenylene)	
PAR (polyaramid or Kevlar®)	

TABLE 5

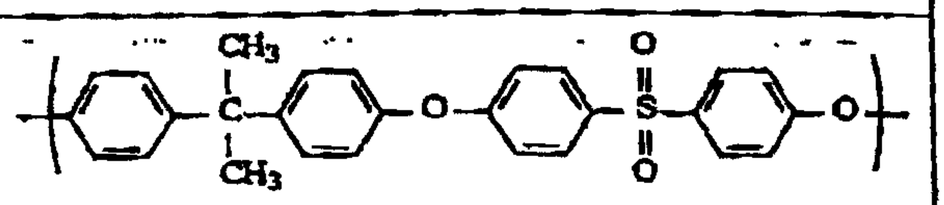
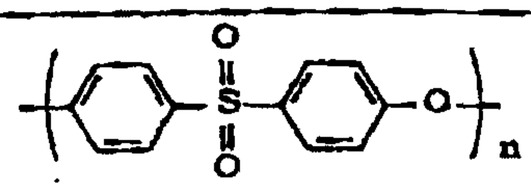
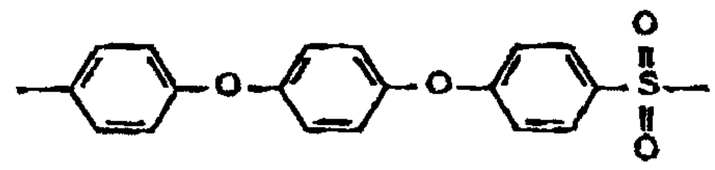
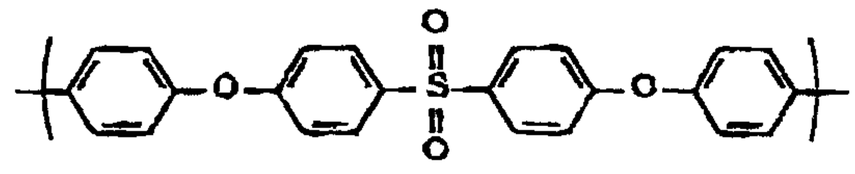
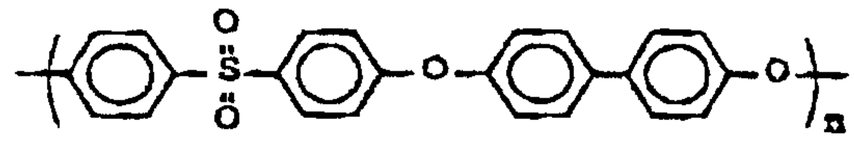
PSU (polysulfone)	
PES (polyether sulfone)	
PEES (polyether-ether sulfone)	
PAS (polyarylether sulfone)	
PPSU (polyphenylene sulfone)	

TABLE 6

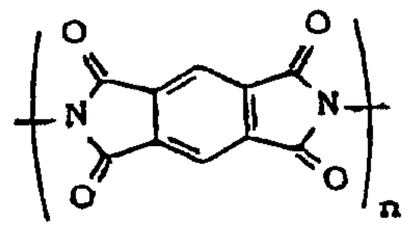
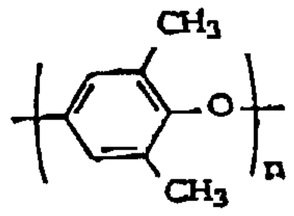
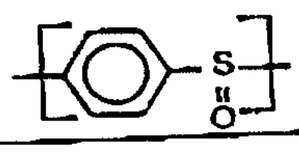
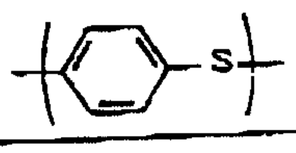
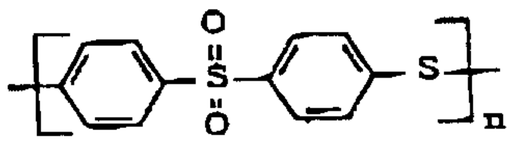
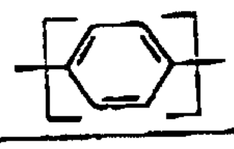
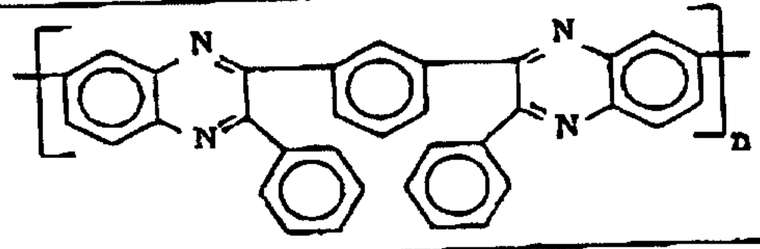
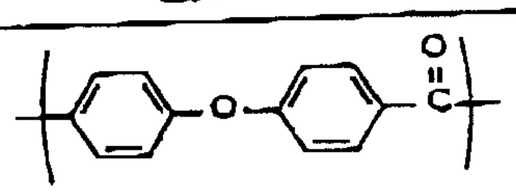
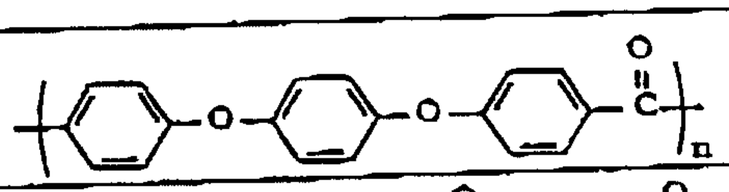
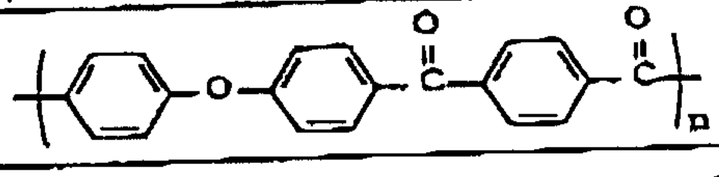
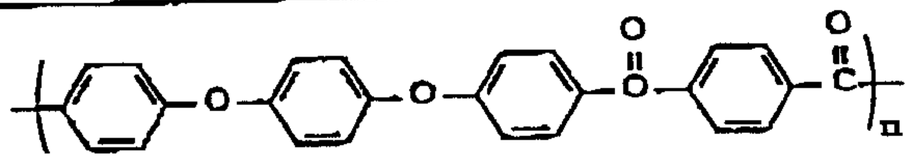
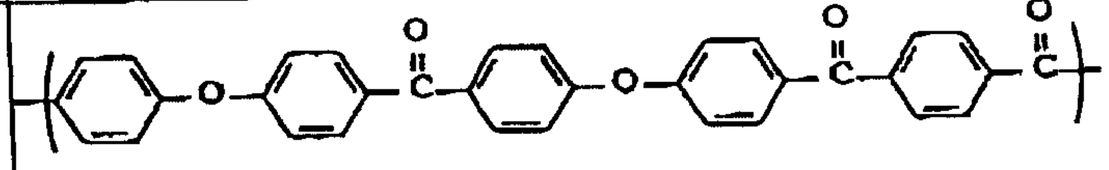
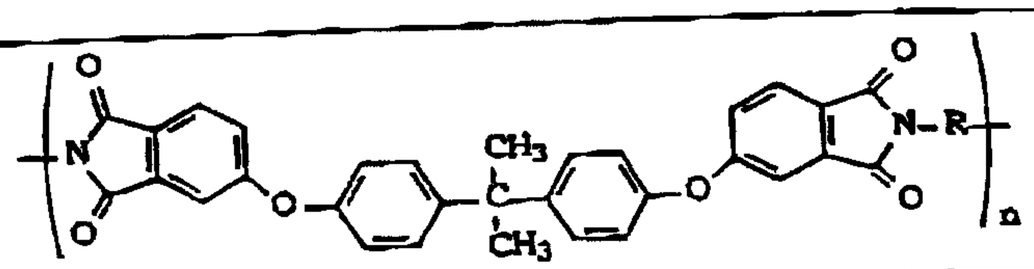
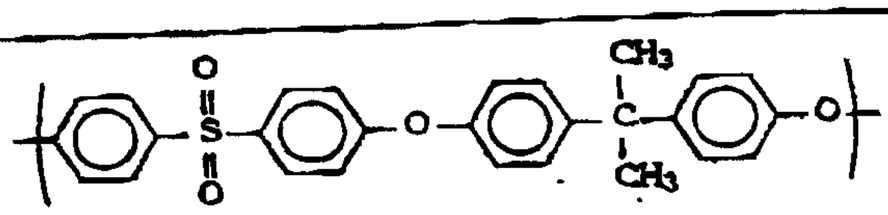
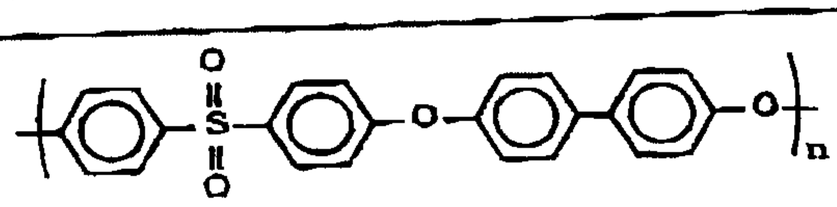
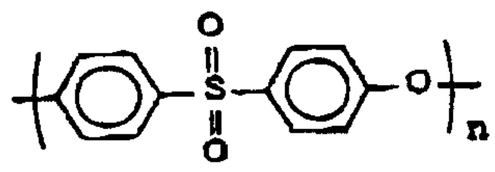
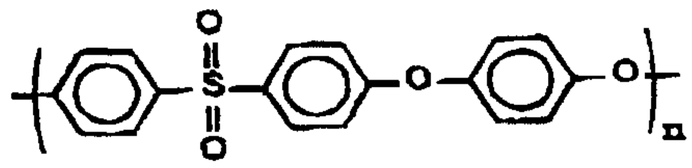
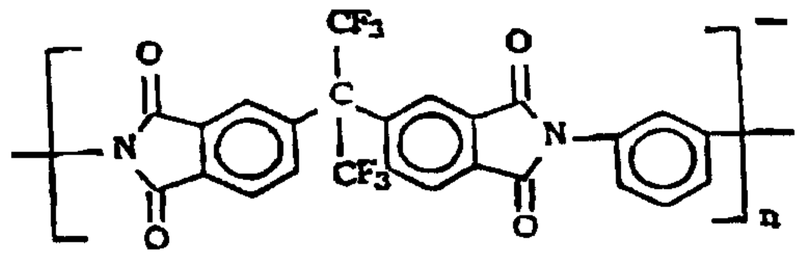
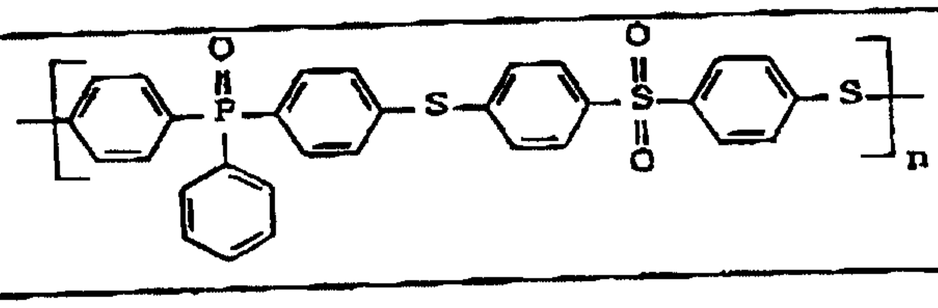
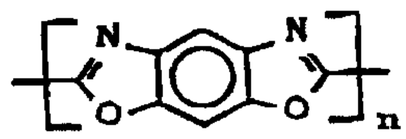
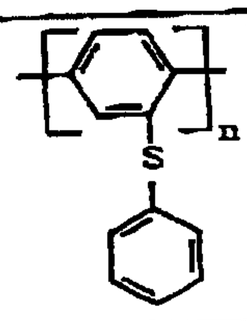
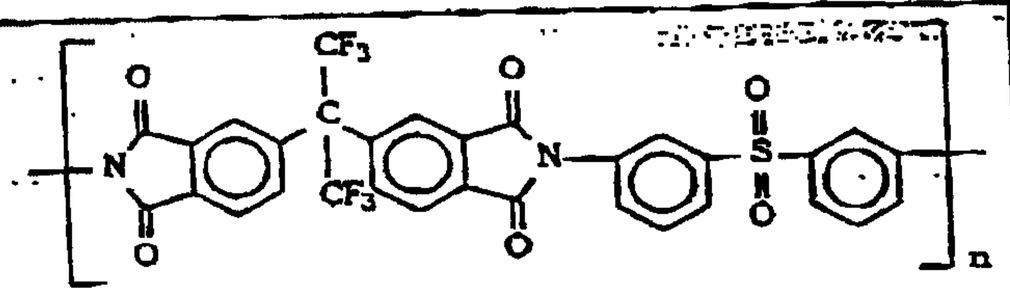
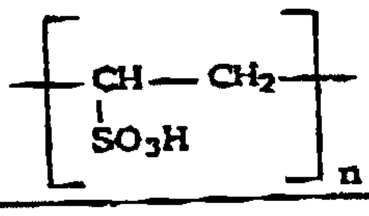
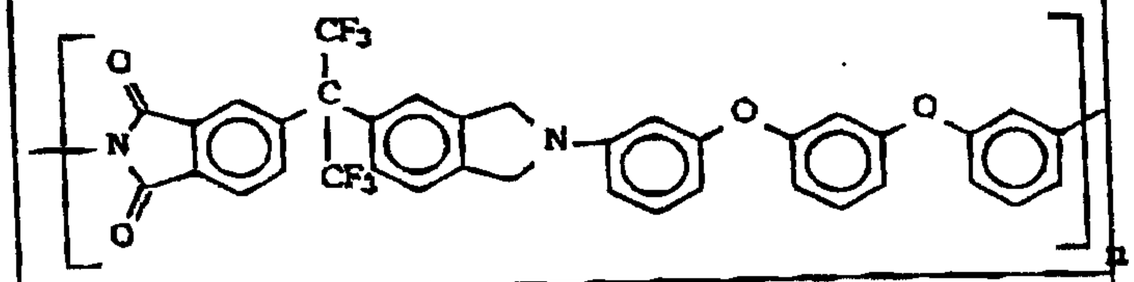
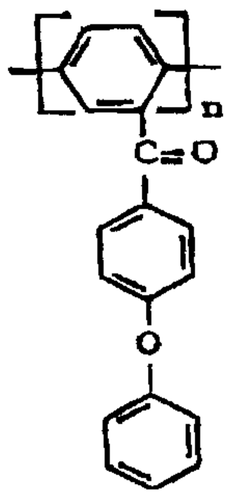
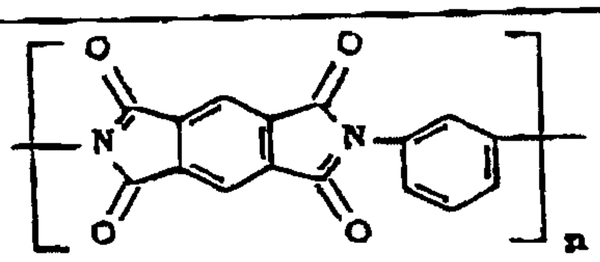
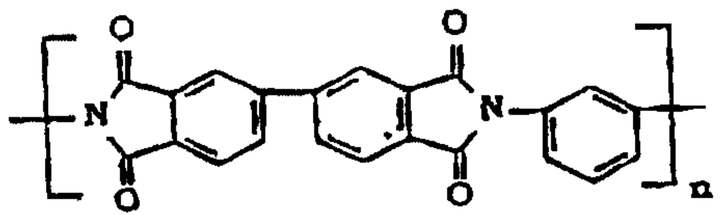
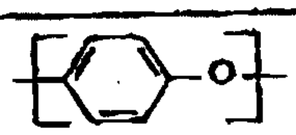
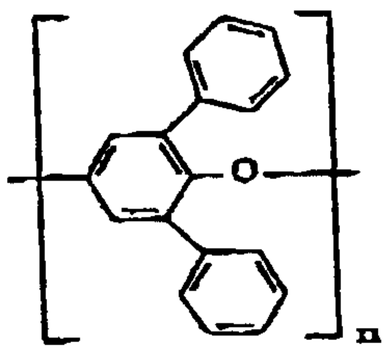
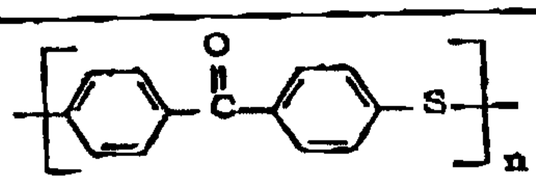
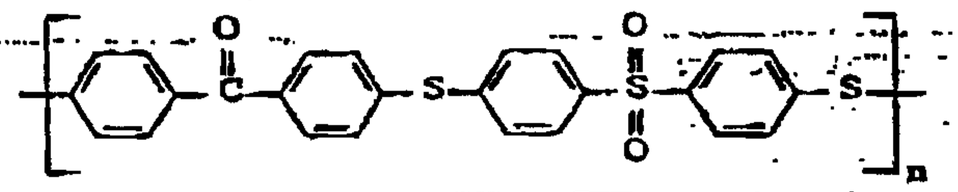
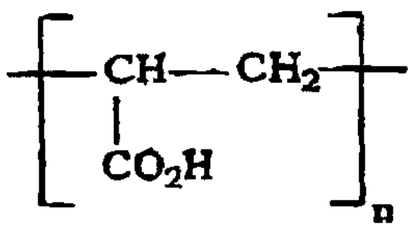
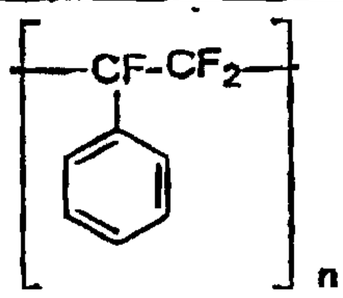
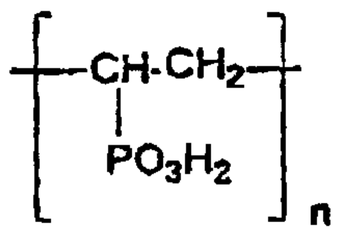
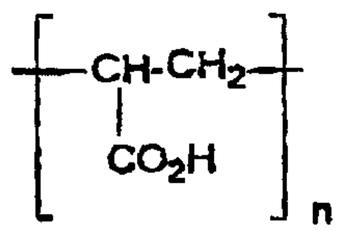
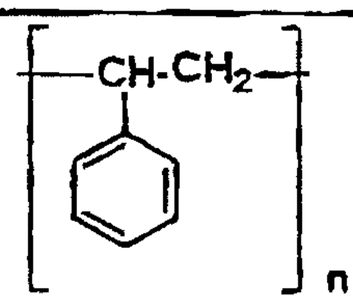
PI (polyimide)	
PPO (polyphenylene oxide)	
PPSO (polyphenylene sulfoxide)	
PPS (polyphnylene sulfide)	
PPS/SO_2 (polyphenylenesulfide sulfone)	
PPP (polyparaphenylene)	
PPQ (poly(penylquinoxaline)	
PEK (polyetherketone)	
PEEK (polyetheretherketone)	
PEKK (polyetherketoneketone)	
PEEKK (polyetheretherketone-ketone)	
PEKEKK (polyetherketone-etherketone-ketone)	

TABLE 7

PEI (polyetherimide) R=aryl, alkyl, aryl ether or alkylether	
Udel polysulfone	
Radel R polyphenylsulfone	
Radel A polyethersulfone	 and 
poly(trifluoro-methyl-bis(phthalimide)-phenylene)	
poly(triphenylphosphine oxide sulfide-phenylsulfone-sulfide)	
(PBO-PI) poly(benz(bis)oxazole	
poly(phenylsulfide 1,4-phenylene)	

poly(trifuoromethyl-bis(phthalimide)-phenylsulfone	
(PVSA) polyvinyl sulfonic acid	
poly(phthalimide ditrifluoromethyl methylene phthalimide-1,3-phenylene ether)	
poly-x (maxdem)	
poly(pyrolmellitic diimide-1,3-phenylene)	
poly(diphthalimide-1,3-phenylene)	
(PPO) poly(1,4-phenylene oxide)	
Diphenyl PPO (poly(3,5-diphenyl-1,4-phenylene oxide)	
PBPS (poly(benzophenone sulfide))	

poly(benzophenone sulfide-phenylsulfone-sulfide)	
polyvinyl carboxylic acid	
trifluoro styrene	
polyvinyl phosphonic acid	
polyvinyl carboxylic acid	
polystyrene sulfonic acid (PSSA)	

SUBSTITUTE SHEET (RULE 26)

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TABLE 8

Serial Number	ICP Type (ID)	ICP (% wt)	Thickness (mils)		% Dry Vol ICP (Estimated)	IEC (meq/g)	Water Content (%)	Resistance (ohm*cm²)	Peroxide Test	IM Me(OH) Permeability M CO_2 per min per cm^2 per mil	Dim Stability
			Dry	Wet							
Nafion 117 Control	Nafion 117 (1100 EW)	100	7.1	87	100	0.90	38	0.203	-3.2%	1.74	-20%
FMI 539-22-1	75% SPSU (Udel)	-30	NT	15	62	0.55	45	0.056	NT	NT	NT
FMI 539-22-2	75% SPSU (Udel)	-30	NT	15	62	0.96	55	0.043	NT	NT	NT
FMI 539-22-3	100% SPSU (Udel)	-30	NT	20	62	NT	NT	NT	NT	0.187	NT
FMI 126-08E	75% SPES (Ultrason E)	12	2.0	31	44	0.23	27	127.0	-38%	NT	NT
FMI 126-08F	75% SPES (Ultrason E)	8	1.6	18	26	0.07	30	2177.1	-36%	NT	NT
FMI 126-16N	1100 EW (DuPont)	10	0.8	09	19	0.29	43	1290.8	NT	NT	nil
FMI 126-16O	1100 EW (DuPont)	10	0.9	10	19	0.39	32	1183.2	NT	NT	nil
FMI 126-17P	150% SPPSU (Radel R)	5.20	1.1	35	67	0.82	87	5.11	NT	NT	nil
FMI 126-17Q	100% SPPSU (Radel R)	5.20	1.2	25	67	0.62	60	16.60	NT	0.073	nil
FMI 126-18T	150% SPPSU (Radel R)	5.20	2.1	47	67	0.54	90	1.85	-63%	NT	nil
FMI 126-18U	100% SPPSU (Radel R)	5.20	3.1	37	67	0.50	92	16.34	-56%	0.179	nil

NT = NOT TESTED

EXAMPLES OF THE INVENTION

The polymers described herein are commercially available from a variety of suppliers (unless otherwise indicated). Suppliers of these polymers include the following: RTP, Ticona, Alpha Precision, Polymer Corp., Amoco Polymers, Greene Tweed, LNP, Victrex USA, GE Plastics, Norton Performance, BASF, Mitsui Toatsu, Shell, Ashley, Albis, Phillips Chemical, Sumitomo Bake, Sundyong, Ferro, Westlake, M.A. Hanna Eng.

The following procedures were employed in the fabrication and testing of samples that were prepared in accordance with the membranes and methods of this invention.

General Procedures

IEC PROCEDURE

1. Cut out pieces of sulfonated films (target weight 0.2g, target film thickness 2 mils).
2. Vacuum dry films at 60°C, record dry weights and note if films are in H+ or Na+ form.
3. Boil deionized water in separate beakers on hotplate.
4. Place films into boiling water.
5. Boil films vigorously for 1/2 hour.
6. Prepare 1.5N H_2SO_4.
7. Place films into H_2SO_4 and soak for 1/2 hour.
8. Remove films and rinse with deionized water.
9. Boil in deionized water again. Repeat until the films have soaked in H_2SO_4 three times.
10. Remove films from boiling water, pat film surface with paper towel, and rinse carefully with deionized water.
11. Place films in another beaker of water and check for pH.
12. Continue to rinse the films with water until pH is neutral to remove any excess acid trapped in the folds of the film.
13. Prepare saturated NaCl solution.
14. Boil the NaCl solution, pour into screw cap vials, add film and cap.
15. Place capped vials with film into water bath at 90°C for 3 hours.
16. Remove capped beaker from water bath and cool to room temperature.

17. Remove the films from NaCl solution by pouring the salt solution into another beaker (save), wash the films with deionized water (save all washings – they will be used for titration).
18. Titrate the NaCl solution with 0.1N NaOH.
19. Take the films, pat with paper towel and take wet weight. (Use wet weight to determine water content of films.)
20. Dry the films under vacuum at 60°C until constant weight.
21. Take dry weight and use this to calculate IEC.

PEROXIDE TEST PROCEDURE

22. Place films into the H+ form by following steps 1-12.
23. Make peroxide solution by adding 4ppm Fe to 3% hydrogen peroxide (28.5mg of ammonium iron (II) sulfate hexahydrate per liter of peroxide obtained from Aldrich).
24. Place the peroxide solution into water bath at 68°C.
25. Add films to the peroxide solution already at 68°C.
26. Peroxide test for 8 hours and record film properties (mechanical, color, handling etc.).
27. If film passes, remove from peroxide, rinse with water to remove all traces of peroxide solution.
28. Follow steps 13-21 to obtain post-peroxide test IEC.

FILM FABRICATION PROCEDURES

Film Casting:

Unoriented, microporous substrate films can be made by dissolving the polymer in a suitable water miscible solvent and casting onto a glass plate or other surface. For example, dry PBO polymer can be dissolved in methanesulfonic acid (MSA). The films are slowly placed into a water bath, where solvent is rinsed from the films forming microporous, water-swollen membranes of PBO polymer. Subsequent washing allows for removal of all traces of the solvent.

Extrusion:

In general, the extrusion of a polymer solution (in a water miscible solvent) followed by its coagulation and washing in a water bath allows the

formation of microporous polymer films. The mechanical properties and porosity are controlled by the characteristics of the polymer solution and the details of the extrusion process.

Microporous, biaxially-oriented films of liquid crystal polymers can be produced using a counter-rotating die (CRD) extrusion process. Solutions of the polymer are extruded using two annular and concentric mandrels that rotate in opposite directions. The rotation of the mandrels creates a transverse shear flow that is superimposed on the axial shear developed as the polymer solution is extruded through the die. The angle that the LCP fibrils make with the longitudinal axis of the tubular extrudate is $\pm\theta$, where θ can be varied from near-zero to about 60 degrees. The die rotation presets the biaxial ($\pm\theta$) orientation of the emerging extrudate. Subsequent post-die blowout (radial expansion) and draw (extrusion direction stretching) are used to further adjust and enhance the biaxial orientation.

The tubular extrudate leaving the die is expanded radially (blown) with pressurized nitrogen and stretched in the machine direction by pinch rolls to achieve the desired film thickness. The blown and drawn PBO bubble is immediately quenched in a water bath where the film structure is coagulated, or "locked-in-place", and the polyphosphoric acid is hydrolyzed into phosphoric acid. The PBO film is collected under water on a spool, which is later transferred to a fresh water storage tank where it is thoroughly rinsed and stored in the water-swollen state until needed.

See e.g., U.S. Patent 4,963,428.

Solvent Exchange:

The water swollen microporous substrate is used to complete a staged "solvent" exchange. The initial solvent (100% water) is exchanged for the desired solvent (e.g. NMP, alcohol, etc.) in a number of stages. To minimize the collapse of the pores, the exposure of the substrate film to the air was minimized. For example, note the 5 part exchange from water to NMP as follows:

	START	FINISH
Exchange #1:	100% Water	75% Water/25% NMP
Exchange #2:	75% Water/25% NMP	50%Water/50% NMP
Exchange #3:	50%Water/50% NMP	25% Water/75%NNP
Exchange #4:	20% Water/80% NMP	100% NMP
Exchange #5:	100% NMP	Fresh (anhydrous) NMP

Microporous substrate films are stored in the exchanged solvent until they are used in composite SPEM formation.

SULFONATION PROCEDURES

Sulfonation Procedure I:

Aromatic PES polymers can be sulfonated to controlled degrees of substitution with sulfonating agents. The degree of substitution is controlled by the choice of and mole ratio of sulfonating agent to aromatic rings of the polymer, by the reaction temperature and by the time of the reaction. This procedure offers a method for carrying out sulfonation in a heterogeneous manner, i.e., sulfonation of precipitated polymer crystals.

The polymer (preferably a polyethersulfone) is first dissolved in the appropriate solvent (preferably methylene chloride) and then allowed to precipitate into a fine crystalline suspension. Sulfonation is carried out by simple admixture of the suspension with a sulfonating agent. Suitable agents include chorosulfonic acid and, preferably, sulfur trioxide (Allied chemicals stabilized Sulfan B® in CH_2Cl_2). The sulfonating agent used should be in sufficient proportion to introduce a number of sulfonate groups onto the polymer that is within the range of between 0.4:1 to 5:1 per polymer repeat unit, although this is not critical. The temperature at which sulfonation takes place is critical to limiting the side reactions but varies with the type of polymer (a preferable temperature is within the range of from -50° to 80°C, referably -10° to +25°C).

When the desired degree of sulfonation has been reached, the sulfonated polymer may be separated from the reaction mixture by conventional techniques such as by filtration, washing and drying.

The polymer products of the process of the invention may be neutralized with the addition of a base, such as sodium bicarbonate, when desired and converted to the alkali salts thereof. The alkali salts of the

polymer products of the invention may be used for the same purposes as the parent acid polymers.

See e.g., U.S. Patent 4,413,106.

Sulfonation Procedure II:

Concentrated sulfuric acid is used as the solvent in this procedure. The content of the sulfonating agent, sulfur trioxide, is based on the total amount of pure (100% anhydrous) sulfuric acid present in the reaction mixture, and is kept to a value of less than 6% by weight throughout the entire sulfonation. The sulfur trioxide may be mixed in dissolved form (oleum, fuming sulfuric acid) with concentrated sulfuric acid. The concentration of the starting sulfuric acid and oleum were determined by measuring their density immediately before use in the reactions.

The temperature of the reaction mixture is kept at less than +30°C throughout the reaction. The sulfonation procedure is stopped with the addition of water to the reaction mixture or by pouring the reaction mixture into water.

More specifically, the polymer is first dried in high vacuum at room temperature to constant weight, then dissolved in concentrated sulfuric acid. Oleum is then added drop-wise over a period of hours with constant cooling below +30°C, and with stirring. When all of the oleum has been added, the reaction mixture is stirred for a further period of hours at the same temperature. The resultant viscous solution is then run into water and the precipitated polymer is filtered off. The polymer is then washed with water until the washings no longer are acidic, and it is then dried.

If these conditions are maintained, a controllable sulfonation of aromatic polyether sulfones is possible and polymer degradation can be substantially or completely prevented.

Though less preferred, another variation of this procedure is to add the sulfur trioxide either in pure solid state or in gaseous state to a solution of the polymer in concentrated sulfuric acid.

See e.g., U.S. Patent 5,013,765.

Sulfonation Procedure III:

This sulfonation procedure is directly analogous to procedure I, however, the polymer remains in solution at least until the addition of the sulfonating agent.

Polymer is first dissolved in a solvent that is compatible with the sulfonating agent (e.g. methylene chloride) in a nitrogen atmosphere. The sulfonating agent is added to this solution over the course of several hours. The resulting solution or suspension (if the polymer precipitates as the reaction occurs) is allowed to react, again for several hours.

When the desired degree of sulfonation has been reached, the sulfonated polymer may be separated from the reaction mixture by conventional techniques such as by filtration, washing and drying. If the sulfonated polymer remains in solution, the solvent can be removed simply by evaporation.

MEMBRANE PREPARATION

Microporous substrate films previously exchanged into the appropriate solvent are placed consecutively into solutions of the various ion-conducting polymers (ICP) with increasing concentration (in the same solvent as the unfilled microporous substrate). This technique is known in the art (see, e.g., U.S. Patent No. 5,501,831). Generally the use of smaller changes in ICP concentration seems to allow the formation of composite films with higher final ICP loadings. In the case of more viscous polymer solutions, the microporous substrates and the imbibing solution are heated (up to 100°C). Once imbibed with the ICP, the composite film is placed between the 6" diameter tension rings. As the rings are bolted together, the composite is carefully stretched to eliminate any veins or defects in the substrate. Once the rings are completely bolted together, the setup was left to air dry (e.g. in the hood) overnight. This will usually remove much of the excess ion-conducting polymer's solvent by evaporation.

The films are further dried by one of two methods. For low boiling solvents the composite films are heated under vacuum with pressure (about 100 psi) to prevent blistering of the films. In these instances porous, Teflon® coated shims are used to allow the solvent vapor to escape. Higher boiling composite films are simply heated under vacuum past the

atmospheric boiling point of the solvent. The overall uniformity of the final composite membrane can be improved by further pressing these composites at elevated temperature and pressure.

COMPOSITE MEMBRANE TESTING METHODS

IEC, % Water Content, Thickness:

During this procedure, films are immersed in distilled H_2O and boiled for a period of 30 minutes. The films are then placed in a solution of 1.5N H_2SO_4 at room temperature and soaked for a period of 30 minutes. This is repeated three separate times to ensure proper H+ ion exchange into the membrane. Films are rinsed free of acid (pH of rinse water > 5.0) and placed into separate beakers, each filled with a saturated solution of NaCl. The salt solution is boiled for a period of three hours. The films, which are now in the Na+ form, are removed from the salt solution, rinsed with distilled water and padded to remove excess water. Now a wet weight and thickness of the sample are measured. While in the Na+ form, the films are dried in an air oven at a temperature of 60°C. The dry weight and thickness of the films are measured and the percent water content is calculated. The salt solutions are titrated with 0.1N NaOH to a phenolphthalein endpoint and IEC dry (meq/g) values calculated.

Ionic Conductivity:

Transverse ionic conductivity measurements are performed on film samples in order to determine the specific resistance (ohm*cm^2). Prior to the ionic conductivity measurements, film samples are exchanged into the H+ form using the standard procedure discussed above. To measure the ionic conductivity, the film samples are placed in a die consisting of platinum-plated niobium plates. The sample size tested is 25cm^2. Prior to assembling in the measuring device, platinum black electrodes are placed on each side of the film sample to form a membrane-electrode assembly (MEA). To insure complete contact during the resistivity measurement, the MEA is compressed at 100 to 500 psi between two platinum-plated niobium/stainless steel rams. The resistance of each film is determined with a 1000 Hz, low current (1 to 5A) bridge, four point probe resistance measuring device and converted to conductivity by using formula 1.

(1) C = t/RxA)

Where: C =Conductivity (S/cm)

R =Sample Resistance (ohm)

t =Wet sample thickness (cm)

A = Sample area (cm2)

Measurements are converted to specific resistance by calculating the ratio of thickness over conductivity (ohm*cm2).

Membrane Degradation:

Accelerated degradation testing is carried out using 3% H_2O_2 solution with 4 ppm Fe++ added as an accelerator. The films are tested for a period of 8 hours at a temperature of 68°C. The percent degradation of IEC was measured in the film samples after the test. After 8 hours, the films are removed from solution, and re-exchanged using 1.5 N H_2SO_4. The IEC is recalculated, and the test result expressed as the % loss in IEC. This test simulates long term (several thousand hours) of actual fuel cell operation. For H_2O_2, fuel cells, <10% IEC degradation in this test would be considered acceptable.

Final Membrane Thickness / Imbibed Volume:

Once hot pressed, each composite is photographed (at the appropriate scale) on its edge side to determine if ICP has been infiltrated into the substrate. To get a good picture of the edge of the composite, the following procedure is used.

A small piece of the composite membrane is cut from the final film and mounted, edge on epoxy. Once mounted and cured, the membrane can be cut and polished to allow examination of the cross section by optical microscopy. Each composite membrane is compared to a "control" substrate which undergoes the same steps (without any ICP). This procedure allows a determination of two important properties: % dry loading of ICP & ICP (outer layer) thickness.

EXAMPLE I
Sulfonation of Radel R®
Using Sulfan B® (100% and 150% Sulfonation)

Sulfonation Procedure I was used in the following example.

Two separate 1000 ml 3 neck resin kettles (with ribs) equipped with an N_2 inlet, addition funnel, and overhead stirrer were charged with the following reactants: 340 ml of dichloromethane and 50.00 grams of Radel R® Polyethersulfone Polymer (beads). These mixtures were stirred until solutions formed (approximately .25 hours). Once solutions formed, they were cooled in ice baths to about a temperature of 0°C (ice bath was maintained throughout the duration of the addition and reaction). (Note that Radel R® was dried at 70°C under full dynamic vacuum for about 12 hours to remove any adsorbed moisture.)

While the above solutions were cooling, the following amounts of Sulfan B® were combined with dichloromethane in two separate 125 ml addition funnels. In funnel #1 (100% sulfonation) 10.00 grams of Sulfan B® was combined with 120 ml of dichloromethane. In funnel #2 (150% sulfonation) 15.00 grams of Sulfan B® was combined with 120 ml of dichloromethane.

As polymer solutions were cooled, the polymer precipitated from solution to form a viscous paste. To each of these polymers approximately 350 ml of dichloromethane was added to aid in the uniform mixing of the suspensions. The diluted suspensions were then cooled to ice bath temperatures once again.

To the rapidly stirring cooled and diluted polymer suspension, the Sulfan B® solutions were added drop-wise over a period of 3.5 to 4.0 hours.

Upon completing the addition of the Sulfan B® /dichloromethane solution, the reaction mixtures were permitted to stir at ice bath temperatures for another 2.5 hours, then the reaction was stopped by adding approximately 10 ml of deionized water to each of the reaction mixtures.

The reaction mixtures (white dispersions) were recovered by filtration using a glass frit. Products (white powder) were washed 3X with 100 ml portions of dichloromethane. The washed products were then permitted to

air dry in the hood. 20% solutions of the dried products were made in NMP and cast on soda lime glass plates. The freshly cast films were left to stand in a dry box with a relative humidity of less than 5% for a period of 24 hours. The cast films were heated at 70°C under full dynamic vacuum for an hour prior to floating the films off with deionized water. The floated films were then permitted to air dry overnight.

The 100% and 150% sulfonated products swell greatly in water and become opaque, but when films are dry they shrink and become clear once again. The mechanical strength of these films allows creasing while resisting tearing. Films of the 100% and 150% products are not soluble in boiling water, and under these conditions also maintain their mechanical properties.

IEC: 100% sulfonated Radel R® unpurified = 1.39 meq./g
150% sulfonated Radel R® unpurified = 1.58 meq./g

These polymers were further purified by dissolving in NMP (at 20wt.%) and then precipitated into a large excess of saturated salt water. The resulting polymers were soaked in sodium bicarbonate, washed several times with water, then dried under vacuum (~100 C). These polymers were also cast into films as described above for characterization.

IEC: 100% sulfonated Radel R® purified = 1.26 meq./g
150% sulfonated Radel R® purified = 1.44 meq./g

Water Pick-up (wt.%):
100% sulfonated Radel R® purified = 56%
150% sulfonated Radel R® purified = 110%

EXAMPLE 2
Sulfonation of BASF Ultrason® Polyether Sulfone Using Sulfan B®
(85%, 75%, and 65% Sulfonation)

Sulfonation Procedure III was used in the following example.

Three separate 1000 ml 3 neck resin kettle (with ribs) equipped with an N_2 inlet, addition funnel, and overhead stirrer were charged with the following reactants: the first resin kettle was charged with 350 ml of dichloromethane and 51.00 grams of BASF Ultrason polyether sulfone polymer (fine powder), the second was charged with double the amount of reactants, and the third was charged with the same ratios as the first. Ultrason was dried at 70°C under dynamic vacuum for about 12 hours prior to use. These mixtures were stirred until solutions formed (approximately 15 min.). Once solutions formed, they were cooled in ice baths to about a temperature of 0°C (ice bath was maintained throughout the duration of the addition and reaction).

While the above solutions were cooling, the following amounts of Sulfan B® were combined with dichloromethane in three separate 125 ml addition funnels. In funnel # 1 (85% sulfonation) 14.94 grams of Sulfan B® were combined with 120 ml of dichloromethane. In addition funnel #2 (75% sulfonation) 26.32 grams of Sulfan B® were combined with 120 ml of dichloromethane. In addition funnel # 3 (65% sulfonation) 11.80 grams of Sulfan B® were combined with 120 ml of dichloromethane. These solutions were then added dropwise to the corresponding rapidly stirring cooled polymer solutions over a period of 4 hours.

Addition of the Sulfan B® solution caused the polymer to precipitate and form a very viscous sludge. These were diluted with the following amounts of anhydrous dichloromethane. Reaction #1 was diluted with 70 ml of anhydrous dichloromethane, #2 was diluted with 600 ml of dichloromethane, and #3 was diluted with 400 ml of dichloromethane. Upon completing the addition of the Sulfan B® /dichloromethane solution, the reaction mixture was permitted to stir and warm to room temperature overnight. The following morning the reaction mixtures (a white dispersion) were filtered using a glass frit. Products (a fine white powder) were washed 3X with 100 ml. portions of dichloromethane. The washed products were then permitted to air dry in the hood for 4 hours.

20wt.% solutions of the dried products were made in NMP. The polymer solutions were filtered using a 2.5 micron glass fiber filter cartridge. The filtered products were then precipitated into approximately 4 liters of water. These products were then washed 2X with deionized water. The

washed products were converted into the sodium form by soaking in a 2.5% sodium hydroxide solution over several days. These were then washed with deionized water until a neutral pH was achieved. Finally, the samples were thoroughly dried in vacuum.

When 85% sulfonated polymer is boiled in water, it swells greatly and partially dissolves. The 75% and 65% sulfonated products do not dissolve in boiling water, however they show considerable swelling.

IEC: 65% sulfonated Ultrason purified = 0.69 meq./g
75% sulfonated Ultrason purified = 0.80 meq./g
85% sulfonated Ultrason purified = 1.08 meq./g

Water Pick-up (wt.%):
65% sulfonated Ultrason purified = 18%
75% sulfonated Ultrason purified = 21%

EXAMPLE 3
Synthesis of Sulfonated Udel® Polyether Sulfone Using Chlorosulfonic Acid (33-100% sulfonation)

Sulfonation Procedure III was used in the following example.

Procedure:

A 1000 ml. 3 neck round bottom flask equipped with a condenser, N_2 inlet, and overhead stirrer; was charged with 175 ml of dichloromethane and 50.0 grams of Udel® Polyethersulfone. This mixture was stirred until a solution formed (approximately 3 hours).

While the above was stirring 11.49 grams of chlorosulfonic acid was mixed with 50 ml. of dichloromethane in a 125 ml. addition funnel. This solution was added dropwise to the rapidly stirring polymer solution over a period of an hour. The reaction mixture changed from a clear amber color to a cloudy caramel color. Upon completing the addition the acid solution, the reaction mixture was permitted to stir at room temperature over night.

After stirring at room temperature for 28 hours the reaction mixture was heated in a water bath until a mild reflux was achieved, and it was kept refluxing under these conditions for an hour. After heating the reaction

mixture for an hour the heat source was removed and the mixture was permitted to cool.

After removal of the solvent, the product was dissolved in THF. Films cast from this solution were transparent and creasible. IR spectra and water absorption were consistent with the formation of sulfonated Udel® Polyethersulfone.

Complete reaction of the chlorosulfonic acid corresponds to the addition of 0.85 sulfonate groups per repeat unit of the polymer (85%). Similarly, sulfonated versions of Udel® Polyethersulfone were made with levels of sulfonation from 33 to 100%.

IEC: 75% sulfonated Udel = 1.10 meq./g
85% sulfonated Udel = 1.19 meq./g

Water Pick-up (wt.%):
75% sulfonated Udel = 12%
85% sulfonated Udel = 93%

EXAMPLE 4

Synthesis of Sulfonated-Polyimides (via Monomers)

Sulfonation procedures described by Sillion [French patent 9,605,707] were used as a guide in the following example. However, alternate monomers and reaction conditions were employed.

Sulfonated polyimides are produced by the reaction of a sulfonated diamine with a dianhydride, using a 1.000 molar ratio of diamine / dianhydride, in a solvent under an inert atmosphere. An exact diamine / dianhydride molar ratio of 1.000 is required in order to achieve high molecular weight polymers. Polyimides are synthesized through an intermediate polyamic acid form which contains an amide linkage and carboxylic acid groups. This polyamic acid may or may not be isolated from the reaction solution. The polyamic acid is converted to the corresponding polyimide by a cyclization reaction involving the amide hydrogen and neighboring carboxylic acid groups, forming a five (or six) membered imide ring, with the evolution of water as a reaction byproduct.

Polyimides can be made via two general procedures: 1) first synthesize, at or below ambient temperatures its solvent-soluble polyamic acid form, then chemically or thermally transform this polyamic acid to the polyimide; and 2) directly synthesize the solvent-soluble polyimide using reaction temperatures in excess of 100°C to distill water from the initial reaction solution. Each of these procedures was used at Foster-Miller to produce sulfonated-polyimides. The details of these reactions are presented below.

Formation of the Sodium Salt of 2,4-Diaminobezenesulfonic Acid (2,4-NaDBS).

2,4-Diaminobenzenesulfonic acid (2,-DBS) (5.00 grams, 26.6 mmoles) was dispersed in 95.29 grams anhydrous methanol at ambient temperatures under a positive nitrogen atmosphere in a reaction flask equipped with a reflux condenser, magnetic spinbar for stirring purposes and pressure equalizing funnel. A cloudy dispersion of sodium hydroxide (1.06 grams, 26.6 mmoles) in methanol (93.4 grams) at a concentration of 1.1 wt. percent was placed in the pressure equalizing funnel and added dropwise to the stirring 2,4-DBS/methanol dispersion at ambient temperatures. Additional methanol (195 grams) was added to transform the dispersion into a brownish orange colored solution after stirring overnight, containing approximately 1.3 wt. percent solids. Initially, 2,4-DBS was found to be insoluble at similar concentrations in methanol, indicating 2,4-DBS has been converted into a more soluble material. The solution was heated at reflux for several hours to ensure the reaction had gone to completion, cooled to ambient temperatures, and filtered to remove any trace amounts of undissolved material. Hexanes (275 mL) were then added to the solution to precipitate a tannish solid. This solid was collected by filtration, washed with hexanes and air dried. The material exhibited a single reproducible endothermic absorption between 246° to 252°C, with a peak width at half height of 5.3°C by differential scanning calorimetry. Its infrared spectrum (IR) showed absorptions typical for a $-NH_2$ amine (3426, 3380, and 3333 cm^{-1}), a primary amine (3199cm^{-1}), aromatic C-Hs (1624 cm^{-1}) and SO_3 salt (1230 and 1029 cm^{-1}) groups. These SO_3 salt absorptions were located at values different than those observed for $HOSO_2$ in 2,4-DBS, which appeared at 1302 and 1134 cm^{-1}. The amine absorption at 3426 cm^{-1} in this material

was also not present in 2,4-DBS. The IR absorption typical for a sulfonic acid (-SO_2-OH) group at 2609 cm^{-1} in 2,4-DBS was also absent. The combination of all this information indicates the tannish solid product is sodium 2,4-diaminobenzenesulfonate (2,4-NaDBS).

This material was be used as an alternative to 2,4-DBS in the synthesis of sulfonated polyimides due to its increased thermal stability and potentially increased reactivity toward polyimide formation (amine groups in the 2,4-NaDBS are more reactive toward the dianhydride monomer due to electron release from the sulfonate group).

Synthesis of the Copolyamic Acid Derived from 6FDA, m-Phenylenediamine (m-PDA) and 2,4-NaDBS (6FDA/m-PDA/2,4-NaDBS PAA).

2,4-DBS (7.75 mmoles) and m-PDA (7.75 mmoles) were easily dissolved in anhydrous dimethylsulfoxide (DMSO) at ambient temperatures under a nitrogen atmosphere. 6FDA (15.5 mmoles) was added all at once to the diamine solution and the mixture was stirred at ambient temperatures under a nitrogen atmosphere. The reaction mixture became warm to the touch as the 6FDA began to dissolve and the resulting, solution was stirred overnight at ambient temperatures. This clear reddish brown solution contained 15.0 wt. percent polymer and exhibited a viscosity similar to warm syrup, indicating polymers with reasonable molecular weights had been produced. The IR spectrum of the reaction solution showed absorptions typical for -NH of an amide (3249 and 3203 cm^{-1}), C=0 amide I stretch (1683 cm^{-1}), aromatic C-Hs (1607 cm^{-1}), N-C=0 amide II symmetric stretch (1548 cm^{-1}) and SO_3 salt (1256 and 1020 cm^{-1}). The IR absorption for -OH of $HOSO_2$ at 2609 cm^{-1} was absent from the spectrum. This IR data is consistent with the formation of the 6FDA/m-PDA/2,4-NaDBS copolyamic acid.

A sample of the polyamic acid solution was cast into a film on a NaCl salt IR disc and the film/disc was heated in a circulating air oven for 1 hour each at 100°, 200° and 300°C to convert the copolyamic acid to its copolyimide form. The IR spectrum of copolyimide film showed absorptions typical for C=0 imide stretch (1787 and 1733 cm-l), aromatic C-H (1603 cm^{-1}), C-N imide stretch (1362 cm^{-1}), $HOSO_2$ acid (1298 and 1145 cm^{-1}), SO_3 salt (1256 and 1029 cm^{-1}) and polyimide (745 and 721 cm^{-1}). IR absorptions

typical for polyamic acids at 1683 and 1545 cm^{-1} as well as the -OH of $HOSO_2$ at 2609 cm^{-1} were absent. Nevertheless, it appears that some of the $NaSO_3$ groups were converted to $HOSO_2$ by free acid generated during the continuing polymerization.

Thermal Imdization of 6FDA/m-PDA/2,4-NaDBS PAA.

A sample of the reaction solution was cast into a large film with an initial thickness of 0.007 inch on a glass substrate using a motorized film casting table located inside a low humidity chamber (<10 percent relative humidity). The resulting clear copolyamic acid film was heated in a circulating air oven for 1 hour each at 100°, 200°, and 250°C to form a reddish brown copolyimide film. A final temperature of 250° rather than 300°C was used to hopefully reduce the conversion of $NaSO_3$ groups to $HOSO_2$ and thermal degradation of the resulting $HOSO_2$, believed to occur at temperatures >200°C. The copolyimide film broke into many very small pieces upon removal from the glass substrate, a sign that the molecular weight of the copolyimide may be quite low.

Synthesis of the Copolyimide Directly from 6FDA, m-PDA, and 2,4-NaDBS (6FDAlm PDA12,4-NaDBS PI) A brownish dispersion of 2,4-NaDBS (7.47 mmoles) and m-PDA (8.01 mmoles) in m-cresol (50 grams) and anhydrous toluene (20 grams) in a 3-necked flask equipped with a thermometer, mechanical stirrer, and Dean Stark trap fitted with a condenser/nitrogen inlet was heated at about 150°C under a nitrogen atmosphere. 6FDA (15.49 mmoles) was added to the hot dispersion, whereupon water immediately began to distill out of the reaction dispersion and become collected in the trap. The temperature of the brownish dispersion was gradually increased to about 200°C, maintained at 200°C for 7.5 hours, and then decreased to ambient temperatures. The resulting dark brown colored, viscous reaction mixture was found to be a dispersion containing significant quantities of crystalline material(s). The IR spectrum of the reaction dispersion showed absorptions typical for or C=0 imide stretch (1781 and 1723 cm^{-1}), C-N imide stretch (1365 cm^{-1}), SO_3 salt (1251 and 1033 cm^{-1}), and polyimide (738 and 720 cm^{-1}). The presence of m-cresol in the film prevents determination of whether $HOSO_2$ groups are present due to overlapping absorptions. IR absorptions typical for polyamic acids at

1683 and 1548 cm^{-1} as well as the OH stretch of $HOSO_2$ were absent. IR data indicated some sodium sulfonate-copolyimide had been produced under the reaction conditions, but the presence of a crystalline dispersion rather than solution suggests a significant amount of the diamine was not incorporated into a polymer.

The consistent problem encountered during these reactions was low molecular weight of the final product. The above syntheses did not provide a creasable, sulfonated polymer film. However, fragments of the polymer are unchanged by the peroxide test and have IECs up to 1.13 meq./g.

It is anticipated that higher molecular weight polymer will be obtained by further purifying the 2,4-NaDBS monomer prior to polymerization. In addition, the use of isoquinoline as a polymerization catalyst may accelerate the reaction.

EXAMPLE 5
Sulfonation of Victrex ® Poly(Ether Ketone) Using H_2SO_4 / SO_3

Sulfonation Procedure II was used in the following example.

Procedure:

30.00 g PEK polymer was dissolved in 270g of concentrated sulfuric acid (93.5wt.%) under nitrogen, stirred by an overhead mechanical stirrer. The polymer was dispersed over several days to form a dark red thick solution.

176g of this solution was left in the three neck flask with overhead stirrer, N_2, etc. To the flask, 208.4g of fuming sulfuric acid (25.5wt. % free SO_3) was added over the coarse of a few minutes with constant stirring to raise the solution to a free SO_3 content of 2wt. %. The resulting solution was immersed in a room temperature water bath to control the temperature.

Samples were removed after approx. 1 hour, 3 hours, and 16 hours, and quenched into deionized water to precipitate.

In order to make films, the 1 and 3 hour products were washed several times with deionized water, soaked overnight in approximately 0.5M NaOH solution, then washed until a neutral pH was achieved. These were blotted dry and placed in the vacuum oven overnight at 50°C. Dried

samples were dissolved in NMP to make a 20wt. % solution. This required heating overnight at 60°C. Films of approx. 6 mils were cast onto a freshly cleaned glass plate. After two days of drying the films were removed by immersion into deionized water.

Soaking the films in water (at room temperature) caused considerable swelling to give a hazy gel-like consistency, but did not dissolve. Films cast from the 1 hour and 3 hour samples did not dissolve in water. Film of the 1 hour product could be hydrated and dehydrated, while maintaining resistance to tearing. The 1 hour sulfonated PEK film IEC was measured to be 2.3meq/g.

EXAMPLE 6
Sulfonation of PPS/SO_2 Using 97.5 % H_2SO_4

Sulfonation Procedure II was used in the following example.

PPS/SO_2 provided by James McGrath of VPI [see Synthesis and Characterization of Poly(Phenylene sulfide – sulfone). *Polymer Preprints* 38 (1), 1997, p.109-112].

Procedure:

250 ml 3 neck round bottom flask was equipped with an overhead stirrer, N_2 inlet, and addition funnel were charged with 100 grams of 93.5% sulfuric acid. To the rapidly stirring sulfuric acid 25.00 grams of the PPS/SO_2 was added. The mixture was stirred at room temperature until a solution formed (approximately 1 hour).

When solution had formed the temperature was lowered to about 0°C, and 60.0 grams of 23.0% fuming sulfuric acid was added dropwise over a period of a 0.5 hours.

Ice bath temperatures were maintained for the first 3.5 hours of the reaction. Aliquots were taken at T=0.5, 1.5, 2.0, and 3.0 hours by precipitation the reaction mixtures were precipitated into deionized water. Precipitated product appeared not to have swollen to any appreciable extent, so the remaining reaction mixture was warmed to room temperature.

Aliquots were taken at t=3:30, 4:30, 7:00, and 8:20 (approximately 4 hours at room temperature).

Products were rinsed 3 times with deionized water, soaked in saturated sodium bicarbonate solution until basic and then washed in deionized water until neutral.

Solubilizing of the sulfonated PPS/SO_2 polymers was attempted after drying the precipitated polymer at 100°C for 3 hours under full dynamic vacuum. The polymer solutions were made with fresh anhydrous NMP and were immediately cast on soda lime glass plates at a thickness of 2 mils. The freshly cast films were placed in a level oven preheated to 100°C and dried under full dynamic vacuum for 1 hour. After drying (at 100°C) for an hour, the oven temperature was raised gradually to 200°C over a period of 3 hours. When the 200°C was achieved, the oven was shut off and the films were permitted to gradually cool to room temperature. Films were removed from the glass plates by floating them in deionized water.

Based on crude observations of the PPS/SO_2 films, this material appears not to have sulfonated to any appreciable extent while kept at 0°C (little dimensional changes were observed on boiling in water). The PPS/SO_2 samples that were reacted at room temperature appear to show some signs of sulfonation (swelling and taking on a rubbery appearance in boiling water).

IEC sulfonated PPS/SO_2:

T=8:20, 0.53 meq./g

Water Pick-up (wt.%) sulfonated PPS/SO_2:

T=8:20, 15%

IEC's of the sulfonated PPS/SO_2 samples were appreciable but further sulfonation should be possible with increased reaction times.

EXAMPLE 7
Sulfonation of Poly(phenylquinoxaline) Film

This procedure has been used for the sulfonation of PBI and PPQ films. See e.g., U.S. Patent No. 4,634,530 and in Linkous, et al., J. Polym. Sci., Vol. 86: 1197-1199 (1998).

The film is soaked in a 50% solution of H_2SO_4 for approx. 2 hour in order to fully sulfate it; then baked at a minimum temperature of 300°C to convert the ammonium sulfate salt to the covalently bonded sulfonic acid.

EXAMPLE 8
Fabrication of SPEM
Using PBO and sulfonated Radel R®

Ion-conducting membranes were fabricated from the polymer substrate film PBO and various sulfonated poly(ether sulfones). The substrate utilized was PBO film extruded and solvent exchanged into NMP as described above in the general procedure. The ion-conducting polymer (100, 150% sulfonated Radel R® - Na+ form) was synthesized according to example 1 given above.

Microporous PBO, having been exchanged into NMP without collapse of the pores, was added to a 5wt.% solution of the sulfonated Radel R® polymers in NMP. After twelve or more hours, the films were removed and placed in a 20wt.% solution of the same ion-conducting polymer (also in NMP). After twelve or more hours at room temperature (or at 75°C) the films were removed, stretched in tensioning rings, and dried of the solvent (see general procedure outlined above). Specifically, the sulfonated Radel R® / PBO films were dried in a low humidity chamber (<5% RH) for 1 to 2 days, vacuum dried in an oven heated from below 60°C to about 200°C.

After all solvent is fully extracted from the membrane, the composite is preferably hot pressed. The hot pressing operation facilitates flow of the ion-conductor to make a homogenous composite structure. Non-porous Teflon® shims were placed on each side of the composite membrane followed by Titanium shims. The entire setup is then loaded into a press and subjected to the following cycle:

High Temperature Hot Press

Step	Temp.	Hold Time	Force	Ramp Rate
1	392°F	5 min	1.0 klb	15 F/min
2	392°F	15 min	28.3 klb	N/A
3	392°F	5 min	28.3 klb	25 F/min

Note that the 28.3 klbf corresponds to a press pressure of 1000 psi.

SPEMs produced via this example were FMI 126-17P, FMI 126-17Q, FMI 126-17T, FMI 126-17U. See Table 8 for various results obtained from SPEMs made via this procedure.

EXAMPLE 9
Fabrication of SPEM
Using PBO and sulfonated Udel ®

Ion-conducting membranes fabricated in this example followed closely those in example 8.

The substrate utilized was PBO film extruded and solvent exchanged into THF as described above in the general procedure. The ion-conducting polymer (75, 85,100% sulfonated Udel) was synthesized according to example 3 given above.

For composite SPEMs of 100% sulfonated Udel ion-conducting polymer, microporous PBO films exchanged into THF were placed into 30wt.% solutions of the polymer (in THF) at room temperature. After more than twelve hours, the films were stretched in tensioning rings and allowed to dry in a low humidity chamber. Final traces of the solvent were removed with the following vacuum pressing shown below.

Low Temperature Vacuum Pressing

Step	Temp.	Hold Time	Force	Ramp Rate
1	122°F	20 min	2.9 klb	15 F/min
2	167°F	20 min	2.9 klb	15 F/min
3	212°F	20 min	2.9 klb	15 F/min
4	257°F	20 min	2.9 klb	15 F/min
5	85°F	5 min	2.9 klb	25 F/min

The force of 2.9 klb corresponds to a press pressure of 100 psi. Films were finally hot pressed without vacuum to fully consolidate the composite structure, as shown below.

High Temperature Hot Press

Step	Temp.	Hold Time	Force	Ramp Rate
1	317° F	30 min	28.3 klb	15 F/min
2	85°F	-----	28.3 klb	25 F/min

The force of 28.3 klb corresponds to a press pressure of 1000 psi.

Composite SPEMs were made with both 75 and 85% sulfonated Udel ion-conducting polymers.

SPEMs produced via this example were FMI 539-22-1, FMI 539-22-2, FMI 539-22-3. See Table 8 for various results obtained from SPEMs made via this procedure.

EXAMPLE 10
Fabrication of SPEM
Using Solubilized Nafion® 1100 EW

Ion-conducting membranes fabricated in this example followed closely those in example 8.

The substrate utilized was PBO extruded film and solvent exchanged into a mixture of water and alcohols (see below) as described above in the general procedure. The ion-conducting polymer used was solubilized Nafion® 1100 EW purchased from Solution Technologies (10wt.% in a mixture of water and propanols). The solvent system used to exchange the PBO films was made to approximate that of the Nafion® solution.

Composite membranes were made by placing the exchanged films directly into the 10wt.% Nafion® solutions. After twelve or more hours, these were removed and stretched into tensioning rings as described above. These films were dried in a low humidity chamber for at least 24 hours. Removal of the final traces of solvent were done by placing porous PTFE shims on each side of the composite membrane followed by the Titanium shims. This setup was then loaded into a vacuum press and subjected to the following cycle:

Low Temperature Vacuum Pressing

Step	Temp.	Hold Time	Force	Ramp Rate
1	125°F	20 min	2.9 klb	15 F/min
2	170°F	20 min	2.9 klb	15 F/min
3	215°F	20 min	2.9 klb	15 F/min
4	274°F	20 min	2.9 klb	15 F/min
5	85°F	5 min	2.9 klb	25 F/min

The force of 2.9 klb corresponds to a press pressure of 100 psi. Films were finally hot pressed without vacuum to fully consolidate the composite structure, as shown below.

High Temperature Hot Press

Step	Temp.	Hold Time	Force	Ramp Rate
1	275°F	5 min	1.0 klb	15 F/min
2	275°F	15 min	28.3 klb	N/A
3	85°F	5 min	28.3 klb	25 F/min

The force of 28.3 klb corresponds to a press pressure of 1000 psi.

SPEMs produced via this example were FMI 126-16N, FMI 126-16O. See Table 8 for various results obtained from these SPEMs. The low IECs obtained from these films and the correspondingly high resistances are a function of the low loading of ion-conductor in the composite structure. It is anticipated that using more concentrated solutions of the ion-conductor in imbibing the substrate will lead to composite SPEMs of low enough resistances for the applications described. The stability of the lateral dimensions of these Nafion® based composite membranes presents a significant improvement over unsupported Nafion® 117 films (which show in plane dimensional changes on hydration of about 20%). Given the exceptional strength of the PBO substrate, the mechanical properties of the composites will be well in excess of current state of the art fuel cell membranes.

EXAMPLE 11
Fabrication of SPEM
Using PBO and sulfonated Ultrason®

Ion-conducting membranes fabricated in this example followed closely those in example 8. The substrate utilized was PBO film extruded and solvent exchanged into NMP as described above in the general procedure. The ion-conducting polymer (75% sulfonated Ultrason purified - Na+ form) was synthesized according to example 2 given above.

Microporous PBO, having been exchanged into NMP without collapse of the pores, was added to a solution of the sulfonated 75% sulfonated Ultrason polymer in NMP (8 or 12 wt.%). After twelve or more hours at room temperature the films were removed, stretched in tensioning rings, and dried of the solvent (see general procedure outlined above). Specifically, the sulfonated Radel R® / PBO films were dried in a low humidity chamber (<5% RH) for 1 to 2 days, vacuum dried in an oven heated from below 60°C to 140°C.

Low Temperature Vacuum Pressing

Step	Temp.	Hold Time	Force	Ramp Rate
1	125°F	20 min	2.9 klb	15 F/min
2	200°F	20 min	2.9 klb	15 F/min
3	275°F	20 min	2.9 klb	15 F/min
4	390°F	20 min	2.9 klb	15 F/min
5	85°F	------	2.9 klb	25 F/min

The force of 2.9 klb corresponds to a press pressure of 100 psi. Films were finally hot pressed without vacuum to fully consolidate the composite structure, as shown below.

After all solvent is fully extracted from the membrane, the composite is preferably hot pressed. The hot pressing operation facilitates flow of the ion-conductor to make a homogenous composite structure. Non-porous Teflon® shims were placed on each side of the composite membrane followed by Titanium shims. The entire setup is then loaded into a press and subjected to the following cycle:

High Temperature Hot Press

Step	Temp.	Hold Time	Force	Ramp Rate
1	390°F	15 min	28.3 klb	15 F/min
2	85°F	5 min	28.3 klb	25 F/min

Note that the 28.3 klbf corresponds to a press pressure of 1000 psi.

5

SPEMs produced via this example were FMI 126-08E, FMI 126-08F. See Table 8 for various results obtained from SPEMs made via this procedure.

CLAIMS

1. A composite solid polymer electrolyte membrane (SPEM) comprising a porous polymer substrate interpenetrated with an ion-conducting material, wherein

(i) the porous polymer substrate comprises a homopolymer or copolymer of a liquid crystalline polymer or a solvent soluble thermoset or thermoplastic aromatic polymer, wherein

said liquid crystalline polymer comprises a lyotropic liquid crystalline polymer, said lyotropic liquid crystalline polymer comprising at least one of a polybenzazole (PBZ) and polyaramid (PAR) polymer,

said polybenzazole polymer comprising a homopolymer or copolymer of at least one of a polybenzoxazole (PBO) and polybenzothiazole (PBT) polymer, and said polyaramid polymer comprising a homopolymer or copolymer of a polyparaphenylene terephthalamide (PPTA) polymer;

said thermoset or thermoplastic aromatic polymer comprises at least one of a polyphenylene sulfoxide (PPSO), polyphenylene sulfide (PPS), polyphenylene sulfide sulfone (PPS/SO_2), polyphenylquinoxaline (PPQ) and polyarylketone (PK) polymer, and

(ii) the ion-conducting material comprises a homopolymer or copolymer of at least one of a sulfonated, phosphonated or carboxylated ion-conducting aromatic polymer or a perfluorinated ionomer.

2. The SPEM of claim 1, wherein the porous polymer substrate comprises a microinfrastructure interpenetrated with the ion-conducting material.

3. The SPEM of claim 1, wherein the porous polymer substrate comprises an extruded or cast film.

4. The SPEM of claim 1, wherein the pore size of the porous polymer substrate is from 10 Å to 2000 Å.

5. The SPEM of claim 4, wherein the pore size is from 500 Å TO 1500 Å.

6. The SPEM of claim 4, wherein the pore size is from 500 Å TO 1000 Å.

7 The SPEM of claim 1, wherein the ion-conducting material has an ion-conductivity from 0.01 S/cm to 0.5 S/cm.

8. The SPEM of claim 7, wherein the ion-conducting material has an ion-conductivity greater than 0.1 S/cm.

9. The SPEM of claim 1, wherein the ion conducting aromatic polymer comprises wholly aromatic ion-conducting polymer.

10. The SPEM of claim 1, wherein the ion-conducting aromatic polymer comprises a sulfonated, phosphonated or carboxylated polyimide polymer.

11. The SPEM of claim 10, wherein said sulfonated, phosphonated or carboxylated polyimide polymer is fluorinated.

12. The SPEM of claim 9 or claim 10, wherein the wholly-aromatic ion-conducting polymer comprises a sulfonated derivative of at least one of a polysulfone (PSU), polyphenylene oxide (PPO), polyphenylene sulfoxide (PPSO), polyphenylene sulfide (PPS), polyphenylene sulfide sulfone (PPS/SO_2), polyparaphenylene (PPP), polyphenylquinoxaline (PPQ), polyarylketone (PK), polyetherketone (PEK), polybenzazole (PBZ) and polyaramid (PAR) polymer.

13. The SPEM of claim 12, wherein

(i) the polysulfone polymer comprises at least one of a polyethersulfone (PES), polyetherethersulfone (PEES), polyarylsulfone, polyarylethersulfone (PAS), polyphenylsulfone (PPSU) and polyphenylenesulfone ($PPSO_2$) polymer,

(ii) the polybenzazole (PPZ) polymer comprises a polybenzoxaxole (PBO) polymer,

(iii) the polyetherketone (PEK) polymer comprises at least one of a polyetheretherketone (PEEK), polyetherketone-ketone (PEKK),

polyetheretherketone-ketone (PEEKK) and polyetherketoneetherketone-ketone (PEKEKK) polymer and

(iv) the polyphenylene oxide (PPO) comprises a 2,6-diphenyl PPO polymer.

14. The SPEM of claim 1, wherein the perfluorinated ionomer comprises a homopolymer or copolymer of a perfluorinated vinyl ether.

15. The SPEM of claim 14, wherein the perfluorinated vinyl ether is carboxyl- (COOH), phosphonyl- ($PO(OH)_2$) or sulfonyl- (SO_3H) substituted.

16. The SPEM of claim 1, wherein the ion-conducting material comprises at least one of a polystyrene sulfonic acid (PSSA), poly(trifluorostyrene) sulfonic acid, trifluorostyrene, polyvinyl phosphonic acid (PVPA), polyvinyl carboxylic acid (PVCA) and polyvinyl sulfonic acid (PVSA) polymer.

17. The SPEM of claim 1, wherein the porous polymer substrate comprises a homopolymer or copolymer of at least one of a substituted or unsubstituted polybenzazole polymer, and wherein the ion-conducting material comprises a sulfonated derivative of a homopolymer or copolymer of at least one of a polysulfone (PSU), polyphenylene sulfoxide (PPSO) and polyphenylene sulfide sulfone (PPS/SO_2) polymer.

18. The SPEM of claim 17, wherein the polysulfone polymer comprises at least one of a polyethersulfone (PES) and polyphenylsulfone (PPSU) polymer.

19. The SPEM of claim 1, wherein the SPEM has a thickness from about 0.1 mil. to about 2.0 mil.

20. The SPEM of claim 19, wherein the thickness is less than about 0.5 mil.

21. A method of producing a composite solid polymer electrolyte membrane (SPEM) in accordance with claim 1, comprising the steps of preparing a mixture

of said polymer substrate and said ion-conducting material and casting or extruding the composite membrane from the mixture.

22. The method of claim 21, wherein the mixture of the polymer substrate and the ion-conducting material is prepared in a common solvent.

23. A method of producing a composite solid polymer electrolyte membrane (SPEM) in accordance with claim 1, comprising the steps of solubilizing the ion-conducting polymer and imbibing the porous polymer substrate with the ion-conducting polymer.

24. A method of producing a composite solid polymer electrolyte membrane (SPEM) in accordance with claim 1, comprising the steps of preparing the substrate polymer, performing a sulfonation reaction within the pores of the polymer substrate by imbibing a sulfonating agent into the pores of the polymer substrate.

25. A device for use in electrochemical applications comprising the composite solid polymer electrolyte membrane in accordance with claim 1.

SUBSTITUTE SHEET (RULE 26)

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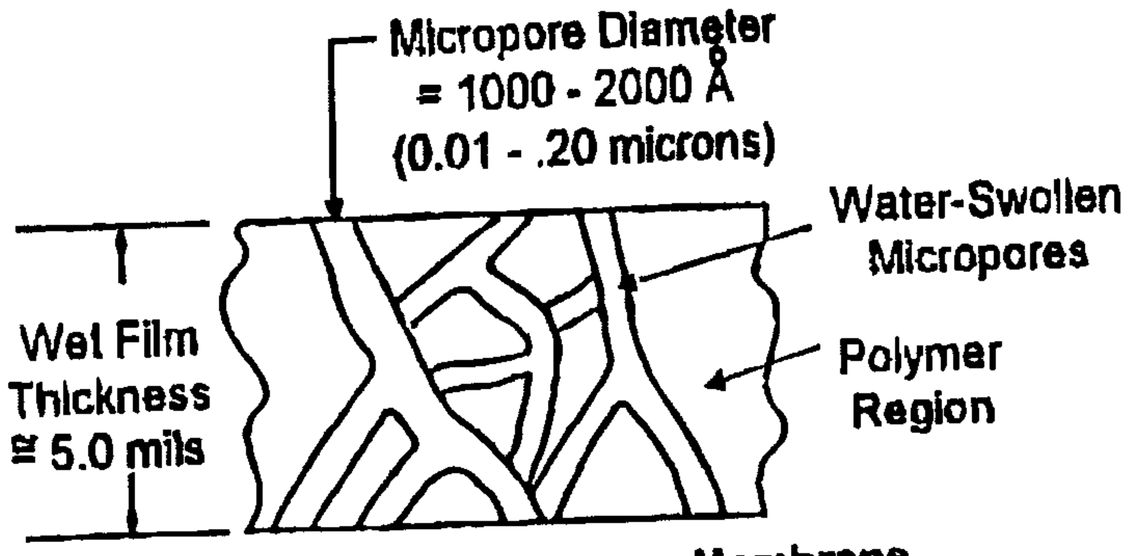
The Gas Permeability and Ionic Conductivity Properties of the Microcomposite Membrane will be Adjusted by Controlling the Concentration of Infiltrated Ion-Conducting Polymer and its Degree of Sulfonation



A. Water-Swollen Microporous Membrane

1. Solvent-Exchange
2. Ion-Conductor Infiltration
3. Drying, Heat-Treatment

Micropore Diameter
≈ 1 - 5 Å (10^{-4} microns)

1. Drying
2. Heat-Treatment
3. Film Shrinkage through the Thickness

Membrane Dry Thickness
≅ 0.5 mil at 0% Ion-Conductor

B. Dried, Heat-Treated, Substrate Membrane

Micropore Diameter and Dry Film Thickness will Decrease with Decreasing Infiltrant Concentration

Ion-Conducting Polymer Regions Interpenetrating Polymer Regions

Micropore Diameter
≈ ~50 - 1000 Å
(0.05 - 0.5 microns)

Dry Film Thickness
≈ ~2.5 mils at 10% Ion-Conducting Polymer Solution Concentration

Substrate Polymer Regions

C. Dried, Heat-Treated Microcomposite Membrane Containing ~ 50 Volume Percent Ion-Conducting Polymer

FIG. 1

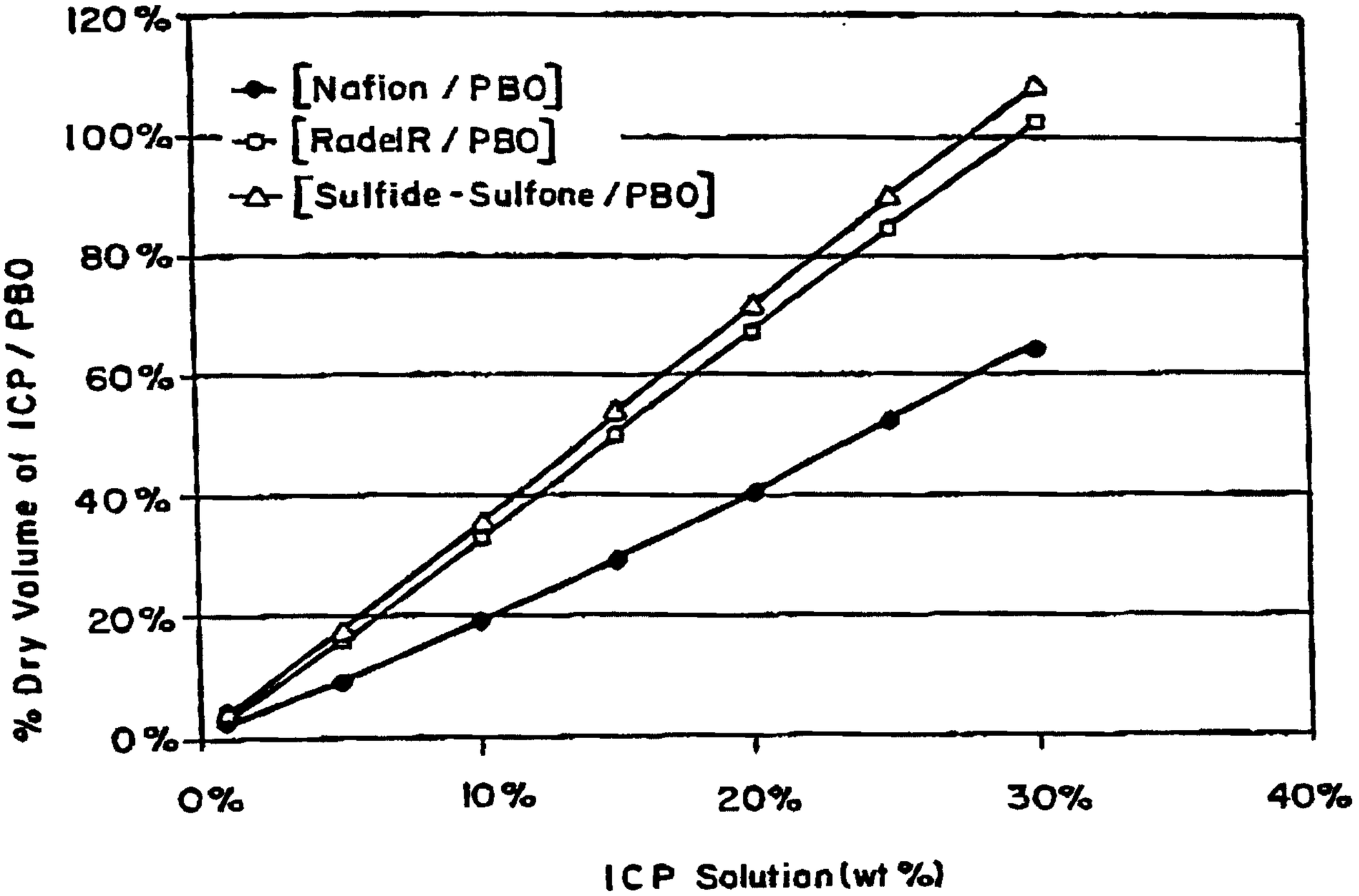

% Dry Loading of ICP/PBO vs. Initial ICP Solution wt%
120 %
100%
80 %
60%
40 %
20%
0 %
% Dry Volume of ICP / PBO
[Nafion / PBO]
[RadelR / PBO]
[Sulfide - Sulfone / PBO]
0%
10%
20%
30%
40%
ICP Solution (wt %)

FIG. 2