

Review

Review and analysis of PEM fuel cell design and manufacturing

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Abstract

Design and manufacturing alternatives for Proton Exchange Membrane (PEM) fuel cells are described and analysed within the context of vehicle applications. Specifically, following a review of many alternatives, 16 polymer electrolyte membranes, 2 types of gas diffusion layers (GDL), 8 types of anode catalysts, 4 types of cathode catalysts and over 100 bipolar plate designs are recommended for further study. This work not only reviews membrane electrode assembly manufacturing options and synthesis processes for many of the membranes and for the gas diffusion layers, but also adds to the bipolar plate fabrication options described in literature. This work is intended to facilitate material and process selection through the consideration of the variety of design and manufacturing alternatives prior to capital investment for wide-scale production.

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1. Introduction

On 9 January 2002, the US Secretary of Energy Spencer Abraham and executives of Ford Motor Company, General Motor Corporation, and DaimlerChrysler announced a new cooperative automotive research partnership between the US Department of Energy and the US Council for Automotive Research (USCAR) called *FreedomCAR*. The partnership, which replaces the partnership for a New Generation of Vehicles program, focuses on the development of fuel cell vehicle technologies. Fuel cell vehicle technologies are those that enable mass production of affordable hydrogen-powered fuel cell vehicles and the hydrogen-supply infrastructure to support them. Among the vehicle technology options, proton exchange membrane (PEM) fuel cells, also referred to as solid polymer fuel cells, are favored for use in automobiles ([1,2], and many others). This preference is due to the high power density, relatively quick start-up, rapid response to varying loads, and low operating temperatures provided by PEM fuel cells.

Fig. 1 depicts the key components of PEM fuel cells in which the oxidative and reductive half reactions are kept separate (i.e. in which the bipolar plates to be impervious to the reactants). As shown, a single PEM cell is comprised of three types of components: a membrane–electrode assembly (MEA), two bipolar (a.k.a. flow field or separator) plates,

and two seals. In its simplest form, the MEA consists of a membrane, two dispersed catalyst layers, and two gas diffusion layers (GDL). The membrane separates the half reactions allowing protons to pass through to complete the overall reaction. The electron created on the anode side is forced to flow through an external circuit thereby creating current. The GDL allows direct and uniform access of the fuel and oxidant to the catalyst layer, which stimulates each half reaction. In a fuel cell stack, each bipolar plate supports two adjacent cells. The bipolar plates typically have four functions: (1) to distribute the fuel and oxidant within the cell, (2) to facilitate water management within the cell, (3) to separate the individual cells in the stack, and (4) to carry current away from the cell. In the absence of dedicated cooling plates, the bipolar plates also facilitate heat management. Individual cells are combined into a fuel cell stack of the desired power. End plates and other hardware (bolts, springs, intake/exhaust pipes and fittings, etc. not shown in Fig. 1) are needed to complete the stack.

Previous works summarizing PEM fuel cell design alternatives are provided by Larminie and Dicks [3], EG&G Services [2], and Gottesfeld and Zawodzinski [1]. Specifically, Larminie and Dicks and EG&G Services provide textbooks on emerging fuel cell technologies. Their discussions of PEM fuel cell design include very general descriptions of materials use and configurations, the advantages and disadvantages of each design, stack performance relationships related to thermodynamics, water management, operating temperatures and pressures, and fuel and oxidant

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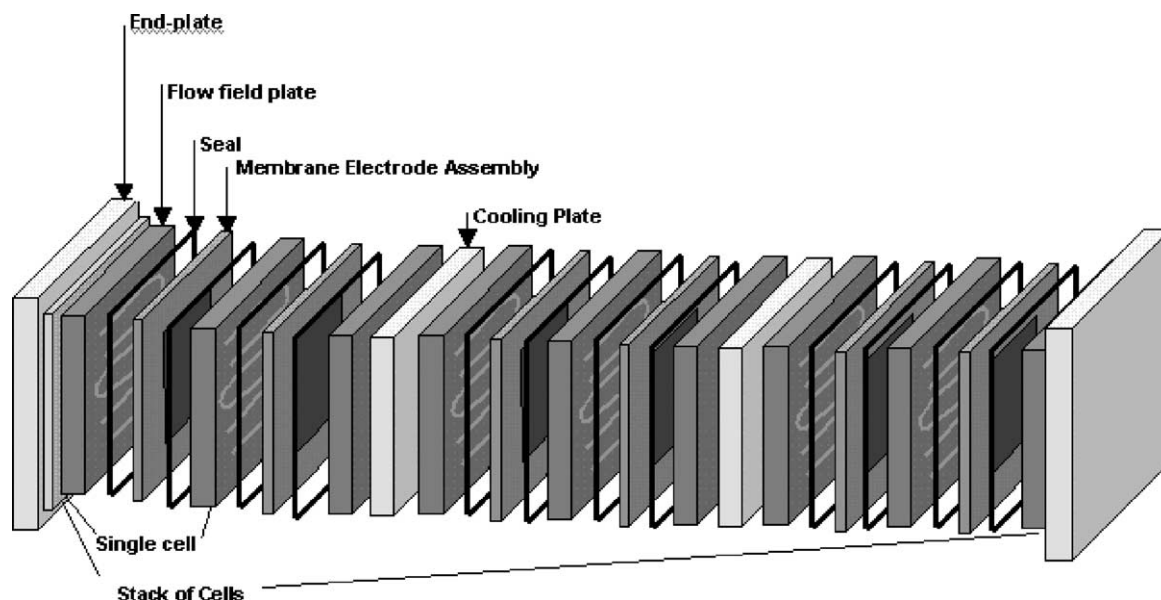


Fig. 1. PEM fuel cell stack hardware.

composition, and potential applications issues. Gottesfeld and Zawodzinski [1] provide a more research-oriented, electrochemistry-based discussion of fuel cell design when compared to these textbooks.

More specific discussions of materials and topologies for design alternatives can be found for specific components, typically accompanying related research or an analysis of that component. In particular, summaries of membrane materials have been published by Glipa and Hogarth from Johnson Matthey Technology Center, UK [4] and Rikukawa and Sanui from Sophia University, Japan [5]. Also, analysis of some bipolar plate materials is presented by Borup and Vanderborgh [6].

Similarly, PEM fuel cell manufacturing information can be found for specific components, especially for novel designs. Unlike PEM fuel cell design, current literature does not include summaries of manufacturing alternatives. Also, little analysis of fabrication options for more typical designs is available.

This paper, based on [7], reviews and extends existing PEM fuel cell design and manufacturing literature within the context of vehicle propulsion. We provide a comprehensive review of design and manufacturing alternatives described in literature for MEAs and bipolar plates. We also critique and broaden this set of alternatives based on a functional analysis of design, the application of process selection techniques with respect to component design features, and analyses of process inputs and outputs.

2. Review and analysis of membrane electrode assembly design and manufacturing

Figs. 2 and 3 provide classifications of MEA material and manufacturing alternatives, described as follows.

2.1. MEA design

Again, an MEA consists of a membrane, a dispersed catalyst layer, and a GDL. The membrane separates the reduction and oxidation half reactions. It allows the protons to pass through to complete the overall reaction while forcing the electrons to pass through an external circuit. The catalyst layer stimulates each half reaction. The GDL further improves the efficiency of the system by allowing direct and uniform access of the fuel and oxidant to the catalyst layer. Design and manufacturing alternatives for each of these three components are reviewed and analyzed as follows.

2.1.1. Membrane design

Gottesfeld and Zawodzinski [1] suggest that perfluoro-sulfonic acid (PFSA) is the most commonly used membrane material for PEM fuel cells. PFSA consists of three regions: (1) a polytetrafluoroethylene (PTFE, a.k.a. DuPont's TeflonTM)-like backbone, (2) side chains of $-O-CF_2-CF_2-O-CF_2-CF_2-$ which connect the molecular backbone to the third region, and (3) ion clusters consisting of sulfonic acid ions [8]. When the membrane becomes hydrated, the hydrogen ions in the third region become mobile by bonding to the water molecules and moving between sulfonic acid sites.

There are two advantages to the use of PFSA membranes in PEM fuel cells. First, because the structure is based on PTFE backbone, PFSA membranes are relatively strong and stable in both oxidative and reductive environments. In fact, durability of 60,000 h has been reported [4]. Second, the protonic conductivities achieved in a well-humidified PFSA membrane can be as high as 0.2 S/cm at PEM fuel cell operating temperatures. This translates to a cell resistance as low as $0.05 \Omega \text{ cm}^2$ for a $100 \mu\text{m}$ thick membrane with voltage loss of only 50 mV at 1 A/cm^2 [1].

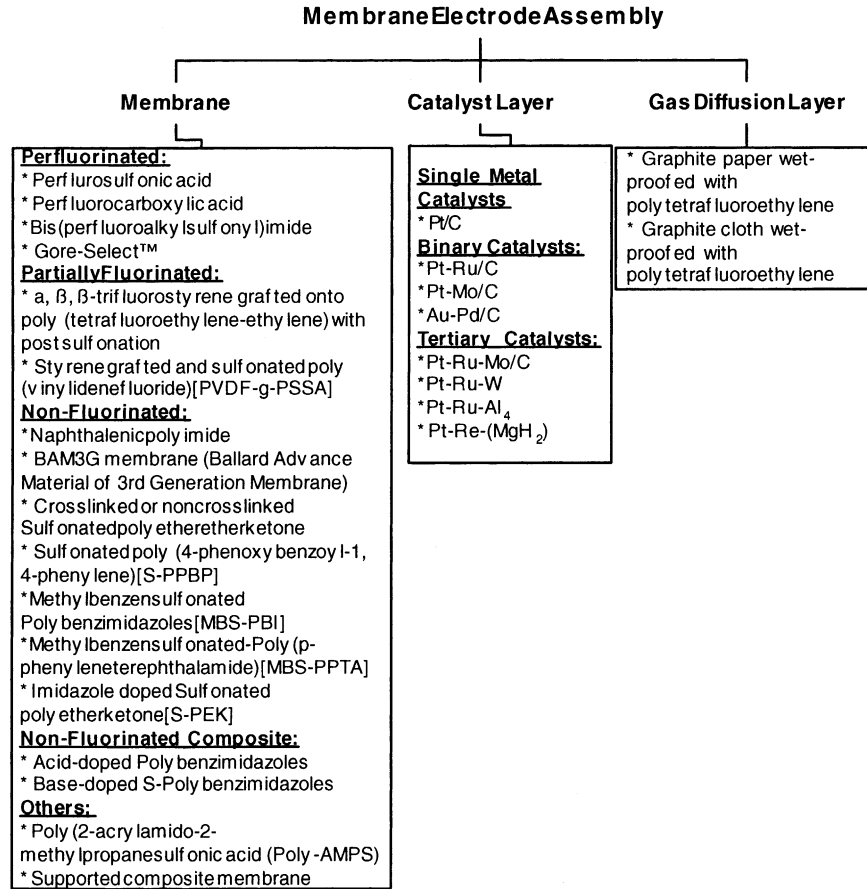


Fig. 2. Classification of MEA materials.

Given these advantages, there are several disadvantages to the use of PFSA membranes in PEM fuel cells. In addition to the membrane material being expensive (currently averaging US\$ 25 kW⁻¹ [4]), disadvantages can be categorized as those related to safety, supporting equipment require-

ments, and temperature-related limitations. First, safety concerns arise from toxic and corrosive gases liberated at temperatures above 150 °C [4,9]. Decomposition products could be a concern during manufacturing emergencies or vehicle accidents and could limit fuel cell recycling options.

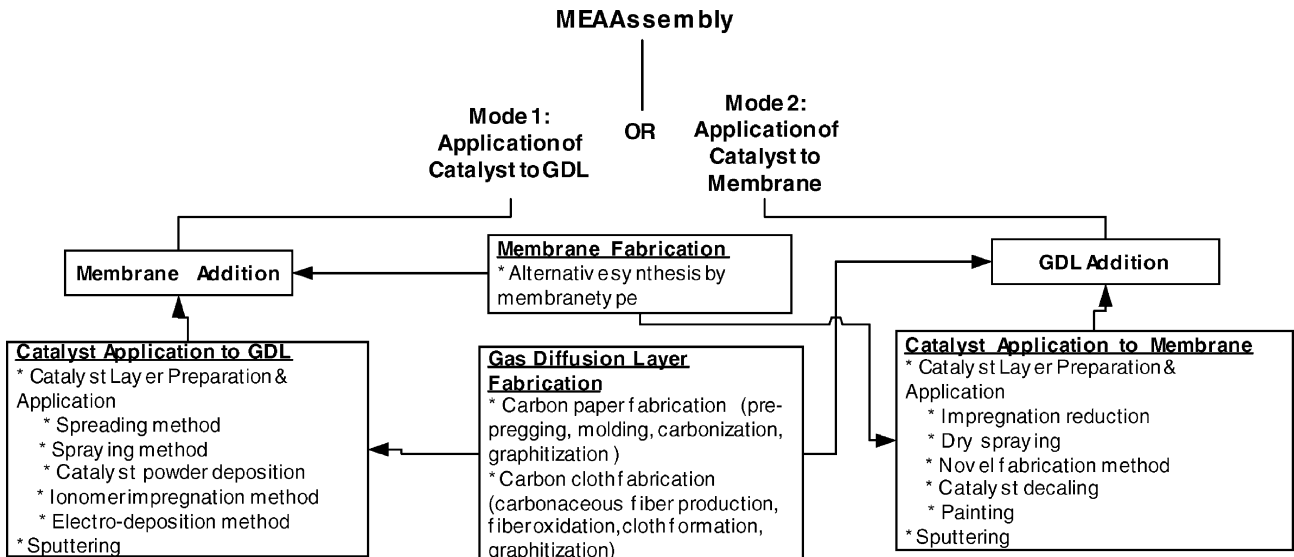


Fig. 3. Classification of MEA manufacturing alternatives.

Second, extensive supporting equipment requirements for use with PFSA membranes are described by Glipta and Hogarth [4] and Crawford [10]. Among the equipment needed, the hydration system adds considerable cost and complexity to the vehicle powertrain. Third, at elevated temperatures PFSA membrane properties degrade. For example, the conductivity at 80 °C is diminished by more than 10 times relative to that at 60 °C [5]. Also, phenomena like membrane dehydration, reduction of ionic conductivity, decreased affinity for water, loss of mechanical strength via softening of the polymer backbone and increased parasitic losses through high fuel permeation are observed at temperature above 80 °C [4]. Making the temperature problems seem worse, Rikukawa and Sanui [5] note that operation of PEM fuel cells improves at elevated temperatures. Specifically, operation at elevated temperatures increases the rates of reaction, reduces problems related to catalyst poisoning by absorbed carbon monoxide in the 150–200 °C range, reduces the use of expensive catalysts, and minimizes problems due to electrode flooding. Because PFSA membranes must be kept hydrated to retain proton conductivity, the operating temperature must be kept below the boiling point of water. Some increase in operating temperature, up to 120 °C, may be possible at the expense of operation under pressurized steam. This alternative will however shorten the life of the cell.

Because of the disadvantages of PFSA membranes, an extensive literature review was done to identify alternatives. Much of the literature is summarized by Glipta and Hogarth from Johnson Matthey Technology Center, UK [4] and Rikukawa and Sanui from Sophia University, Japan [5]. Particularly, Rikukawa and Sanui suggest the foremost challenge is to produce materials that are cheaper than PFSA. They note that some sacrifice in material lifetime and mechanical properties may be acceptable, providing the cost factors are commercially realistic.

Among the different alternatives, Rikukawa and Sanui suggest the use of hydrocarbon polymers even though they had been previously abandoned due to low thermal and chemical stability. Hydrocarbon membranes provide some definite advantages over PFSA membranes. First, they are less expensive. Second, many types are commercially available. Third, polar groups can be formed to have high water uptakes over a wide temperature range with the absorbed water restricted to the polar groups of polymer chains. Fourth, decomposition of hydrocarbon polymers can be depressed to some extent by proper molecular design. Finally, it is possible membranes made from hydrocarbon polymers will be recyclable by conventional methods.

Glipta and Hogarth [4] extend upon Rikukawa and Sanui's list of alternatives. Their final taxonomy includes five categories of membranes: (1) perfluorinated, (2) partially fluorinated, (3) non-fluorinated (including hydrocarbon), (4) non-fluorinated (including hydrocarbon) composite, and (5) others. These authors also note the wide range of material properties among and between membranes in each

category. Specifically, they cite membranes with degradation temperatures ranging from 250 to 500 °C, water uptake from 2.5 to 27.5 H₂O/SO₃H, and conductance from 10⁻⁵ to 10⁻² S/cm.

Together, Glipta and Hogarth and Rikukawa and Sanui identify over 60 alternatives to PFSA membranes. Among these, we identified 46 membranes with characteristics that make them ill-suited for use as automotive PEM fuel cells based on the recommendations of and personal communications with Glipta [11] Rikukawa [12] and with DesMarteau [13]. Table 1 lists these 46 membranes, rejected on the basis of 13 reasons shown as column headings. After removing the 46 'ill-suited' membranes, 16 membranes remain for further study. Table 2 provides design information for these 16 acceptable membranes.

2.1.2. Catalyst layer design

In PEM fuel cells, the type of fuel used dictates the appropriate type of catalyst needed. Within this context, tolerance to carbon monoxide (CO) is an important issue, particularly when hydrogen is formed from methanol by steam reforming. Methanol reformat contains as much as 25% carbon dioxide (CO₂) along with a small amount (1%) of carbon monoxide (CO). It has been proven that PEM fuel cell performance drops with a CO concentration of only several parts per million. This is due to the strong chemisorption force of CO onto the catalyst [25].

There are two techniques to counter the problem of CO poisoning: fuel reforming or catalyst alloying. First, the fuel can be reformed to reduce the CO level in fuel. If using on-board fuel reforming, it has been determined that the PEM fuel cell must be capable of tolerating a CO concentration of at least 100 ppm in order to reduce the size of the reformer unit. Reforming techniques include [2,26]:

- *Selective oxidation*: Selective oxidation is usually the preferred method for CO removal because of the parasitic system loads and energy required by the other methods. In selective oxidation, the reformed fuel is mixed with air or oxygen either before the fuel is fed into the cell or within the stack itself. Another approach involves the use of a selective oxidation catalyst that is placed between the fuel stream inlet and the anode catalyst. Current selective oxidation technologies can reduce CO levels to <10 ppm, but this is difficult to maintain under actual operating conditions.
- *Catalysis*: Ballard Power Systems has demonstrated that the CO level in fuel cell can be significantly reduced (to 100 ppm) by passing reformed methanol and small amount of oxygen over a Pt on aluminum catalyst.
- *Hydrogen peroxide bleeding*: The use of hydrogen peroxide (H₂O₂) in an anode humidifier successfully mitigated 100 ppm CO in an H₂ rich feed [27]. It was reported that mitigation appears to be provided by an unintended O₂ bleed produced by the decomposition of H₂O₂ in the humidifier rather than by H₂O₂ vapors transported from the humidifier to the anode.

Table 2
Possible alternatives to PFSA membranes

| Membrane no. | Membrane type (category) | Design information |
|--------------|---|---|
| 1 | α,β -Trifluorostyrene grafted membrane (partially fluorinated) | This membrane is based on grafting of α,β -trifluorostyrene and PTFE/ethylene copolymers [1] |
| 2 | Acid-doped polybenzimidazoles [PBI] membrane (non-fluorinated composite) | This membrane is based on polybenzimidazole (PBI) and acids like phosphoric acid. Polybenzimidazole (PBI) is a basic polymer ($pK_a = 5.5$) which can readily be complexed with strong acids. The immersion of a PBI film in aqueous phosphoric acid leads to a membrane which has high conductivity and thermal stability [14] |
| 3 | BAM3G membrane (Ballard Advance Material of Third Generation Membrane) (non-fluorinated) | This membrane is based on polymerization of α,β,β -trifluorostyrene and includes monomer(s) selected from a group of substituted α,β,β -trifluorostyrene. The polymers possess favorable properties, such as high heat stability, chemical resistance and favorable mechanical properties, such as tensile strength, compared to the homopolymeric material formed from α,β,β -trifluorostyrene (TFS) alone [15] |
| 4 | Base-doped <i>S</i> -polybenzimidazoles membrane (non-fluorinated composite) | This membrane is based on the introduction of organic or inorganic Bronsted bases to sulfonated PBI [4] |
| 5 | Bis (perfluoroalkylsulfonyl)imide membrane (perfluorinated) | Bis (perfluoroalkylsulfonyl) imide is based on the copolymerization of sodium 3,6-dioxo- <i>d</i> ⁷ -4-trifluoromethyl perfluorooctyl trifluoromethyl with tetrafluoroethylene (TFE). This membrane is thermally stable to nearly 400 °C in the acid form. It has excellent conductivity and its water uptake is typically 40% by weight [13] |
| 6 | Crosslinked or noncrosslinked sulfonated polyetheretherketone membrane (non-fluorinated) | This membrane is based on polyetheretherketone. Direct sulfonation of polyetheretherketone results in materials with wide range of equivalent weights. The initial results obtained with the crosslinked and non-crosslinked <i>S</i> -PEEK membranes show very good thermal stability, proton conductance and water uptake compared to PFSA at even elevated temperature [16] |
| 7 | Gore-Select™ membrane (perfluorinated) | This is an ultra-thin integral composite membrane, which includes a base material and an ion exchange material or ion exchange resin with 0.025 mm thickness. The preferred base material is an expanded-polytetrafluoroethylene (e-PTFE) membrane with thickness of less than 0.025 mm and a porous microstructure. The ion exchange resin substantially impregnates the membrane. Suitable ion exchange materials include perfluorinated sulfonic acid resin, perfluorinated carboxylic acid resin, polyvinyl alcohol, divinyl benzene, styrene-based polymers and metal salts with or without a polymer. A surfactant is preferably employed with the ion exchange material to ensure impregnation of the interior volume of the base material. Alternatively, the composite membrane may be reinforced with a woven or non-woven material bonded to one side of the base material. Suitable woven materials may include, scrim made of woven fibers of expanded porous polytetrafluoroethylene; webs made of extruded or oriented polypropylene or polypropylene netting [17] |
| 8 | Imidazole doped sulfonated polyetherketone [<i>S</i> -PEK] membrane (non-fluorinated) | Sulfonated poly(arylether ketone) membranes and in particular sulfonated polyetherketone (<i>S</i> -PEK) exhibit high proton conductivities when in their hydrated forms. <i>S</i> -PEK can be complexed with imidazole to give membranes with high proton conductivities around 2×10^{-2} S/cm at a high temperature of 200 °C [4,18] |
| 9 | Methylbensulfonated polybenzimidazoles membrane (non-fluorinated) | These alkylsulfonated aromatic polymer electrolyte possess very good thermal stability even above 80 °C. Water uptake and proton conductivity are also reported to be higher than PFSA membranes above 80 °C [5] |
| 10 | Methylbensulfonate poly(<i>p</i> -phenylene terephthalamide) membrane (non-fluorinated) | These alkylsulfonated aromatic polymer electrolyte possess very good thermal stability even above 80 °C. Water uptake and proton conductivity are also reported to be higher than PFSA membranes above 80 °C [5] |
| 11 | Perfluorocarboxylic acid membrane (perfluorinated) | Perfluorocarboxylic acid is based on a copolymer of tetrafluoroethylene and perfluorovinyl ether having a carboxylated group instead of a sulfonated group. The molar ratio of functional perfluorovinyl ether to tetrafluoroethylene in the copolymer is directly related to ion exchange capacity of resulting polymeric acid. Copolymerization of tetrafluoroethylene and functional perfluorovinyl ether is carried out by using a radical initiator [19] |
| 12 | Poly(2-acrylamido-2-methylpropanesulfonic acid [poly-AMPS] membrane (Other) | This membrane is made from polymerization of AMPS [®] monomer. AMPS [®] monomer is made from acrylonitrile, isobutylene and sulfuric acid [20] |
| 13 | Styrene grafted and sulfonated poly(vinylidene fluoride) membranes [PVDF- <i>g</i> -PSSA] (partially fluorinated) | This membrane is based on the pre-irradiation grafting of styrene onto a matrix of poly(vinylidene fluoride) (PVDF) after electron beam irradiation. It can be cross-linked with divinylbenzene (DVB) or bis (vinylphenyl) ethane (BVPE). The proton conductivity of membrane is influenced by degree of cross linking [21] |
| 14 | Sulfonated naphthalenic polyimide (non-fluorinated) | This membrane is based on sulfonated aromatic diamines and dihydrides. It gives a performance very similar to PFSA membranes [4] |
| 15 | Sulfonated poly(4-phenoxybenzoyl-1, 4-phenylene) (<i>S</i> -PPBP) (non-fluorinated) | This membrane is based on poly(4-phenoxybenzoyl-1, 4-phenylene). This material is a poly(<i>p</i> -phenylene) derivative and is structurally similar to PEEK. The direct sulfonation of PPBP is reported to give a membrane that gives water absorption and proton conductance better than <i>S</i> -PEEK membranes [23] |
| 16 | Supported composite membrane (other) | Composite membrane is made of ion conducting polymer (ICP) and poly- <i>p</i> -phenylene benzobisoxazole (PBO) substrates [24] |

Table 3
Anode catalyst materials [22,25,28–34]

| | Single metal catalyst | Binary catalyst | Tertiary catalyst |
|---------------------------|-----------------------|-----------------|-------------------|
| Pt/C | X | | |
| Pt-Co/C | | X | |
| Pt-Cr/C | | X | |
| Pt-Fe/C | | X | |
| Pt-Ir/C | | X | |
| Pt-Mn/C | | X | |
| Pt-Mo/C | | X | |
| Pt-Ni/C | | X | |
| Pt-Pd/C | | X | |
| Pt-Rh/C | | X | |
| Pt-Ru/C | | X | |
| Pt-V/C | | X | |
| Au-Pd/C | | X | |
| Pt-Ru-Al ₄ | | | X |
| Pt-Ru-Mo/C | | | X |
| Pt-Ru-Cr/C | | | X |
| Pt-Ru-Ir/C | | | X |
| Pt-Ru-Mn/C | | | X |
| Pt-Ru-Co | | | X |
| Pt-Ru-Nb/C | | | X |
| Pt-Ru-Ni/C | | | X |
| Pt-Ru-Pd/C | | | X |
| Pt-Ru-Rh/C | | | X |
| Pt-Ru-W/C | | | X |
| Pt-Ru-Zr/C | | | X |
| Pt-Re-(MgH ₂) | | | X |

When alloying the catalyst to counter the problem of CO, one (a binary catalyst) or sometimes two elements (a ternary catalyst) are added to the base catalyst. Table 3 lists 26 anode catalyst alloys. As shown, binary and ternary anode catalysts are typically, but not always, Pt-based and supported on carbon (or “/C”). It can be summarized that for hydrogen contaminated with CO there are at least seven Pt-based catalysts that give performance equal or similar to that given by Pt/C with pure hydrogen cell: Pt-Ru/C, Pt-Mo/C, Pt-W/C, Pt-Ru-Mo/C, Pt-Ru-W/C, Pt-Ru-Al₄, and Pt-Re-(MgH₂).

Table 3 lists 13 binary catalysts. Specifically, Iwase and Kawatsu [25] investigated 10 of these catalysts: Pt-Ru/C, Pt-Ir/C, Pt-V/C, Pt-Rh/C, Pt-Cr/C, Pt-Co/C, Pt-Ni/C, Pt-Fe/C, Pt-Mn/C, and Pt-Pd/C. Each catalyst was made of a 20-wt.% alloy on carbon with a Pt loading rate of 0.4 mg/cm² in a 5-wt.% PFSA solution. They found that only the Pt-Ru catalyst showed cell performance equivalent to that of pure hydrogen cell with a single metal Pt/C catalyst when exposed to reformat gas with 100 ppm of CO. Also, they found that Ru in the binary catalyst absorbs water and facilitates the oxidation of CO. Although adequate CO tolerance can be obtained over a Ru-range of 15–85%, the optimum ratio of Pt/Ru was determined by Iwase and Kawatsu to be 50:50.

Other researchers add Pt-Mo/C and a non-Pt-based alloy Au-Pd/C to the list of possible binary catalysts. Specifically, Bauman et al. [28] found Pt-Mo/C to achieve high tolerance to low levels (10–20 ppm) of CO in reformat without the need of an air bleed. However, at CO levels above 20 ppm,

the benefit of this catalyst is lessened. Although Pinheiro et al. [35] also found Pt-Ru/C to outperform Pt-Mo/C, Bauman et al. [28] found better performance with Pt-Mo/C as compared to Pt-Ru/C catalyst. Finally, Lawrence Berkeley researchers [33] have developed a non-platinum-based binary catalyst. They reported a three-fold improvement in electro-oxidation of CO/H₂ with their Au-Pd catalyst as compared to a Pt-Ru catalyst.

Tertiary catalysts are typically based on a Pt-Ru alloy. The largest number of tertiary catalysts along with some binary catalyst has been investigated by scientists at ECI Laboratories [29] and performances were compared to pure Pt/C catalyst performance. They investigated Pt-Ru alloys with Ni, Pd, Co, Rh, Ir, Mn, Cr, W, Zr, and Nb. They found that out of all the catalyst investigated, in the presence of CO, the binary catalysts Pt_{0.53}-Ru_{0.47} and Pt_{0.82}-W_{0.18} were far superior to pure platinum. Of the two, Pt-Ru was better in the low potential region while Pt-W proved superior in the plateau region except at very high current densities. But the performance of ternary Pt_{0.53}-Ru_{0.32}-W_{0.15} alloy exceeded both binaries in the low potential and potential plateau regions. Similarly, Pinheiro et al. [35] analyzed the performance of Pt-Ru, Pt-Mo, and Pt-Ru-Mo/C and found the tertiary catalyst to have the best performance.

In another ternary catalyst development, Denis et al. [30] investigated the ternary electrocatalyst of Pt-Ru-Al₄ with no carbon support. Their results show that an unsupported Pt-Ru-Al₄ catalyst produced by high-energy ball milling gives equal performance to Pt-Ru/C when exposed to reformat gas with 100 ppm of CO. Using similar kind of ball milling technique, Dodelet et al. [31] produced a ternary catalyst Pt-Re-(MgH₂) without carbon support that performed better than Pt-Ru/C when exposed to reformat gas with 100 ppm of CO.

Little information was found on cathode catalysts for PEM fuel cells, which do not have to be CO tolerant. Notably, in addition to the use of Pt/C, Ross et al. [33] at Lawrence Berkeley National Laboratory report the use of Pt-Ni/C and Pt-Co/C as cathode catalyst. Also, Faubert et al. [34] produced a special, non-platinum based cathode catalyst. The catalyst is produced by pyrolysis of iron acetate adsorbed on perylenetetracarboxylic dianhydride in Ar:H₂:NH₃ under ambient conditions. Also, at the National Renewable Energy Laboratory [32], a ‘rapid throughput’ system has been developed to identify catalysts for oxygen reduction. This study investigates 1200 bimetallic complexes. Approximately 20 complexes were found suitable for fuel cells although detailed information about what these complexes was not included in the report.

2.1.3. Gas diffusion layer design

The GDLs, one next to the anode and the other next to the cathode, are usually made of a porous carbon paper or carbon cloth, typically 100–300 μ thick. The porous nature of the GDL material ensures effective diffusion of each reactant gas to the catalyst on the membrane/electrode

assembly. The structure allows the gas to spread out as it diffuses so that the gas will be in contact with the entire surface area of the catalyzed membrane [8,36].

The GDL also assists in water management during the operation of the fuel cell. A GDL that allows the appropriate amount of water vapor to reach the membrane/electrode assembly keeps the membrane humidified and improves the efficiency of the cell. The GDL allows the liquid water produced at the cathode to leave the cell so it does not flood. The GDL is typically wet-proofed to ensure that at least some, and hopefully most, of the pores in the carbon cloth or paper do not become clogged with water, which would prevent the rapid gas diffusion necessary for a good rate of reaction to occur at the electrodes [8,36]. PTFE is the wet-proofing agent used for carbon-based PEM GDLs by several research groups [1,37,38].

A literature review did not reveal any research group who has studied both carbon paper and carbon cloth with the specific objective of identifying the most favorable among these two in a PEM fuel cell. In a study of water management, Ralph et al. [39] found that carbon cloth offered a distinct advantage at high current densities in Ballard Mark V cells. In fact, the slope of the pseudolinear region of the cell potential versus current density plot was lowered from 0.27 to 0.21 $\Omega \text{ cm}^2$ and the limiting current was substantially raised by the use of the carbon cloth. Also, the cloth was found to enhance mass transport properties at the cathode derived from improved water management and enhanced oxygen diffusion rates. Finally, the surface porosity and hydrophobicity of the cloth substrate are more favorable for the movement of the liquid water.

2.2. MEA manufacturing

2.2.1. Membrane and GDL fabrication

Whereas the catalyst layer is typically prepared and applied during MEA assembly, the membrane and GDL are fabricated prior to assembly. Considering membranes first, a variety of polymerization processes are used in the fabrication of PFSA membranes and the alternatives listed in Table 2. Table 4 presents the processing steps and the primary inputs and outputs for many of these membranes. Notably, the processing steps include many chemical processes and a number of energy intensive heating and drying steps. Process flow diagrams and additional synthesis information is available in [7].

Like the membrane, the GDL is fabricated prior to assembly. Carbon paper is fabricated in four steps: pre-pegging (continuous strands are aligned with spools and a surface treatment is followed by a resin bath and formation of a layered structure), molding, carbonization, and graphitization [24]. Carbon cloth is also fabricated in four steps: carbonaceous fiber production (made from mesophase pitch spun by melt spinning, centrifugal spinning, blow spinning, etc.), fiber oxidation, cloth formation by weaving or knitting, and graphitization [42]. Finally, the carbon cloth or paper is

wet-proofed, typically using PTFE. Specifically, Bevers et al. [37] describe their wet-proofing process in which a carbon/PTFE suspension is applied to both sides of the carbon cloth or paper substrate. Application of the carbon/PTFE mixture flattens out any roughness of the cloth or paper and improves the gas and water transport properties.

2.2.2. MEA assembly

As shown in Fig. 4, there are two modes of MEA assembly: (1) application of the catalyst layer to the GDL followed by membrane addition or (2) application of the catalyst layer to the membrane followed by GDL addition. No matter the mode of assembly, the catalyst layer can be prepared and applied in two separate steps (catalyst preparation and application) or using a single sputtering process. As described later, several manufacturing options exist within these two modes of MEA manufacturing.

For either mode, early catalyst preparation methods were based on the use of platinum black. Later, Raistrick [43] used 10% carbon-supported platinum (Pt/C, 2 nm size particles) and a 100 μ thick catalyst layer instead of platinum black. The obvious advantage was a higher degree of platinum dispersion. Raistrick impregnated the Pt/C//PTFE catalyst layer on carbon cloth with a solution of PFSA, in order to fill it, or at least a significant part of it, with recast ionomer prior to hot pressing the impregnated electrode onto the membrane. This process overcame cell performance problems related to the lack of protonic access to the majority of catalyst sites not in intimate contact with membrane. Ticianelli et al. [44] further improved cell performance by optimizing the percentage of PFSA impregnant. They replaced a 10% Pt/C-100 m catalyst layer with a 20% Pt/C-50 m catalyst layer. Although this work was considered a major breakthrough by Gottesfeld and Zawodzinski [1], not all methods use ionomer impregnation, as follows. As described later, spreading method, spraying method and catalyst powder deposition method do not use ionomer impregnation.

For mode 1, we identified five methods for catalyst preparation and application to prepare a GDL/catalyst assembly.

- *Spreading*: The spreading method described by Srinivasan et al. [45] consists of preparing a catalyzed carbon and PTFE dough by mechanical mixing and spreading it on a wet-proofed carbon cloth using a heavy stainless steel cylinder on a flat surface. This operation leads to a thin and uniform active layer on the GDL/catalyst assembly for which the Pt loading is directly related to the thickness.
- *Spraying*: In the spraying method described by Srinivasan et al. [45], the electrolyte is suspended in a mixture of water, alcohol, and colloidal PTFE. This mixture is then repeatedly sprayed onto wet-proofed carbon cloth. Between each spraying, the electrode is sintered in order to prevent the components from re-dissolving in the next layer. The last step is rolling of the electrode. This

Table 4
Analysis of membrane synthesis methods

| Processing steps | Primary process inputs | Primary process outputs |
|---|--|--|
| Synthesis of PFSA membranes [40] | | |
| 1. Partial fluorination | HF, antimony fluoride, chloroform | Chlorodifluoromethane |
| 2. Pyrolysis | Chlorodifluoromethane | Tetrafluoroethylene (TFE) |
| 3. Pyrolysis [290–370 °C] | Diacyl fluoride | Perfluorinated vinyl ether |
| 4. Copolymerization | TFE, perfluorinated vinyl ether | PFSA solution |
| 5. Casting | PFSA solution | PFSA film |
| 6. Sulfonation | PFSA film, sodium/potassium hydroxide | Sulfonated PFSA membrane |
| Synthesis of perfluorocarboxylic acid membranes [19] | | |
| 1. Reaction | Oleum, 1,4-diiodo-perfulorobutane | Cyclic lactone |
| 2. Reaction | Methanol, cyclic lactone | 3-Methoxycarbonyl perfluoro-propionyl fluoride |
| 3. Pyrolysis | 3-Methoxycarbonyl perfluoro-propionyl fluoride, HFPO | Carboxylated perfluorovinyl ethers |
| 4. Partial fluorination | Hydrogen fluoride (HF), antimony fluoride, chloroform | Chlorodifluoromethane |
| 5. Pyrolysis | Chlorodifluoromethane | TFE |
| 6. Co-polymerization | Carboxylated perfluorovinyl ethers, TFE | Perfluorocarboxylic acid (PFCA) solution |
| 7. Casting | PFCA solution | PFCA film |
| 8. Sulfonation | PFCA film, sodium/potassium hydroxide | Sulfonated PFCA membrane |
| Synthesis of poly-AMPS membranes [1] | | |
| 1. Reaction | Acrylonitrile, Isobutylene, Sulfuric acid | AMPS monomer |
| 2. Addition (40 °C) | Distilled water, AMPS monomer | Dissolved AMPS monomer |
| 3. Addition | Dissolved AMPS monomer, ammonium persulfate in distilled water | AMPS with ammonium persulfate |
| 4. Polymerization (60 °C) | AMPS with ammonium persulfate, sodium metabisulfite in distilled water | Poly-AMPS |
| 5. Casting | Poly-AMPS | Poly-AMPS membrane |
| α,β-Trifluorostyrene grafted onto poly(tetrafluoroethylene-ethylene) with post sulfonation membranes [1] | | |
| 1. Fluorination at α, β position | HF, vinylbenzene | Fluorinated vinylbenzene |
| 2. Grafting | Fluorinated vinylbenzene, PTFE/ethylene | PTFE grafted fluorinated vinylbenzene |
| 3. Sulfonation | PTFE grafted fluorinated vinylbenzene, sulfuric acid | α,β -Trifluorostyrene grafted poly(tetrafluoroethylene-ethylene) membrane |
| Styrene grafted and sulfonated PVDF membranes [21] | | |
| 1. Electron beam irradiation | PVDF films | Irradiated films |
| 2. Mixing | Styrene, DVB or BVPE, toluene | Monomer |
| 3. Grafting (immersion into monomer) | Monomer, irradiated films | Styrene grafted membranes |
| 4. Sulfonation | Styrene grafted membranes, sulfuric acid | PVDF-g-PSSA membrane |
| Synthesis of bis(perfluoroalkylsulfonyl) imide membranes [13] | | |
| 1. Polymerization | Monomer, TFE, $C_8F_{17}CO_2NH_4$, $(NH_4)_2S_2O_8/NHSO_3$ | Emulsion |
| 2. Filtration | Emulsion, acid | Bulk polymer |
| 3. Drying | Bulk polymer | Dried polymer |
| 4. Sonication | Dried polymer, DMF | Sonicated polymer |
| 5. Removal of DMF in vacuum oven | Sonicated polymer | DMF free polymer |
| 6. Annealing at 220–250 °C | DMF free polymer | Annealed polymer |
| 7. Boiling | HNO_3 , annealed polymer | Bis(perfluoroalkylsulfonyl) imide membrane |
| Synthesis of Gore-Select™ membranes [17] | | |
| 1. Roll lamination/ultrasonic lamination/adhesive lamination | Polypropylene woven fabric, expanded polytetrafluoroethylene (ePTFE) | Laminated e-PTFE sheets |
| 2. Mixing | HC/FC based surfactant, PFSA/PFCA | Solution |
| 3. Roll coating/Reverse roll coating/Gravure coating | Laminated e-PTFE sheets | Coated sheets |
| 4. Removal of excess solution | Coated sheets, solution | Excess solution free sheets |
| 5. Oven drying | Excess solution free sheets | Dried sheets |
| 6. Repeat steps 3–5 several times | | |
| 7. Soaking | Water/ H_2O_2 / CH_3OH , dried sheets | Surfactant free membrane |
| 8. Boiling in swelling agent | Surfactant free membrane | Gore-Select™ membrane |

Table 4 (Continued)

| Processing steps | Primary process inputs | Primary process outputs |
|---|---|--|
| Synthesis of BAM3G membranes [15] | | |
| 1. Mixing (35–96 °C, 24–74 h, inert atmosphere) | α,β,β -Trifluorostyrene monomer, substituted- α,β,β -trifluorostyrene comonomers, free radical initiator, emulsifying agent | Base copolymer |
| 2. Dissolve in solvent | Base copolymer, dichloroethane, tetrachloroethylene and chloroform | Dissolved copolymer |
| 3. Sulfonation | Dissolved copolymer, chlorosulfonic acid | BAM3G membrane |
| Synthesis of crosslinked or noncrosslinked sulfonated PEEK membranes [16] | | |
| 1. Polymerization | EEK monomer | PEEK |
| 2. Sulfonation 60% | PEEK, 95–96.5% sulfuric acid | Sulfonated PEEK |
| 3.1. Conversion of sulfonic acid group to sulfonyl chloride | Sulfonated PEEK, PCI5/Thionyl chloride | Sulfonyl PEEK |
| 3.2. Crosslinking by high-energy radiation or heat | Sulfonyl PEEK, Aliphatic/Aeromatic amine, chloroform or dichloroethane | Crosslinked S-PEEK |
| OR | | |
| 3.1. Intra/inter chain polymerization (120 C, under vacuum) | Sulfonated PEEK | Crosslinked S-PEEK |
| 4. Casting | Crosslinked S-PEEK | S-PEEK membrane |
| Synthesis of sulfonated PPBP membranes [23] | | |
| 1. Mixing | Triphenylphosphine, nitrogen bis (triphenylphosphine) nickel(II) chloride, sodium iodide, zinc dust, anhydrous <i>N</i> -methylpyrrolidinone (NMP) | Solution |
| 2. Stirring overnight | Solution | Solution |
| 3. Coagulation in acetone bath | Solution | Coagulated solution |
| 4. Blending | Coagulated solution | Crude polymer |
| 5. Removal of excess zinc | Crude polymer, hydrochloric acid in ethanol | Excess zinc free crude polymer |
| 6. Filtration | Excess zinc free crude polymer | Filtrate |
| 7. Washing | Filtrate, water/acetone | Washed filtrate |
| 8. Dissolve | Methylene chloride, washed filtrate | Dissolved solution |
| 9. Filtration with polypropylene membrane | Dissolved solution | Filtrate |
| 10. Coagulation | Acetone, filtrate | Coagulated polymer |
| 11. Filtration | Coagulated polymer | Filtrate |
| 12. Drying | Filtrate | Poly(4-phenoxybenzoyl-1,4-phenylene (PPBP) |
| 13. Dissolve | Chloroform, PPBP | Dissolved PPBP |
| 14. Reprecipitation | Dissolved PPBP, methanol | Solid polymer |
| 15. Drying | Solid polymer | Dried polymer |
| 16. Pulverization | Dried polymer | Dried PPBP |
| 17. Dissolve in H ₂ SO ₄ | Dried PPBP, H ₂ SO ₄ | Dissolved PPBP |
| 18. Add | Dissolved PPBP, Water | Water mixed PPBP |
| 19. Filtration | Water mixed PPBP | Precipitate |
| 20. Washing | Precipitate, Water | Washed precipitate |
| 21. Pulverization | Washed precipitate | Pulverized precipitate |
| 22. Washing | Pulverized precipitate | Pulverized precipitate |
| 23. Dialyzation | Pulverized precipitate, distilled water | Sulfonated polymer |
| 24. Dissolve | NMP, sulfonated polymer | Dissolved polymer |
| 25. Reprecipitation in tetrahydrofuran | Dissolved polymer, tetrahydrofuran | Re-precipitated polymer |
| 26. Drying | Re-precipitated polymer | Dried polymer |
| 27. Dissolve | NMP, dried polymer | 2% wt. Solution |
| 28. Casting | 2% wt. Solution | Cast films |
| 29. Drying | Cast films | Dried films |
| 30. Washing | Dried films, methanol | Washed films |
| 31. Vacuum drying | Washed films | Sulfonated PPBP membrane |
| Synthesis of acid-doped polybenzimidazoles (PBI) membranes [41] | | |
| 1. Casting | Dimethylacetamide | Cast films |
| 2. Boiling | Water, cast films | Films |
| 3. Doping | Film, phosphoric acid | Acid doped PBI membrane |
| OR | | |
| 1. Casting | PBI | Cast films |
| 2. Boiling | Water, cast films | Films |
| 3. Doping | Film, phosphoric acid | Acid doped PBI membrane |

Table 4 (Continued)

| Processing steps | Primary process inputs | Primary process outputs |
|---|--|------------------------------|
| Supported composite membranes [24] | | |
| 1. Water quench of substrate | Bi-axially oriented PBO extruded polymers, water | Hydrated substrate |
| 2. Sulfonation of ion conducting polymer | PFSA, H ₂ SO ₄ | Sulfonated PFSA |
| 3. Solvent exchange | Hydrated substrate, sulfonated PFSA | PFSA rich substrate |
| 4. Tension drying | PFSA loaded substrate | Dried substrate |
| 5. Degassing for complete solvent removal | PFSA loaded dried substrate | Composite membrane |
| 6. Hot pressing | Composite membrane | Supported composite membrane |

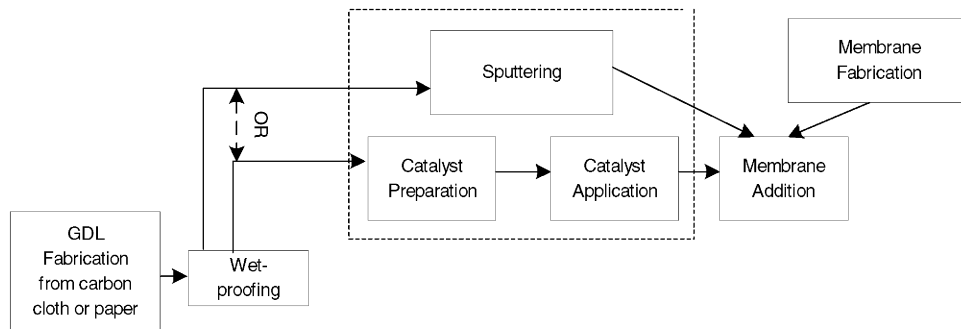
operation has been found to produce a thin layer of uniform thickness and of low porosity on the GDL/catalyst assembly.

- **Catalyst powder deposition:** In catalyst powder deposition described by Bevers et al. [37], the components of the catalytic layer (Vulcan XC-72, PTFE powder, and a variety of Pt/C loadings) are mixed in a fast running knife mill under forced cooling. This mixture is then applied onto a wet-proofed carbon cloth. Also applying a layer of carbon/PTFE mixture flattens out the roughness

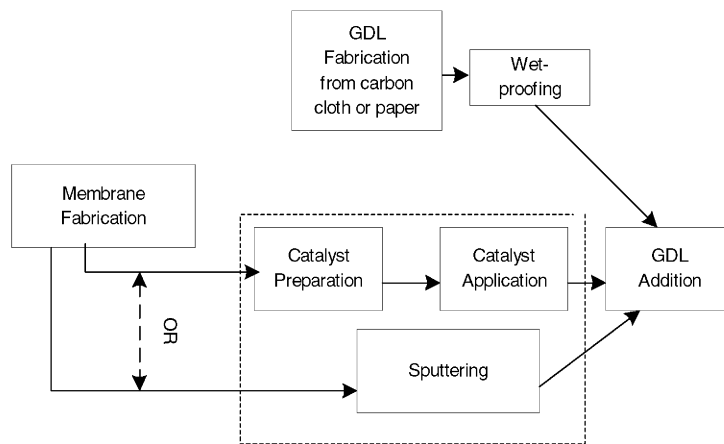
of the paper and improves the gas and water transport properties of the MEA.

- **Ionomer impregnation:** In the ionomer impregnation method described by Gottesfeld and Zawodzinski [1], the catalytically active side of GDL is painted with solubilized PFSA in a mixture of lower aliphatic alcohols and water. To improve reproducibility of the GDL/catalyst assembly, the catalyst and ionomer are premixed before the catalyst layer is deposited, rather than ionomer impregnation of Pt/C//PTFE layer.

Mode:1 application of the catalyst layer to the GDL



OR



Mode:2 application of the catalyst layer to the Membrane

Fig. 4. Modes of MEA assembly.

- *Electro-deposition*: Electro-deposition as described by Gottesfeld and Zawodzinski [1] and Taylor et al. [46] involves impregnation of the porous carbon structure with ionomer, exchange of the cations in the ionomer by a cationic complex of platinum and electrodeposition of platinum from this complex onto the carbon support. This results in deposition of platinum only at sites that are accessed effectively by both carbon and ionomer.

In mode 2, we identified six methods for catalyst application to prepare a membrane/catalyst assembly.

- *Impregnation reduction*: In impregnation reduction (a.k.a. electroless deposition) as described by Foster et al. [47] and Fedkiw and Her [48], the membrane, ion exchanged to the Na^+ form is equilibrated with an aqueous solution of $(\text{NH}_3)_4\text{PtCl}_2$ and a co-solvent of $\text{H}_2\text{O}/\text{CH}_3\text{OH}$. Following impregnation, vacuum dried PFSA in the H^+ form is exposed on one face to air and the other to an aqueous reductant NaBH_4 . The method has been found to produce metal loadings of the order of 2–6 mg Pt/cm² on the membrane/catalyst assembly.
- *Evaporative deposition*: In evaporative deposition as described by Foster et al. [47] and Fedkiw and Her [48], $(\text{NH}_3)_4\text{PtCl}_2$ is evaporatively deposited onto a membrane from an aqueous solution. After deposition of the salt, metallic platinum is produced by immersion of the entire membrane in a solution of NaBH_4 . The method has been found to produce metal loadings of the order of ≤ 0.1 mg Pt/cm² on the membrane/catalyst assembly.
- *Dry spraying*: In the dry spraying method described by Gulzow et al. [49], reactive materials (Pt/C, PTFE, PFSA powder and/or filler materials) are mixed in a knife mill. The mixture is then atomized and sprayed in a nitrogen stream through a slit nozzle directly onto the membrane. Although adhesion of the catalytic material on the surface is strong, in order to improve the electric and ionic contact, the layer is fixed by hot rolling or pressing. Depending upon the degree of atomization, a completely, uniformly covered reactive layer with thickness down to 5 μm can be prepared with this technique.
- *Novel fabrication method*: In a novel method suggested by Matsubayashi et al. [50], PFSA solution is mixed with the catalyst and dried in a vacuum. Then, the PFSA coated catalyst is mixed with a PTFE dispersion, calcium carbonate used to form pores, and water. The mixture is passed through a filter and the filtrate is formed into a sheet. The sheet is then dipped in nitric acid to remove any calcium carbonate. The sheet is then dried and PFSA solution is applied to one side of the electrode catalyst layer. Finally catalyst layer is applied to the membrane.
- *Catalyst decaling*: In the catalyst decaling method described by Gottesfeld and Wilson [51,52] and Gottesfeld and Zawodzinski [1], Pt ink is prepared by thoroughly mixing the catalyst and solubilized PFSA. The protonated form of PFSA in the ink is next converted to the TBA⁺ (tetrabutylammonium) form by the addition of TBAOH in

methanol to the catalyst and PFSA solution. The paintability of the ink and the stability of the suspension can be improved by the addition of glycerol. Membranes are catalyzed using a “decal” process in which the ink is cast onto PTFE blanks for transfer to the membrane by hot pressing. When the PTFE blank is peeled away, a thin casting layer of catalyst is left on the membrane. In the last step, the catalyzed membranes are rehydrated and ion-exchanged to the H^+ form by immersing them in lightly boiling sulfuric acid followed by rinsing in deionized water.

- *Painting*: In the painting method described by Gottesfeld and Wilson [51,52] and Gottesfeld and Zawodzinski [1], Pt ink is prepared as described for the decaling method. A layer of ink is painted directly onto a dry membrane in the Na^+ form and baked to dry the ink. When using thinner membranes or heavy ink applications, there will be considerable amount of distortion of the painted area. The distortion is managed through drying on a specially heated and fixtured vacuum table. Also, the bulk of the solvent is removed at a lower temperature to alleviate cracking and the final traces of solvent are rapidly removed at higher temperatures. In the last step, the catalyzed membranes are rehydrated and ion-exchanged to the H^+ form by immersing them in lightly boiling sulfuric acid followed by rinsing in deionized water.

In modes 1 and 2, sputtering can also be used as a single step option to catalyst preparation and application. In mode 1, Srinivasan et al. [45] describe a method in which a ~ 5 μm layer is sputter deposited on the wet-proofed GDL. Also, a remarkable improvement in performance was achieved when the catalyzed GDL was over-coated with a very thin layer of sputter deposited catalyst at the anode. Alternatively, they did not find over-coating improved performance at the cathode. In mode 2, Cha and Lee [38] describe a method in which the catalyst is sputtered onto both sides of the membrane. To enhance the performance, a mixture of PFSA solution, carbon powder, and isopropyl alcohol is brushed on the catalyzed surfaces of membrane/catalyst assembly. The assembly is then dried in a vacuum chamber to remove any residual solvent. Sputtering and application of the ink is repeated to form a second layer of catalyst.

Tables 5 and 6 present processing steps and the primary inputs and outputs for catalyst preparation and application in two steps or by sputtering. Again, process flow diagrams and additional manufacturing information is available in [7].

The final step in modes 1 and 2 is the addition of the membrane and GDL respectively. Hot pressing is used in both modes. During the hot pressing procedure, the membrane will dry out but becomes re-hydrated adequately after insertion in the stack with humidified gases. Also, in mode 1, Ticianelli et al. [44] suggest that prior to hot pressing, the membrane be treated with a $\text{H}_2\text{O}_2/\text{H}_2\text{O}$ solution heated to the boiling point, rinsed in deionized water, immersed in hot dilute sulfuric acid, and treated several times in boiling

Table 5
Analysis of catalyst preparation and application for MEA assembly mode 1

| Processing steps | Primary process inputs | Primary process outputs |
|--|---|-------------------------|
| Catalyst preparation and application: spreading method [45] | | |
| 1. Dough making | Carbon supported metal-catalyst, PTFE | Dough |
| 2. Spreading | Dough, wet-proofed GDL | Coated GDL |
| 3. Rolling | Coated GDL | GDL/catalyst assembly |
| Catalyst preparation and application: spraying method [45] | | |
| 1. Composite mixture making | Carbon supported metal-catalyst, water, PTFE, alcohol | Mixture for spraying |
| 3. Spraying | Mixture, wet-proofed GDL | Coated GDL |
| 4. Sintering | Coated GDL | Coated and sintered GDL |
| 5. Rolling | Coated and sintered GDL | GDL/catalyst assembly |
| Catalyst application: catalyst powder deposition method [37] | | |
| 1. Mixing | Carbon supported metal-catalyst, PTFE | Reactive powder |
| 2. Powder application | | |
| 2.1. Using a line funnel under gravity | Powder, wet-proofed GDL | Coated GDL |
| OR | | |
| 2.1. Horizontal powder application | Powder, wet-proofed GDL | Coated GDL |
| 3. Rolling | Coated GDL | GDL/catalyst assembly |
| Catalyst preparation and catalyst application: ionomer impregnation method [1] | | |
| 1. Mixing | Carbon supported metal-catalyst, PTFE, PFSA in aliphatic alcohols and water | Catalyst solution |
| 2. Painting | Catalyst solution, wet-proofed GDL | GDL/catalyst assembly |
| Sputtering [45] | | |
| 1. Sputtering | Wet-proofed GDL, metal-catalyst | Sputter deposited paper |
| 2. Rolling | Sputter deposited paper | GDL/catalyst assembly |

water. The process oxidizes organic impurities, removes any metallic impurities, and removes traces of acid from the finished MEA.

No matter the mode of assembly, the primary challenge in the assembly of MEAs is to achieve good contact between the membrane, the GDL, and the catalyst layers. Good contact maximizes catalyst utilization during cell operation. Gottesfeld and Zawodzinski [1] suggest good reproducibility is gained by hot pressing Pt/C//ionomer layers (that is Pt/C impregnated with premixed catalyst and ionomer) to the membrane as opposed to ionomer-impregnation of the GDL. This is because ionomer-impregnation is hard to achieve due to hydrophobic nature of GDL. Alternatively, Stuve [53] suggests that pressing a catalyzed GDL against the membrane might cause some ionomer particles to embed in the electrode structure and thereby improve protonic access.

3. Review and analysis of bipolar plate design and manufacturing

Figs. 5 and 6 provide classifications of bipolar plate material and manufacturing alternatives, described as follows.

3.1. Bipolar plate design

Bipolar plates perform a number of functions within the PEM fuel cell. They have been used to distribute the fuel and

oxidant within the cell, separate the individual cells in the stack, carry current away from each cell, carry water away from each cell, humidify gases, and keep the cells cool. Plate topologies and materials facilitate these functions. Topologies can include straight, serpentine, or inter-digitated flow fields, internal manifolding, internal humidification, and integrated cooling. Materials have been proposed on the basis of chemical compatibility, resistance to corrosion, cost, density, electronic conductivity, gas diffusivity/impermeability, manufacturability, stack volume/kW, material strength, and thermal conductivity [6,8,36]. Given the criteria found in literature, non-porous graphite, a variety of coated metals, and a number of composite materials have been suggested for use in bipolar plates, as described later.

3.1.1. Non-porous graphite plates

Long experience has shown that non-porous graphite has the chemical stability to survive the fuel cell environment. Natural as well as synthetic graphite has been used to make non-porous bipolar plate material for PEM fuel cells.

3.1.2. Coated metallic plates

Aluminum, stainless steel, titanium, and nickel are considered possible alternative materials for the bipolar plate in PEM fuel cells. Although typically metallic plates are based on a single piece of metal, Allen [54] developed a modular metallic bipolar plate. The design provides for parallel flow of coolants within each sub-section arranged perpendicular to the direction of manufacture. The plate design combines

Table 6
Analysis of catalyst preparation and application for MEA assembly mode 2

| Processing steps | Primary process inputs | Primary process outputs |
|--|---|--------------------------------------|
| Catalyst preparation and application: impregnation reduction method (electroless deposition method) [48] | | |
| 1. Platinum salt impregnation | Membrane, (NH ₃) ₄ PtCl ₂ (aq) | Membrane loaded with metal salt |
| 2. Reduction of (NH ₃) ₄ Pt ²⁺ | Membrane loaded with metal salt, NaBH ₄ (aq) | Membrane/catalyst assembly |
| Catalyst preparation and application: evaporative deposition [47] | | |
| 1. Metal salt evaporation | Membrane, heat, metal salt such as (NH ₃) ₄ PtCl ₂ (aq) | Membrane impregnated with metal salt |
| 2. Reduction of metal ion | Membrane impregnated with metal salt, NaBH ₄ (aq) | Membrane/catalyst assembly |
| Catalyst preparation and application: dry spraying method [49] | | |
| 1. Composite powder making | Metal-catalyst supported C, PTFE, membrane material powder | Composite powder |
| 2. Atomization | Composite powder | Atomized powder |
| 3. Dry spraying | Atomized powder, membrane | Coated membrane |
| 4. Hot rolling | Coated membrane | Membrane/catalyst assembly |
| Catalyst preparation and application: novel fabrication method [50] | | |
| 1. Catalyst preparation | PFSA, metal-catalyst | PFSA coated catalyst |
| 2. Vacuum drying | PFSA coated catalyst | Dried catalyst |
| 3. Mixing catalyst with other elements | Catalyst, PTFE, CaCO ₃ , water | Composite mixture |
| 4. Filtration | Composite mixture | Filtrate |
| 5. Rolling | Filtrate | Rolled sheet |
| 6. CaCO ₃ removal | HNO ₃ , sheet | CaCO ₃ free sheet |
| 7. Drying | Sheet | Electrode catalyst assembly |
| 8. Hot pressing at 150 °C | Electrode catalyst assembly, membrane | Membrane/catalyst assembly |
| Catalyst preparation and application: catalyst decaling method [1] | | |
| 1. Mixing | Metal-catalyst supported C, solubilize ionomer | Metal ink |
| 2. Conversion of ink to TBA+ form | Metal ink, TBAOH | TBA + ink |
| 3. Apply TBA+ ink to PTFE blank | TBA+ ink, PTFE blank | Coated blank |
| 4. Drying | Coated blank | Dried blank |
| 5. Hot press to Na ⁺ membrane | Membrane, dried blank, heat | Membrane/blank assembly |
| 6. Peel of blank | Membrane/blank assembly | Coated membrane |
| 7. Protonation | Coated membrane, boiling H ₂ SO ₄ | Protonated membrane |
| 8. Rinsing | Deionized water, membrane | Clean, protonated membrane |
| 9. Air drying | Clean, protonated membrane | Membrane/catalyst assembly |
| Catalyst preparation and application: painting method [1] | | |
| 1. Painting of ink on Na ⁺ polymer electrolytemembrane | TBA+ ink, Na ⁺ membrane | Coated membrane |
| 2. Oven dry in a vacuum table | Heat, coated membrane | Semi-dried coated membrane |
| 3. Rapid heating | Semi-dried membrane | Dried coated membrane |
| 4. Protonation | Coated membrane, boiling H ₂ SO ₄ | Protonated membrane |
| 5. Rinsing | Deionized water, membrane | Clean, protonated membrane |
| 6. Air drying | Clean, protonated membrane | Membrane/catalyst assembly |
| Sputtering [38] | | |
| 1. Mixing | PFSA solution, carbon powder, Isopropyl alcohol | Ion conducting polymer ink |
| 2. Sputtering | Membrane | Sputtered membrane |
| 3. Brushing | Ion conducting polymer ink, sputtered membrane | Coated membrane |
| 4. Repeat 2 and 3 | | Membrane/catalyst assembly |

nested subplates. The difference in depth of the nested subplates produces a center-cooling chamber with the interior surfaces of the subplates not in contact. Flat wire current collectors are bonded to the diffusion electrode or to the flow channels of the bipolar plate.

No matter the plate configuration, because bipolar plates are exposed to an operating environment with a pH of 2–3 at high temperatures, if not designed properly, dissolution or corrosion of the metal will occur. Specifically, when the metal plate is dissolved, the dissolved metal ions diffuse into the membrane and are trapped at ion exchange sites, result-

ing in a lowering of ionic conductivity. In addition, a corrosion layer on the surface of a bipolar plate increases the electrical resistance in the corroded portion and decreases the output of the cell.

Because of these issues, metallic bipolar plates are designed with protective coating layers. Borup and Vanderborgh [6] suggest that coatings for bipolar plates should be conductive and adhere to the base material properly to protect the substrate from the operating environment. They present an overview of carbon-based and metallic bipolar plate coating materials. Carbon-based coatings include: (1)

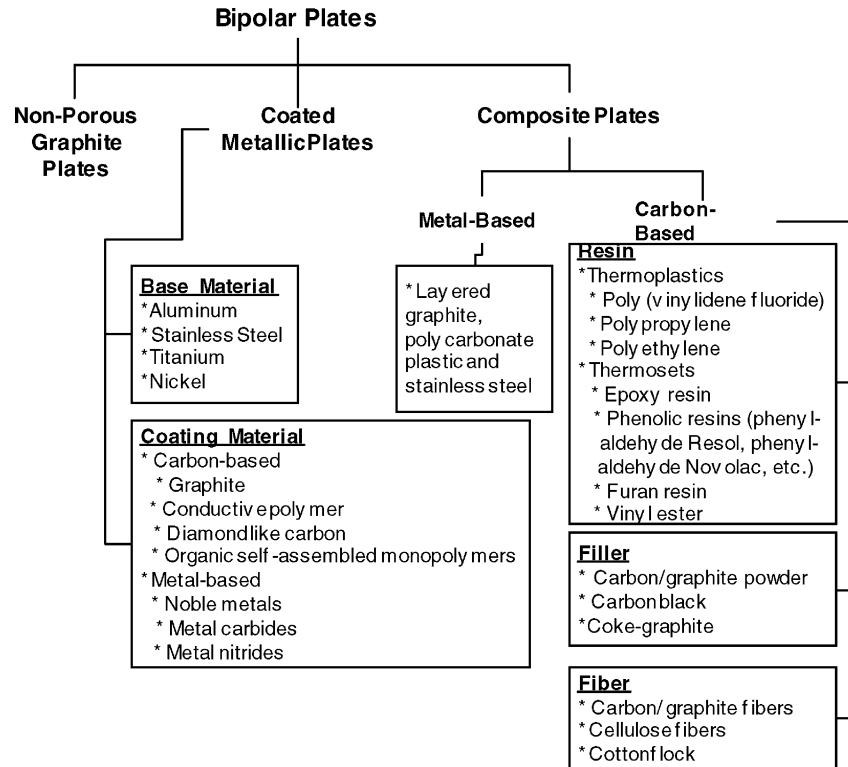


Fig. 5. Classification of bipolar plate materials.

graphite, (2) conductive polymer, (3) diamond like carbon, (4) organic self-assembled monopolymers. Metal-based coatings include: (5) noble metals, (6) metal nitrides, (7) metal carbides. Table 7 lists bipolar plate coatings suggested by Borup and Vanderborgh and others. The coating techniques for these methods can be found in Table 10.

Woodman et al. [55] studied the corrosion failure mechanism for coated bipolar plates. They concluded that the coefficient of thermal expansion (CTE), corrosion resistance of coating, and micro-pores and micro-cracks play a vital role in protecting the bipolar plate from the hostile PEM fuel cell environment. Woodman et al. also state that even though PEM fuel cells typically operate at temperatures less than 100 °C, vehicle service would impose frequent startup and shut down conditions, and temperature differentials of 75–125 °C would be expected. This is an important consideration for metal coated bipolar plates because the two metals may expand and contract at different rates. The resulting micro-pores and micro-cracks may lead to failure if the base metal becomes exposed to the acidic fuel cell environment. A large difference in the CTE of the substrate and coating materials may lead to coating layer failure. One technique to minimize the CTE differential is to add intermediate coating layers with CTEs between that of adjacent layers.

3.1.3. Composite plates

Composite plates can be categorized as metal-or carbon-based. A metal-based composite bipolar plate has been

developed by Los Alamos National Laboratory [24]. This design combines porous graphite, polycarbonate plastic and stainless steel in an effort to leverage the benefits of the different materials. Since producing porous graphite plates is not as time consuming or expensive as producing non-porous graphite plates, it can be used while impermeability is provided by the stainless steel and polycarbonate parts. Stainless steel also provides rigidity to the structure while the graphite resists corrosion. The polycarbonate provides chemical resistance and can be molded to any shape to provide for gaskets and manifolding. The layered plate appears to be a very good alternative from stability and cost standpoints.

Extensive literature was found citing the use of carbon-based composite bipolar plates in fuel cells. Table 8 summarizes notable citations. As shown, carbon composite bipolar plates have been made using thermoplastic (polypropylene, polyethylene, poly(vinylidene fluoride)) or thermosetting resins (phenolics, epoxies and vinyl esters) with fillers and with or without fiber reinforcement. In the early years of development, thermoplastics were preferred as the resin material. However, in the late eighties the preference changed to thermosets. Wilson [60] suggests this preference was due to short processing cycles. However, more recently select bipolar plate manufacturers, such as Micro Molding Technology [61], are producing bipolar plates using thermoplastic resin because they are more readily recyclable.

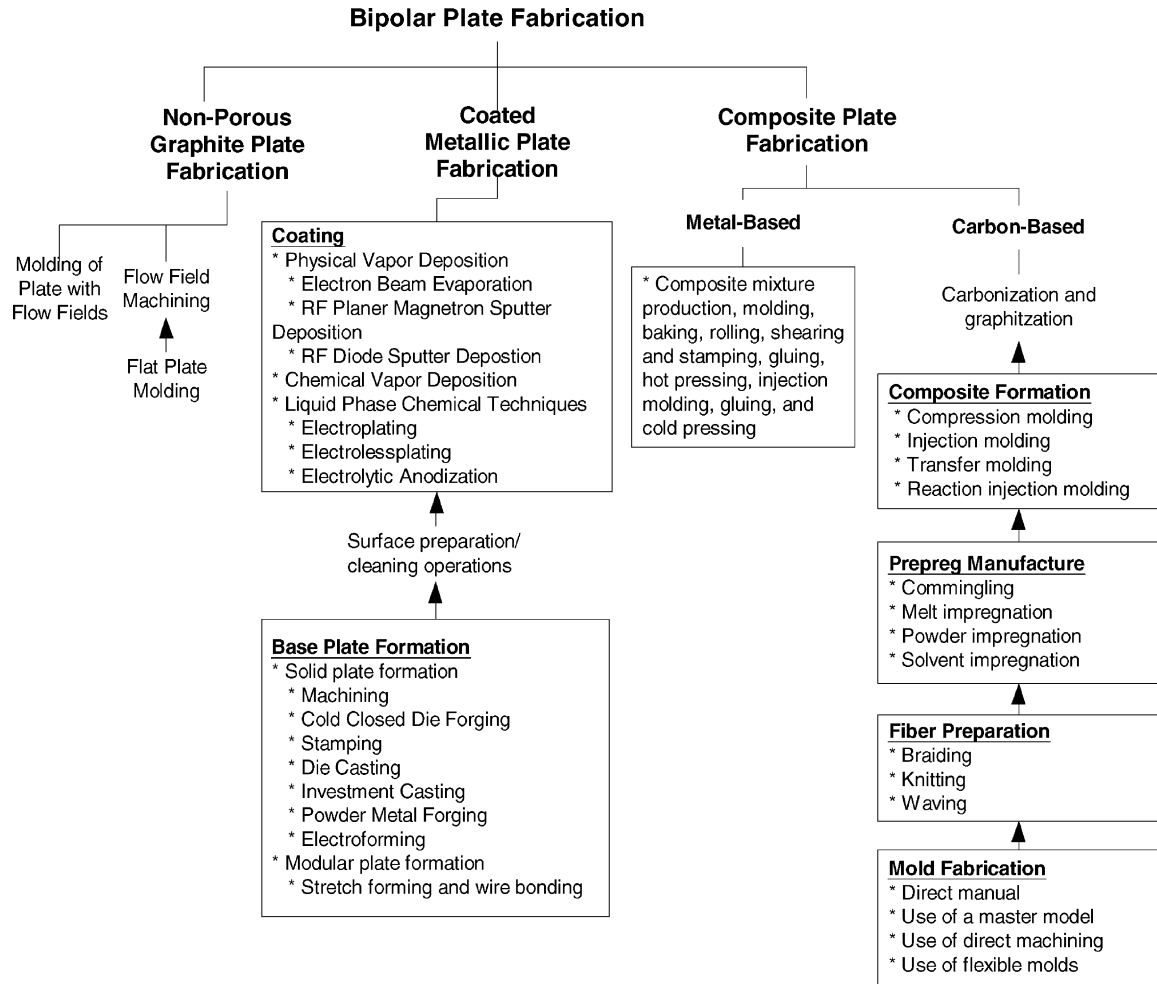


Fig. 6. Classification of bipolar plate manufacturing alternatives.

Table 7
Coating materials for metallic bipolar plates

| Coating method | Coating materials | Applicable base plate materials | | | |
|---|--|---------------------------------|----|----|----|
| | | Al | SS | Ti | Ni |
| Conductive polymers coating [6] | Conductive polymers | Not specified | | | |
| Diamond-like carbon coating [6] | Diamond-like carbon | Not specified | | | |
| Gold topcoat layering [55,56] | Gold over nickel over copper | x | | | |
| Graphite foil layering [57] | (1) Sublayer—sonicated graphite particles in an emulsion, suspension or paint (e.g. graphite particles in an epoxy resin thinned by an organic solvent, such as toluene); (2) topcoat—exfoliated graphite in the form of sheets of flexible, graphite foil | x | | x | x |
| Graphite topcoat layering [57] | (1) Sublayer—titanium over titanium–aluminum–nitride; (2a) overcoat—transient metal sublayer of Cr (Ti, Ni, Fe, Co) followed by sulfuric/chromic acid OR; (2b) topcoat—graphite | x | x | x | x |
| Indium doped tin oxide layering [58] | Indium doped tin oxide (Sn(In)O ₂) | | x | | |
| Lead oxide layering [58] | (1) Sublayer—lead; (2) topcoat—lead oxide (PbO/PbO ₂) | | x | | |
| Organic monopolymer coating [6] | Organic self-assembled monopolymers | Not specified | | | |
| Silicon carbide layering [58] | (1) n-Type silicon carbide (SiC); (2) Gold | | x | | |
| Stainless steel layering [59] | (1) Sublayer—chromium/nickel/molybdenum-rich stainless steel OR nickel-phosphorus alloy; (2) topcoat—titanium nitride | x | x | x | |
| Titanium–aluminum nitride layering [58] | Titanium–aluminum–nitride layer | x | | | |
| Titanium nitride layering [58] | Titanium nitride (TiN) layer | | | x | |

Table 8
Summary of carbon composite materials used in bipolar plates [62–71]

| Resin | Type of resin | Filler | Fiber |
|---|---------------|-------------------------------|--|
| Poly(vinylidene fluoride) | Thermoplastic | Carbon/graphite particles | |
| Poly(vinylidene fluoride) | Thermoplastic | Carbon/graphite particles | Carbon/graphite fibers |
| Polypropylene | Thermoplastic | Carbon black, graphite powder | |
| Mixture of an epoxy resin and an aromatic amine hardener] | Thermoset | Graphite powder | |
| Phenyl-aldehyde resol OR phenyl-aldehyde novolac | Thermoset | Graphite powder | Graphite fibers or whiskers |
| Phenyl-aldehyde resol OR phenyl-aldehyde novolac | Thermoset | Coke-graphite particles | |
| Reichhold 24-655 phenolic resin | Thermoset | Graphite powder | Cellulose fibers (but not rayon and cellulose acetate) |
| Phenol resin or furan resin | Thermoset | Graphite powder | Cellulose fibers (but not rayon and cellulose acetate) |
| Phenolic resin | Thermoset | | Carbon fibers (PAN-based) |
| Vinyl ester | Thermoset | Graphite powder | Cotton flock (graphite/carbon, glass, cotton, and polymer) |

3.2. Bipolar plate manufacturing

3.2.1. Non-porous graphite plate fabrication

Woodman et al. [55] states that state-of-the-art PEM fuel cells contain graphite bipolar plates that are machined or molded with flow fields. Although no other citation was found that discussed machined graphite bipolar plates, compression molding is discussed by Meissner [72]. In this method, graphite mixtures that contain crystalline graphite with additives and/or binders are compression molded and preferably subjected to a heat treatment in the absence of oxygen. Suitable additives include aluminum oxide, zircon dioxide, silicon dioxide, titanium dioxide, silicon carbide, and powdered coke. Suitable binders are cokable from 300 to 800 °C and include carbohydrates such as fructose, glucose, galactose and mannose and oligosaccharides such as sucrose, maltose and lactose.

3.2.2. Coated metallic plate fabrication

The process for fabricating coated metallic bipolar plates includes formation of the base plate, surface preparation and cleaning operations, and coating processes. For the more typical solid metallic bipolar plate designs, formation of the base plate by machining or stamping is suggested by Woodman et al. [55]. Mehta [7], in an effort to extend Woodman's suggestions, applied the process selection system, *Cambridge Engineering Selector* by Granta Designs to identify additional solid plate formation processes. Using design information such as materials, part shape and size, tolerance, surface finish, production quantity and a "quality factor" (used to select among processes prone to defects), Mehta added five fabrication alternatives to Woodman, et al.'s original two: cold closed die forging, die casting, investment casting, powder metal forging, and electroforming. The result of Mehta's analysis, which assumed production quantities above 10,000, is presented in Table 9 for two basic plate designs. The analysis captures changes in quality (factors 5–10), tolerance (from 0.05 to 0.1 mm) and surface finish (10–100 µm) for the two basic designs. In general, the

number of manufacturing options increases as tolerances increase and as surface finish and quality requirements decrease. No differences were noted above these ranges, and literally no processes fall below them. A significant observation was that more processes were identified for the larger faced plate. Specifically, investment casting and powder metal forging and often die-casting were not compatible to produce the smaller faced design.

For Allen's less typical modular metallic bipolar plate [54] discussed in Section 3.1.2, plate formation is more specialized. In plate formation, flow channels and manifolds are "stretched formed" into finite subsections by progressive tooling. The tooling is designed such that the tool may be closed to any engagement to produce any depth for the flow ribs within the elongation constraints of the material being formed. As such, a subplate stretch formed to the maximum extent will nest with a subplate stretch formed to less than the maximum extent. Finally, parallel flat wire current collectors are continuously slit from coiled material and bonded to the diffusion electrode or to the flow channels of the bipolar plate prior to assembly.

Coating processes for solid or modular metallic bipolar plates include a variety of deposition processes as listed in Table 10. Processes include physical vapor deposition techniques like electron beam evaporation, sputtering and glow discharge decomposition, chemical vapor deposition technique, and liquid phase chemical techniques like electro- and electroless deposition, chemical anodization/oxidation overcoating, and painting.

3.2.3. Composite plate fabrication

For the layered metal composite bipolar plates developed at Los Alamos [24] described in Section 3.1.2, a multi-step process is used in fabrication. First, a stainless steel layer is produced using shearing and stamping methods. Next, graphite powder and resin are mechanically mixed and molded to the required shape by conventional compression or injection molding. The resulting graphite plate is baked in an oven. Next, a conductive adhesive is applied to the graphite

Table 9
Analysis of process options for solid metallic bipolar plates

| | Basic design | | | | | | | | | | | | |
|-----------------------------|---|-----|------|------|------|--------|--|-----|-----|-----|-----|-----|--------|
| | Smaller faced, thicker plate ^a | | | | | | Larger faced, thinner plate ^b | | | | | | |
| | 5–6 | 7–8 | 9–10 | 8 | 8 | 8 | 5–6 | 7–8 | 9 | 10 | 8 | 8 | 8 |
| Quality factor ^c | 5–6 | 7–8 | 9–10 | 8 | 8 | 8 | 5–6 | 7–8 | 9 | 10 | 8 | 8 | 8 |
| Design tolerance (mm) | 0.1 | 0.1 | 0.1 | 0.05 | 0.08 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | .05 | .08 | 0.1 |
| Surface finish (μm) | 10 | 10 | 10 | 10 | 10 | 50–100 | 10 | 10 | 10 | 10 | 10 | 10 | 50–100 |
| Aluminum | | | | | | | | | | | | | |
| Machining | x | x | x | x | x | x | x | x | x | x | X | x | x |
| Cold closed die forging | x | x | x | – | – | x | x | x | x | x | – | – | x |
| Stamping | x | x | – | – | x | x | x | x | – | – | – | x | x |
| Die casting | x | – | – | – | – | – | x | – | – | – | – | – | – |
| Investment casting | – | – | – | – | – | – | x | x | – | – | – | – | x |
| Powder metal forging | – | – | – | – | – | – | x | x | x | x | X | x | x |
| Stainless steel | | | | | | | | | | | | | |
| Machining | x | x | x | x | x | x | x | x | x | x | X | x | x |
| Cold closed die forging | x | x | x | – | – | x | x | x | x | x | – | – | x |
| Stamping | x | x | – | – | x | x | x | x | – | – | – | x | x |
| Die casting | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Investment casting | – | – | – | – | – | – | x | x | – | – | – | – | x |
| Powder metal forging | – | – | – | – | – | – | x | x | x | – | X | x | x |
| Titanium | | | | | | | | | | | | | |
| Machining | x | x | x | x | x | x | x | x | x | x | X | x | x |
| Cold closed die forging | x | x | x | – | – | x | x | x | x | x | – | – | x |
| Stamping | x | x | – | – | x | x | x | x | – | – | – | x | x |
| Die casting | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Investment casting | – | – | – | – | – | – | x | x | – | – | – | – | x |
| Powder metal forging | – | – | – | – | – | – | x | x | x | – | X | x | x |
| Nickel | | | | | | | | | | | | | |
| Machining | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Cold closed die forging | x | x | x | – | – | x | x | x | x | x | – | – | x |
| Stamping | x | x | – | – | x | x | – | – | – | – | – | – | – |
| Die casting | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Investment casting | – | – | – | – | – | – | x | x | – | – | – | – | x |
| Powder metal forging | – | – | – | – | – | – | x | x | x | – | x | x | x |
| Electroforming | x | x | x | x | x | x | – | – | – | – | – | – | – |

^a Maximum surface area 100 mm × 150 mm; thickness 5.4 mm; flow channel width 1.6 mm; maximum hole diameter 6.4 mm; minimum section 1.6 mm; aspect ratio 30.

^b Maximum surface area 250 mm × 600 mm; thickness 4.7 mm; flow channel width 1.6 mm; maximum hole diameter 6.4 mm; minimum section 1.6 mm; aspect ratio 49.

^c The quality factor is assessed on a numerical scale of 1–10 such that processes that are prone to produce defects receive a 1 and processes that minimize defects receive a 10.

plate using a screen-printing method. Next, a hot-press is used to join the stainless steel and graphite plates. Finally, to form the polycarbonate plates, polycarbonate resin is injection molded to the required shape and adhesive is applied to bond the plate with the stainless steel/graphite plate assembly using cold pressing.

For carbon-based composite bipolar plates, fabrication includes mold fabrication (direct manual, fabrication using a master model, fabrication through direct machining, fabrication through flexible molds), fiber preparation (braiding, knitting, weaving), prepreg manufacture (commingling; melt, powder, or solvent impregnation), and composite formation. Post-processing steps include carbonization and graphitization. In carbonization, the resin is converted to carbon by controlled decomposition of the carbon-hydrogen bonds. In graphitization, the structure gets denser.

Mehta [7] again applied *Cambridge Engineering Selector* to identify composite plate formation options. The result of Mehta's analysis, which again assumed production quantities above 10,000, is presented in Table 11 for the smaller faced plate design. Again, the number of manufacturing options increase as tolerances increase and as surface finish and quality requirements decrease. Again no differences were noted above the quality, tolerance, and surface finish ranges analyzed, and no processes fall below them or were recommended for production of the larger-faced plate.

4. Discussion

For use in PEM fuel cells, this work identified sixteen polymer electrolyte membranes, two types of GDLs, and

Table 10
Coating processes for metallic plates

| Coating method ^a | Coating processes |
|------------------------------------|---|
| Gold topcoat layering | Pulse current electrodeposition |
| Stainless steel layering | Physical vapor deposition (PVD) (e.g. magnetron sputtering), or chemical vapor deposition (CVD), and electroless deposition for Ni-Ph alloy |
| Graphite topcoat layering | PVD (closed-field, unbalanced, magnetron sputter ion plating) and chemical anodization/oxidation overcoating |
| Graphite foil layering | Painting OR pressing |
| Titanium nitride layering | RF-diode sputtering |
| Indium doped tin oxide layering | Electron beam evaporation |
| Lead oxide layering | Vapor deposition and sputtering |
| Silicon carbide layering | Glow discharge decomposition and vapor deposition |
| Titanium aluminum nitride layering | RF-planar magnetron (sputtering) |

^a Also see Table 7.

over 100 bipolar plate designs that are promising and require further study for use in PEM fuel cells. This work also reviews synthesis processes for many of the membranes and GDLs and added several processes to the bipolar plate fabrication options described in literature.

The review presented here combines the work of many researchers. As such, the designs and manufacturing methods can for the most part not be directly compared based on the information presented because there is no reason to believe fuel cell operating conditions or manufacturing process parameters are comparable. For example, for the process steps listed in the input-output tables (Tables 4–6), the level of abstraction presented is dependent upon that provided by the citations listed. This, and the lack of consistent data on input and output quantities, makes quantitative comparison impossible and qualitative comparison of processes difficult. But, we can recommend a basis for future comparisons, as provided in Table 12.

MEA design is dominated by a variety of materials issues. For membrane materials, issues relate to the dependence on

Table 11
Analysis of process options for carbon composite bipolar plate designs

| | Basic design | | | | |
|----------------------------|---|------|------|------|--------|
| | Smaller faced, thicker plate ^a | | | | |
| Quality factor | 5–6 | 7–10 | 8 | 8 | 8 |
| Design tolerance (mm) | 0.1 | 0.1 | 0.05 | 0.08 | 0.1 |
| Surface finish (μm) | 10 | 10 | 10 | 10 | 50–100 |
| Compression molding | x | – | – | – | X |
| Injection molding | x | – | – | x | X |
| Transfer molding | x | – | – | x | X |
| Reaction injection molding | x | – | – | x | X |

^a Maximum surface area 100 mm by 150 mm; thickness 5.4 mm; flow channel width 1.6 mm; maximum hole diameter 6.4 mm; minimum section 1.6 mm; aspect ratio 30.

complicated polymers (fluorinated, sulfonated or otherwise) that solve one problem while having repercussions (safety, temperature limitations, etc.) at the MEA, stack, and systems (supporting equipment) levels. For catalyst materials, tertiary alloys seem to offer the best performance when CO poisoning is of concern. However, in spite of environmental, social, and political concerns surrounding the use of Pt and other more rare and valuable metals in fuel cells, the use of non-Pt-based alloys has been limited to investigation of only one binary catalysts. Finally, for the GDL, although the carbon cloth offered superior performance in the Ballard Mark V cell study, no corroborating study was found. Also, properties like density, thickness, pore-size distribution, electrical conductivity should also be investigated.

For MEA manufacturing, catalyst preparation and application dominates research opportunities. With several processes able to prepare a catalyst layer with thickness down to 5 μm, the ability to maximize fuel cell performance and still meet the speed requirements of mass production will be the basis for final selection. With respect to performance, there is still disagreement on the preferred mode of application. Also, although sputter deposition is considered as one of the better approaches to apply catalyst to either of GDL or membrane, it is quite a slow process.

Bipolar plate design is dominated by the management of cost and stack mass and durability in the low pH, high

Table 12
Areas for future research

| Area for future research | Recommended basis for comparison of alternatives |
|--|---|
| Membrane materials | Fuel cell performance, cost, safety, supporting equipment requirements, synthesis issues (such as hazardous materials used in processing), and temperature-related limitations |
| Catalyst materials | Fuel cell performance, cost, abundance of materials and related social and political concerns, recyclability |
| GDL materials | Density, thickness, pore-size distribution, electrical conductivity |
| Catalyst preparation and application methods (in one or two steps) | Fuel cell performance, metal loadings of the order of ≤ 0.1 mg/cm ² ; degree of metal dispersion; energy use, hazardous material use and waste |
| Bipolar plate materials | Fuel cell performance, chemical compatibility, resistance to corrosion, cost, density, resistance to dissolution (for metallic plates), electronic conductivity, gas diffusivity/impermeability, manufacturability, recyclable/recycled, stack volume/kW, strength, surface finish requirements, thermal conductivity, and tolerance requirements |
| Bipolar plate fabrication | Fuel cell performance, tolerance and surface finish capability, capacity relative to mass production needs, and flexibility relative to incorporating unique features (seals, manifolding, cooling systems, etc.) |

Table 13
Design criteria for bipolar plate materials [6–8,36]

| S. no. | Material selection criteria | Limit |
|--------|--------------------------------|--|
| 1 | Chemical compatibility | Anode face must not produce disruptive hydride layer; cathode face must not passivate and become nonconductive |
| 2 | Corrosion | Corrosion rate < 0.016 mA/cm ² |
| 3 | Cost | Material + fabrication < US\$ 0.0045 cm ⁻² |
| 4 | Density | Density < 5 g/cm ³ |
| 5 | Dissolution | Minimization of dissolution (for metallic plates) |
| 6 | Electronic conductivity | Plate resistance < 0.01 Ω cm ² |
| 7 | Gas diffusivity/impermeability | Maximum average gas permeability < 1.0 × 10 ⁻⁴ cm ³ /s cm ² |
| 8 | Manufacturability | Cost of fabrication (see 3) should be low with high yield |
| 9 | Recyclable | Material can be recycled during vehicle service, following a vehicle accident, or when the vehicle is retired |
| 10 | Recycled | Made from recycled material |
| 11 | Stack volume/kW | Volume < 1 l/kW |
| 12 | Strength | Compressive strength > 22 lb/in. ² |
| 13 | Surface finish | >50 μm |
| 14 | Thermal conductivity | Material should be able to remove heat effectively |
| 15 | Tolerance | >0.05 mm |

temperature fuel cell operating environment. Bipolar plate design criteria, compiled from this and other research, are presented in Table 13. Among the bipolar plate materials presented in Section 3.1, none meet all the design criteria. Specifically, when compared to metal bipolar plates, non-porous graphite provides high corrosion resistance without the need for coating (<15 μ per year) and thermal conductivity (~4 W/cm K) at a low density. Although tending to be lower in electrical conductivity, compressive strength, and recyclability, graphite plates have been preferred for space applications over other materials. Also, graphite plates are expensive, from both material and processing standpoints [24]. Composite plates, although processing can include many steps, have the advantage of being flexible for incorporating seals, manifolding, cooling systems, and other features.

For bipolar plate manufacturing, two non-porous graphite plate formation options, eight metal plate formation processes and nine coating processes, and five composite formation processes are presented. Although forming non-porous graphite plates can be a time-consuming and therefore expensive process, hazardous materials costs related to purchasing, handling/training, and the management of wastes in all of the composite fabrication processes and most of the coating processes investigated could balance costs.

The research described here is part of a larger project analyzing the environmental life cycle of fuel cells for transportation applications. The project applies Life Cycle Assessment (LCA), a protocol for assessing the environmental aspects (for example, oil and platinum consumption, greenhouse gas emissions, etc.) of a product from various points in their life cycle: from raw materials acquisition through production, use, and disposal [73–75]. Understanding product design is important to the development of a bill-of-materials for the identification of materials used in the

product for the application of LCA. Because the bills-of-materials used in LCA need to represent equivalent products (for example, a variety of fuel cells capable of moving the same automobile), linking the design alternative above to fuel cell performance is an important research need. Also, understanding manufacturing alternatives allows the production phase and ultimately materials acquisition to be modeled. For both design and manufacturing, understanding the variety of alternatives that exist prior to wide-scale production facilitates product design and process selection based on environmental criteria prior to large capital investment.

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