# Fuel Cell Manufacturing: An Introduction to Opportunities and Challenges

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## Abstract

Recent events have lead to surging interest in alternative energy sources and their utilization. One example is the fuel cell. Fuel cells are seen as clean energy sources for a number of applications, including automobiles and power supplies for homes. As a result, there are significant research efforts being made to develop fuel cells and to improve their competitiveness in cost per kilowatt compared to more conventional energy sources. In addition, if fuel cells are to be used in high volume products, they must be manufactured efficiently and in quantity.

This situation presents opportunity for both professionals and educators in the manufacturing field. Currently, fuel cells are low volume products that are often built to order, with resulting higher costs and longer lead times. Many of the key components of fuel cells are not made using high production techniques. Successful evolution of the fuel cell industry requires production research and the application of modern manufacturing principles, as well as a supply of graduates from manufacturing programs in which these principles have been emphasized.

This paper introduces readers to some aspects of fuel cell manufacturing impeding efficient production. A brief description of proton exchange membrane (PEM) fuel cell technology, components, and the current state of the art of their manufacture are presented. Educational challenges and specific efforts to address them currently underway within in the College of Technology and Applied Sciences (CTAS) at Arizona State University (ASU) are discussed. An annotated bibliography related to fuel cell manufacturing is also included as an aid to others interested in the topic.

## Introduction

Recent events have led to renewed efforts to reduce the nation's dependence on fossil fuels, and to reduce the impact of energy conversion processes on the environment. A technology with potential to solve both of these problems is the fuel cell. Fuel cells are direct energy conversion devices that use an electrochemical reaction to produce power in an external circuit. Suitable reactions involve the exchange of ions across an electrolyte, with the electrons flowing through an external circuit from which electrical power can be utilized. There are many electrochemical reaction/electrolyte combinations used to produce power in this manner. A particularly promising and widely used technology is the Proton Exchange Membrane (PEM) fuel cell utilizing hydrogen as the fuel and oxygen as the oxidizer, separated by a solid Nafion layer (polytetrafluoroethylene, or PTFE, treated with perfluorosulfonic acid), which becomes an ionic conductor for hydrogen ions (protons) if properly hydrated. PEM fuel cell systems are relatively straight-forward, they operate at low temperatures (~80°C), can be started quickly, and produce only pure water as a *direct* exhaust product. Consequently, this technology has received a great deal of attention for both residential and transportation applications. In this paper, some of the manufacturing issues relevant to PEM fuel cell systems are introduced. Efforts underway at Arizona State University that address selected issues are also discussed, as well as how these issues are being integrated into the curriculum.

A primary reason for the large scale interest and investments in PEM fuel cells is the large potential market for this technology. For example, in his January 28, 2003 State of the Union address, President Bush recommended the commitment of 1.2 billion dollars in research funding for the development of hydrogen technologies[1]. Most major automotive manufacturers have fuel cell development programs underway, and have produced prototype vehicles for the consumer market[2]. The stationary fuel cell market, including residential applications, is projected to grow to $40 billion by the year 2010[3].

A complete fuel cell system consists of the fuel cell stack (in which power is generated) and accessory systems that provide process flows, control thermal, stoichiometric and psychrometric operating conditions, and control and condition electrical power. In addition, in many cases a separate fuel processing unit is provided which extracts hydrogen from a more conventional fuel, such as methane or methanol. The stack support systems are commonly referred to as the "balance of plant." For the fuel cell system to function effectively, all of the subsystems must be matched and properly integrated, resulting in a complex systems engineering problem. On the surface, it would seem that the balance of plant components can be purchased off the shelf, but in practice many of the available components are poorly suited to fuel cell applications. There is substantial engineering work needed to develop optimal accessory components for fuel cell systems, and these components present their own unique manufacturing challenges, as well as opportunities for graduates of manufacturing programs. In this paper, we will confine our discussion to manufacturing challenges within the fuel cell stack.

## Basic Electrochemistry of Fuel Cells

A PEM fuel cell operating with hydrogen utilizes the hydrogen oxidation reaction to produce power. However, instead of the direct production of heat, in a fuel cell the hydrogen is oxidized at the anode of an electrochemical cell, and oxygen is reduced at the cathode. The anode half-reaction is:

$$H_2 \rightarrow 2H^+ + 2e^- .$$

The Nafion electrolyte layer is an ionic conductor for protons, but it does not conduct electrons. Consequently, the hydrogen ions (protons) from this half-reaction pass through the Nafion electrolyte to the cathode and the electrons are directed through an external circuit, and eventually back to the cathode side. The cathode half-reaction is:

$$\frac{1}{2}O_2 + 2e^- + 2H^+ \rightarrow H_2O\,.$$

A more detailed discussion of the electrochemistry, cell potential, efficiency, and other topics may be found in Larminie and Dicks[4]. However, an important fact that directly impacts manufacturing cost is that the half-reactions on both the anode and cathode side must be accelerated by the presence of a catalyst, which is usually platinum.

In addition to hydrogen, PEM fuel cell have been designed to operate with liquid methanol. While there are distinct advantages to utilizing a liquid fuel, in practice the performance of Direct Methanol Fuel Cells (DMFC) has suffered because of fuel cross-over and less than ideal electrode reaction kinetics[5]. While research continues in this area, at present most large scale residential and transportation applications of PEM fuel cells envision gaseous hydrogen as the fuel and air as the oxidizer. Since the fundamental design and construction of these technologies differ only in detail, the manufacturing challenges are similar.

## Design of the Fuel Cell Stack

Publications which describe in detail the design and construction of PEM fuel cell stacks include Larminie and Dicks[4] and Mehta and Cooper[6]. As illustrated in figure 1, the basic construction of the stack include the Membrane Electrode Assembly (MEA), current collecting ("bipolar") plates, and seals to prevent gas leakage.

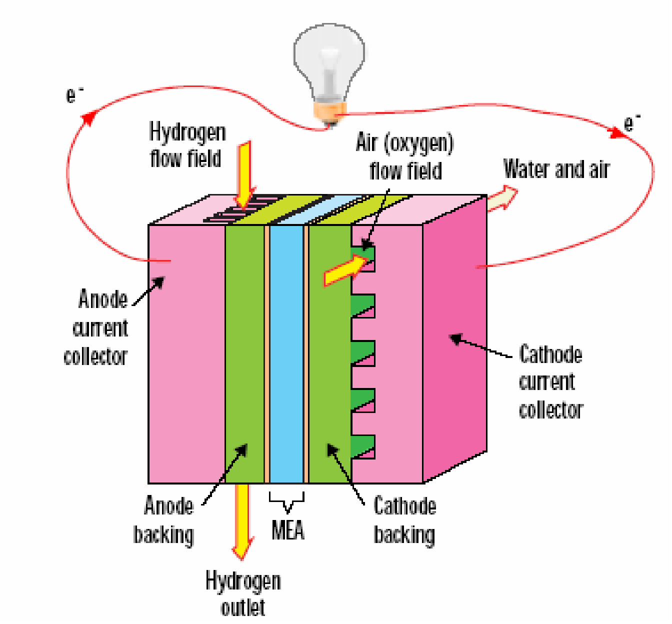

Figure 1. Fuel Cell Components[7].

At operating conditions, a single stage produces about 0.7 Volts, and cells must be connected in series to produce adequate voltages for most applications. The most common method is to separate adjacent cells with bipolar plates, so that one side of the plate forms the cathode while the other side forms the anode (at higher potential) of the adjacent cell, as illustrated in figure 2.

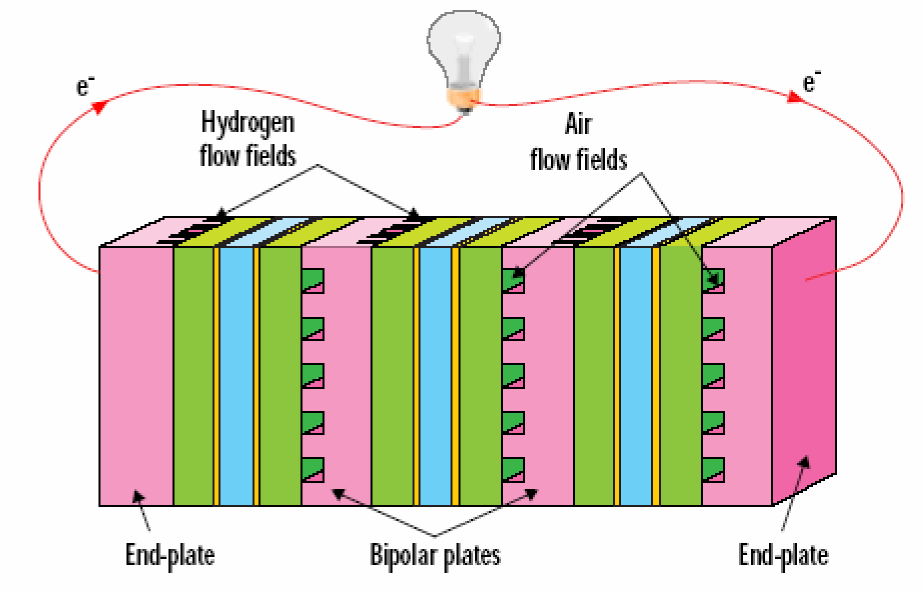

Figure 2. Fuel Cell Stack Construction using Bipolar Plates[7].

In addition to providing structural integrity to the stack, bipolar plates serve to conduct electricity through the membrane electrode assembly, and to dissipate heat. They also have channels on each face to direct the flow of reactant gases over the backing layers of the membrane electrode assembly, and to allow expulsion of water produced in the cathode reaction. Consequently, basic requirements are that they should be good conductors of both heat and electricity, be chemically stable, and be non-porous to maintain separation of the hydrogen and the oxygen. The most common material for bipolar plates is solid graphite, with the flow passages machined into the face. At ASU, various manufacturing techniques for these components are being investigated.

The membrane electrode assembly (MEA) consists of the Nafion proton exchange membrane, which separates the anode and cathode catalytic reaction layers, both of which are covered by a porous backing called the gas diffusion layer, as illustrated below in figure 3. The gas diffusion layers allow hydrogen or oxygen to diffuse to the surface of the catalyst layer, and conducts electricity to or from the bipolar plates as appropriate. The most common base material for this layer is porous carbon cloth.

The catalyst layer is of particular interest in fuel cell manufacturing because of the expense of the platinum catalyst. For a successful reaction to occur at a catalyst site, all of the following must occur. First, the gas must reach the site, whether directly or by diffusing through a thin Nafion coating. Second, there must be a path for the electron conduction into the external circuit. Finally, there must be a path for proton conduction into the Nafion electrolyte. These conditions are not met at most catalyst sites, resulting in the need to "overload" the layer with platinum, thus driving up cost. If the utilization of platinum can be increased, a direct savings in the capital costs of the fuel cells will be realized. At ASU, an innovative manufacturing technique using the properties of an electrorheological fluid is being investigated and has the potential to drastically increase platinum utilization.

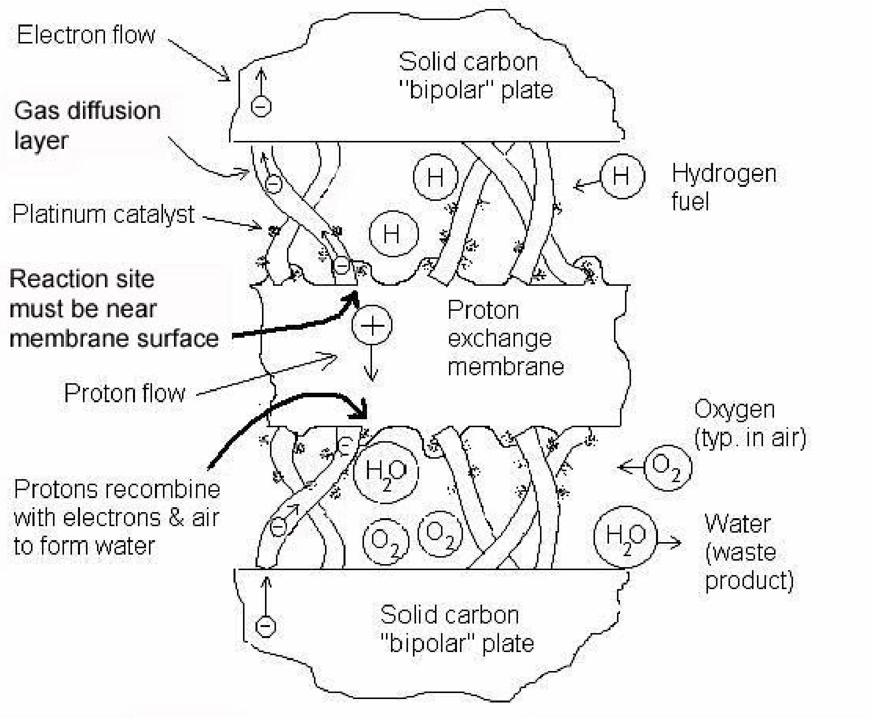

Figure 3. Details of the Membrane Electrode Assembly

## Manufacturing Issues

Reliable, functional fuel cell systems can be built and installed today; in fact, the Solar Photovoltaic Laboratory building at ASU-East is powered by a prototype fuel cell system that has produced over 12 MW-hrs in the past 6 months, with no maintenance. The main issue in using fuel cells is cost. A fuel cell stack, without the 'balance of plant', today costs about $2000-$3000/kw. To become competitive in the marketplace for more general use, complete stationary systems *with* balance of plant should cost about $1000-$1500/kw[8], and automotive systems will need to cost far less, perhaps $50/kw[9]. Studies show these cost reductions are ultimately achievable[8,9]. While better understanding of fuel cell electrochemistry will contribute to these goals, improved manufacturing will have a major impact. Some of the improvement will come from a transition to mass production, some will come from design improvements to stack components that address manufacturability issues, and some will come from manufacturing process improvements for individual stack components.

## Membrane Electrode Assembly, MEA

The PEM, (which also stands for polymer electrolyte membrane), is itself expensive to manufacture because many chemical processing steps are necessary, and hazardous materials are involved. PEM manufacturing is essentially a chemical process, and the material presently costs about $25/kw. The membrane is part of a sub-assembly in the fuel cell stack consisting of the membrane, the Gas Diffusion Layer (GDL), catalyst, and a bonding agent that must be a proton conductor like the membrane (see figure 3). In typical cells the GDL is a paper or cloth product that can be thought of as a sponge initially coated with the platinum catalyst. This process is inefficient, since most of the platinum is dispersed to locations that do not provide a conduction paths for both protons and electrons, simultaneously. This platinum, typically 85% of the amount applied, is never able to catalyze reactions. Platinum catalyst currently costs about $8/kw or more. The electrode sponges are also coated with PTFE plastic, in an attempt to link more of the platinum particles with a proton conduction path. The GDL layers are then either hot-pressed or solvent-bonded to each side of the membrane. This multi-step process is time-consuming, and if the membrane overheats to just 150 C, it can release toxic gas[6].

To overcome problems with both efficiency and manufacturability, numerous approaches are under study that would change the traditional design of the membrane and the GDL. An option being explored at Arizona State University East is to incorporate the catalyst inside the PEM, along with micro-organized carbon conductors, as illustrated on figure 4. This approach is intended to improve utilization of the catalyst, but it may eliminate the need to bond the GDL to the PEM, and it may increase the power output per square cm as well. Although the catalyst resides below the surface of the membrane in this design, both hydrogen and oxygen will diffuse into the membrane to reach the reaction sites, and the byproduct, water, can still escape.

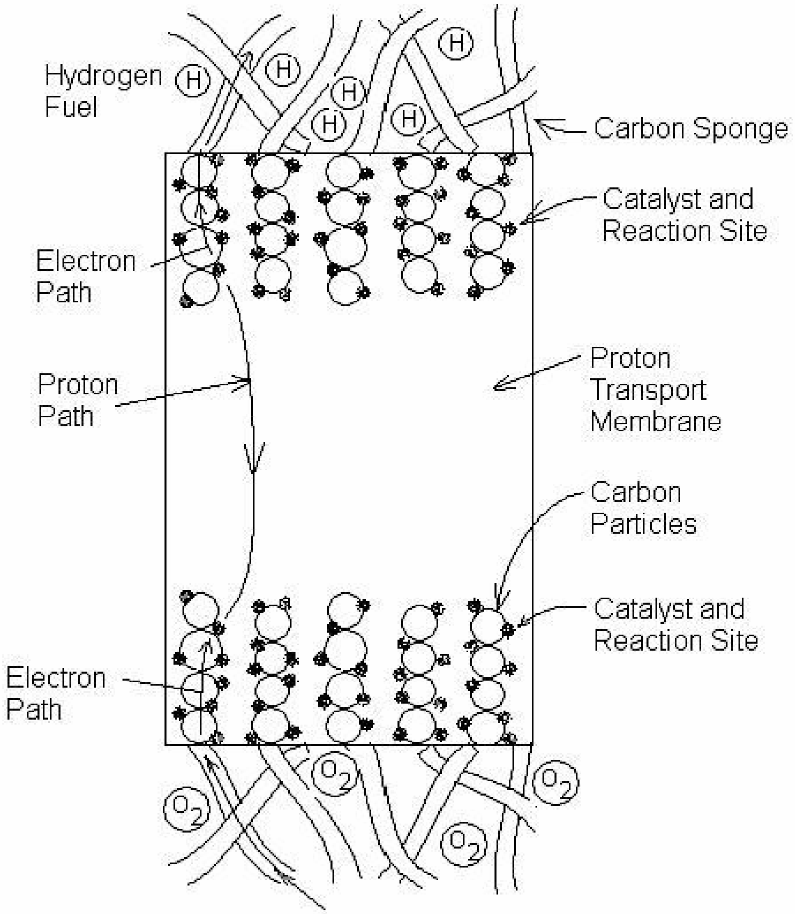

Figure 4. A micro-organized PEM incorporating catalyst.

PEM micro-organization as shown in figure 4 will be achieved with the Winslow effect commonly used in electrorheological (ER) devices. A slurry of liquid polymer and carbon particles hosting catalyst will be placed in a high electric field, which causes the particles to organize into columns, as illustrated in figure 5. Particulate densities in ER fluids are typically in the 15-40% range, so carbon columns can be closely packed. The slurry will then be solidified, and the resulting thin layers of micro-organized material will be bonded to a central layer of standard PEM to produce the cross-section shown in figure 4. With this design, almost all catalyst sites can be utilized. It is anticipated that a wide ribbon of the final product can be made in a continuous process at a reasonable cost, although a suitable process has yet to be detailed.

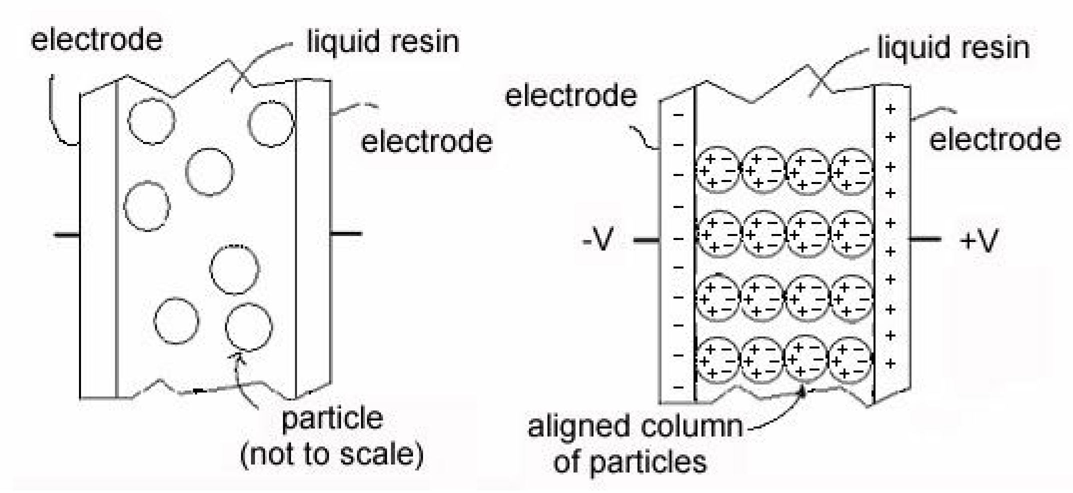

Figure 5. Electrorheological fluid behavior

## Bipolar Plates

Bipolar plates are one of the more straight-forward elements of a fuel cell stack. They must provide structural support for the membrane electrode assembly, permit fuel distribution and water removal through a pattern of channels, conduct heat and electricity, be impermeable to fuel, and resist corrosion. Corrosion is a key issue, since the environment is wet, may approach 100C, and has a pH of 2-3. Additionally, the plates should be recyclable. These objectives can be achieved in many ways, and design choices are mostly made to minimize manufacturing cost.

Manufacturing techniques available for fabrication of bipolar plates are partly determined by the selection of the material. Solid graphite is the most common material used. It is easily machined, and with CNC technology, mass production is straightforward. However, graphite is more expensive than many metals, it is brittle and easily damaged, significant machining time is required, and the necessary machines and dust collection equipment are expensive. Carbon composite materials can be produced with electrical and thermal properties similar to pure graphite, but with greater mechanical strength. These materials also have the advantage that they may be injection or compression molded. Some carbon composite plates are made with a porous graphite, because it is easier to work with. However, a corrosion-resistant metal or plastic surface layer is required to block leakage of fuel. Metal plates are also made, but although they are impermeable, they also require a special surface layer to prevent corrosion. Aside from the damage it can do to the bipolar plate, even small amounts of corrosion products can poison the catalyst layer and reduce efficiency. Surface coatings on metal plates must adhere well, without cracking or forming micro-pores, even after significant thermal cycling inside the cell.

At ASU, solid graphite bipolar plates have been machined for both research and instructional purposes, and an example is shown in figure 6.

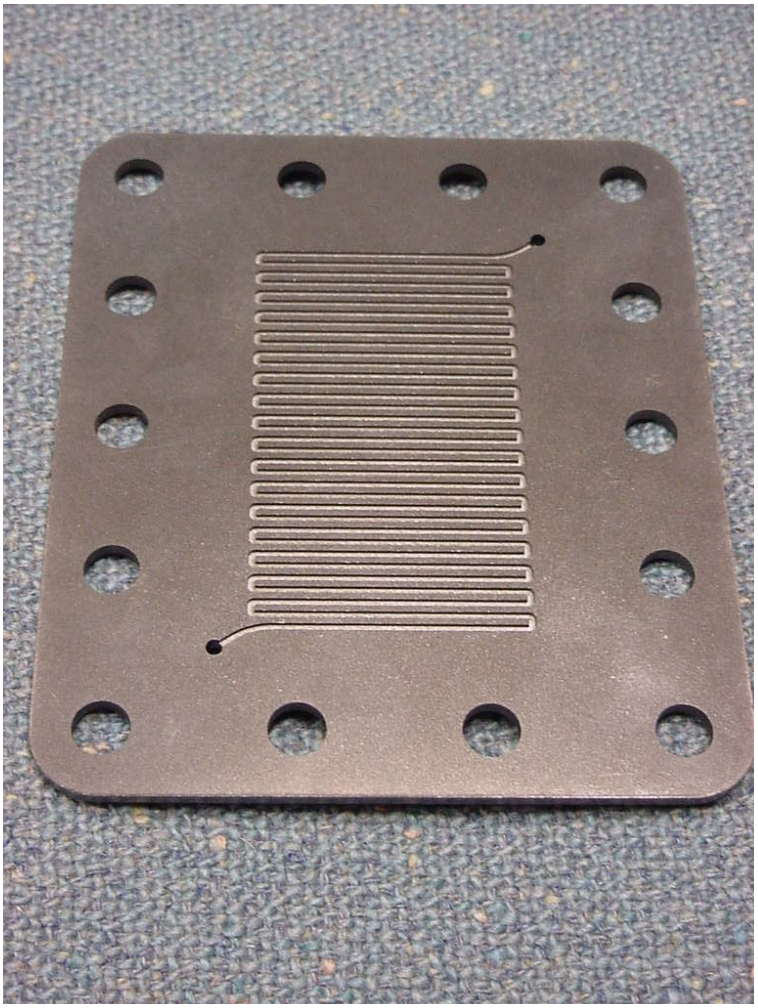

Figure 6. Graphite bipolar plate machined at ASU

Bipolar plates currently cost about \$200/kw[8]. In mass production, costs of \$10/kw for molded bipolar plates should be attainable[9], and estimates of \$5/kw have been made. For reference, the \$5/kw number corresponds to about 1500 square cm of plate[8].

The electrorheologically organized structure previously described for membrane construction may be applicable to bipolar plates as well. Carbon chains passing through the thickness of a composite bipolar plate could conduct electricity, and the matrix material may be chosen to satisfy other design requirements. Researchers at ASU East are evaluating this possibility.

## Assembly of Fuel Cells

High cost has limited the production quantities of fuel cells, and fuel cell stacks are usually assembled by hand. A 12-volt fuel cell stack will require about 20 cells, and a stack intended to replace an auto engine may require about 400 cells, each cell having a bipolar plate, an MEA, and two seals all carefully aligned.

Assembly is complicated by the need to seal the individual cells in the stack to prevent fuel leakage, and because the PEM is fairly delicate. PEM is stored in liquid, and assembled wet, because it requires a controlled amount of water to function. While no serious obstacles to automation of the stack final assembly seem to exist, design for manufacturability will become more important in mass production.

## Educational Challenges

The field of fuel cells is interdisciplinary, and, since it is difficult for a single departmental unit to assemble the expertise necessary to offer an integrated curriculum, interdepartmental cooperation in the development of fuel cell related courses and curricula is beneficial. At ASU, the introductory fuel cell course is taught by a team of three faculty made up of an electrical engineer, an electrochemist, and a mechanical engineer.[10] Each faculty member teaches the material appropriate to their background. The goal of this course is to provide technically mature students with broad based understanding of fuel cell physics and technology at an introductory level.

The philosophy of the ASU programs is based on the recognition that fuel cell technology will be developed by teams of experts, and that few individuals will attain a depth of expertise in all fields related to fuel cells. At the same time, a broad based understanding of the fundamental principles of fuel cell systems is important for two reasons. First, the progress of the fuel cell team will be maximized through improved communication and understanding between specialists working toward a common goal. Second, as the careers of graduates progress and expand into management or entrepreneurial endeavors, a knowledge of the challenges and limitations facing individual specialists is important.

After mastery of fuel cell fundamentals, students are encouraged to specialize in specific topics related to fuel cells. For example, in the MMET Department, students may pursue further study and research in aspects of manufacturing, as discussed in this paper. Thus, the approach at ASU is to *embrace breadth*, while at the same time *encouraging specialization* in the field.

Finally, it is worthwhile to point out that general understanding of the physics and technology of fuel cells requires a certain technical maturity from the students. These topics are accessible to advanced undergraduates in engineering technology programs, or they may be offered as part of graduate programs. On the other hand, undergraduate students beginning as early as the sophomore year may contribute in significant ways to the solution of many of the manufacturing challenges that have been described in this paper.

## Conclusion

Fuel cells are attracting considerable attention by industry, government, and the general public. Thus, research on various aspects of fuel cells and their manufacture are receiving funding. Manufacturing improvements are important to fuel cell's ultimate market acceptance. Opportunities exist to improve the manufacturing efficiency of most cell components. This situation offers an opportunity for graduates of manufacturing programs to exercise their skills to help solve these challenges. The College of Technology and Applied Sciences at Arizona State University is helping its graduates be successful in the alternate energy industry via specialized engineering technology education. Also, an annotated bibliography is included in the appendix and may help the reader become more familiar with fuel cell manufacturing issues.

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