Getting Back into Gear: Fuel Cell Development after the Hype

by Jeremy P. Meyers

Just over a decade ago in this magazine, the question was posed, "Is There a Fuel Cell in Your Future?" While the author of that article wisely refrained from explicit predictions and carefully spelled out a lot of the key challenges that lay ahead for fuel cell development at the time, readers who read the article and who read about fuel cells in the mainstream press could be forgiven for assuming that the answer might well be "Yes. And soon." The late 1990s saw many companies investing heavily in fuel cells with the clear implication that clean energy technology was about to take off in the same way those contemporary internet startups had. Fuel cell developers saw their stocks take off as investors sought the next big thing, and clean energy seemed like it was poised to be that very opportunity. The stock market bubble burst, however, and, not long after, the success of hybrid vehicles suggested that they might achieve prominence in the marketplace before we might expect fuel cell vehicles to become widespread.

Fuel cells promise clean and efficient energy conversion, low-to-zero emissions at the point of use (a major boon for urban environments in particular), and flexibility in terms of the primary source of power that is used to generate the hydrogen or hydrogen-rich fuel. Industry and government have partnered in North America, Europe, and Asia to develop proton-exchange membrane fuel cells (PEFCs) for stationary, portable, and transportation applications.[1, 2] This class of fuel cells has benefited from more than a decade of industrial research and development for these uses, with the lion's share of development devoted to transportation applications. Because of this prolonged development effort, we have seen marked improvements in power density, energy conversion efficiency, and lifetime, and yet, very few of us are using fuel cell vehicles for our daily commutes.

The fuel cell industry is regrouping and re-directing its energies after a period of exuberance and subsequent disappointment. Fuel cell vehicle demonstration programs continue, albeit not at the pace that they were once projected to achieve. We find fuel cells moving closer to entering into specific niche markets such as cogeneration, forklift traction power, backup power/industrial battery replacement and consumer electronics, all of which have great promise, albeit smaller markets than automotive markets might someday become. While investors have become more cautious about fuel cells, given the long period in which investments did not yield large growth as hoped, the current state of the technology continues to advance, and is certainly more mature than it was when this wave of investment began. Now is a good time for a review of fuel cell technology, its promise, and its remaining challenges. ECS is an excellent forum to discuss these challenges, as many of the opportunities lie at the interface of electrochemistry, electrochemical engineering, mass transport, and materials science.

Where Are the Fuel Cell Vehicles?

So, in the year 2008, at a time of record gasoline prices and increased environmental awareness, why aren't we driving around in fuel cell cars? First of all, fuel cells and the hydrogen delivery and storage infrastructure needed to support them still cost far too much to be competitive with internal combustion engines. Secondly, they simply don't last long enough. When trying to compete in the automotive market where cars routinely run well in excess of 100,000 miles, durability is a difficult challenge.

What can be done? We must first identify where the sticking points are, and figure out what we can do to get them unstuck. We will consider the problem of market acceptance, and the improvements that are still needed in cost and durability.

Match-making: Technology and Marketplace

PEFCs have been the technology of choice for transportation because of their low-temperature operation, rapid startup capability, and flexibility in terms of the source of the hydrogen fuel. After researchers at Los Alamos demonstrated that a low-loading catalyst layer could be fabricated, significant investment was poured into the technology.[3] While PEFCs have yet to meet all of the requirements for automotive applications, the past decade has seen considerable progress in power density and durability. It makes sense, however, to consider the opportunity for fuel cells in other markets.

Fuel cells are not re-charged, as with a rechargeable battery; instead, they are simply fed fuel and air, just like a combustion engine. The fuel must be replenished after extended operation because the duration of power provided is limited by the fuel storage available. However, the fuel can potentially be replenished during operation, which makes fuel cells and generators the best options during prolonged electric-grid outages. Additionally, fuel cells are inherently simpler than internal combustion engines, although the balance-of-plant equipment required is not produced in the volumes that the accessories for gasoline engines are, and are not as integrated in their functionality as a result.

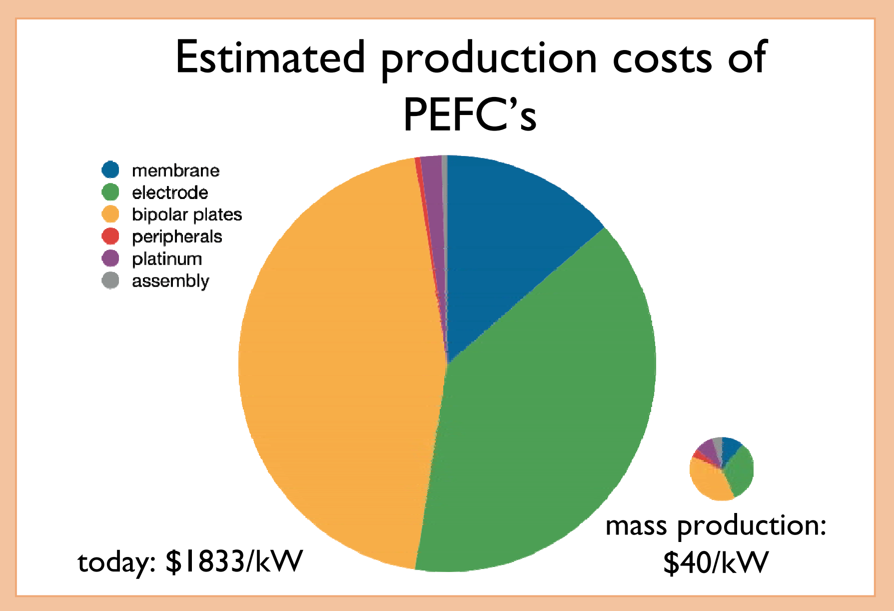

Fig. 1. *Estimated costs per kW for fuel cell stack. Cost estimates from Tsuchiya* et al. *(Reference 5).*

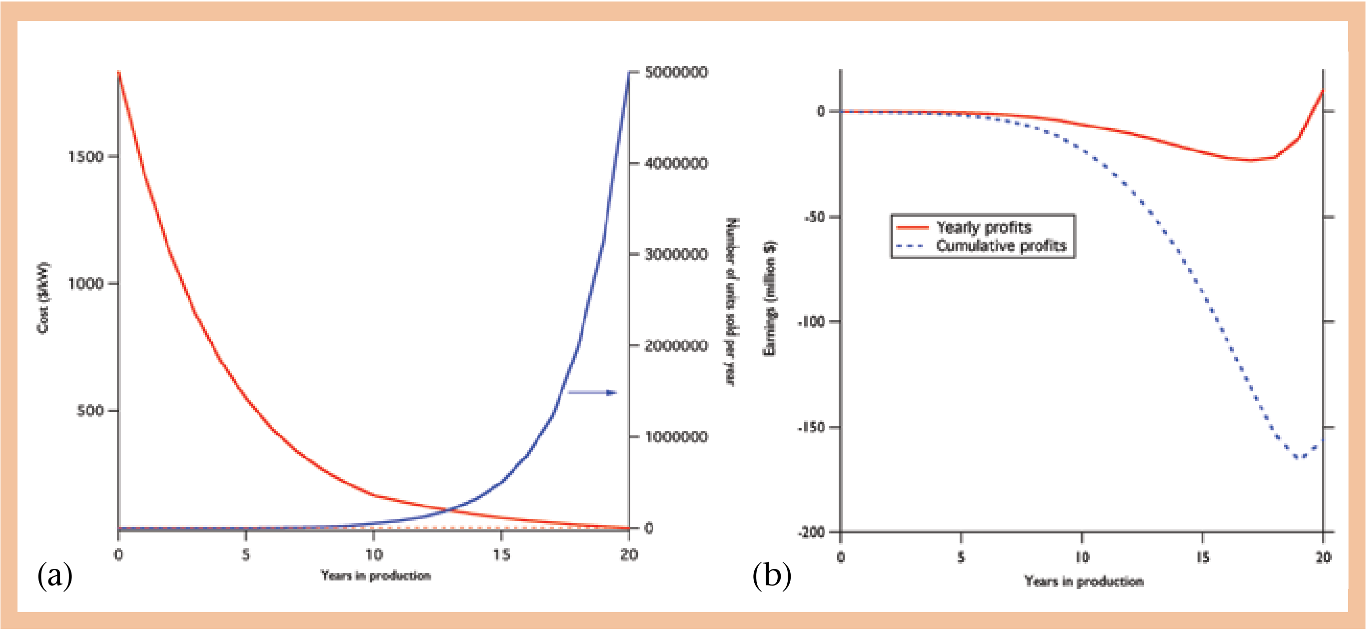

Fig. 2. *(a) Projections for cost reduction and product introduction from Tsuchiya* et al. *(Reference 5). (b) Projected losses/ profits assuming only a single point of entry into the market. Assumes $40/kW is price market will bear and cost projections from Figure 2(a).*

In general, the electrodes for electrochemical energy conversion devices must be placed very close to one another to minimize Ohmic losses associated with the passing of current. Given the slow diffusion and migration rates in electrolytes, all of the active material in a closed system such as a battery must be placed very close to the electrodes. The distances over which reactants can be carried are very small relative to convective flow, so fuel cells—with external fuel storage that is conveyed to the electrodes in the gaseous of liquid state—can generally provide much longer duration of power for a given size and cost than conventional batteries. Therefore, applications with extended times between refueling are places where batteries struggle to meet requirements, and are frequently supplemented with a generator, running on fuel.

While fuel cells are efficient relative to combustion engines, they are not as efficient as batteries, due primarily to the inefficiency of the oxygen reduction reaction (and, it must be pointed out, the oxygen evolution reaction, should the hydrogen be formed by electrolysis of water). At this stage of development, they make the most sense for operation disconnected from the grid, or when fuel can be provided continuously. The device must be reliable, and it must be readily available when called upon. Batteries tend to dominate these markets because of their favorable attributes, in terms of response time and complexity of operation. They start up essentially instantaneously, most require low to zero maintenance, and have no local emissions or noise. Until quite recently, fuel cells were too expensive even for these markets, and had durability and reliability problems that precluded them from consideration. However, as PEFC technology has matured in anticipation of the automotive markets, they have become much more favorable. For applications that require frequent and relatively rapid start-ups (on the order of seconds) where zero emissions are a requirement, as in enclosed spaces such as warehouses, and where hydrogen is considered an acceptable reactant, a PEFC is becoming an increasingly attractive choice.

By targeting niche markets that pay high costs for their power or have issues with their current energy-storage systems, PEFCs can be sold at commercially viable prices in relatively low volumes. An example of such a target application is for industrial utility vehicles that can be rapidly refuelled. These users currently rely on the labor-intensive process of mechanically exchanging battery sets of battery sets. Such niche markets can provide the production volumes necessary to achieve further cost reductions, which will open up additional market segments. This is shown conceptually in Fig. 2. The automotive target of $40/kW is an aggressive target, and a sample commercialization rollout as shown in Fig. 2a reveals the rate of adoption of the technology and the accompanying cost reductions. The dashed line shows the competitive cost per kW that the market is likely to bear. As long as production costs are higher than the acceptable price, then someone—either the producer or a government agency—must make up the difference between the cost of production and the price at which it is sold. Figure 2b suggests that for such an approach to the market, it will take nearly 20 years before producers start to see profits, and will have 20 years of sunk costs to overcome, or must rely upon a very patient government subsidy program to make it to profitability. If, however, other niche markets can be entered at higher price points (and the fuel cell can compete favorably with incumbent technologies at those points), then profits can be realized much sooner. Recent market studies suggest that fuel cells can compete favorably with lead-acid batteries for forklift applications at today's costs, at least in some markets.[4] If they can enter this market, then manufacturers can achieve profitability and prove out longer lifetimes and lower costs for other markets while turning a profit.

It's the Economics

If cost is a problem, then it behooves us to ask why fuel cells cost so much. Ask someone who hasn't worked in the industry and he or she is likely to say, "It's the platinum." It is true that, to date, all fuel cells use platinum catalysts, and platinum is a very expensive material, one that has only become more expensive in recent years. It is perhaps surprising to learn, however, that, even if the platinum were free, the fuel cells would still cost too much to enter into markets. As shown in Fig. 1, from a recent survey of fuel cell manufacturing,[5] the low-volume costs for fuel cells are still in excess of $1800/kW and the lion's share of cost is estimated to lie in either the membrane-electrode assembly or bipolar plate manufacturing, even neglecting the material costs. To date, manufacturers still haven't made very many fuel cells, and they have neither the experience

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with, nor the capital equipment for, high-volume manufacturing to bring the costs down. While material costs should remain fixed with volume, it is anticipated that production costs will come down with volume.

As PEFC technology tries to enter the marketplace, it is important to identify processes that can be scaled up for mass production of MEAs. There is currently little information available about the actual MEA fabrication processes that are used by industry. The processes currently used are often more amenable to batch manufacturing rather than continuous web processes. Commercial MEA fabrication processes aim to scale and improve on the above mentioned thin-film electrode fabrication processes, the foremost goal being to reduce the costs associated with manufacturing a MEA, while maintaining the performance levels. It behooves developers to understand how to manufacture an MEA for high performance, especially since higher power density increases the number of applications where fuel cells can be considered, but also because higher power density means that less total material is ultimately required. We therefore want to design cells that deliver high power per unit area.

The proper construction of a stable catalyst layer is one of the most critical determinants of performance for a proton-exchange membrane (PEM) fuel cell. For any electrochemical device that needs to sustain high rates of reaction, electrocatalysis plays an essential role, but maintaining access to that catalyst is also crucial. At present, all practical fuel cells operating with acid electrolytes employ expensive platinum or platinum-alloy catalysts to ensure a high reaction rate at the cathode.[6] In order to enhance reaction rates, the mass activity of the catalyst must be enhanced, either through modifications to the catalyst surface or by enhancement of the surface-to-volume ratio; in order for a fuel cell to maintain high performance over its lifetime, the catalysts must retain their specific activity and microstructure. The catalytic reaction in a fuel cell depends critically on the nature of the electrocatalyst, the catalyst support, and on the electrode and membrane-electrode assembly (MEA) structures.

Optimized MEAs require architectures that establish reactant transport pathways to the dispersed electrocatalysts: in the oxygen reduction reaction, for instance, one must maintain pathways for both protonic and electronic conduction, while still permitting efficient molecular transport of gas- or liquid-phase reactants and products to and from the carbon supported nanoscale electrocatalyst.[7]

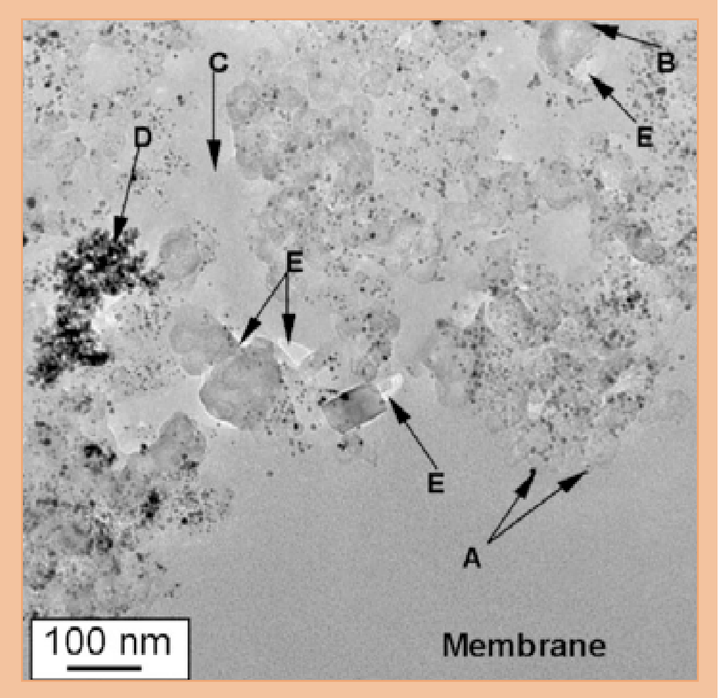

Fig. 3. *Image of a catalyst layer indicating the multiple phases that must be brought into intimate contact: the ionomer, the catalyst and supports, and voids or phase boundaries that allow for gas reactant transport. Image from Reference (8).*

Catalyst layers are carefully constructed to maintain these interfaces and transport pathways; degradation that results in changes to these interface or in interruption of the transport pathways will result in lowered performance and can potentially obscure any advantage of catalysts with inherently superior activity. Understanding how to create these catalyst layers and how to specify the manufacturing processes that deliver these is a critical challenge. We see in Fig. 3 an image of a catalyst layer and can see the multiple phases that must be brought into intimate contact: the ionomer, the catalyst and supports, and voids or phase boundaries that allow for gas reactant transport.[8] Ultimately, it is important to understand how effective transport properties depend upon catalyst layer morphology and how to specify the manufacturing processes in such a way that they will yield an optimized, stable structure.

While perfluorinated membranes and precious-metal platinum group metal catalysts are likely to be used to meet near-term cost reduction goals, the ultimate requirements suggest that either drastically lowered loadings or non-precious metal catalysts are required. The search for alternative materials must be guided by a greater understanding of the performance, and device-level targets must be translated to challenges that can be met by material science by carefully isolating and understanding the mechanisms that give rise to high performance.

Built to Last

While performance is important both for product requirements and as an enabler of cost reduction, lifetime is also critical. The PEFC operating environment exposes all of the cell elements to a battery of potentially harmful conditions: extremes in potential, liquid water in a strongly acidic environment, and possibly reactive reaction intermediates.[6]

Membranes are critical components of the fuel cell stack and must be able to perform over the full range of system operating temperatures with less than 5% loss of performance by the end of life and without external humidification. Membranes can fail suddenly, without gradual performance degradation.[9] The durability of catalysts is a critical problem, particularly as PEFCs start to incorporate lower catalyst loadings; small losses in electrocatalytic activity become proportionately greater as the initial area for the electrochemical reactions decreases. The performance of the catalyst layer degrades by platinum sintering and dissolution, especially under conditions of load-cycling and high electrode potentials. Furthermore, the carbon supports that provide electrical contact to the platinum nanoparticles can be electrochemically oxidized under some operating conditions.[10]

Fuel cells for transportation applications will need to show >150,000 miles, or roughly 5,000 hours of operation under aggressive cyclic conditions. Performance of fuel cells for stationary applications of up to 20,000 hours has been demonstrated, but for fuel cells to displace conventional generators, developers will have to more than 40,000 hours of reliable operation over the full range of external environmental conditions (-35°C to 40°C). Demonstration of these lifetimes suggests either an intimate understanding of all of the possible modes of failure, or a very long development and validation cycle. Greater understanding of all of the processes leading to failure—chemical and mechanical attack of the membrane, dissolution, corrosion, etc.—is necessary to ensure that developers can rationally trade cost versus performance and lifetime. Many more fundamental studies are needed, and access to long-term performance data at the scale and under the typical operating conditions of end-use applications are required. While we anticipate that the niche applications outlined above will be accessible with the current state of the technology, it still must be shown that the peculiarities of the operating envelope in these new applications will not open up new modes of failure that are less important in the transportation and stationary applications that have been tested already. Soon, time will tell.

The Way Forward

The initial stages of PEFC development have given way to a more sober, practical approach wherein it is acknowledged that less attention-grabbing applications are likely to lead the way to commercialization, and where fundamentals are being studied to unlock mechanisms, design guidelines, and templates for new materials. Battery-based hybrid vehicle technology will likely exist alongside fuel cells, and may well win out in some transportation applications, but fuel cells have a list of characteristics that suggest that they will find their own niches as well. Now is a time ripe for collaboration between researchers, to look at the wealth of data that has been created in the early stages, to take a hard look at which (and to seize) the early market opportunities that fuel cells are poised to enter.

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