Journal of Power Sources 181 (2008) 378–381

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Short communication

Meeting the challenges in the transport sector

Jan van Dokkum, Andrew Dasinger*

UTC Power, 195 Governor's Highway, South Windsor, CT 06074, United States

ARTICLE INFO

Article history:
Received 6 November 2007
Received in revised form 20 February 2008
Accepted 22 February 2008
Available online 13 March 2008

Keywords:
Fuel cells
Transportation

ABSTRACT

This paper provides an industry leader's perspectives on the potential for transportation fuel cells, reviewing their development progress, describing their advantages and barriers, and identifying paths to successful commercial deployment. UTC Power has developed proton exchange membrane (PEM) fuel cell technology for transportation since 1998, building upon applicable innovations from the company's space fuel cell and stationary fuel cell programs. PEM fuel cell durability improvements are discussed, highlighting achievements in the understanding of decay mechanisms and the design of effective mitigations. The potential for high-volume production to make automotive fuel cells cost competitive with internal combustion engines is explained. The paper underscores the important role that initial deployment of PEM technology for transit buses can play, although development of automotive fuel cells must continue in parallel as the hydrogen infrastructure develops. Suggestions are offered on how policies and regulations, communication and education, and improved codes and standards can all help to promote the widespread use of fuel cells in transportation.

1. Introduction

UTC Power has supported the development and commercialization of fuel cells for almost 50 years. With strong ongoing programs in automotive and bus fuel cell applications, the company understands the challenges and opportunities in the transport sector. Commercialization of fuel cells has begun for buses, with public transit companies now operating fuel cell-powered buses in full revenue service, providing valuable operational data that will help the industry continuously refine the technology. Fleets will continue to provide an early test bed and a viable market for transportation fuel cells until a hydrogen fuel infrastructure is developed for personal automobiles. Government and industry should continue to work together to overcome barriers to more widespread deployment of fuel cells in transportation applications.

2. Historical perspective

UTC Power is a world leader in the development and commercialization of fuel cells for transportation, on-site building power, space exploration, and defense. This leadership role is the result of the company's long track record in fuel cells dating back almost 50 years. In 1958, what was then United Aircraft Corporation initiated a program to develop a fuel cell power system for space applications. Ongoing advancements in fuel cell technology over the years illustrate the significant progress that has been achieved in the fuel cell sector [1]. The foundation is firmly in place to enable further improvements to fuel cells for transportation applications. The company continues on a path to mass-market fuel cells for a variety of transportation applications.

With roots in the U.S. space program, UTC Power fuel cells provide on-board power and drinking water to space shuttle crews to this day. Produced only in low volumes, these fuel cells did not offer the opportunity to develop low-cost, high-volume manufacturing processes. However, a great deal was learned about how to construct highly reliable fuel cell power systems, and UTC Power continues to apply this experience to the development of fuel cell systems for both stationary power and transportation applications [2].

To grow the business beyond a single U.S. government customer, UTC Power turned to the development of an on-site power plant based on a phosphoric acid electrolyte, and in 1992 released for commercial sale what is now known as the PureCell® Model 200 power system. The high reliability and durability of the phosphoric acid fuel cell (PAFC) has been demonstrated in numerous applications. These cell stacks have achieved more than 60,000 operating hours and the entire fleet has generated over 1.3 billion kilowatt hours of power [3].

To attain better economics for on-site power, we expanded development work with proton exchange membrane (PEM) fuel cell technology in 1998. However, a standard stack life of 40,000 h for

* Corresponding author. Tel.: +1 860 727 2891; fax: +1 860 660 8274.
E-mail addresses: Jan.vanDokkum@UTCPower.com (J. van Dokkum), Andrew.Dasinger@UTCPower.com (A. Dasinger).

0378-7753/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2008.02.090

on-site power systems, which the company had already achieved and demonstrated for PAFCs, was simply not attainable in a reasonable time frame using PEM technology. It was at this time that UTC Power also began development of automotive fuel cells. Consequently, we discontinued developing a large PEM stationary fuel cell power system, while maintaining work on PEM fuel cells for transportation. Currently, UTC Power is investing in improvements to PAFC technology that vastly enhance the customer value proposition for on-site power, including a doubling of stack life from 5 to 10 years. At the same time, we are transferring relevant technology improvements to our PEM transportation programs.

3. Transportation fuel cell potential

The current cost of transportation fuel cells is a major barrier to their commercialization today, but there are solid reasons to believe that fuel cells have a good potential to become cost competitive [4]. One unequivocal advantage is that the fuel cell is made of repeating parts – membrane electrode assemblies – that are stacked in the quantity needed to produce the desired level of power output. This modular construction is in stark contrast to the internal combustion engine, which has a considerable number of different individual parts, each of which has to be made separately, with different tooling and processes, prior to assembly. The second advantage is that precision machining necessary to achieve high levels of dimensional tolerance is not prevalent in fuel cell part manufacturing to the degree it is in producing internal combustion engines. These two distinctions suggest fuel cells can attain cost competitiveness at comparable manufacturing volumes.

Another area where cost comparisons can be made is the materials used in fuel cells and internal combustion engines. An obvious potential disadvantage for low-temperature fuel cells is in their precious metal content. Substantial progress has been made, however, in reducing the platinum loading of fuel cells as power densities continue to be improved [5]. Reclamation and recycling are also viable options for dealing with platinum costs. Creative strategies, such as platinum leasing, also may take hold as a solution for this issue.

UTC Power also believes that today's trend to hybrid vehicle drives supports the future adoption of fuel cells because hybrids provide the avenue to an all-electric platform, with efficiency and emissions remarkably better on a well-to-wheels basis. The cost of a single all-electric platform will be much more economical than supporting internal combustion engines and electric systems in a hybrid configuration. Higher volume production of common hybrid drive components, such as batteries and controllers, also will ultimately reduce fuel-cell hybrid vehicle (FCHV) costs later on.

Performance and cost go hand-in-hand, and transportation fuel cells still do not meet all performance targets. Fuel cell durability, however, a critical performance attribute, has been steadily enhanced through better understanding of the fundamental mechanisms [6,7]. For example, water management in the form of internal humidification, which enables a liquid-water equilibrated membrane, has been demonstrated to significantly extend membrane life (Fig. 1). Porous water-transport plates used by UTC Power play an important role in achieving these advantageous water management properties in PEM fuel cells [8]. UTC Power has also shown that voltage control can successfully mitigate start–stop losses, demonstrating 14,000 start–stop cycles in a 20-cell stack. Effective strategies to counteract the effects of sub-freezing temperatures have been developed and demonstrated [9]. For example, performance of a 20-cell stack after 200 boot-strap starts from a temperature of −10 °C shows little if any change from initial performance (Fig. 2). Table 1 summarizes a variety of durability issues, decay or failure mechanisms, and corresponding mitigations. UTC Power continues to work on these critical concerns, supported in part by government funding and development contracts with automakers, in order to meet industry goals. A substantial body of intellectual property now surrounds these areas of technology performance.

Of course, the major difference driving the disparity in today's costs of fuel cells and conventional vehicle engines is the produc-

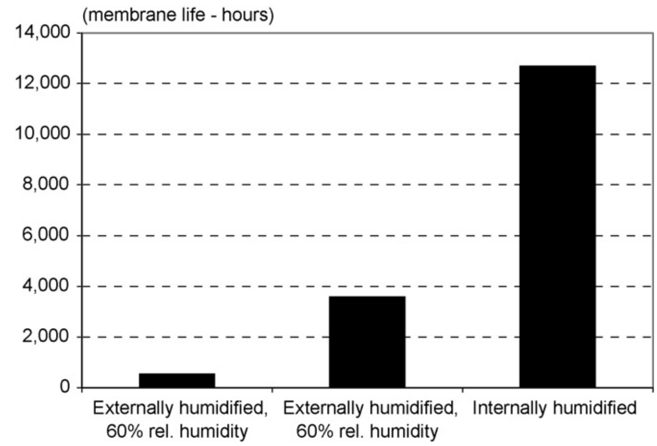

Fig. 1. Influence of humidification on membrane life in short cell stacks.

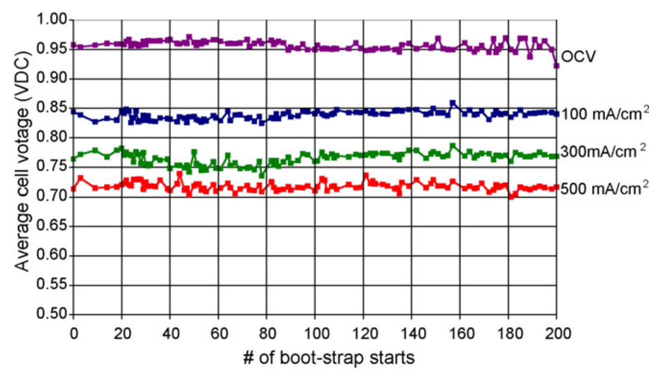

Fig. 2. Performance of a 20-cell stack for 200 boot-strap start cycles from −10 °C for a range of current densities.

Table 1
PEM fuel cell durability issues, decay mechanisms, and mitigations

Issue	Decay/failure mechanism	Mitigation
Membrane degradation	Chemical attack	Reduce impact of peroxide
	Dry-out and mechanical failure	Membrane composition Seal design Internal humidification
Seal degradation	Compression set Chemical decomposition	Materials Cell design
Catalyst degradation	Platinum dissolution (accelerated by cyclic operation)	Potential control
		Catalyst composition
Carbon support degradation	Fuel starvation and reverse current	Potential control
Low-temperature water management	Low-temperature starts	Materials
	"Frost heave"	Cell design

Fig. 3. PureMotion® Model 120 fuel cell power module.

Fig. 4. PureMotion® Model 120 fuel cell power module installed in a transit bus engine bay.

tion volume. Internal combustion engines are a mature technology developed over 100 years ago and manufactured in the tens of millions of units each year, while annual fuel cell manufacturing is on the order of 1000 units. An independent review, developed by TIAX under the DOE Hydrogen Program using a bottoms-up cost estimation method, concluded that a cost of $108 kW^{-1} was credible for a PEM transportation fuel cell, based on 2005 cell stack technology and assuming a production of 500,000 units per year [10].

4. Absence of hydrogen infrastructure points to fleet applications

Production volumes for transportation fuel cells are inherently limited by the lack of a market-enabling hydrogen infrastructure to provide fuel conveniently and economically. Today we have abundant choices on where to purchase gasoline and diesel fuel, the infrastructure for which has developed since the advent of the automobile. It will take considerable time to develop a hydrogen infrastructure capable of supplying automotive fuel cells on a comparable scale. Consequently, we need to focus on building momentum through hydrogen-powered fleet vehicles, such as transit buses, delivery trucks, airport ground support vehicles, and forklifts, which all operate on a centralized fueling model.

UTC Power, while maintaining a strong program of automotive fuel cell development, has begun offering its first commercial transportation fuel cell system in transit bus applications. The PureMotion® Model 120 system is a 120-kW PEM fuel cell. Its ambient-pressure design eliminates the need for an external compressor, reducing noise, associated parasitic loads, and cost. A potential drawback of the system is the specialty material used in the water-transport plates, which must be made using a manufacturing process that has yet to be scaled up to high-volume production. The modular, self-contained design can be packaged in the engine bay designed for conventional diesels and features simplified interfaces and ease of maintenance (Figs. 3 and 4).

Table 2
Comparison of fuel cell bus to conventional diesel bus performance

Parameter	Van Hool A330 fuel cell bus[a]	Diesel bus
Acceleration (sec to 48 km/h)	15	20
Acceleration (sec to 80 km/h)	36	31
Interior noise (dB stopped)	56	72
Interior noise (dB@80 km/h)	69	78
Fuel consumption (kg/100 km)	8.2	16.9

[a] *Source*: AC Transit, Oakland, CA and SunLine Transit Agency, Thousand Palms, CA.

The fuel cell is integrated into the bus in a hybrid-electric configuration. Taking the bus as a whole, Table 2 highlights the performance advantages of a fuel cell hybrid-electric bus over a traditional diesel bus. Acceleration is faster at lower speeds, where transit buses typically operate. The fuel cell bus has a much lower sound profile, a valuable benefit in urban settings. Beginning-of-life fuel economy on an equivalent energy basis is about twice that of a diesel bus, while over an 8-month period a 73% fuel economy improvement was measured in the Alameda–Contra Costa Transit District [11]. In addition, fuel cell bus fuel economy was found to be 2.5 times greater than compressed natural gas buses and 71% greater than a hydrogen hybrid internal combustion engine bus on routes served by the SunLine Transit Agency [12]. Emissions of air pollutants, such as nitrogen oxides and fine particulate matter (soot), which are linked to a variety of urban health problems, are virtually eliminated with the fuel cell power system. The bus also can climb an 18% grade and has a range of more than 480 km using pressurized hydrogen cylinders mounted on the roof.

UTC Power's PureMotion® Model 120 fleet includes a total of six buses operated by public transit agencies in California, Connecticut, and Belgium. All buses are 12.2-m A330 models manufactured by Van Hool (Fig. 5), except the one operated by DeLijn in Antwerp, Belgium, which is a 13.1-m dual rear-axle Van Hool bus. These demonstrations are building credibility and experience, and are essential to the further development and improvement of transportation fuel cell technology [13].

Fig. 5. Hybrid-electric fuel cell transit bus operated by CT Transit, Hartford, CT.

5. The path forward

To be successful, transportation fuel cells require continued investment and the lowering of those barriers that restrict their growth. There are several changes that will be particularly beneficial to the commercialization of transportation fuel cells, which will come about through the action of government policymakers, codes and standards organizations, and corporations.

Carbon accountability is one of these changes. Implementing policies where costs are assigned to carbon emissions, either with a carbon tax, cap-and-trade scheme or other approach, will improve the value proposition for hydrogen fuel cells (with the greatest benefit accruing for hydrogen derived from renewable energy sources). Recognizing the value of reduced noise and avoiding other harmful air emissions is also a way to enhance the value proposition.

Education will likewise play a strong role in raising society's awareness and promoting public acceptance. The benefits of clean hydrogen fuel cells for transportation need to be widely disseminated and recognized so that their value is acknowledged and demanded by the public. There is strong agreement that global climate change is being caused by the world's insatiable levels of fossil fuel consumption. There needs to be equally strong agreement on the need for effective solutions such as fuel cells in the transportation sector.

A multitude of overlapping and inconsistent codes and standards creates an unfavorable environment for progress on hydrogen and fuel cell market acceptance. Commercialization of hydrogen and fuel cells would be greatly accelerated by the uniform and rapid adoption of consistent requirements by all government jurisdictions. Close cooperation is needed among national and local governments across continents.

Government support in Europe, the United States and other locales will remain crucial to commercialization. The fuel cell industry continues to need increased R&D and an expansion of demonstration programs. Public/private partnerships need to be promoted. Governments need to provide the appropriate incentives to drive behavior. Ongoing leadership at all levels – municipal, state, and federal – will be necessary to advance transportation fuel cells beyond the stages of early technology commercialization.

UTC Power and other fuel cell companies are making progress, but the needs for clean, energy-efficient vehicles are urgent, so we must do everything we can to accelerate commercialization of transportation fuel cells, starting first with fleet vehicles. While this occurs, we will continue to develop automotive fuel cell technology as the hydrogen infrastructure gains momentum.

References

[1] M.L. Perry, T.F. Fuller, J. Electrochem. Soc. 149 (7) (2002) S59–S67.
[2] K. Poast, M. Burghardt, L. Mustin, H. DeRonck, Fuel Cell Seminar 2003, Miami Beach, FL, November 3–7, 2003.
[3] F. Preli, S. Motupally, T.D. Jarvi, Fifth International ASME Fuel Cell Science, Engineering, and Technology Conference, New York, NY, June 19, 2007.
[4] Fuel Cell Tech Team, TIAX, LLC, DOE contract DE-SCO2-98EE50526, Detroit, MI, October 20, 2004.
[5] TIAX, LLC, Report to DOE, DOE contract DE-FC04-01AL670601, December 2003.
[6] T. Jarvi, Third Annual Conference on Fuel Cells Durability and Performance, Miami, FL, November 15, 2007.
[7] M.L. Perry, T. Patterson, C. Reiser, ECS Trans. 3 (1) (2006) 783–785.
[8] A.Z. Weber, R.M. Darling, J. Power Sources 168 (1) (2007) 191–199.
[9] M. L. Perry, T. Patterson, J. O'Neill, DOE Hydrogen Program Annual Merit Review, Project ID# FCP5, Washington, DC, May 15, 2007.
[10] D. Wheeler, National Renewable Energy Laboratory, Golden, CO, NREL/BK-150-40160, October 2006.
[11] K. Chandler, L. Eudy, National Renewable Energy Laboratory Technical Report, NREL/TP-560-42249, October 2007.
[12] K. Chandler, L. Eudy, National Renewable Energy Laboratory Technical Report, NREL/TP-560-41001, February 2007.
[13] M. Steinbugler, International Conference and Trade Fair on Hydrogen and Fuel Cell Technologies, Hamburg, Germany, October 26, 2006.