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SMALL BATTERY – FUEL CELL ALTERNATIVE TECHNOLOGY DEVELOPMENT

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Abstract

Fuel cells are currently attracting significant publicity and attention for applications as diverse as transportation and cellular phones, yet they are probably still some years away from any sort of meaningful commercial utilization. In the effort described here, two general postulates are being followed in an attempt to increase the speed and probability of commercial success for fuel cells. The first axiom is that fuel cells need to be as simple as possible to compete against well-established and entrenched technologies. With simplicity comes reliability and low costs. To a large degree then, simplicity is more important than the absolute top performance that can be attained. The second premise is that the most vulnerable market for fuel cell penetration is the one occupied by batteries for relatively low power applications such as personal electronics, etc. While conventional batteries currently have a lock on such applications, they are expensive (often thousands of dollars per kilowatt – hour), have low energy densities and frequently contain environmentally suspect materials. With these issues in mind, for the past two years we have been developing "Air-Breather" fuel cells, which are exceedingly simple and most effective for small battery types of power levels. This year, in addition to further development and testing of air-breather fuel cell stacks and systems, we are also exploring approaches that address the fuel storage issues that may be the primary obstacles to commercialization.

Introduction

Depending upon the fuel storage technology, portable fuel cell systems can provide substantially higher energy densities than similar-sized battery packs and are typically much more environmentally benign. Correspondingly, interest in fuel cells for portable power applications is rapidly increasing and, in all likelihood, the first widespread consumer applications of hydrogen technologies will be in such portable fuel cells. Previously, the challenges introduced with fuel cell water management and/or fuel storage issues invariably resulted in discouragingly complex portable power systems. Where we thus primarily differ from most other portable power efforts is our emphasis that success will require the development of extremely simple fuel cells and systems. Simplicity beneficially influences cost, durability and reliability. A particularly simple and effective fuel cell system, the "air-breather," was the basis for a Cooperative Research and Development Agreement (CRADA) between Los Alamos National Laboratory (LANL) and DCH Technology/Enable Fuel Cell Corporation covering the first two years of this project. The air-breather is a unique low-power portable fuel cell and system that can be sufficiently inexpensive and is reliable enough to eventually compete head-to-head with batteries in electronics-type applications. The advantage of this fuel cell system over previous fuel cell designs is that it is inherently stable and self-regulating without the need for peripherals such as cooling or reactant flow fans. It can operate effectively with no active humidification, no active cooling, and no pressurization or forced flow of the cathode air (Wilson 1996). More details on some of the systems under development and testing by Enable FCC over this past year will be presented below.

Now that the air-breather is at a relatively advanced stage of development, the CRADA has been extended for a third year (FY'01) to allow LANL to primarily address fuel issues and continue to assist Enable FCC in their product development. While a number of storage options exist for hydrogen fuel cells (e.g., metal hydrides, chemical hydrides, pressurized, etc.), none are particularly amenable for consumer applications at this point. Ideally, the fuel storage subsystem would be symbiotically integrated with the fuel cell side such that consumer-friendly, inexpensive and reliable overall systems can be realized. While the requirements of portability and simplicity render many complex fuel-side approaches impractical that would otherwise be viable for, say, transportation, it is conversely possible to consider approaches for the portable applications that would not be feasible or tolerable for large scale systems. For example, high costs per kWh of capacity or low system efficiencies that would not be attractive for most (larger) applications may possibly provide costs and/or energy densities that are still very attractive when compared to batteries.

Discussion

Fuel Issues

Some perspective on the hydrogen storage possibilities can be gained from a comparison of generic hydrogen storage technologies as shown in Figure 1. This figure depicts the theoretical hydrogen energy densities of various potential hydrogen sources such as methanol (MeOH), low temperature metal hydrides (Metal-H), high-pressure hydrogen gas (20kpsi H2) and chemical hydrides, such as sodium borohydride ($NaBH_4$). Also shown for the methanol and sodium borohydride cases are the differences if the water for the CH_4OH + H_2O and $NaBH_4$ + 2 H_2O reactions is supplied from water carried along with the system or supplied with product water from the fuel cell. It should be stressed that these are ideal numbers, the inclusion of factors such as void fractions, containment vessels and conversion efficiencies significantly decrease the actual values attainable. The point is, however, that despite the attention paid to methanol (i.e., direct methanol fuel cells) and chemical hydrides because of their significant gravimetric hydrogen storage densities, even lowly metal hydrides, of only about 1.5% hydrogen by weight, are most likely superior when considered on a volumetric basis. Particularly as systems become smaller, a smaller size is more important than a lighter weight. In such cases, integrating a metal hydride into a fuel cell system is much simpler for portable applications than the other options where water and/or the chemical reactions need to be managed in some manner. As such, one of the specific tasks that LANL is addressing this year is how a portable hydride/fuel cell system based on otherwise well established storage materials can be made robust and user-friendly and its use "transparent" to the consumer. The particular approach LANL is pursuing hinges on technologies previously developed elsewhere within the laboratory.

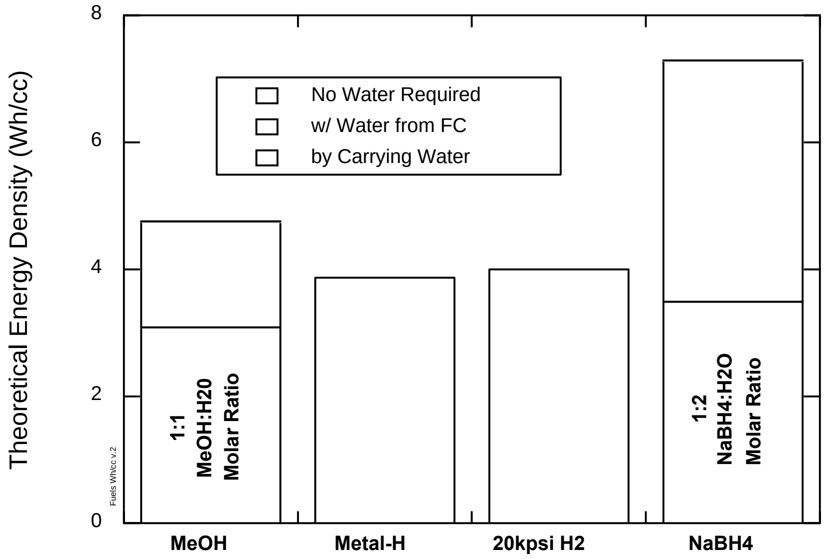

Figure 1 – Theoretical Energy Densities for Various Fuel Options.

The second approach initiated this year at LANL brings the "simplicity" theme, as described in the introduction, to the fuel side as well as the fuel cell. For portable power applications, this can be accomplished in ways that would not be practical or possible in larger systems. Research is progressing on combining the fuel and fuel cell symbiotically such that the net package is extremely simple, e.g., no moving parts, etc. On the other hand, a considerably larger fraction of the theoretical energy densities (as shown in Figure 1) needs to be sacrificed due to the approach. However, the remainder is still quite compelling when compared to conventional batteries and the inefficiencies and complexities inherent in more conventional fuel cell systems are avoided. As such, the net result may be that the systems are not so very different overall. The simpler system would then conceivably prevail in the commercial arena because it would correspondingly be more robust and less expensive than more conventional systems.

While advances have been made in the two fuel approaches being pursued by LANL this year, the efforts are still very much in their infancy and more explicit details can not be provided at this point. While this year's LANL portion of the CRADA has primarily focussed on addressing fuel issues, Enable FCC has continued to develop and test air-breather fuel cell stacks as well as develop new packages and systems for general and specific applications.

Air-Breather Stack and System Development and Testing

Figure 2 provides a photograph and specifications of the first air-breather fuel cell commercial product, the Enable™ 12 Watt PFC (Personal Fuel Cell). The assembly is protected by a shroud with elongated openings that allow air to freely convect over the stack to provide cooling. Although pictured in a recumbent position, the PFC can also be mounted vertically and affixed atop the hydrogen supply in a tower configuration that is then suitable for supporting, for example, a camping lantern.

Power	**12 watts**
Voltage	**12 volts**
Current	**1 amp**
Weight	**1.4 pounds**
Length	**Approx. 8"**
Diameter	**Approx. 2.75"**
Design	**PEM**
Efficiency	**50-57%**
Controls	**On/Off; Check; Purge Valve**

Figure 2 – Photograph and specifications of the Enable™ 12 Watt PFC.

To compete with batteries, fuel cells will need to be able to function at least as well under environmental extremes as the technologies they are trying to replace. Enable FCC subjected a damaged 20-cell stack to a variety of temperature and humidity conditions in an environmental test room at the University of Wisconsin. Figure 3 depicts a family of polarization curves for the stack. As can be seen, the curves are rather tightly clustered ranging from slightly below freezing (-1˚C or 30˚F) to a rather aggressive 42˚C (107˚F). The single curve outside the cluster is for –16˚C operation (ca. 3˚F). The already sub-par performance of the damaged stack probably lessens the severity of the high temperature situation (i.e., less power, less heat to eliminate). However, the low temperature performance should be exacerbated (less heat to sustain itself) and it is quite impressive that it does as well as shown under the sub-freezing conditions. Curiously, one of the possible advantages of the air-breather in this case is that it is a relatively dry system. Thus damage due to water freezing in flow-fields or other passages is avoided, and the water in the membrane is less likely to freeze because the freezing point is suppressed as the water content drops. As suggested by the one higher temperature curve that deviates from the rest, the relative humidity also has somewhat of an effect in the most extreme cases. Since it appears to be mostly a mass transport limitation effect, perhaps the slight increase in water vapor content is sufficient to unduly limit oxygen access, but this is only speculation at this point.

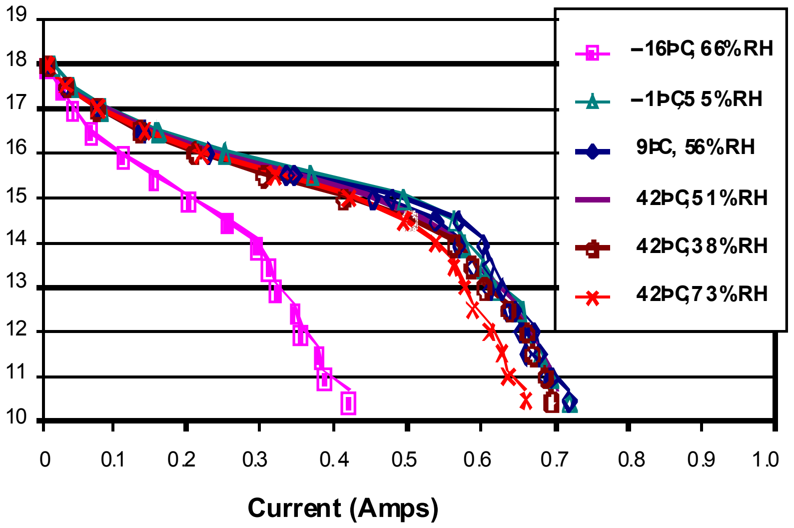

Figure 3 – Polarization curves of a passive air-breather fuel cell stack obtained in an environmental chamber.

For cost considerations, it is naturally desirable for the fuel cell to provide all of the necessary power without requiring a battery in the system for start-up or surge. In such cases, the fuel cell stack will need to offer quick start-up and load following as well as stability. Figure 4 depicts start-up and load following for an off-the-shelf 3-cell Enable™ stack. As can be seen, it comes up quickly and also responds rapidly and stably as the load is varied.

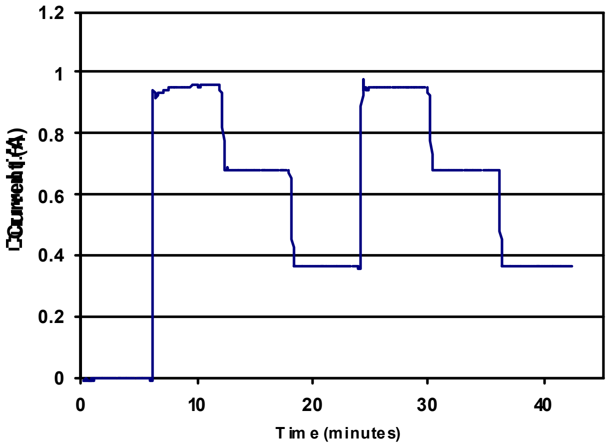

Figure 4 – Startup and passive load following for a 20-Cell PFC stack.

Enable FCC is performing substantial materials testing to assure the longevity and performance of the fuel cell stack components. Most of this testing is performed on 3-cell stacks, and one such test is shown in Figure 5. Aside from occasional performance losses due to hydrogen supply difficulties, the stack performance was quite stable for the roughly 1500 h shown. The stack has operated an additional 500 hours since this plot was compiled with virtually identical results. To some extent, the stable performance may also be partially attributable to an inherently dry system, as many degradation mechanisms such as catalyst ripening (particle growth) and corrosion are dependant upon the amount of water present.

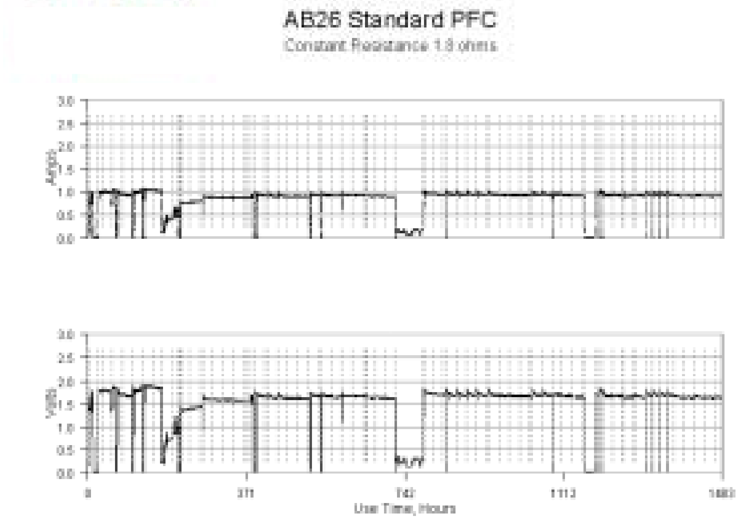

Figure 5 – Life test of a 3-Cell stack.

On the right side of Figure 6 are shown the 12-watt PFC alongside a 70 standard liter metal hydride canister. As the canister is exhausted, it can be replaced with a new one and later refilled for reuse. On the other hand, the entire device may possibly be returned for recharging. In this case, the metal hydride would be an integral part of the package. One such example of this packaging approach is shown on the left side of Figure 6. Here, a roughly 6 volt (i.e., shorter) version of the PFC stack is packaged in a commercial lantern battery housing along with a tailor-made 24 standard liter metal hydride canister as well as the pressure regulator, shut-off valve and other requisite fittings. Since the package provides 6 volts, it can serve as a drop-in alternative to a conventional lantern battery, although provision must be made to allow air access to the slots around the base.

The stack next to the lantern battery is a 3-cell test stack for a smaller diameter version of the PFC stack that has a footprint roughly the size of a D-cell battery. The active area per unit cell of these "D-cell" series of stacks of about 4 cm^2 is less than a third that of the PFC stack, yet it provides roughly half the current of the larger stack. Higher current densities can usually be attained in the smaller stacks because diffusion and heat transfer path lengths are shorter and the higher surface area to volume ratios that are attained with smaller devices further facilitates cooling.

One of the applications for a 14-cell version of the "D-cell" size stacks is shown in Figure 7. Here, a fuel cell version of a heavy-duty flashlight is shown alongside the alkaline batteries that are replaced by the fuel cell system. The specifications of the two systems are provided in Table 1. While the fuel cell light is somewhat heavier, it burns brighter, lasts another 50% longer, and is rechargeable (the comparison would be even more favorable against rechargeable batteries). The fuel cell stack is very similar in overall size to a D-cell and is partially visible through the air slots in the neck of the flashlight. The metal hydride canister is the bulge at the base of the flashlight.

Figure 6 – A 6V Lantern Battery fuel cell package, a 3-cell "D-Cell" stack, a 12-watt PFC and its metal hydride canister.

Figure 7 – Fuel Cell Light and Comparable Batteries.

Table 1 – Specifications of the Fuel Cell Light and Comparable Alkaline Batteries.

	Average Voltage	Energy Watt-hrs	Duration hours	Volume in3	Weight lbs	Energy Density Wh/in3	Wh/lb
Conventional alkaline 6 D-cell battery basis	**6.75**	**49**	**14**	**20**	**1.88**	**2.4**	**26.1**
PFC 70 liter hydride PRC D-cell	**7.5**	**81**	**20**	20.4 3.68 **24**	1.9 0.36 **2.26**	**3.36**	**35.8**

Figure 8 portrays the internal components of the fuel cell light. As shown in the figure, at least 10 cm (4 in) of the length is taken up by the quick-connect, alignment flange and pressure regulator. Ultimately, more compact elements can be introduced and the metal hydride tank could be streamlined such that the fuel cell package would have the same profile as the battery light with the same hydride capacity as before. Alternatively, the original size canister could still be used and the entire package significantly shortened.

Figure 8 – Flashlight housing, fittings and hydride.

Because of the higher voltage of the fuel cell over the battery shown in Table 1, about 15% more power is provided to the bulb than with the batteries and it is correspondingly brighter. Figure 9 provides the voltage/current curves for the flashlight bulb and the 14-cell fuel cell stack. Conversely, using a bulb with a slightly higher bulb impedance that provides the same brightness as the battery system would then yield a 15% longer use time.

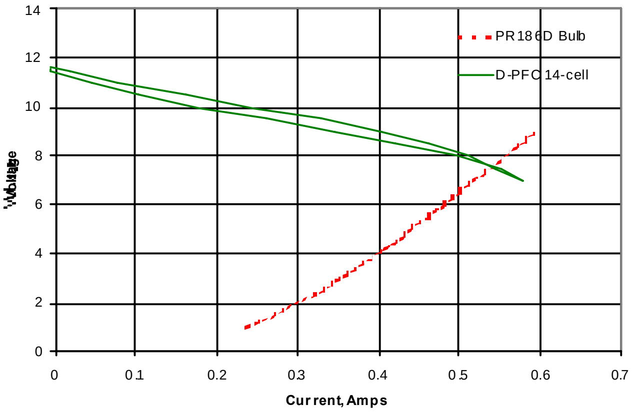

Figure 9 – Characteristic V/I curves of the flashlight fuel cell and bulb.

Conclusions

The air-breather design has demonstrated its versatility and adaptability for a number of packaging options developed by Enable FCC. In testing, the particular attributes of the air-breather have shown it to be surprisingly tolerant to a wide range of environmental conditions and display the operating characteristics that will be needed to be competitive for commercial applications. The only real missing aspects are cost-effective and “transparent” fuel storage systems and their integration into the overall fuel cell system as it would appear in the hands of a consumer. LANL is developing two separate approaches to help address these needs.

References

Wilson, M. S., 1996. “Annular Feed Air Breathing Fuel Cell Stack.” *U. S. Patent No. 5,514,486*.