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The Ovonic® Regenerative Fuel Cell, A Fundamentally New Approach

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The Ovonic® Regenerative Fuel Cell utilizes Ovonic metal hydride materials in place of traditional noble metal catalysts in the hydrogen fuel electrode. This provides unique features including the ability to capture and utilize regenerative braking energy at high efficiency and the ability to operate for a significant period upon interruption of the hydrogen fuel supply. Additionally, this novel fuel cell does not use high price components, such as platinum catalysts, microporous membranes, and graphite bipolar plates, used in PEM fuel cells. Proof of concept has been demonstrated in full-size multicell prototypes delivering about 100 W power. The Ovonic® Regenerative Fuel Cell is yet another component of ECD Ovonic technology contributing to the emerging hydrogen economy which already includes Uni-Solar PV solar cells, Ovonic solid-state hydrogen storage devices, and Ovonic nickel-metal hydride batteries from Cobasys, a joint venture between ECD Ovonics and ChevronTexaco.

Introduction

The development of fuel cells has had a long history dating back to the basic discovery of Grove in 1839. The alkaline fuel cell (AFC) developed by F. T. Bacon in 1930 was the first practical device. Alkaline fuel cells with platinum electrodes were predominantly the system of choice for manned space applications by NASA since the time of Apollo [1]. They were also utilized in early demonstration programs for transportation applications such as the GM Electrovan [2].

Subsequent to the development of the AFC, other fuel cell types have been developed that utilize other electrolyte media [1,2] including the proton exchange membrane fuel cell (PEMFC), the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). Since 1990, the development of PEM fuel cells has received focused attention from the U.S. Department of Energy and the industries associated with fuel cell development [3]. Significant and substantial progress has been achieved, particularly in terms of power performance, where there are now claims of power performance around 1000 W/kg [3]. PEMFC systems have been developed and demonstrated in a variety of applications including automotive propulsion. Hurdles remain in meeting application life targets and particularly cost targets. High cost due to inherently high cost PEMFC materials are the main obstacle to commercialization. Life and cost issues have also retarded the commercial introduction of high temperature MCFC and SOFC technologies aimed at large stationary applications [4].

The Ovonic® Regenerative Fuel Cell is a fundamentally new approach to fuel cells that utilizes hydrogen storage technology such as Ovonic metal hydrides in the hydrogen electrode active material. This provides intrinsic energy storage functionality in the fuel cell stack, and unique performance attributes utilizing non-noble metal catalysts as a low cost approach. Attributes include instant start and the unique capability to store regenerative braking energy in the fuel cell stack also with excellent low temperature operation. Additionally, this new approach provides alternative reaction pathways to enable higher voltage operation with the potential for dramatic improvements in efficiency.

Ovonic Metal Hydride Technology

Our parent company, Energy Conversion Devices, Inc. (ECD Ovonics, see www.ovonic.com) has pioneered the development of metal hydride materials [5] and their subsequent commercialization into Nickel Metal-Hydride (NiMH) batteries [6] and solid state hydrogen storage devices [7]. NiMH consumer batteries are now a billion dollar a year business with billions of cells manufactured and sold annually under ECD Ovonics licenses. NiMH batteries have also become the battery of choice for the emerging electric and hybrid vehicle industries. Cobasys (see www.cobasys.com), a joint venture between ECD Ovonics and ChevronTexaco, is gearing up to be a volume manufacturer of large NiMH batteries for transportation and stationary applications. Rare Earth Ovonic Battery Company, a joint venture between ECD Ovonics and Inner Mongolia Baotou Steel Rare Earth High-Tech Holding Co., Ltd. in China, manufactures metal hydride materials for the global NiMH battery business.

Additionally, ECD Ovonics has developed novel solid state hydrogen storage technology applicable to several aspects of the emerging hydrogen economy [8]. ECD Ovonics has recently demonstrated the utilization of metal hydride storage systems to enable a hydrogen-powered Toyota Prius to achieve a range of 150 miles [9,10].

Most recently ECD Ovonics has developed a new fuel cell technology, the Ovonic® Regenerative Fuel Cell, which utilizes Ovonic metal hydride materials in the fuel cell anode. Ovonic Fuel Cell Company has been formed to commercialize this new technology.

The Ovonic® Regenerative Fuel Cell

The Ovonic® Regenerative Fuel Cell utilizes an anode active material having hydrogen storage capacity [11] and can also utilize a cathode active material having oxygen storage capacity [12-14]. This provides for a fuel cell with intrinsic energy storage functionality resulting in several unique and exceptional performance attributes. The Ovonic® Regenerative Fuel Cell concept can be utilized in conjunction with any ionic electrolyte type and thus the full variety of fuel cell technologies including AFC, PEMFC, PAFC, SOFC, and MCFC technologies. This is a fundamentally new concept that for the first time provides fuel cell stacks with intrinsic energy storage.

Our initial product direction utilizes alkaline electrolyte as shown in Fig. 1. This allows for the facile introduction of metal hydride materials developed for NiMH battery applications. These materials have already fully demonstrated their capability for high energy and high power with excellent durability in the alkaline environment. The choice of alkaline electrolyte also provides for better kinetics at the air cathode and enables the utilization of non-noble metal catalysts at this electrode as well. Finally, the utilization of alkaline electrolyte avoids the necessity of expensive membrane materials utilized in PEMFC technology. We are initially utilizing a circulating potassium hydroxide (KOH) electrolyte which minimizes the impact of carbon dioxide absorption and provides for an electrolyte replacement option to maximize life.

Additionally, the circulating electrolyte provides an excellent and very effective method for heat rejection needed in high power applications.

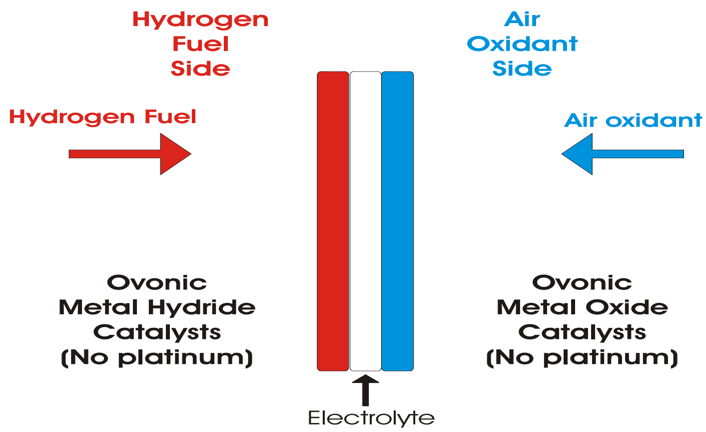


Fig.1 Schematic diagram of Ovonic® Regenerative Fuel Cell.

The energy storage functionality is provided by the metal hydride material in the anode which can be charged chemically from gas phase hydrogen or electrochemically from the oxidation of water. Additional energy storage functionality can be provided by proprietary metal oxide materials that can be oxidized chemically by oxygen or electrochemically. The energy storage functionality provides several key features including regenerative operation, instant start, and excellent low temperature performance.

Regenerative Operation

The most exceptional feature of the Ovonic® Regenerative Fuel Cell is the ability to store energy in the fuel cell stack in regenerative mode operation. This fuel cell can be run backwards and store energy within the fuel cell stack without resorting to the electrolysis of water to hydrogen and oxygen gases. Regenerative mode operation is illustrated in Fig. 2 showing charge-discharge operation.

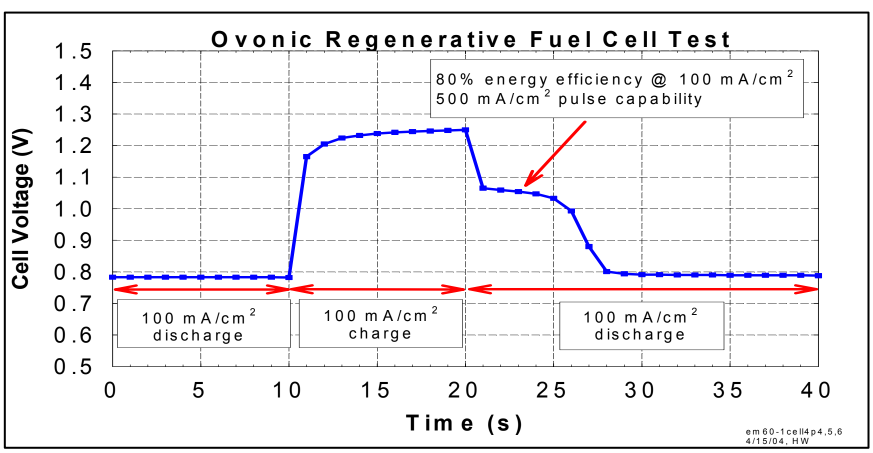


Fig. 2 Regenerative operation.

In Fig. 2, a fuel cell stack operated at 100 mA/cm^2 is interrupted by a 100 mA/cm^2 charge pulse. During the 10-second pulse, the cell voltage increased to about 1.25 V, indicating the storage of energy without the electrolysis of water. Upon return to discharge operation, the operational voltage was elevated from 0.8 V to over 1 V as a result of energy stored in the charge pulse. The charge-discharge energy efficiency is estimated to be about 80% under these operating conditions.

The elevated cell voltage during discharge subsequent to the charge pulse also indicates a high pulse capability. In a series of experiments, we found the pulse discharge capability was increased to over 500 mA/cm^2 when preceded by a 100 mA/cm^2 charge pulse. This is a very promising characteristic for applications requiring high pulse power capability, such as vehicle propulsion which requires pulse charge and discharge capability for braking and acceleration which normally alternate over time in automotive applications.

Our term "regenerative" in regenerative fuel cell refers in part to its ability to accept regenerative braking energy. The Ovonic® Regenerative Fuel Cell is not to be confused with the more "conventional" regenerative fuel cells that combine fuel cell and electrolyzer functions to store energy albeit with low efficiency in hydrogen and oxygen gases stored externally to the fuel cell stack. Our regenerative fuel cell provides for the high efficiency solid state storage of hydrogen in metal hydride materials internally in the fuel cell stack.

Instant Start Operation

Also as a consequence of the energy storage functionality, the Ovonic® Regenerative Fuel Cell provides for instant start operation on the order of microseconds as shown in Fig. 3. Cold start has been a development issue, not only for high temperature fuel cells such as PAFC, MCFC, and SOFC where hours can be required to reach operating temperatures, but even for lower temperature PEMFC systems which do not operate below freezing and require warming from room temperature to achieve rated power performance. In contrast, the Ovonic® Regenerative Fuel Cell provides excellent power instantly even at temperatures well below freezing.

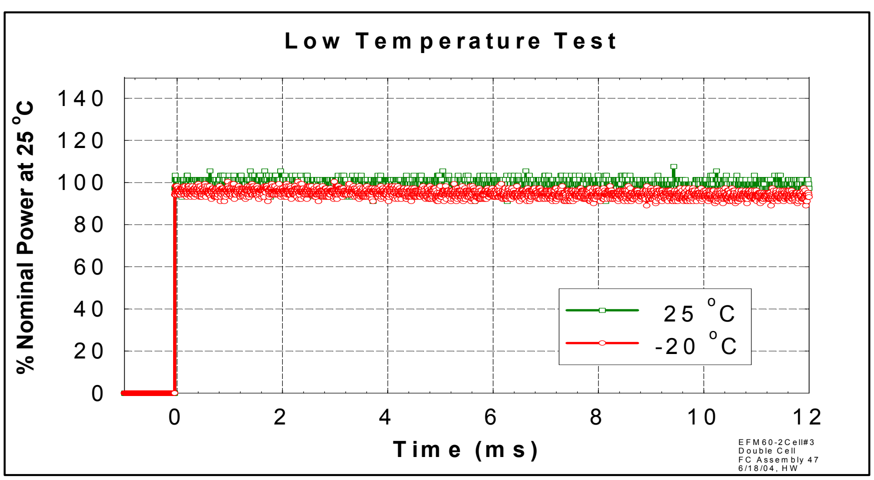


Fig. 3 Instant start operation at ambient and low temperatures.

Furthermore, other fuel cell types require the fuel cell anode to be in direct contact with hydrogen gas to generate power. With the Ovonic® Regenerative Fuel Cell, power is available even in the absence of hydrogen gas flow to the anode. Operation without hydrogen is illustrated in Fig. 4 where power was sustained for several minutes at near peak levels. Instant start without hydrogen again is a result of the intrinsic hydrogen storage in the metal hydride anode. An energy storage capacity of about 5 Wh/kg was demonstrated.

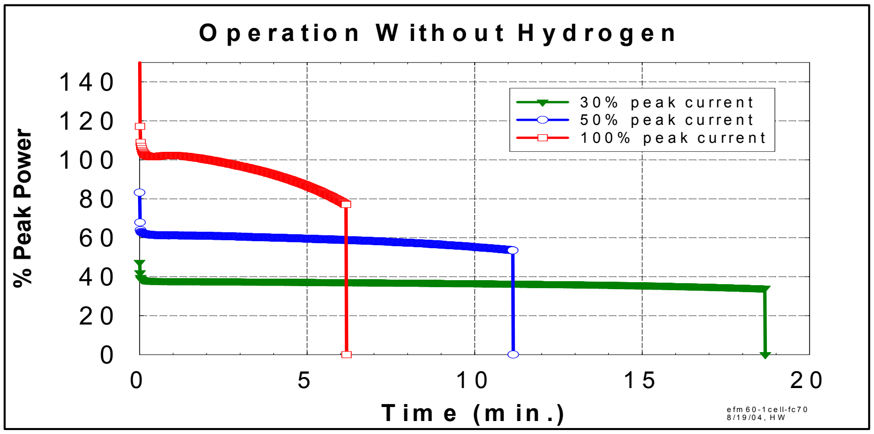


Fig. 4 Instant start operation without hydrogen gas fuel supply.

Low Temperature Performance

Another attribute of the charge storage capability of our fuel cell is its exceptional low temperature performance. Metal hydride batteries operate well at low temperatures and this battery functionality in the Ovonic® Regenerative Fuel Cell also provides for excellent low temperature performance as shown in Fig. 5. PEMFC stacks operate best at 60°C or higher. Although systems solutions have provided for operation at lower ambient temperatures, PEMFC devices typically do not operate below the freezing point of water and PEMFC manuals caution against operation below 5°C. Our fuel cell stack generates 75% of peak power performance at 25°C, 50% of peak power at 0°C, and operation down to below -20°C.

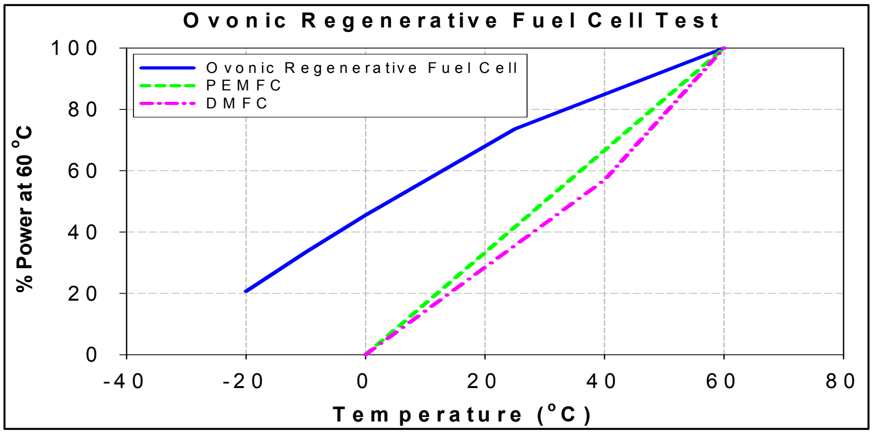


Fig. 5 Low temperature performance.

Power Performance

We have built full size multi-cell stack prototypes up to over 100 W in size. An example of the electrical performance data is shown in Fig. 6. The voltage and power as a function of current are shown. Early prototypes have shown peak power operation at about 150 mA/cm^2, a cell voltage of 0.6 V, and a temperature of 60°C. In more recent results, higher power operation has been demonstrated with current densities up to 250 mA/cm^2 in continuous mode operation and current densities exceeding 500 mA/cm^2 in power pulse mode operation.

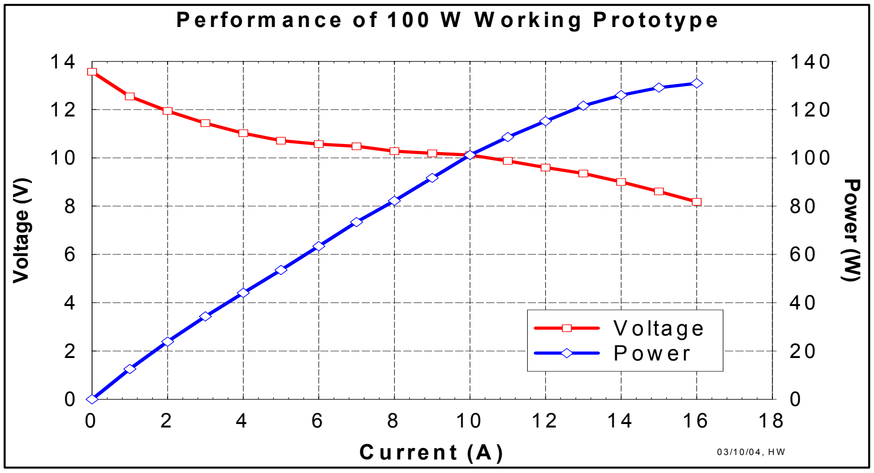


Fig. 6 Voltage and power vs. current for early 100 W prototype stack.

Life Performance

Life tests of Ovonic® Regenerative Fuel Cell prototypes are underway and initial results are promising. Individual electrode half cell tests have exceeded 5000 hours of continuous operation at rated currents. Full cells and full cell stacks are also under test. An example is shown in Fig.7 with over 1000 hours of continuous operation. Utilizing alkaline electrolyte, we can avoid membrane degradation modes. When early AFC devices developed for space applications were adapted for terrestrial applications, absorption of atmospheric carbon dioxide was an acute issue because of the limited electrolyte available in these static (starved) electrolyte systems [2]. Our system which utilizes a more ample electrolyte volume in a circulating liquid electrolyte system is much slower to carbonate and carbonation can be easily handled by electrolyte change out [2]. Additionally, disposable and regenerative scrubber technologies are now available [1].

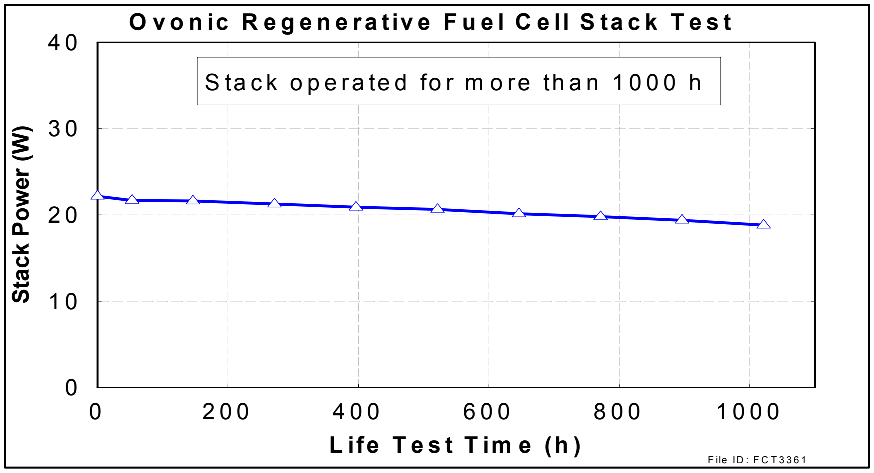


Fig. 7 Early life test of prototype fuel cell stack.

Low Cost Opportunities

One of the biggest obstacles to the commercialization of PEM fuel cells and fuel cells in general is cost. Despite diligent effort for many years, the costs of PEM fuel cells remain high and efforts to achieve cost targets have been discouraging. This is largely due to high materials costs in the fundamental components of the PEM fuel cell including the platinum catalysts, the Nafion membrane, and the graphite bipolar plates. While impressive cost reduction of other components has been achieved, the costs of these components remain over 80% of the total materials costs in high volume production.

Initial cost projections for the Ovonic® Regenerative Fuel Cell indicate materials costs lower by more than a factor of two, principally due to the costs of active materials for the electrochemical catalyst layer (ECL) and electrolyte being an order of magnitude less expensive than the noble metal catalysts and membrane used in the PEMFC membrane electrode assemblies. Our preliminary materials costs are principally in auxiliary hardware components such as the nickel screens and tabs used as current collectors in our existing monopolar design. Volume costs for these commodity materials can be expected to decline dramatically in mass production. These components are currently priced typically at more than an order of magnitude over the raw materials cost.

Finally, our fuel cell technology also has the capability to otherwise lower system cost and complexity by obviating the need for a startup or buffer battery or a battery to handle regenerative braking energy storage.

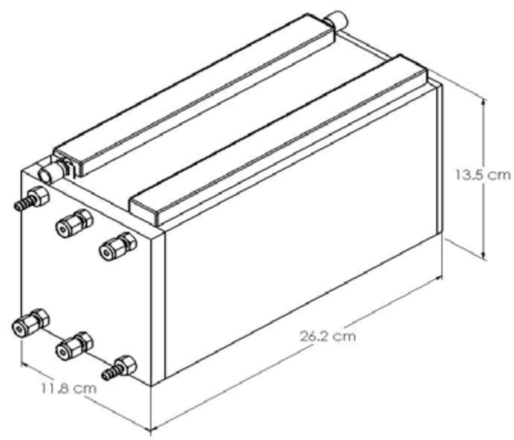
Prototype Products

After several years of intensive R&D yielding 8 issued U.S. Patents and over 25 published U.S. Patent Applications, we are now involved in prototype product development. A wide variety of cells and stacks sized from a few watts to about 100 W have been built and tested. We are now pursuing a low cost modular approach with molded electrode frames that provides a rugged product. For demonstration purposes, we have selected an electrode surface area of 60 cm^2 for our early prototypes. A 40 cell module provides over 250 W with a conservative monopolar design. Our baseline prototype product is specified in Table I. With our modular approach, shorter or longer stacks can be produced. Additionally, a variety of systems are available by connecting stacks in series and parallel.

Table I Specifications for OV-60 Prototype Product

OVONIC 40-OV-60 FUEL CELL STACK

Configuration:	40 cells in series
Electrode Surface Area:	60 cm^2
Module Dimensions:	
Width	11.8 cm
Length	26.2 cm
Height	13.5 cm
Volume	4.2 L
Module Weight:	3.9 kg
Nominal Performance:	
Power	260 W
Voltage	26 V
Current	10 A
Specific Power	67 W/kg
Power Density	62 W/L
Temperature	60 ^{o}C



Several-fold improvements in specific power and power density are under development utilizing improved electrodes and current collection. Enhanced pulse power is also available utilizing regenerative mode operation. Improved specific power is also available in larger sizes through the improved design to reduce the contributions of hardware.

Our technology is easily scalable to applications requiring 50 W to 100 kW.

Market Opportunities

The Ovonic® Regenerative Fuel Cell has strong favorable attributes for fuel cell electric vehicle applications, including the capability to store regenerative brake energy. This capability is critical to achieve sufficient overall system efficiency to provide a net improvement in greenhouse gas avoidance. Additional useful features include the instant start capability and excellent low temperature performance, both also derived from the energy storage functionality. However, the strongest advantage over PEM fuel cells now under development for automotive applications is probably in the area of cost. After many years of intensive development there are increasing doubts about whether PEM fuel cells will ever be able to meet the automotive cost requirements of less than $100/kW. We believe the Ovonic® Regenerative Fuel Cell offers the best approach to meet the challenging cost goals of the automotive application.

Particularly because of concerns about fuel cell costs, it is now acknowledged that fuel cell electric vehicle introduction may be delayed by at least one decade and the initial focus of fuel cell commercialization is being diverted to alternative applications including UPS (uninterruptible power supply), emergency power, portable electronics, telecommunications, electric scooters, forklifts, and various military applications. For these applications, the regenerative operation, the instant start operation, and the excellent low temperature performance of the Ovonic® Regenerative Fuel Cell are invaluable attributes. Additionally, the low cost opportunity with our new technology applies across the board, as the cost issue has been the single largest issue holding back the commercialization of the fuel cell industry.

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