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Development of a PEM fuel cell powered portable field generator for the dismounted soldier

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Abstract

The increasing use of electronic technologies by the dismounted soldier is placing a growing burden on the power sources required to operate them. Battery technology, which is close to the limit of development cannot provide for the soldiers power needs at an acceptable weight. Air breathing proton exchange membrane (PEM) fuel cells in combination with advanced hydrogen generation technologies, are suggested as a viable alternative, providing greatly increased energy densities. An application as a portable field generator is suggested, with the fuel cell system acting as a charger coupled to rechargeable batteries.

Keywords: PEM fuel cell; Dismounted soldier; Energy density; Air breathing; Hydrogen

1. Introduction

In order to maintain their present battlefield superiority, achieved largely through the application of technology, modern Armed Forces must continue to field the latest and the most effective equipments. Battlefield dominance is increasingly viewed as being directly dependent upon information dominance. That is, the successful use and protection of information, while denying the enemy the use of his. This is part of a process commonly referred to as the digitisation of the battlefield, which is being applied across a whole range of weapons platforms and operating systems, one of which is the dismounted soldier. The dismounted soldier (one who fights on foot) of the near future is considered to be a weapons platform in his own right. He will carry a wide range of enabling electronic technologies such as computers, personal radios, GPS, head up displays and thermal imaging, all of which are intended to increase his effectiveness, lethality and survivability.

This increased reliance on technology, does however, come at a price. An increased amount of electronics brings with it a concomitant increase in the burden on the power sources required to operate them. The future soldier programme, future integrated soldier technology (FIST) in the UK, for example, is likely to require an average power output of 30 W, for mission durations of 72 h, a total requirement of over 2 kWh of energy. Batteries have provided portable power to the military for many decades, but present day technologies have an inadequate energy density for the mission profiles envisaged. No battery either in service or due to enter in the near future, can provide for the energy needs of the future soldier at an acceptable weight. Providing power to the dismounted soldier therefore, has been widely identified as one of the most critical issues facing today's military.

The proton exchange membrane (PEM) fuel cell is considered to be a viable portable power source for the future soldier. A low temperature, reliable and lightweight fuel cell with a solid electrolyte, which when combined with a suitable fuel, can provide power for missions, far beyond the capacity of batteries.

At present, batteries limit the mission duration of the soldier, this is despite the fact that the military generally uses the best battery technology available. Primary batteries, for long the workhorse of the soldier's power provision armoury, do not have sufficient energy density for intended mission profiles. They are very expensive and also pose serious safety, availability, inventory and disposal problems. Rechargeable batteries, unlike the primary, are not discarded after a single discharge, and can usually be cycled at least several hundred times. This makes them much less expensive in terms of energy cost, however, the best rechargeable batteries only possess energy densities of approximately a third of their primary counterparts.

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PEM fuel cells are attractive for small format (e.g. portable and battery replacement) applications for a number of reasons. Extended operating times are facilitated because of the "separated" nature of the power and energy components. The PEM fuel cell system can be designed to carry increased amounts of fuel without adding to the weight of the power generating part of the system. This is in contrast to the situation with batteries, where the power and energy components are enclosed in the same container and this flexibility is lost. Fuel cells therefore, are high power, high energy density devices, which can act in effect like a "continuous" battery, but whereas batteries require either replacement or recharging of the whole unit after discharge, a fuel cell system needs only to replace the fuel component (e.g. clip-on, clip-off metal hydride pack).

Unlike most other fuel cell types, PEM fuel cells are suitable for small, low power applications. They can be scaled down to small size without compromising performance, and are suitable for applications ranging from microwatts to hundreds of kilowatts. They have a low battlefield signature as they are quiet, operate at low temperature (<80 °C), and they are reliable.

A particular type of PEM fuel cell which is appropriate for man-portable applications, is the air breathing PEM fuel cell. This represents the simplest of PEM fuel cell systems. Low-pressure hydrogen (<5 psi) is supplied as fuel, while oxygen is extracted from air in the immediate atmosphere. The air is usually directed to the stack either by natural convection or with the assistance of small fans. Unlike pressurised systems, air breathing PEM fuel cells do not rely on critical sub-systems, consequently no air compressor, cooling system or external humidifiers are required. This reduces the parasitic losses due to auxiliary equipment from typically 15–20%, down to less than 5% (possibly zero), and not only facilitates small scale applications, but also reduces the cost. This technology provides lower power outputs than pressurised versions, typically up to hundreds of mW cm^{-2}, as compared to W cm^{-2}.

Fuel cells are viewed by many as a replacement technology for batteries, and there are many applications to which fuel cells are better suited. However, fuel cells and batteries can be used together very effectively, either as a hybrid power source [1] or by using the fuel cell as a charging unit coupled to rechargeable batteries.

Before fuel cells can be considered for military power source use, certain key issues need to be addressed. Although fuel cells can provide higher energy densities than rechargeable batteries, even with the modest hydrogen storage densities that secondary metal hydrides possess, this system is still considered too heavy for future soldier needs. A major challenge therefore, is the provision of a hydrogen source of acceptable performance that is also practical for military use.

Many different systems are under investigation, including pressurised composite gas bottles, rechargeable metal hydrides and various methods for the chemical generation of hydrogen. Miniaturisation of fuel reforming technology is a further option, attractive in part because it could allow the use of existing logistical fuels.

It is possible that a variety of hydrogen generation or storage methods will be utilised by the military, each tailored to meet the demands of specific energy ranges and mission profiles, however, whichever systems are used, they will have to be simple to use, safe, low cost, convenient to carry, be rugged and have a low battlefield signature.

Ruggedisation of the fuel cell is a major, although not insurmountable area of concern. The fuel cell power source should, if possible, be as robust as the batteries presently in use. If metallic bipolar plate technology is utilised [2], it should be relatively simple to toughen PEM fuel cell stacks against the rigours of physical abuse. However, guaranteeing the security of oxidant supply to the stack does present more of a challenge. Air breathing fuel cells require access to the oxygen in the atmosphere. If this access is restricted or the quality of the air is severely compromised [3], the performance of the stack can suffer. Immersion in water and operation in the presence of various types of air contamination are examples of the problems that have to be taken into consideration. A combination of stack, packaging and container design, operating regimes and positioning may all be used to successfully address these issues, however, at present, an air breathing PEM fuel cell system does not provide an all terrain power source guaranteed to operate in all of the conditions anticipated for the dismounted soldier.

An application for the air breathing PEM fuel cell that has been identified for early entry into the Armed Forces is that of a front line portable field generator/battery charger. The unit must still be man-portable, but need not be carried continually and it would possess the high energy density required to extend mission durations without being part of the soldiers integrated system, and it would not be required to function at all times throughout the mission, so that periods where conditions could adversely affect performance can be avoided.

A portable generator of this type, used to recharge batteries in the field, could be the entry point for fuel cells into the British Armed Forces. In the US, the Board on Army Science and Technology has described the combination of rechargeable batteries with a fuel cell battery charger as the most practical energy source for the dismounted soldier, while France, as part of their FELIN project, is adopting a similar approach for the future soldier.

A 2-year programme to develop a PEM fuel cell power source for the dismounted soldier has recently got underway. The work will focus on providing a front-line battery charger for use with advanced rechargeable batteries. Funded jointly by industry and the MOD, the programme aims to build on the work carried out by Intelligent Energy Ltd. and the DERA (now QinetiQ Ltd.) in the field of military man-portable and battery replacement fuel cells. The full list of development partners are Intelligent energy, who will provide the fuel cell technology, Black & Decker, who will provide the power interface between charger and batteries, Ineos Chlor, who will supply bipolar plate coatings and QinetiQ, who will supply hydrogen generation technology.

The specific technical objectives of the work are to develop, build and demonstrate a 100 W PEM fuel cell power source with an energy density of 600 Wh kg^{-1}, in the form of an air breathing PEM fuel cell and associated hydrogen generator. The completed unit will be a 3 kWh power source weighing 5 kg.

2. Results and discussion

Intelligent Energy Ltd., in conjunction with the DERA, have been developing air breathing PEMFC technology for prospective military use for over 5 years. They have recently produced portable stacks capable of peak gravimetric and volumetric power densities of 140 W kg^{-1} and 160 W l^{-1}, respectively. Fig. 1 shows a polarisation plot taken from such a stack.

The use of metallic bipolar plate technology produces stacks, which are both compact and rugged. The anodic and cathodic elements of the bipolar plates are made of Stainless Steel 316 (0.3 mm thick) and produced in a single pressing operation. All other non-electrochemical components of the stacks are either currently mass producible or a clear route to mass production can be envisaged. Small fans, which are both temperature and load responsive, are used to provide increased air flow for cooling and oxidant supply.

A 50 W power source consisting of an Intelligent Energy stack, rechargeable metal hydride and voltage regulation equipment, was recently demonstrated by the DERA. The system was positioned inside an empty lithium ion power source (LIPS) battery case for comparison against both the LIPS battery itself and the Clansman NiCd battery. The battery case was modified to allow air access (Fig. 2).

The LIPS battery is due shortly to enter service, whereas the Clansman is one of the existing batteries of choice for the Armed Forces. Table 1 shows a comparison of the fuel cell system with the two battery types.

No weight optimisation was carried out on any of the component parts, yet, on the first attempt, using a commercially available metal hydride, with about 1 wt.% hydrogen storage, the performance of the fuel cell system exceeded that of the batteries. The duty here was 24 V and 2 A.

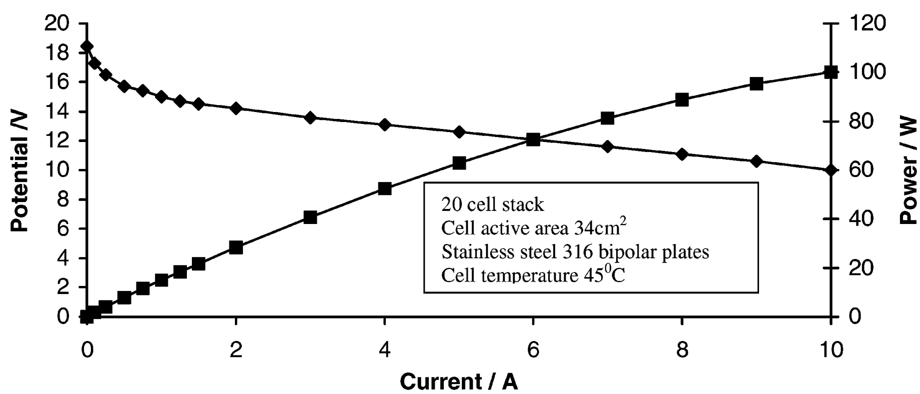

Fig. 1. Polarisation performance of nominal 50 W air breathing PEM fuel cell.

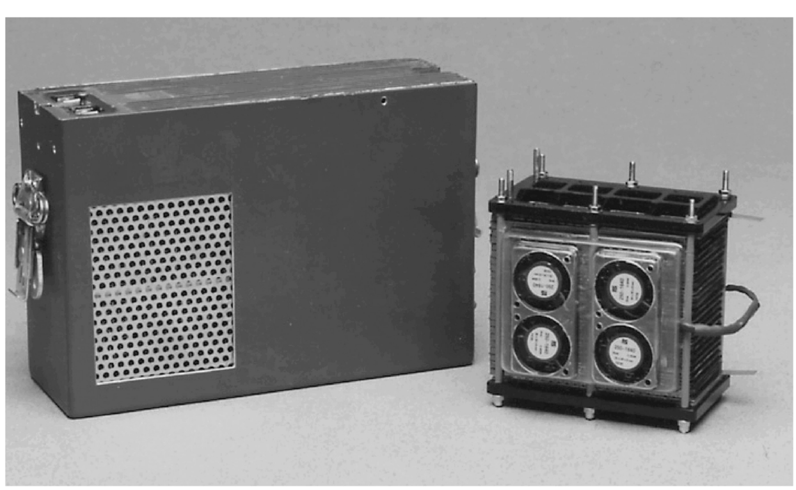

Fig. 2. Battery replacement system (in case) and 50 W air breathing PEM fuel cell stack.

Table 1
System comparison between air breathing PEM fuel cell, lithium ion and nickel cadmium batteries

	Nickel cadmium (Clansman)	Lithium ion (LIPS)	PEM fuel cell and rechargeable hydride
Weight (kg)	3.3	2.5	3.3
Volume (l)	1.6	2.3	2.3
Energy (Wh)	96	180	282
Energy density (Wh kg^{-1})	29	72	85
Energy density (Wh l^{-1})	60	78	123

The technology demonstrated to date has been constructed using untreated stainless steel 316 bipolarplates, which are prone to corrosion in the fuel cell environment and can also give reduced performances due to oxide layer phenomena which increase resistance losses within the cell. It is intended that these stainless steel plates be replaced by titanium. Titanium is a better conductor than stainless steel and is 40% lighter, and so is attractive when considering portable applications. However, it corrodes in the fuel cell environment forming an insulating oxide. It must therefore be protected without compromising conductivity. PEMcoat, a propriety titanium coating developed by Ineos Chlor, provides such protection and additionally produces improved performance.

On the polarisation curve shown in Fig. 3, measured from pressurised test cells, the current density obtained at 0.7 V with stainless steel is approximately 0.4 A cm^{-2}, as compared to 0.7 A cm^{-2} for the coated titanium. The data was taken from a cell operating with identical MEAs, reactant hydrogen and air pressures of 2 bar (g) and a temperature of 70 °C. Lifetime testing of PEMcoat under these conditions has been carried out for over 10,000 h with no significant drop-off in performance observed.

It is expected that, the use of coated titanium, and the weight saving and performance uplift it will bring, combined with some design improvements, will yield peak power densities in the 300 W kg^{-1} and 300 W l^{-1} region.

The opportunity for major weight saving gains, lie not with the stack, but in the development of novel, high performance hydrogen generation technology. Traditional compressed gas cylinders and rechargeable metal hydrides do not provide sufficient energy density for the dismounted soldier. The recently demonstrated composite cylinders with hydrogen weight percentages of over 11%, have very good energy storage at the scale used for automobiles, but are still bulky for man-portable applications and what is more, utilise very high pressure (350 bar) hydrogen gas, which would be a major concern to the dismounted soldier carrying it in the battlefield.

The hydrolysis of primary hydrides, such as lithium aluminium hydride and sodium borohydride has been much investigated as a means of chemically generating hydrogen. These can offer hydrogen yields of over 8 wt.%, however, the reactions require more water than is predicted from the chemical equation, leading to significant weight penalty. They are also exothermic and difficult to control, particularly with respect to response time and thermal runaway.

Two alternative methods of chemically generating hydrogen will be investigated and developed during the programme, a mid-term and a longer-term option.

As part of the International Exchange Agreement on Power Sources for the Dismounted Soldier, advanced hydrogen generators will be provided for assessment by US Army CECOM. The system presently in development under a joint CECOM, ARO and DARPA programme, uses the ammoniolysis of lithium aluminium hydride:

$$3LiAlH_4 + 4NH_3 = Li_3N + 3AlN + 12H_2$$

This has a theoretical hydrogen yield of 13.2 wt.% hydrogen, and the target energy density for the complete fuel

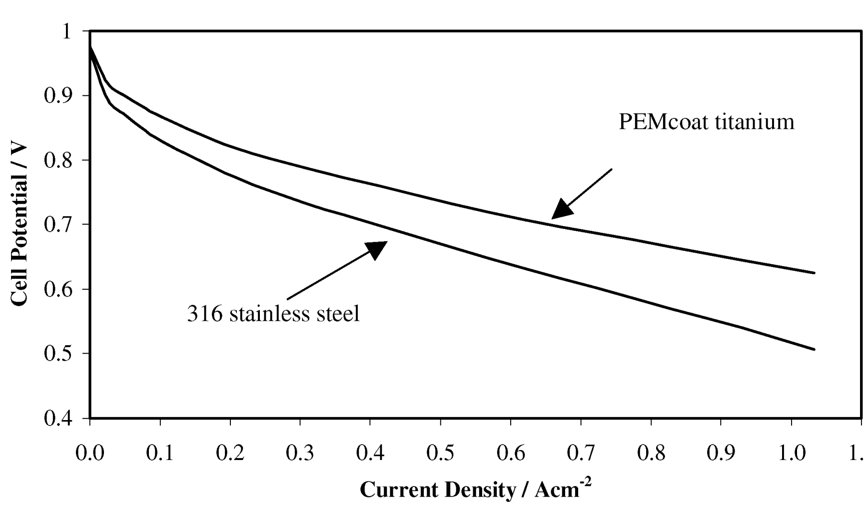

Fig. 3. Comparison of polarisation performance of Stainless Steel 316 and coated titanium.

delivery system is 1 kWh kg^{-1}. The work on this system has been underway for some time and it will be made available for assessment and integration.

A longer-term hydrogen generation option is under development by QinetiQ. This relies on the thermal decomposition of ammonia borane:

$$NH_3BH_3 = BN + 3H_2$$

This reaction has a theoretical hydrogen yield of 19.6 wt.%. Heating is required as the decomposition takes place between 120 and 300 °C, and a thermolysis system is required. This system is presently the subject of a patent application, and so propriety details must remain confidential. However, it can be said that the process is low pressure and load responsive, uses low hazard reagents and produces no dangerous products. The complete fuel delivery system is expected to provide an energy density of 1.5 kWh kg^{-1}.

3. Conclusions

PEM fuel cells are attractive for military man-portable power, but require ruggedisation before introduction as an integrated power source for the dismounted soldier. A battery charger application is a suitable entry point for PEM fuel cell technology into the military, as it allows advantage to be taken of the increased energy density of the fuel cell system without endangering power supply.

Even when using commercially available, secondary metal hydrides for hydrogen storage, air breathing PEM fuel cell systems can be assembled today that provide extended mission durations, when compared to rechargeable batteries. Advanced hydrogen generation technologies, such as the ammoniolysis of lithium aluminium hydride or the thermal decomposition of ammonia borane, will yield energy densities 6–8 times that of the most advanced rechargeable lithium batteries.

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