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Portable fuel cell systems for America's army: technology transition to the field

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Abstract

The US Army Communications, Electronics Research Development and Engineering Center (CERDEC) envisions three thrust areas for portable fuel cell systems for military applications. These areas include soldier power (<500 W), sensor power (0–100 W), and auxiliary power units or APUs (0.5–10 kW). Soldier and sensor fuel cell systems may be man-portable/backpackable while APUs could be employed as squad battery chargers or as 'Silent Watch' APUs where low signature (acoustic, thermal, etc.) operation is a requirement.

The Army's research and development efforts are focusing on methods of either storing or generating hydrogen on the battlefield. Hydrogen storage technology is considered critical to small military and/or commercial fuel cell systems, and is being pursued in a host of commercial and government programs. CERDEC, in a joint effort with the Army Research Office (ARO) and the Defense Advanced Research Projects Agency (DARPA), is developing several promising hydrogen generating technologies. The goal of this program is a safe, reliable hydrogen source that can provide rates up to 100 W with an energy density of greater than 1000 Wh/kg.

For larger fuel cell units (>500 W), it is imperative that the fuel cell power units be able to operate on fuels within the military logistics chain [DOD 4140.25-M, DOD Directive 4140.25 (1993)]. CERDEC is currently conducting research on catalysts and microchannel fuel reformers that offer great promise for the reforming of diesel and JP-8 fuels into hydrogen. In addition to research work on PEM fuel cells and enabling technologies, the Army is also conducting research on direct methanol and solid oxide fuel cells, and combined heat and power applications utilizing new high temperature fuel cells.

Keywords: Applications/military (manpack and APU); Fuel cells/PEM; Fuel cells/solid oxide; Hydrogen storage

1. Introduction

The Army develops and deploys a vast array of powered equipment necessary to accomplish its mission. Advancements in micro-electronics during the 1980s and 1990s have resulted in the introduction of new equipment with powerful capabilities such as night vision devices, global positioning systems, laser range finders and target designators, digital communications systems, intelligence gathering sensors, and others. These systems are part of the Army's plan to 'digitize' the battlefield. The use of these advanced electronic systems will provide commanders and soldiers with a common picture of the battlefield and enable them to conduct operations at a tempo in which the enemy will be unable to react.

These electronic systems are creating an ever-growing demand for power sources that are power dense, reliable, and affordable. In an effort to simultaneously improve upon the existing power storage and generation devices while continuing to supply America's war fighters with state-of-the-art equipment, the US military has focused on fuel cell technology for various military applications. CERDEC is currently working with low power (<20 W) systems for soldier and sensor power, mid power (200 W–2 kW) for silent power generation and battery recharging, and larger (2 kW and up) for mobile power generation and APUs [2].

CERDEC has adopted a 'system of systems' approach to the development of military fuel cell units. While there is a great need for further basic research into key technology

Abbreviations: APU, auxiliary power unit; ARL, Army Research Lab; CERDEC, Communications-Electronics Research, Development and Engineering Center; DARPA, Defense Advanced Research Projects Agency; DMFC, direct methanol fuel cell; DOD, Department of Defense; DOE, Department of Energy; PEM, proton exchange membrane; VTB, visual test bed; Whr, Watt-hour

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Fig. 1. Land warrior.

areas, CERDEC strives to develop completely packaged systems in order to rapidly transition fuel cell technology from the labs to the users. CERDEC has been a leader in the development and demonstration of several complete military fuel cell prototypes for soldier systems, robotics, sensors, and APUs. Examples include a 100 W fuel cell based battery charger, a 20 W direct methanol fuel cell (DMFC) for soldier power, and a 2 kW methanol reforming fuel cell used as a Silent Watch APU [2].

The Army has selected proton exchange membrane (PEM) and direct methanol fuel cells as the leading near-term technology candidate for soldier and sensor power because of their high power density, quick start capability, and technology maturity (Fig. 1). PEM fuel cell stack performance has improved dramatically in recent years as the result of better design, effective thermal management, and better membrane electrode assemblies. The result is enhanced specific power density and reduced cost. However, the effective use of fuel cells in the military will require a safe, high energy dense, transportable, and reliable source of hydrogen. Therefore, the military has recently shifted its focus from the ‘cell’ to the ‘fuel’ in order to develop high-energy dense hydrogen storage and generation devices [2].

A hydrogen delivery subsystem, whether it stores hydrogen or generates it from a chemical or fuel, must have high energy density to sustain long missions (>24 h). Two types of hydrogen delivery systems are being considered for hydrogen fed systems: physical storage and generation-on-demand. Physical storage includes compressed cylinders, metal hydrides, carbon nanotubes, etc. Generation-on-demand includes reacting chemicals to liberate hydrogen and reforming liquid fuels. Chemical reaction based subsystems tend to provide higher hydrogen storage (5–7%) compared to physical storage (1–2%). Reforming offers even higher energy density and better economics versus the other delivery subsystems. There are a number of techniques to generate hydrogen by reforming liquid hydrocarbons such as methanol, gasoline, and diesel/JP-8. Methanol is the leading candidate fuel to provide hydrogen for near term niche military applications. Diesel, JP-8, and other military logistics fuels remain as the ultimate goal as a source for hydrogen on the battlefield.

2. Army fuel cell applications

Hybrid power sources consisting of a fuel cell and a rechargeable battery have high potential for satisfying a wide variety of requirements for mobile/portable and silent power sources in the range of 20–2000 W. Batteries are best suited for short mission durations (<24 h) at low power requirements (<20 W). At power requirements of 2000 W or more, military standard diesel fueled generator sets are available. However, these small diesel sets are noisy, pose operational problems where stealth is required and are not as efficient over a full operating cycle as fuel cells. The 20–2000 W range is a ‘gray area’ in the military where power requirements are too high for batteries and too low for logistic fueled generators. Many approaches for smaller power sources (20–150 W) utilizing PEM fuel cells have been explored and have shown high potential.

In addition, future applications for fuel cells could include mobile power generation. The Army is focused on minimizing the total life-cycle costs of fielded systems. The high logistics costs of providing fuel to fielded equipment is a major life-cycle cost driver that has caused the Army to emphasize fuel efficiency on current and future development programs. PEM fuel cell power plants offer high efficiency (~40%) operation and compare favorably with diesel generating units at around 30% efficiency [3]. The obstacle to the introduction of large (>2 kW) fuel cells is the need to operate from the existing logistic fuels (diesel and JP-8). These fuels contain sulfur compounds that are difficult to remove. In addition, when hydrogen fuel must be generated from a logistic fuel, the overall system efficiency and environmental impact are comparable to current internal combustion engine technology. Current research within the Army is focusing on the use of microchannel reforming techniques for the reforming of hydrocarbon fuels.

An increasingly important combat vehicle application is a tactical mode of operation termed Silent Watch. This mode of operation usually requires that all mission requirements, other than mobility, be met while also meeting stringent acoustic and infrared signature levels. Silent Watch requirements usually preclude main engine operation (or small diesel engine auxiliary power units operation) due to the large acoustic signature. Additionally, many of today’s combat vehicles often have a large communications and situational awareness suite of electronic equipment that cannot be supported by the batteries alone. Fuel cell APUs may provide a solution to meeting the military requirements of Silent Watch.

CERDEC recently installed a ruggedized 2 kW methanol/water reforming fuel cell APU onto a prototype command and control combat vehicle (see Fig. 2). The fuel cell unit provided power to mission critical communication and electronic equipment during Silent Watch exercises. As a result of not having to start the vehicle’s diesel engine, the soldiers at the Silent Watch site were able to avoid detection, hear and identify the opposition force’s exact location, and

Fig. 2. Command and control combat vehicle with 2 kW fuel cell APU mounted on the roof.

successfully call for reinforcements. While not officially fielded, this unit was one of the first military fuel cell systems to be 'used and abused' for an extended period of time out in real world environments (rain, dust, cold, and hot weather, vibration, etc.). However, the US military's one fuel forward policy demands that America's joint forces must rely on diesel, JP-8, and other logistics fuels to power the force [1]. While methanol/water reforming systems are available today for niche APU applications, CERDEC and its joint partners continue to develop other reformer approaches that will demand less water (as a fuel load) and will use higher hydrocarbon feeds such as diesel. The fuel issue continues to be a major challenge to broad acceptance and deployment of fuel cells in higher power applications.

3. Hybrid advanced power sources (HAPS)

CERDEC has sponsored a multi-disciplinary effort at the University of South Carolina to develop hybrid power sources based on fuel cells, batteries, and capacitors for various military applications. This program focuses specifically on power/electronic systems in the 0–100 W range. The HAPS program will develop first order models of various electronic devices and components, which will then be used in a combined model capable of simulating various component combinations/configurations. The electronics used to combine the various technologies will be a part of the model and will provide a method of analyzing various fuel cell stack configurations and their impact on overall system size and weight. The model will be used to optimize the interaction of electrochemical devices for several different power consumption scenarios. It will include load characteristics that will be used to simulate actual military equipment. These load profiles will include a capability for steady state, random and various peak to average pulsed power demands that will simulate actual loads encountered by the soldier. The models will be incorporated into a visual test bed (VTB) simulation environment that will provide the capability to do virtual prototyping of multi-technology systems. Hardware will be procured and tested to verify the accuracy of the models and prototype HAPS will be delivered. The HAPS program can also model hydrogen sources, such as metal hydrides, and fuel processing systems. Since most of the applications include a fuel cell, the hydrogen source is a critical part of the overall system. Depending on the hydrogen source, the fuel cell may need to operate at near steady state load for optimum energy density. When using a fuel processor the transient response of the processor will determine the size of the battery used for peak loads/load leveling. The term hybrid is also relevant from a different perspective. For applications such as fording a river, the battery is used not as a peaking device but as a source of power when air is not available to provide the oxidant for the fuel cell cathode reaction. This reserve/emergency battery could be primary or rechargeable and would also provide the soldier with a degree of confidence in the event that the fuel cell fails. Issues such as these can be rapidly simulated using the VTB to 'pick and play' with different components of HAPS.

4. Direct methanol fuel cells (DMFC)

The Army is focusing on the development of fuel cell systems that utilize a liquid hydrocarbon fuel directly without fuel processing. The near-term commercial fuel of choice for this application is methanol although the ultimate goal for military systems would be diesel fuel or JP-8. The use of a liquid fuel for fuel cells has several advantages. The primary advantage is the high energy density of hydrocarbon based liquid fuels. Methanol (CH_3OH) has a much higher energy density (∼6 kWh/kg), even when stored in ruggedized, lightweight containers, than current battery technology. The fuel could be supplied in small cartridges or from an external container depending on mission scenarios. For a soldier application, a few small cartridges along with a fuel cell power source could be used in place of low energy dense batteries. Although the power section of these fuel cell systems are still heavier and more complicated than comparable hydrogen consuming systems, the advantage of using a high-energy liquid fuel cannot be disregarded on a system basis. Even at this stage of development, the DMFC can offer an advantage for a mission that requires several thousand watt-hours of energy. In addition, liquid fuels are often much safer and easier to package, ship, and distribute than compressed gasses.

State-of-the-art technology has been demonstrated under the joint DMFC program sponsored by ARL/CERDEC/DARPA/LANL and conducted at Ball Aerospace Corporation in Boulder, CO. This program has produced a 60-W prototype unit (Fig. 3) that weighs about 7 kg and contains enough fuel for 1400 Wh. The advantage of liquid fuel is apparent when more energy is required. An additional 5000 Wh can be achieved by simply providing 3 kg of additional methanol. This is equivalent to about 1600 Wh/kg and 1250 Wh/l for the fuel source. A second-generation 20 W, 3 lb (dry weight) prototype is currently being built under the same joint program.

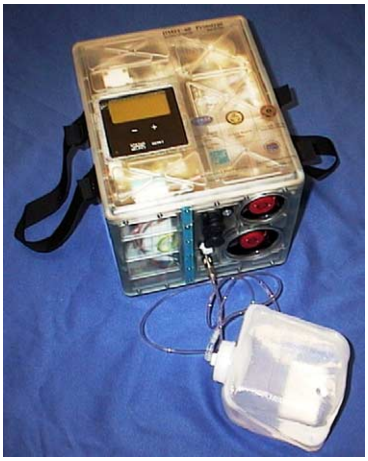

Fig. 3. DMFC prototype (60 W).

The performance of DMFC systems can be improved significantly if the cross-over of methanol from the anode to the cathode can be reduced or eliminated. The cross-over causes a loss of fuel and also depresses the cell voltage. The cells currently operate at less than 0.5 V and require large catalyst loadings and careful water management. There are numerous research and development programs trying to resolve these issues. The Army Research Lab (ARL) is conducting research to formulate membrane electrode assemblies with methanol tolerant cathodes. ARL will also be developing membranes with low cross-over rates and delivering a low power DMFC stack based on lightweight strip cell technology. If the cross-over can be eliminated the fuel source metrics could exceed 2200 Wh/kg and 1750 Wh/l.

5. Hydrogen delivery to PEM fuel cells

One of the critical barriers to fuel cell use in the Army is the absence of an acceptable hydrogen delivery system. This acceptability involves two factors. First, the hydrogen delivered to the fuel cell must be free of constituents and conditions detrimental to the fuel cell membrane electrode assembly. Diluents such as nitrogen, while not harmful to the fuel cell, add additional weight and complexity to the system. The second factor is the weight/volume claimed by the storage system and its recharging system. Table 1 summarizes the various alternatives to hydrogen supply module on a timeline into the future. The current technology, compressed hydrogen tanks and rechargeable metal hydrides, do not have the utility of use to meet the Army's tactical requirements. Their energy density is too low although the cost per watt-hour is very attractive versus batteries.

For these reasons, chemical systems, such as ammonia-based systems, are being developed in cooperation between US Army CERDEC, DARPA, and the British Military of Defense. CERDEC has tested several ammonia reactors under various power profiles and temperature conditions. CERDEC verified that current ammonia-based systems can achieve almost 500 Wh/kg and can operate autonomously for over 50 h (at 20 W) at near freezing temperatures [3]. Further developments are underway to increase yields to 1000 Wh/kg. These systems can produce electric power at a cost of 25 cents/Wh (US$ 0.25), which is substantially less than power from primary military batteries (US$ 0.56/Wh) [4].

More energy dense and cost effective sources of hydrogen are being investigated to supply hydrogen to portable power systems. These sources include an examination of direct methanol fuel cells, hydrogen storage in carbon nanotubes, and microchannel reformers for hydrocarbon based fuels. Reforming is discussed in the subsequent paragraph on fuel processing.

6. Fuel processing

Hydrogen can be generated from hydrocarbon fuels by a number of reforming techniques with the most common practices being steam reforming and autothermal reforming. A multi-stage process is needed to convert the hydrocarbon fuel to a hydrogen rich stream suitable for a PEM fuel cell. The first stage is a catalytic steam reforming or autothermal reforming process. This process step requires high temperatures (700–850 °C) to convert the hydrocarbons, steam and/or air to a stream containing hydrogen, carbon monoxide, carbon dioxide, water, and trace amounts of low molecular weight hydrocarbons (for simple hydrocarbons lower temperatures can be used). This stream must then be cooled and passed over another catalyst to increase hydrogen content and to reduce carbon monoxide. A third stage is then required to remove remaining carbon monoxide so that the stream is suitable for PEM fuel cell consumption. For those reforming systems using commercial and military grade fuels, an additional stage may be needed within the process to remove sulfur and other impurities.

Results from research in heavy hydrocarbon reforming indicate that the initial reforming step takes place at high reaction rates. Therefore, the catalyzed reactions are heat and mass transfer limited and the overall design of the beds

Table 1
Hydrogen supply for portable fuel cells

Today	Tomorrow	Future
Compressed hydrogen 4500 psi (450 Wh/kg)	Ammonalysis of $LiAlH_4$ (1000 Wh/kg)	Carbon nanotubes (? Wh/kg)
Rechargeable metal hydrides (230 Wh/kg)	Direct methanol liquid fuel (1000 Wh/kg)	Fuel reformers (1500 Wh/kg)

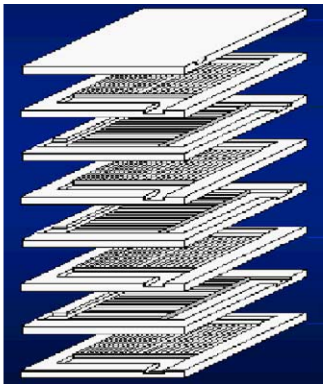

Fig. 4. Microchannel reformer concept (courtesy of Battelle, Pacific Northwest National Laboratories).

can be significantly reduced if designs that enhance the heat and mass transfer could be developed. Microchannel reactors appear to provide just such a solution. Fig. 4 shows a planar microchannel concept. The overall concept of microchannel reactors is to closely couple exothermic and endothermic reactions and to provide controlled heat transfer close to reactions sites. The Army is sponsoring several programs on microchannel fuel processing.

A program with Pacific Northwest National Laboratories (PNNL) is oriented toward the low to medium power range (20–500 W) for man-portable applications. A 40 W equivalent, microchannel fuel processor operating on methanol was successfully demonstrated (Fig. 5). The fuel processor consists of a vaporizer, steam reformer, and recuperative heat exchanger with the entire system weighing less than 80 g. Future work is oriented to optimizing components and integration of components into a compact efficient fuel processor. For low power applications, clean hydrocarbon or methanol fuels are permissible.

A second program with Innovatek Inc. is oriented toward JP-8/diesel fuel reforming for applications larger than 500 W. The challenges of using a logistic fuel are great but early progress is highly encouraging. A new catalyst for microchannel reforming of JP-8/diesel fuel has shown tolerance to reforming sulfur-laden logistic fuels. If this early result holds true, then one large obstacle to a compact reformer will be eliminated. Down stream hydrogen clean up will still be required but these steps are well understood.

Fig. 5. Microchannel fuel processor (40 W).

Considerable progress has been made over the past year, but much more needs to be done. There is heightened interest by DOE and the fuel cell community to utilize diesel fuels. Catalyst manufactures are now offering better catalysts. The Army plans to pursue the microchannel approaches because initial work has been promising and they offer the greatest potential for weight and size reduction.

7. Technology transition to the user

Despite the progress and advances made in the component and process areas, there has been very low emphasis placed on fuel cell system integration. While several commercial companies claim market penetration by 2004, especially with DMFC power devices for portable electronics such as cell phones and laptop computers, few have developed a reliable, rugged unit that will be affordable for an average consumer. Military fuel cell systems will need to be even more reliable and rugged due to the nature of their operating environments. To date, most test and evaluation on fuel cells in real world environments have shown that balance of plant parts, such as fuel pumps and fans that are unrelated to the fuel cell stacks, often fail first. While optimal system and component performance has been established in lab environments, more focus must be placed on developing ruggedized systems that will reliably operate while being ‘used and abused’ in the field.

CERDEC maintains its ‘system of systems’ approach in all of its fuel cell efforts and strives to operate programs that will produce prototype units. To that effect, CERDEC is managing a Foreign Comparative Test Program that specifically seeks out foreign produced systems that have near-term commercial and/or production potential. Through this program, CERDEC will test and evaluate several fuel cell systems from vendors in Europe, Canada, and Asia. These systems will first be validated and tested in lab environments and will then transition to field and user tests in order to assess reliability and mission suitability. The primary goal of the program is to identify possible sources for near-term acquisition of portable fuel cell systems that are lightweight, power dense, and reliable in real world environments.

8. Conclusion

The United States Army in conjunction with government, academia, the national labs and industry is actively pursuing fuel cell technology. There has been considerable success in reducing the weight of the fuel cell stacks, and power systems have been developed and demonstrated in a variety of critical military applications. These systems compete well as battery replacements in most environments. There is a definite weight advantage when compared to secondary batteries and depending on mission length, weight and cost can be lower than primary batteries (1 gallon of methanol weighing 6.6 lb and costing less than US$ 0.50 is equivalent to 62 lb of primary batteries at US$ 2240).

Electrical power for the future battlefield will become a critical enabling technology for robotics, sensors, auxiliary power, soldier systems, microclimatic devices, and other systems being proposed to meet the tactical requirements of the future battlefield. The success of fuel cell power sources for military applications depends largely on the development of acceptable hydrogen sources and the success of commercial programs. Key applications such as the objective force warrior and land warrior will require fuel cells and hydrogen sources that are energy-dense, non-cumbersome and above all safe to carry and operate. Fuel processing efforts could provide future systems that would operate on logistic fuels. Primary barriers to this scenario involve the miniaturization of systems and the ability to tolerate fuels containing sulfur.

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