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Development and evaluation of portable and wearable fuel cells for soldier use

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HIGHLIGHTS

- Test and evaluation of systems developed for portable and wearable military applications.
- Laboratory results and soldier feedback from limited test events included.
- Portable FC systems require power density improvements for widespread use.
- Based on feedback, desirable wearable system attributes include thin form factor.
- Wearable systems based on Alane demonstrated high power density offering an attractive power source.

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ABSTRACT

A number of fuel cell systems have been recently developed to meet the U.S. Army's soldier power requirements. The operation and performance of these systems are discussed based on laboratory results and limited soldier evaluation. The systems reviewed are primarily intended for soldier use in an austere environment with minimum access to resupply and vehicular transportation. These applications require high power and energy density sources that are portable (300 W) and wearable (20 W) to minimize the soldier's load burden. Based on soldier field evaluations of portable fuel cell systems, improvements in power density and compatibility with logistical fuels are required to be successfully deployed. For soldier worn applications, a novel chemical hydride system has shown significant advances in power and energy density while maintaining a small form factor. The use of a high energy dense fuel cartridge (800 Wh kg^{-1}) based on AlH_3 (Alane) thermolysis, allows a power density of (28 W kg^{-1}) which offers promising weight savings compared to the standard military batteries.

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1. Introduction

Power and energy are critical to the modern soldier. Power sources enable communications and situational awareness capabilities such as the tactical war fighter information network (WIN-T) and the Nett Warrior system. These capabilities allow the soldier continuous access to a secure mobile network without the need for a fixed infrastructure potentially resulting in improved mission execution.

The aforementioned capabilities are especially valuable to applications with minimum access to resupply and vehicular transportation, generally referred to as *dismounted soldier* use in an austere environment. The austere environment may include limited access to a reliable source of electricity, environmental hazards (e.g. heat, cold, altitude) without climate control, and operation with the prolonged use of body armor [1]. However, to effectively deploy these capabilities on the dismounted soldier, the soldier's total gear weight cannot increase, as higher weight leads to lower mobility and increased risks of musculoskeletal injuries [2–4]. This requirement has resulted in the US Army, together with other government agencies and industrial partners, supporting fuel cell development [5–10] resulting in a number of fuel cell prototypes. The application, operation and performance of these fuel cells systems, specifically for dismounted soldier applications, are discussed in this article.

1.1. Previous work

Recently Shaw et al. [11] investigated requirements for man portable systems and identified military personnel power

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generators, consumer battery rechargers, and specialized laptop computers as potential applications of fuel cell technology. A significant commercialization barrier identified was the lower energy density of H_2 storage systems vs. batteries, resulting from low H_2 storage capacity and fuel cell system components.

Earlier reviews of portable fuel cells [8,12,13,14] have discussed the application of methanol based fuel cells to the US Army for power requirements less than 500 W. Previous work on these systems included the development of micro channel based methanol reformers in a small form factor for methanol based fuel cell.

This article discusses the performance and application of recently developed methanol/propane and chemical hydride based fuel cell systems for military use.

1.2. Description of power sources for dismounted soldier use

Similar to the civilian market, the US military's incumbent solution for portable and wearable power is battery technology. The advantages of low life cycle cost, logistics simplification and mature technology have resulted in rechargeable batteries being accepted by the Army and partially displacing primary batteries. However, major drawbacks of the existing rechargeable technology are: the requirement for a recharging infrastructure; the relatively lower energy density of these systems vs. primary systems. Both of these attributes are undesirable on the modern battlefield.

Fuel cells offer a potential solution to these issues. Their use of high energy density fuels, which can be packaged as replaceable cartridges, offers significant weight savings for extended mission duration. For dismounted soldier use, fuel cell systems can be utilized in two distinct applications as described below.

1.3. Description of fuel cell applications for the dismounted soldier

A *portable* fuel cell would be utilized as an auxiliary power unit (APU) for recharging batteries. These units can meet the need for power at stationary, temporary locations that are difficult to resupply. Portable fuel cells should have minimal resupply requirements and be packable in a soldier's rucksack.

A *wearable* fuel cell would be utilized as a small power source worn on the solider for localized power. The wearable fuel cell provides power to different peripheral devices, such as tactical radios, Global Positioning System (GPS) receivers, and other End User Devices (EUD). The fuel cell can be integrated with the devices via an Integrated Soldier Power and Data System (ISPDS) or power manager configured to allow the user to monitor and manage energy consumption of the peripheral systems as well as fuel level in the fuel cell system.

2. Portable fuel cell systems

Based on the projected use of a portable fuel cell as a battery charger and user input, the continuous power output was identified at $\geq$300 W with a weight target $\sim$14 kg. The power selected was based on a recharge of six 150 Wh secondary batteries at a maximum recharge time of 4 h. Three different fuel cell technologies were developed [15], solid oxide fuel cell (SOFC), reformed methanol fuel cell (RMFC), and direct methanol fuel cell (DMFC) and their performance results are summarized below.

2.1. Portable fuel cell systems test results

Based on the $\geq$300 W, $\sim$14 kg targets, Communications Electronics Research Development and Engineering Center (CERDEC) collaborated with industry to develop three different 300 W man portable systems. Each was tested and the results are shown in Table 1.

All the systems contain an internal battery which is required for start up. The SOFC prototype has the highest power and energy density, while the DMFC prototype system's weight is significantly higher than the other systems.

Based on user interest, the SOFC and RMFC systems were tested as part of a limited user field test. The following feedback was received and is described below.

2.2. Feedback based on limited user test results with portable fuel cell systems

i. System size and weight limited the fuel cells to missions with vehicle access or at a permanent outpost. Although the systems fit in a rucksack, they were still considered too large and displaced other mission required equipment [16].
ii. The fuel resupply logistics were perceived as burdensome vs. other portable power technology such as a portable solar system.
iii. From a logistics point of view the users indicated a preference for propane over methanol. Propane is a fuel utilized globally for various applications, while fuel cell grade methanol has a much smaller distribution network.
iv. Users noted the quiet operation of the devices as a key positive. The systems did generate fan noise but it was significantly quieter than combustion generators.
v. Start up & shut down wait time was a key negative to the users. For the RMFC and SOFC systems, a start up time of $\sim$20 min is required to bring the reformer and stack to the operating temperature.
vi. Not enough test data was obtained to measure the system lifetime. System lifetime is critical to ensure the life cycle acquisition costs are competitive with existing solutions.

2.3. Future portable fuel cell system efforts

Future efforts in portable fuel cells must take into consideration the recent development of a portable 600 W spark ignition generator with multi-fuel (JP-8, gasoline, alcohol, propone, etc.) capabilities while providing acceptable performance, as shown in Table 2.

Table 1
Description of portable fuel cell prototype systems.

Requirement	SOFC	RMFC	DMFC
Max output power	300	300	300
System Weight (no fuel, kg)	14	16	20
Dimensions (cm)	40 × 36 × 20	38 × 30 × 25	29 × 51 × 29
Internal Li-ion Battery (Whr)	165	326	80
Voltage (VDC)	28	28	28
Fuel	Propane	Methanol/Water	Methanol
Runtime	1 lb Propane = 4 h	Cartridge (1.2 L) = 4 h	Cartridge (2 L) = 8 h
Capability	APU only	APU + Battery Charging	APU + Battery Charging
Start-up/Shutdown Time (min)	25/25	20/instant	2/instant
Fuel efficiency (%) (LHV)	22	34	16
Specific Power (W kg^{-1})	22	18	15
Power Density (W L^{-1})	10	10	6.9
Specific Energy (72 h mission, Wh kg^{-1})	720	618	591
Energy Density (72 h mission, Wh L^{-1})	554	423	349