Journal of Power Sources 91 (2000) 27–36

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Man portable power needs of the 21st century I. Applications for the dismounted soldier. II. Enhanced capabilities through the use of hybrid power sources

Terrill B. Atwater *, Peter J. Cygan, Fee Chan Leung

US Army Communications-Electronics Command, Research Development and Engineering Center, AMSEL-RD-C2-AP-B, Fort Monmouth, NJ 07703, USA

Abstract

The Army is facing a number of challenges now and in the future. One of the major challenges is in the power sources arena. As the Army continues to move toward digitizing the battlefield, the need for portable power is increasingly becoming a technological hurdle that must be overcome in order for a soldier to exercise his electronics capabilities without being overburdened by the power sources size, weight and operating/logistical costs. Advanced electronic devices are becoming a critical piece of the soldier's personal battlefield equipment. A soldier with the latest version of the Single-Channel Ground and Airborne Radio System (SINCGARS) is one of the most dangerous weapon systems on the modern battlefield. The ability to accurately navigate and communicate multiplies the soldier's advantage over a less electronic capable enemy. Keeping his personal electronics operational is crucial to giving the soldier the capability to complete his mission successfully. Inherent in keeping the electronic equipment operating is keeping it supplied with batteries. Due to the increased emphasis placed on the modern soldiers electronic equipment, the importance of the portage of the power sources needed to keep this equipment operational has also increased.

Recent efforts have focused on hybrid power sources that may enhance discussed capabilities by taking advantage of both high energy sources and high power systems for intermittent power application. This development could lead to a power source with enough energy to meet the Army's preference for a 72-h mission life before the need for resupply. Published by Elsevier Science S.A.

Keywords: Portable power; Army systems; 21st Century forward area battlefield

1. Introduction

Before discussing the military battery needs in more detail, one must appreciate the fact that batteries used by the military are required to operate under more extreme conditions than their commercial counterparts. In the civilian world, portable devices are used in places where digital relays and phone lines are abundant and the user rarely operates at temperatures lower than 0°C or higher than 50°C. The consumer does not operate in an environment of imminent urgency and he/she can afford to have power management exploited to the fullest in the devices and wait 3 to 10 s for the device to power up from sleep mode. With the assistance of relays, mild-temperature-operating conditions, and power management, the devices can be operated by "high" price, small and slim rechargeable battery packs or lower price alkaline nonrechargeable cells.

The technology and life cycle span for personal consumer electronic devices is short. The current trend is for these devices to be outdated and replaced within 3 years with a completely different and improved successor (including a new and unique battery pack). This has produced a proliferation of battery types for the consumer and has been made worse by the short stock life for certain battery packs as its availability is dependant on the life span of the device for which it was designed. Despite these complications, the consumer has not been hampered by the problem of battery type proliferation, because AC power is always available, stores stocked with a variety of batteries are within walking distance. If the battery packs are too expensive or unavailable, the lower cost of new generation electronic devices makes it more cost-effective for the consumer to throw the old system away and replace it with the new one.

* Corresponding author. Tel.: +1-732-427-3549; fax: +1-732-427-3665.

E-mail address: atwater@mail1.monmouth.army.mil (T.B. Atwater).

0378-7753/00/$ - see front matter. Published by Elsevier Science S.A.
PII: S0378-7753(00)00484-5

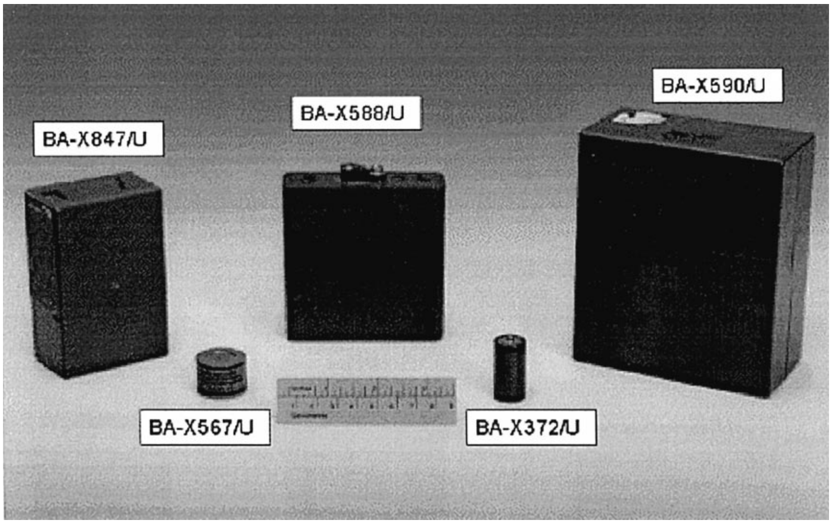

Fig. 1. Standard army configurations.

Unlike the civilian portable electronic user, the military must be prepared for the worst operating conditions and support the forces with the simplest logistics possible. The planners must assume that there is very little or no infrastructure on the battlefield to relay voice, data and image transmission among the users. Military radio designs must be able to transmit/relay information to distances of 2 to 5 km (in urban, and heavy foliage terrain as well as adverse weather conditions). Unless the power draw of future radios and devices drop drastically, the military user cannot depend solely on slim and small commercial batteries for power. Frontline units will depend heavily on portable power sources and batteries for power, while rear area units will operate from tactical mobile generators. Frontline light forces face the most severe challenge in meeting their power needs, because these units have a limited number of vehicles available and most of their power sources must be carried on the backs of the soldiers. These light forces are most likely to be the first units to be deployed and they must be capable of sustaining themselves before the heavier forces arrive with the logistics support. Some military contingencies require light forces to sustain themselves (and power their electronics) for 72 h or more.

The military devices are rugged, able to operate at temperature conditions of $-40°C$ to $60°C$ and are hard to detect/jam in order to survive typical battlefield conditions. Substantial investments are made in developing these capabilities into the devices and the military will keep them in the inventory for 20 to 30 years as it transitions from frontline to reserve units. The battery configuration needed to power the devices must also be available in that timeframe. In order to keep logistical costs down and simple for frontline and reserve forces, the US Army maintains a family of standard battery configurations that are used in legacy and frontline electronics, and assigned to new equipment design whenever possible. The standard battery configurations are depicted in Fig. 1 and their basic characteristics are tabulated in Table 1. Many of the standard battery configurations are over 20 years old and will continue to serve the US military into the 21st century. This approach has insured that there will be large volume procurements of each battery type (keeping unit costs low as possible and sustaining production base) and simple frontline logistics will be preserved for the military users. New and improved technologies will be packaged into the standard configurations whenever possible.

The military currently relies on lithium based non-rechargeable batteries to meet the size, weight, peak power and energy requirements for the equipment. These systems use lightweight, reactive metallic lithium to produce a battery system that can provide high energy and power per

Table 1
General characteristics of standard army batteries

Battery configuration	Voltage range (V)	Dimensions (cm)	Weight (kg)	Current chemistry	Energy (W h)	Power (W)
BA-X847/U	4 to 6	3.81 × 2.55 × 3.75	0.24	$LiSO_2$	40	12
BA-X588/U	10 to 15	3.55 × 1.22 × 3.49	0.30	$LiSO_2$	36	7.5
BA-X590/U	10 to 15 or 20 to 30	11.18 × 6.22 × 12.07	1.02	$LiSO_2$	160	40
BA-X567/U	2 to 3	2.54 dia × 0.718	0.02	$LiSO_2$	2.5	0.60
BA-X372/U	4 to 6.5	1.66 dia × 3.30	0.02	$LiMnO_4$	2.5	0.04

Table 2
Comparison of electrochemical characteristics military battery systems

Electrochemical system	Cell voltage (V)	Specific energy (W h/kg)	Energy density (W h/L)	Specific power (W/kg)	Operating temperature range (°C)
Primary					
Li/SO_2	3.0	260	415	50	−55 to 70
Li/MnO_2	3.0	230	550	40	−30 to 55
Zn/MnO2 (Alk)	1.5	125	330	30	−10 to 55
Rechargeable					
NiCd	1.2	35	105	60	−40 to 45
NiMH	1.2	50	175	45	−20 to 45
Li(ion)	4.0	90	200	40	−20 to 55

unit weight, operate in cold and hot temperatures, and withstand extreme field storage conditions. The principal military battery system is based on the lithium sulfur dioxide ($LiSO_2$) chemistry. $LiSO_2$ batteries have an energy density of 175 W h/kg and a power density of 55 W/kg. This battery can operate at temperatures as low as −40°C and as high as 60°C, and has a storage life of five plus years (where temperatures cycle between −65°C to 60°C). Table 2 compares the electrochemical characteristics of common and future military battery systems.

The large $LiSO_2$ cells desired by the military (size D) for its batteries have very limited usage in the commercial sector except for special industrial. This requires that the $LiSO_2$ batteries must be stockpiled to meet contingencies, unused stocks must be rotated and expired batteries disposed, thus making them more expensive to use (typically US$0.40/W h) when compared to common commercial alkaline cells (approximately US$0.05/W h). Because of the relatively high cost, the US is one of the few nations that can afford to equip its military with this technology.

2. Part I. Applications for the dismounted soldier

2.1. Background

The US military envision that most future conflicts will require the projection of military forces overseas. The first ground forces that can be rapidly deployed will probably be light motorized or infantry forces (such as airborne, air assault or mountain infantry units). These forces face the greatest challenge in surviving the earliest phases of a conflict, because they will be called upon to delay heavier and larger enemy forces until relieved by mechanized reinforcements from the US.

Desert Shield/Storm and various warfighter experiments have shown that mechanized forces, if properly enhanced with electronics, can outmaneuver and outfight larger, but electronically blind adversaries because they know the enemy's location at all times and under any weather conditions. This allows the digital forces to accurately attack and inflict damage on the enemy with stand off weapons/ordinance and avoid any countermoves. This process is repeated until the enemy formations are reduced or destroyed. The US Army is in the process of developing the same electronic capabilities for the rapid deployment light forces, especially the frontline dismounted infantryman.

Described below are some of the Army systems that may be found on the 21st century forward area battlefield that will require technical solutions for portable energy storage to reduce the size, weight, cost and logistics for the individual soldier.

2.1.1. Land warrior

The Army plans to field the Land Warrior system for as many infantrymen as possible in the 21st century. The system shown in Fig. 2 is basically manworn electronics that will enhance the soldier's ability to shoot, move and communicate on the battlefield. The system's computer/radio and helmet-mounted electronics will allow the sol-

Fig. 2. Prototype land warrior system with AN/PAS-13 thermal weapon sight.

Fig. 3. Prototype of the objective individual combat weapon.

dier to interface within a squad wireless information network, voice communicate with squad members, interface with his integrated sensors (video, laser detectors, image intensifiers, thermal) to detect, navigate, identify and shoot at unfriendly targets in day, night and limited visibility conditions. The Squad Leader can command and control his squad without the need for line of sight to the individual riflemen, know his squad's location via GPS/inertial navigation which is critical during movement, calling in accurate artillery fire and precise air support. The Land Warrior System is required to use two BA-X847/U type batteries. The Land Warrior will have an AN/PAS-13 rifle-mounted thermal weapon sight which is powered by its own BA-X847/U type battery. The minimum mission life for the Land Warrior is 12 h. In a combat scenario, the current prototype Land Warrior System will draw 25 W nominally with 40 W continuous peak power. The AN/PAS-13 draws 5 W nominally and can ramp up to 8 W peak power [2].

2.1.2. Objective individual combat weapon

The Land Warrior infantry squad will have selected individuals who will be issued the Objective Individual Combat Weapon (OICW). The OICW shown in Fig. 3 has

Fig. 5. Objective crew serve weapon.

integrated electronics that will enhance the operator's ability to detect, acquire and fire at a target in all weather conditions. The weapon has two barrels, one to shoot 5.56 mm NATO ammunition like a conventional rifle and one to shoot 20 mm high explosive (HE) rounds. Majority of the casualties caused by the OICW will be from the HE rounds. The integrated electronics of the OICW will allow the operator to aim and range a target, program the HE rounds to explode at the proper range and height of the target. The weapon is designed to power its electronics with one BA-X847/U type battery. The OICW prototypes draw approximately 14 W in daylight, 32 W at night/limited visibility, and pulses at 50 to 60 W [3].

2.1.3. Advanced Single-Channel Ground and Airborne Radio System (SINCGARS) improved product

The US Army is in the process of equipping its light forces with a new generation lightweight SINCGARS known as the Advanced SINCGARS Improved Product (ASIP). Fig. 4 shows both the SINCGARS radio and the ASIP radio. This radio utilizes frequency hopping techniques to maintain low detection, and the improved design reduced its size and weight to half of the older SINC-

Fig. 4. SINCGARS and advanced SINCGARS improved product (ASIP).

GARS radios by using 3.5 VDC circuit technology and innovative power management. In the early 21st century, the ASIP will be the likely radio utilized by light forces (including Land Warrior rifle platoons) to communicate with higher echelons. The radio operates on one BA-X590/U type battery, and draws 5 W nominally and peaks at 18 W continuously during transmit [4].

2.1.4. Objective crew serve weapon

The Objective Crew Serve Weapon (OCSW) shown in Fig. 5 is a crew-operated, vehicle- or tripod-mounted weapon system. The OCSW and crew can be assigned to provide additional direct fire support for Land Warrior platoons in fixed defense or prepared assault. The weapon has a battery-powered Fire Control to enhance the operator's ability to detect, acquire and range targets in day, night and bad weather conditions. The Fire Control uses target's range data to electronically set the fuzzes on the 25 mm HE rounds so the rounds will explode at the appropriate range and height. The OCSW is designed to operate from two BA-X847/U type batteries. The OCSW is projected to draw 16 W nominally in daylight and 25 W nominally at night/limited visibility [5].

2.1.5. Javelin manportable antitank weapon

Fig. 6 shows the Javelin, a manportable medium range, recoilless, antitank, assault weapon capable of defeating armor and stationary targets. The weapon and its operator can be assigned to Land Warrior rifle squads to provide antitank and medium range attack capabilities. The Javelin has a battery-powered Command Launch Unit (CLU). The CLU allows the operator to acquire targets in daylight, night and bad weather conditions, select the attack mode for the Javelin missile and fire the missile. Depending on the attack mode selected, the missile's seeker will lock onto the target, chose the appropriate travel path to the target (for heavy armor vehicles, such as tanks, the missile will approach the target and attack it from the top down where the armor is the thinnest). The CLU operates from one BA-X590/U type battery and draws 40 W nominally with 80-W pulses [6].

Fig. 6. Javelin antitank assault weapon.

3. Part II. Enhanced capabilities through the use of hybrid power sources

3.1. Background

The development of portable power sources for the individual soldier is one of the focal points in the power sources area. The objectives of this program are to lighten the soldier's load, provide critical pulse-power components, and reduce logistics and disposal costs by developing superior batteries, fuel cells, and capacitors. Components developed from this effort are the building blocks of a hybrid power source, possibly a new power system for increasing number of Army applications where a pulse operation mode takes precedence. The increased overall power need with more electronic devices and greater reliance on them could make the development and implementation of such system necessary. This is especially true as the battlefield advanced technologies such as digitization are being implemented. On top of this, there is a need for power sources with better performance that would extend mission time and reduce weight for the soldier.

Some of the technologies that could benefit from Hybrid Power Sources are the following: Soldier System, personal communication systems, GPS, remote sensors, automatic targeting, advanced I&E warfare technologies, silent watch systems, vehicle ignition/starter systems, power generation/conversion/conditioning, backup power systems and any other application where periodical high current pulses are required. Hybrid power sources also represent a possible consumer product with the potential for use in a wide variety of commercial products such as backup power, power conversion and generation, startup power, GPS, satellite communication, notebook computers, cellular phones, and other state-of-the-art electronic devices. Therefore, the possibility of dual use for these devices is unquestionable, as these technologies are common and accessible to everyone.

To recoup the above, a development of hybrid power sources may have potential gains in the better power management, lighter components, higher power density, and lower overall cost. This, in turn, could provide more reliable, efficient and lighter (or at least allowing longer operation times) power systems with a high peak-power capability. In contrast to this, at present time, whenever high power batteries are required either the battery service time is reduced or the battery is enlarged to compensate the load.

3.1.1. Hybrid power source

In general, a hybrid power source consists of a high energy density but low power-density component, and high power density but low energy density component. Addi-

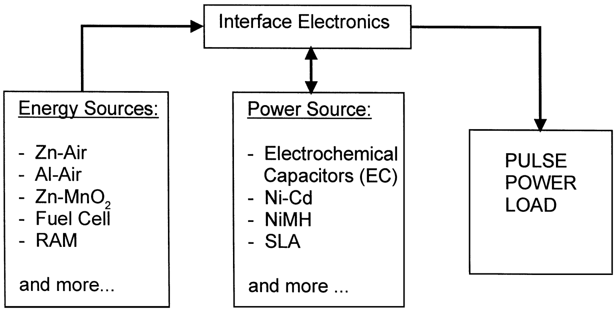

Fig. 7. Block diagram of hybrid power system.

tionally, the power management may be introduced by means of an interface circuitry that would monitor and control the power distribution between the components and the load. Such system could provide much needed capabilities of high current pulses and, through load leveling, extend the operational life of a battery. As the additional benefit, battery chemistries with high energy density but low power density, such as zinc-air, may become feasible as a possible energy component of such systems with the cost of replacement significantly lower than present batteries. Fig. 7 shows in a block diagram these three major components: power, energy and electronic interface. It also shows some of the suitable technologies for hybrid system's components.

Hybrid systems take advantage of the energy density of the primary battery (typically high energy-density batteries have low power densities) for long operational time and the power density of the rechargeable system (typically with low energy densities) for load leveling and pulse power requirements. The load leveling ability of the rechargeable system will only be utilized when the system is in an environment where current pulses are required. In this scenario, the primary battery delivers the background current and the current needed to recharge the power component (capacitor or rechargeable battery), which, in turn, delivers the current pulse required by the load.

As is implied by Fig. 7, such a hybrid system could be a partially rechargeable (electrochemical capacitor/battery) or fully rechargeable (electrochemical capacitor/fuel cell) system, depending on the components used. Pending its design, a power component could be made a permanent feature of an equipment or a modular part of a power pack, thus, further contributing to the overall cost reduction.

3.1.2. Zinc-air / electrochemical capacitor hybrid [10]

Due to their high specific energy and low operating, and service costs zinc-air batteries have been considered as a power source for communications electronics. However, because of low power density and the fact that most of these applications require high pulse power zinc-air battery use is limited. The advent of electrochemical capacitors with their high specific-power density allows for the development of a hybrid system comprised of zinc-air cells and electrochemical capacitors. This hybrid system allows for full utilization of the energy available in the zinc-air batteries over extended periods of time by accommodating high power pulses with the power capability of the electrochemical capacitor. This combination utilizes the advantages of both systems yielding a hybrid power source with coupled energy and power densities greater than that of a single chemistry battery. To be able to use an electrochemical capacitor in a hybrid system with the battery, it has to posses such characteristics as low internal leakage current (stable open-circuit voltage over extended period of time) and low internal resistance (equivalent series resistance — ESR). These characteristics are essential for minimizing the drain on the battery and its ability for recharging the capacitor — limited only by the battery output.

Current state-of-the-art zinc-air batteries have a specific energy of greater than 500 W h/kg (900 W · hr/l). This specific energy is one of the highest of all battery systems. The zinc-air system at a reduced specific energy, less than 200 W h/kg, can deliver 25 W/kg of power [7]. Fully packaged electrochemical capacitors have a specific power of up to 2000 W/kg and a specific energy of up to 4.5 W h/kg [8,9]. These characteristics of the zinc-air system and the electrochemical capacitor are ideal for a hybrid system for applications where pulse power is required.

A zinc-air/electrochemical capacitor hybrid power system has been evaluated at US Army CECOM RDEC. This evaluation concentrated on establishing the feasibility of the design. Due to its high specific energy and inherent safety, zinc-air (oxygen) electrochemical systems are an attractive energy source.

Fig. 8 shows three discharge characteristics: specific energy, specific power and battery voltage (12 cell) vs. discharge current density for the 50 A h zinc-air cell [7]. The 12-cell battery represents a common battery design with a nominal 15 V open-circuit voltage and a 10 V cut off. The curves for the 0.5 A h button cell were similar, with the exception of lower gravimetric densities due to the greater packaging vs. active material ratio.

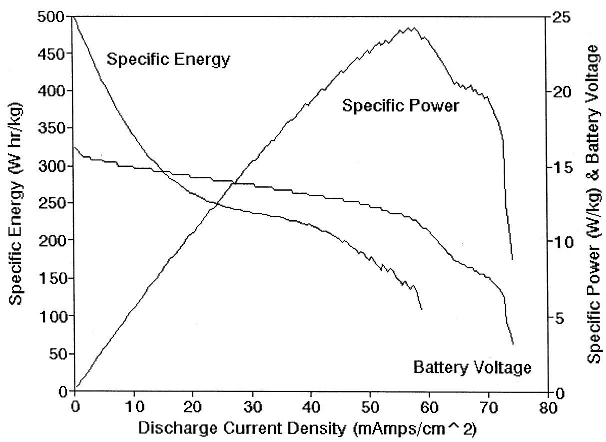

Fig. 8. Discharge characteristics vs. discharge current density for 50 Amp-hr Zinc-air cell [1].

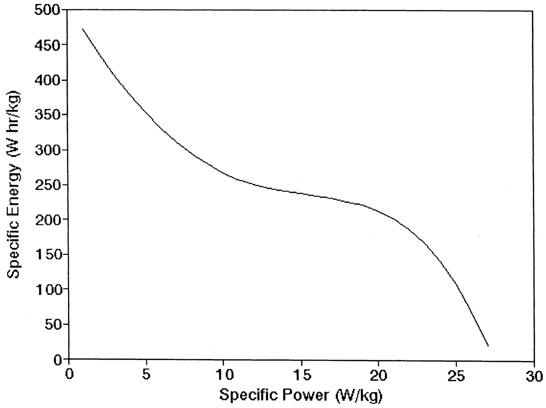

Fig. 9. Specific energy vs. specific power for 50 Amp-hr Zinc-air cells [1].

Fig. 9 graphically portrays W h/kg vs. W/kg for the 50 A h zinc-air electrochemical system [7]. This graph clearly shows the increase in specific energy achievable by lowering the power requirement on the zinc-air system.

These two figures are typically true for any battery technology considered for the hybrid, of course with different values and performance dependent on the particular technology. The zinc-air button cells used in this hybrid represent current state-of-the-art zinc-air technology. Two zinc-air button cells were connected in series. These batteries delivered 0.32 A h of capacity.

Electrochemical capacitor with its high power capability is an excellent match for high specific energy but low specific power zinc-air battery in applications requiring high power pulses. These capacitors are electrochemical systems, which are characterized by large capacitance thanks to a large surface area of the electrodes. High capacitance is achieved at the double layer created by polarization of charge at the electrode/electrolyte interface.

The electrochemical capacitor used in the test was commercially available Panasonic "Gold" power series. It had all of the required characteristics as described above.

The system of Zinc-Air/Electrochemical capacitor was used in the simplest and most desirable setup, i.e. without any electronic interface as shown in Fig. 10. Depending on the technology, it may not always be the case. The results from this hybrid are summarized by the following section and concluding remarks.

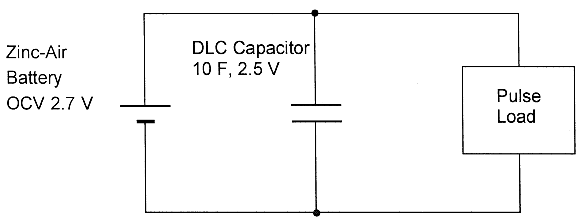

Fig. 10. Circuit layout for Zinc-air/electrochemical capacitor hybrid (DLC — double layer capacitor).

3.1.3. Results of zinc-air / EC hybrid

The battery (two cells in series) on its own maintained a constant 40 mA drain. This corresponds to a discharge rate of greater than 50 mA/cm^2. The cells, when discharged at 45 mA, could not maintain an operating voltage above the cut-off voltage of 1.66 V after 2 min of such discharge.

A hybrid system, with the Panasonic capacitor as described above, was discharged with a 1-min 100-mA pulse followed by a 4-min-rest duty cycle. This discharge profile is typical for portable electronics and over two times more than the battery on its own could handle.

Fig. 11 is representative of the data collected. Regions "1", "2" and "3" on the graph show the activation of the zinc-air cells, the initial charging of the capacitor by the cells, and the initial cycles, respectively. Region "4" on the graph shows the last 60 min of the 100 mA duty cycle, starting at 1000 min into the discharge.

The zinc-air/electrochemical capacitor hybrid power sources tested showed:

- hybrid can handle more than double pulse discharge of the battery alone;
- the pulse discharge of over 1000 min for 100 mA (1 min on–4 min off) was achieved.

3.1.4. Fuel cell / electrochemical capacitor hybrid [11–13]

In another example of a possible hybrid system for a portable power source, a hybrid of a fuel cell and electrochemical capacitors was investigated. Due to their high specific energy and portable design, the proton exchange membrane fuel cell (PEMFC) was chosen. Even though the PEMFCs demonstrate good power capability during continuous operation, the response to instantaneous power demands is relatively poor. The utilization of high cycle-life electrochemical capacitors in the power assistance of fuel cell stack would allow for a system that has the specific energy advantage of fuel cells and the high power-output capability of electrochemical capacitors.

A six-cell Proton Exchange Membrane (PEM) fuel stack was used with the nominal potential of 4.0 V. The

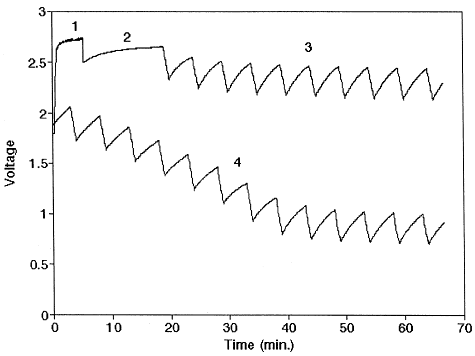

Fig. 11. Zinc-air/electrochemical capacitor hybrid 100 mA pulse discharge (1 min on, 4 min off) for over 1000 min.

stack used ambient air to supply both the reactant oxygen and as the coolant. Zero grade (99.999%) compressed hydrogen, regulated to 1 psig, was used as the fuel.

The electrochemical capacitors used in the hybrid were commercially available Panasonic "Gold" power-series capacitors. These are the same capacitors as the ones used in the zinc-air hybrid. They are rated at 2.5 V and 10-F capacitance. Twenty-eight of these capacitors were connected in series and in parallel into the bank of capacitors. This capacitor bank had a nominal capacitance of 70 F and voltage of 5.0 V. The total capacitance of the bank measured at charge/discharge cycles under constant current of 1.0 A was 114.5/107.3 F at voltage of 5.0 V. This capacitor bank was connected in parallel to the fuel cell stack.

The tests were initially conducted at 4.4°C, room temperature, RT (23–25°C), and 37.7°C. The limits of the PEMFC alone at 18.0-W continuous power at the three temperatures were quantified. Performance of the hybrid was measured at various radio simulation transmit and receive durations at 4.4°C and RT. Tests were designed to last 25.0 h continuous. Operating voltage and current, and internal stack temperatures were monitored and recorded.

3.1.5. Results of fuel-cell / EC hybrid

The PEMFC stack by itself could not power the high-load pulse of high/low power cyclic regimes. The baseline profile of 18.0 W for 2 min followed by 2.5 W for 18 min was too much for the stack alone. During the 18.0-W pulse, the stack operating potential substantially dropped and became very erratic. Within 10 s, the stack voltage fell below the 3.0 V cut-off voltage.

A 70-F capacitor bank connected in parallel with the 25-W PEMFC successfully powered the baseline load described above. Fig. 12 is representative of this test. The hybrid successfully powered the first ten cycles. The operating voltage never dropped below 3.0 V, even during the high 18.0-W load. Following the 2-min high-load sequence of the 11th cycle, the capacitor was disconnected from the fuel cell (point A in Fig. 12). At this instance, the PEMFC alone was successfully powering the low-load section of cycle 11. Following the 18 min of low load, the PEMFC alone failed to power the 18.0-W pulse of cycle 12 (point B). The stack potential immediately fell below 3.0 V and never recovered.

A PEMFC becomes excessively polarized when a power load is instantaneously applied. This is due mainly to mass transfer limitations within the membrane of the PEMFC. The hybrid configuration allows for a gradual increase in mass transfer within the membrane allowing for the establishment of steady state diffusion without subjecting the stack to deep polarization. This is a result of the capacitors assuming the initial load and the fuel cell gradually providing the required power as the capacitors' voltage drops. At cold temperatures, the power handling device of the hybrid requires higher capacity (capacitance) to overcome the additional transport resistance introduced with temperature.

At 4.4°C, the hybrid successfully powered the cyclic regime of maximum 1-min high load (18.0 W) followed by 3-min low load (2.5 W) for 25 h continuous. This means that the PEMFC stack required 3 min to recharge the 70-F capacitor assembly to a charge state sufficient to "assist" the stack for the next high-load pulse of 18.0 W.

At RT, the hybrid successfully powered cyclic scenarios consisting of transmit duration of up to 3 min. At RT and 18.0 W continuous discharge, the hybrid capacity was enough for approximately 250 s of operation down to 3.0 V. Transmit duration of 1, 2, and 3 min required receive period lengths of as low as 1.5, 3, and 4.5 min; respectively. This means, for example, that for 3 min transmit

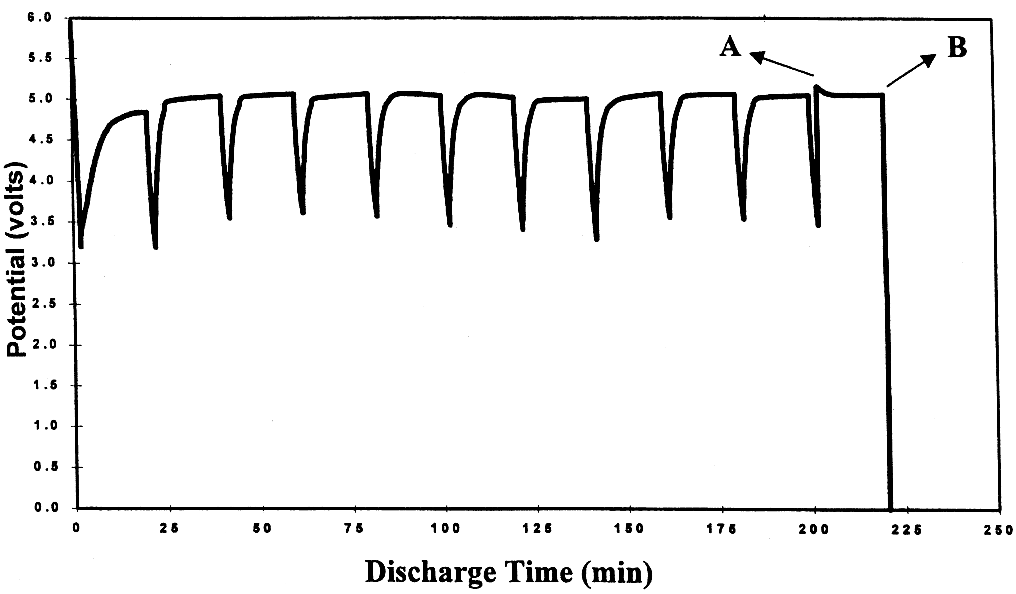

Fig. 12. Six-cell PEMFC/EC capacitor bank hybrid discharge at baseline profile with capacitor bank disconnected after 11th cycle [5].

(18.0 W) the PEMFC stack required 4.5 min of receive (2.5 W) period to recharge the capacitors for the next cycle. In fact, the hybrid could run any cyclic scenario with transmit:receive ratio of 1:1.5 for up to 3-min transmit (18.0 W). This specific duty cycle provides sufficient charging time for the capacitor assembly that would allow continuous operation of the hybrid.

3.1.6. Fuel cell / super lead-acid hybrid [14]

In a similar fashion to the previous hybrid, a hybrid of PEMFC and sealed lead acid batteries was tested. Bolder Technologies developed Thin Metal Foil (TMF) lead-acid cells capable of extremely high power output with excellent capacity maintenance. These cells exhibit a flat discharge profile at all currents and are capable of very rapid recharge. The utilization of such lead-acid cells in the power assistance of fuel cell stacks would allow for a system that has the specific energy advantage of fuel cells and the high power-output capability of these lead-acid cells.

The TMF lead-acid batteries are cylindrical cells. The cells are sealed (with a vent) in a plastic case with positive and negative connectors at opposite ends of the cell. The cell dimensions, excluding the current end busses are 2.27 cm in diameter and 7.12 cm in length — providing a cell volume of approximately 28.7 cm^3. Cell weights range from 78.9 to 81.7 g. These TMF lead-acid cells, rated at 1.2 A h, are capable of 8 kW/kg peak power density and recharging in less than 7 min.

Two lead-acid cells were connected together in series to form a two-cell assembly with a nominal rating of 4.0 V and 1.2 A h. The total weight and volume of the assembly was 160.7 g and 60 cm^3. This assembly of two-cells was connected in parallel to the PEMFC stack to form the hybrid. At the start of all tests, the lead-acid cells were fully charged via a constant current two step process of 1 A to 2.6 V, then 0.1 A to 2.6 V.

All testing was conducted at RT (23–25°C). Initially, the limit of the PEMFC stack alone at 18.0 W (transmit) continuous power was quantified. Performance of the hybrid was measured at various radio simulation transmit and receive durations. The transmit/receive ratios tested included 3/4.5, 6/9, 12/18, and 24/36. Each ratio represents a cyclic regime of transmit duration in minutes followed by receive length in minutes. For example, the 3/4.5 ratio represents a cyclic regime of 3-min transmit (18.0 W) followed by 4.5-min receive (2.5 W). In addition, the lead-acid assembly, alone and in the hybrid, were then tested with 18.0-W continuous discharge. At specific times into each run continuous transmit, ranging from 15.0 to 1.5 min, the lead-acid assembly was electrically disconnected from the stack. At this point, the PEMFC stack alone was powering the regime.

3.1.7. Results of fuel-cell / lead-acid hybrid

As in previous hybrid, the 25 W PEMFC stack by itself could not power the high-load pulse of high/low power cyclic regime. This represents a worst case scenario. The operating stack potential dropped immediately. Within 12 s, the potential fell to 0 V.

The hybrid successfully powered various pulse power load simulations synonymous with electronics and communications equipment. The load simulations included transmit/receive ratios of 3/4.5, 6/9, 12/18, and 24/36. Once stabilized, the system produced a flat operating potential. This is especially important during transmit (18.0 W) where the battery voltage is critical. Throughout all runs, the operating voltage never dropped below 3.9 V.

The hybrid successfully ran continuous transmit discharge. In addition, in as short as 2.5 min into the test, even the PEMFC stack alone continued to successfully power the 18.0-W continuous discharge. In each successful run, the operating potential immediately dropped when the assembly of lead-acid cells was disconnected. Within 2–5 min, the operating voltage of the PEMFC stack increased to the stable value of approximately 4 V. Throughout the successful tests, the operating potential never dropped below 3.5 V.

When the lead-acid assembly was disconnected from the hybrid 1.5 min into the test, the PEMFC stack failed to successfully power the 18.0-W (transmit) continuous discharge. Approximately 90 s after removal of the lead-acid assembly, the stack operating potential fell below 3.0 V.

The utilization of such lead-acid batteries in the power assistance of fuel cell stacks would allow for a system that has the specific energy advantage of fuel cells and the voltage stability during high power output of lead-acid batteries.

4. Conclusions

The hybrid power sources successfully operated loads beyond the capabilities of single chemistry systems with each of the components offering specific benefits for a particular application:

- Zinc-air/EC capacitor hybrid: allowed extended time of operation at more than double the current output of zinc-air alone;
- PEMFC/EC capacitor hybrid: allowed the fuel cell to operate at high power densities;
- PMFC/SLA hybrid: allowed the fuel cell to operate at high power densities with a stabilized voltage.

The above, and other, features of hybrid systems and their components have tremendous potential for applications into a variety of military and commercial systems. They would offer not only a better performance but also potential of lower costs through the use of rechargeable components.

References

[1] Reducing The Army Battery Usage and Costs, Army Research, Development and Acquisition, May–June 1998.

[2] Force XXI Operations, TRADOC PAM 525-51, Aug. 1994.

[3] US Army Aberdeen Test Center Website, http: //www.atc.army.mil/atcglobe/content98/winter98/landwar.html, 10 March 1999.

[4] US Army Fort Gordon Website, http: //www.gordon.army.mil/acd/tcs/31 unews.htm#NEW ASIP Radio, 26 March 1999.

[5] US Army Fort Benning Website , http: //www.benning.army.mil/dcd/sad.htm, 1 Oct. 1998.

[6] Operator and Organization Maintenance Manual JAVELIN, Army TM 9-1425-687-12, 1 June 1996.

[7] T.B. Atwater, R. Putt, D. Bourland, B. Bragg, Proc. 36th Power Sourc. Conf., Cherry Hill, NJ, 1994, pp. 129–131.

[8] US Department of Energy, Capacitor State-of-the-Art Overview, Proceedings IAPG Meeting, 9–11 May 1995, Newport, RI (1995) .

[9] T.C. Murphy, G.H. Cole, P.B. Davis, Proc. 5th Int. Seminar on Double Layer Capacitor and Similar Energy Storage Devices, Boca Raton, FL, 1995.

[10] T.B. Atwater, P.J. Cygan, Proc. 37th Power Sourc. Conf., Cherry Hill, NJ, 1996, pp. 17–20.

[11] L.P. Jarvis, T.B. Atwater, P.J. Cygan, US Army R&D Tech. Rep., CECOM-TR-97-5, 1997.

[12] L.P. Jarvis, T.B. Atwater, P.J. Cygan, 12th Annual Battery Conference on Applications and Advances, 1997.

[13] P.J. Cygan, T.B. Atwater, L.P. Jarvis, 13th Annual Battery Conference on Applications and Advances, 1998.

[14] L.P. Jarvis, T.B. Atwater, P.J. Cygan, J. Power Sources 70 (2) (1998) 254–258.