High-Energy Portable Fuel Cell Power Sources

by S. R. Narayan and Thomas I. Valdez

The energy density requirement for portable power sources is ever on the increase. Technology companies are working to find ways to enhance the run time of mobile devices such as portable computers, MP3 players, and mobile phones. For example, the video-streaming offered in present-day mobile phones is a power-hungry feature that reduces the run-time for phones powered with even the most advanced of lithium-ion batteries. The U.S. military has also had a persistent demand for compact, long-life power sources for meeting the field needs of the soldier. The future-day soldier will be outfitted with high-tech electronics that significantly increase awareness of the combat environment. Radios, night-vision devices, portable computers, and personal cooling systems are all examples of power-hungry devices to be used by the future-day soldier. There are also other areas that need high-energy portable power sources: (a) extending the run-time of materials handling equipment, (b) meeting on-board power needs in recreational vehicles, and (c) powering remote electronics equipment. Achieving longer run-times will eliminate the need for the frequent replacement of discharged batteries, reduce the downtime resulting from recharging or replacing batteries, and eliminate the logistics needed for recharging batteries. Some of the applications of portable power sources and the corresponding power levels are shown in Fig. 1.

For mobile devices, the energy density target is to increase the device run-time by five to ten times, without increasing the size or mass of the power source. A recent call for proposals from the U.S. Department of Energy (DoE) identifies these targets. To meet the energy and power density targets for future mobile devices, it would be desirable to achieve a specific energy of 500 Wh/kg or greater, an energy density of 1000 Wh/liter or greater, and a specific power not less than 50 W/kg. Typical power levels in mobile devices vary from 1-25 W with run-times varying from 10 to100 h. Further, any next-generation power source for mobile devices must include battery features, namely, quiet operation, ruggedness, ease-of-use, operability in any orientation, operability over a wide temperature range (-40°C to +60°C), and operability in confined environments. There may also be other requirements such as underwater operation that are specific to military applications. For large portable systems such as those used in material handling equipment, the high-energy power source supplies the base load and charges a battery during the off-period or serves as a power back-up. Typical power levels for this category of applications vary from 50 to 1000 W and the power density can be as low as 10 W/kg. The target is usually to increase the run-time of large portable systems by at least five times the current values.

The above requirements present significant technical challenges. However, in the last decade or so, there have been focused efforts in the commercial and government sectors to develop fuel cell based power sources operating on high-energy fuels such as hydrogen, methanol, and propane to meet the requirements of next-generation portable power sources.

Types of Fuel Cells

Portable fuel cell power sources can be categorized by the fuel and type of fuel cell used for operation. Methanol can be directly utilized in a polymer-electrolyte membrane (PEM) type of fuel cell; this type of fuel cell is known as a direct methanol fuel cell (DMFC). The typical operating temperatures for DMFCs are in the range of 40-60°C. Methanol can also be reformed to hydrogen at about 300°C, and the resulting "reformate" fuel is then supplied to a PEM fuel cell that operates at 180°C. Sodium borohydride can be decomposed to hydrogen at ambient temperatures; the liberated hydrogen is then utilized in a PEM fuel cell. Butane and JP-8 are processed to hydrogen at 600°C and the products are fed to a solid oxide fuel cell (SOFC) that operate with internal temperatures as high as 1000°C. Thus, each fuel combined with an appropriate fuel cell type results in a different portable fuel cell power source. These differences are summarized in Table I.

When the topic of high-energy density portable power sources was reviewed in 2002-2003,[1,2] the direct methanol fuel cell was primarily the technology of interest. The research at that time was focused on demonstrating various types of cells and compact stacks, and proving the feasibility of system concepts. Much of this initial work from the conception of the

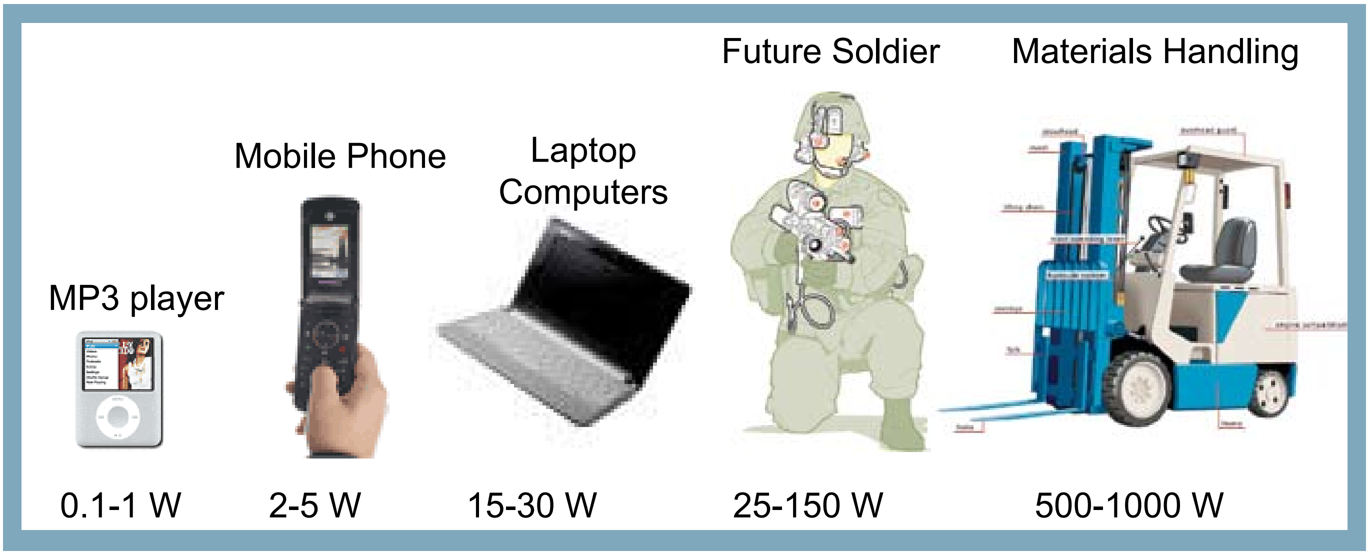

Fig. 1. *Portable power applications require high-energy power sources.*

Table I. Characteristics of various fuel cell types suitable for portable power sources.

Fuel Cell Type	Fuel	Free Energy Content of Fuel Wh/kg	Fuel Processing requirements	Internal Operating temperature of fuel cell	Electrolyte	Catalysts
Direct Oxidation	Methanol	6,000	None	45 - 60 °C	Proton Conducting membrane (Nafion)	Pt-Ru on anode, Pt on cathode
Indirect Methanol Fuel Cell	Methanol	6,000	Steam reforming at 250-300°C	180- 200°C	High temperature polymer electrolyte	Pt on anode and cathode
Solid oxide Fuel Cell	Propane, Butane, JP-8	10,000	Partial oxidation at 650°C	800- 1000°C	Yttria-Stabilized Zirconia	Nickel on anode and perovskite oxide on cathode
Hydrogen/air	Hydrogen stored in metal and chemical hydrides	3,000-9,000	Catalytic decomposition at near ambient temperature	45- 60°C	Proton conducting membrane (Nafion)	Pt on anode and cathode

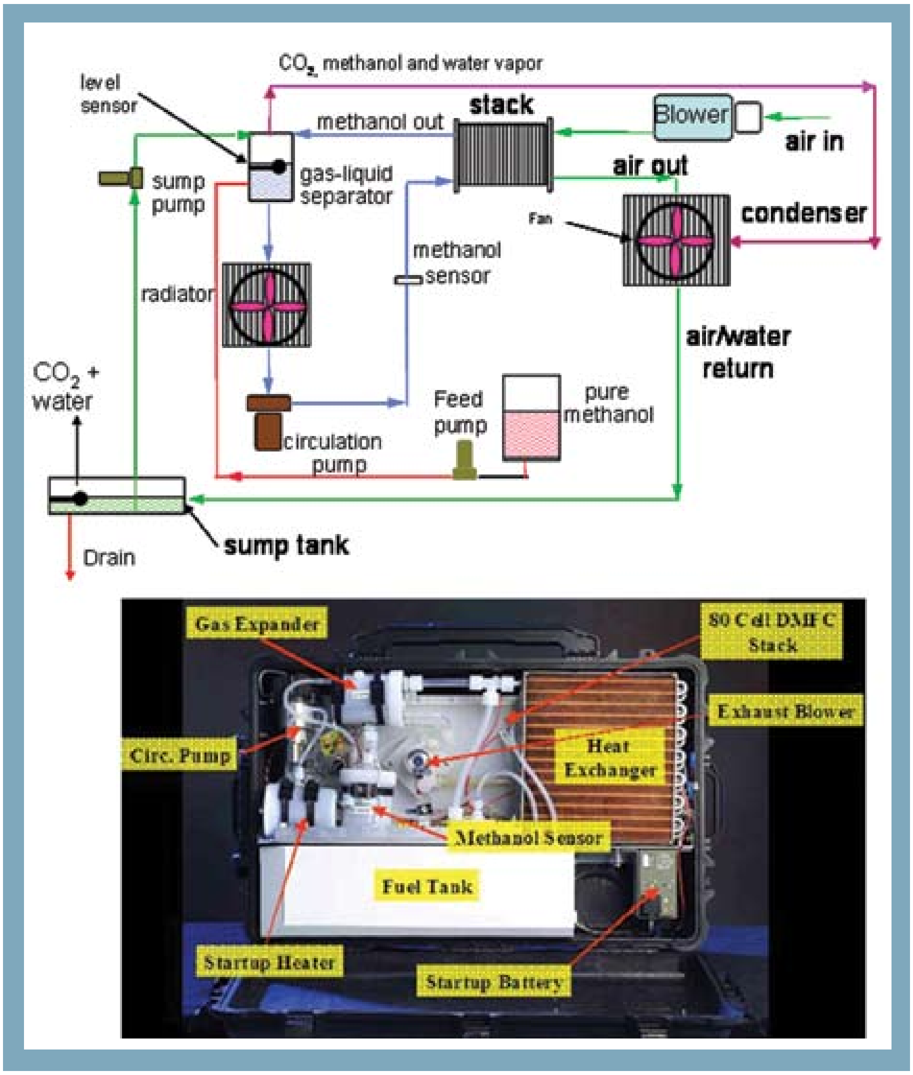

Fig. 2. *Schematic of a DMFC system and the internal distribution of components in a 300 W DMFC system fabricated at JPL.*

technology to the demonstration of stack and systems was carried out in the U.S. under research programs funded by the Department of Defense at the Jet Propulsion Laboratory (JPL), Los Alamos National Laboratory (LANL), U.S. industry, and universities[3-5] and by research groups in the UK and India.[6] Since then there has been substantial progress in the commercialization of portable DMFC systems particularly suitable for use by the military. Also, there has been more development of systems based on the other fuel cell types listed in Table I.

Direct Methanol Fuel Cell Systems

DMFC systems are based on the ability to achieve the complete electro-oxidation of methanol to carbon dioxide in a liquid-fed PEM cell. In a DMFC, methanol is diluted into an aqueous solution and fed to the anode of the fuel cell. Air or oxygen is supplied to the cathode of the fuel cell. DMFC systems are configured to allow for the continuous supply of fuel solution at the appropriate concentration to the stack, removal of by-product water and carbon dioxide, recovery of water needed for the anode reaction, and rejection of the heat generated. A schematic of a DMFC system is shown in Fig. 2. This figure also shows the internal construction of a 300 W system fabricated at JPL.

In a DMFC, nano-particulate platinum-ruthenium anode catalysts are the choice for the electro-oxidation of methanol. Platinum black is the

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Table II. Summary of performance characteristics of methanol fuel cell systems.

			Power Source			Fuel			System Specifications				
System	**Fuel Cell Type**	**Fuel**	Power (W)	Volume (L)	Mass (kg)	Volume (L)	Mass (kg)	Energy Output (Whr)	Run Time, h	Specific Power (W/kg)	Power Density (W/L)	Energy Density (Whr/kg)	Energy Density (Whr/L)
SFC JENNY	DMFC	Methanol	25	2.8	1.3	0.6	0.36	480	19	15.1	7.4	289.2	141.2
EFOY 1600-M5	DMFC	Methanol	65	24.00	7.3	7.8	4.3	4,500	69	5.6	2.0	387.9	141.5
EFOY 1600-M10	DMFC	Methanol	65	24.00	7.3	14.00	8.4	9,100	140	4.1	1.7	579.6	239.5
EFOY 1600-M28	DMFC	Methanol	65	24.00	7.3	41.5	24.00	25,200	388	2.1	1.0	805.1	384.7
Oorja Pac	DMFC	Methanol	1,000	51.00	125	22.00	17.6	20,000	20	7.0	13.7	140.3	274.0
Ultra-Cell XX25	Indirect PEM	Methanol-Water	25	1.48	1.24	0.24*	0.131	166	7	18.2	16.9	121.1	112.2

**Fuel cartridge integrated within the system*

preferred catalyst for the cathode. Unsupported precious metal catalyst at the loading level of 2 to 4 mg/cm^2 is needed to achieve practical power densities in DMFCs. There is a growing interest in developing alternate catalysts with reduced platinum loading, but the progress in this area has been rather slow. The phenomenon of methanol crossover is another issue being addressed in DMFC research.[7] Nafion®-based membranes are still the most widely used polymer electrolyte in DMFCs. Multi-layer Nafion membranes have been shown to provide 50% reduction in methanol cross-over over standard Nafion 117 membranes.[8] Other membrane materials such as composites with cross-linked polystyrene sulfonic acid have been shown to be quite efficient at suppressing methanol crossover from the anode to the cathode.[9] Suppressing methanol cross-over without compromising on the proton conductivity is a technical challenge. Research on alternate membranes continues to be actively pursued worldwide since the benefit of reduced methanol cross-over and reduced membrane cost are very important to the widespread deployment of DMFC systems. Many commercial entities are now offering membrane-electrode assemblies (MEAs) for DMFCs.

Smart Fuel Cell Inc. of Germany has been leading the development of small packaged DMFC systems in the range of 15 to 150 W. Several thousand units of this company's fuel cell systems are already aboard recreational vehicles, boats, and vacation homes. DMFC systems present a clear advantage over conventional technologies such as generators by being quiet and non-polluting. The SFC units shown in Fig. 3 are in two ranges of power levels, namely, 25 W and 65 W typified by the Jenny Tactical and the EFOY 1600 product lines, respectively.

Metrics on the power source and fuel storage are summarized in Table II. The specific energy of a Jenny with one fuel cartridge is 290 Wh/kg. The specific energy of the EFOY 1600, paired with the 5 and 28 L fuel tanks, are 388 and 805 Wh/kg respectively. These specific energy values clearly exceed that of lithium ion batteries. It is important to note that higher specific energy values can be achieved when the fuel mass fraction of the system package increases. Consequently, specific energy and specific power values quoted for portable fuel cell systems must be qualified by the power level and the run-time. This type of description is principally different from that of rechargeable batteries wherein the specific energy and specific power values do not change dramatically with the energy content of the battery.

Toshiba Corporation, MTI, Sony, and Samsung have claimed development of small DMFC systems for portable electronics applications and some of these companies have exhibited their prototypes at various trade-shows.

Fig. 3. *Jenny and EFOY DMFC Systems from Smart Fuel Cell. (Graphics reproduced with permission from SFC Inc.)*

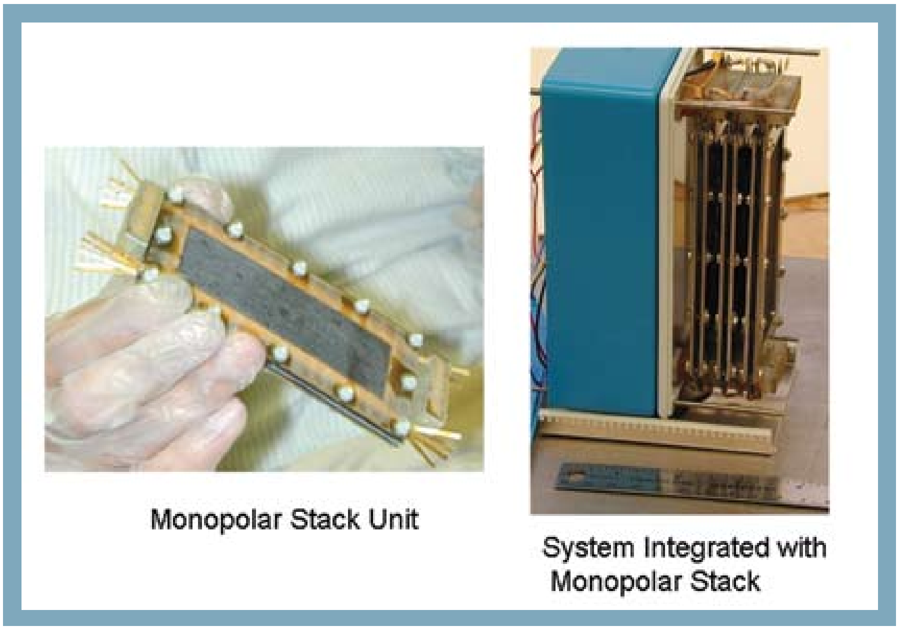

Fig. 4. *Lightweight monopolar stack implemented in a portable 5 W DMFC system.*

However, these systems have not yet been commercialized. The technology advances for the next-generation of portable DMFC systems aim at reducing the size and increasing the power density. Some of the approaches to improvement include simplifying or eliminating the components required for liquid circulation, gas handling, and thermal management. This is achieved by either using a diffusion feed of the methanol reactant or by having multifunctional components in the balance-of-plant. Most of these modifications to make a DMFC system compact, limit the power output. Reducing stack mass is another approach being pursued for advancing portable DMFC systems. One approach to reduce stack mass is to use monopolar configurations that eliminate the use of heavy bipolar plates. The power density of the stack can be increased by at least three times by this approach. Details of such designs are not easily available in the public domain. However, an example of a 5 W DMFC system developed at JPL that incorporates a lightweight monopolar stack is shown in Fig. 4. One of the more straightforward approaches to increasing power density of DMFC power source is to construct a hybrid of the fuel cell with high-power lithium ion battery.[10] In this case the battery is sized to handle the peak power demands, and the fuel cell is sized to handle the base load and charge the batteries during off-peak periods.

Another commercially available DMFC system is the OorjaPac™ manufactured by Oorja Protonics Inc. The OorjaPac is a 1 kW DMFC power source designed to be an onboard battery charger for material handling vehicles. The unit is mounted inside the battery tray of the vehicle and the fuel cell continuously charges the vehicles battery. The power metrics for the fuel cell system alone are 10 W/kg and 15 W/L. In the OorjaPac, six gallons of methanol provide 20,000 Wh of energy, enough for a whole day of operation. The fuel-to-electric efficiency of this system is about 20%. Several units have passed extensive field testing to demonstrate over 2000 h of durability.

Indirect Methanol Fuel Cell

A compact portable power source that uses methanol and an indirect fuel cell configuration has been developed by Ultracell Corporation. The UltraCell XX25™ shown in Fig. 5 supplies 20 W continuously with a peak capability of 25 W.

The XX25 is aimed at providing power to field computers and communications equipment for extended periods. The unit has a total volume of 1.5 L and mass of 1.24 kg. It incorporates a 240 mL methanol-water fuel cartridge on its side that can be hot-swapped to refuel. A fueled UltraCell XX25 has specific energy of 121 Wh/kg with the use of a single fuel cartridge. Additional cartridges each offer about 180 Wh of energy and weigh about 350 g. Thus, with 9 fuel cartridges, specific energy values as high as 400 Wh/kg can be achieved for a 72 h mission. This type of implementation emphasizes again the role of the fuel fraction in determining the specific energy of fuel cell based systems. Since this fuel cell incorporates a steam reformer and a high temperature polymer membrane fuel cell, the system takes about 12 min to reach steady state operation and to deliver full power. However, the packaging of this unit is impressive in that it is rugged and contains high-temperature components assembled in a compact configuration. The U.S. military is in the process of field testing these units for soldier applications.

Larger systems based on the indirect methanol fuel cell concept are being offered by Idatech and Protonex Inc. and are in the initial stages of deployment as commercial products. The iGen™ is IdaTech's 250 W portable fuel cell. This system uses a methanol-water fuel processor in conjunction with a metallic separation membrane to produce pure hydrogen that is then fed to a PEM fuel cell. The Valta™ M250 is a system designed by Protonex Inc. to provide a nominal 250 W also uses a reformed methanol feed in conjunction with a PEM fuel cell. These 250 W systems aim at providing continuous power for battery charging, replacing conventional generators for backup power, and providing auxiliary power for boats and recreational vehicles. Because of the use of a reformer, these systems tend to be larger, heavier, and have longer start up times than a corresponding DMFC system.

Direct Hydrogen Fuel Cell

Hydrogen-fueled systems were among the first high-power density portable fuel cell concepts to be developed. However, hydrogen systems have always had to contend with the logistics of supplying the fuel and the inability to store adequate fuel to achieve reasonable run times. Jadoo Systems has commercialized the N-Gen™ a 100 W system that uses

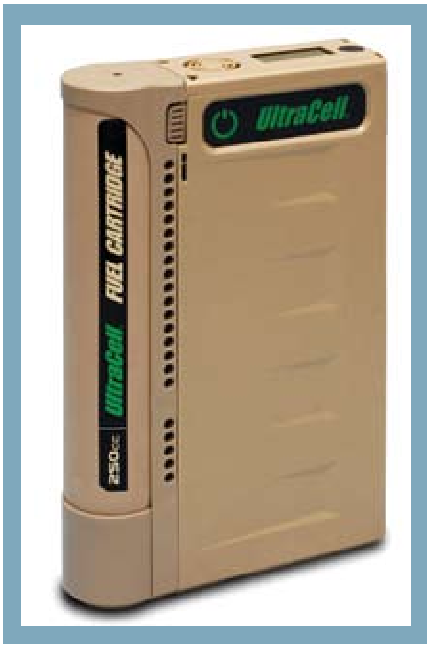

Fig. 5. *25 W Ultracell XX25 Reformed Methanol Portable Power Source. (Graphics reproduced with permission from Ultracell Inc.)*

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hydrogen supplied from a uniquely designed and user-friendly metal hydride canister (N-Stor^{TM}) that can be rapidly re-filled using Jadoo's portable fill station. This system has found acceptance as a battery replacement for video cameras and field equipment. This system offers about 3.6 h of operation on a single cartridge, which calculates to 78 Wh/kg at the system level. What distinguishes this system from other direct hydrogen fuel cells is that once installed, the user swaps out the fuel cartridges to recharge the power source. The cartridges provided with the N-Gen are "hot-swappable" and have a specific energy of 180 Wh/kg. These portable systems face competition with lithium-ion batteries that can provide specific energy values as high as 150 Wh/kg in large battery package. To overcome the challenge of poor fuel storage capacity, hydrogen generation from chemical hydrides has been investigated. To this end, Protonex Inc. and Millenium Cell Inc. have demonstrated fueling by hydrogen generated from sodium borohydride solutions. Specific energy values as high as 375 Wh/kg have been demonstrated for systems that operate for 12 h on a single charge. This type of chemical hydride based portable fuel cell has been shown to increase the run-time of unmanned aerial and ground vehicles used by the U.S. Air Force and Army.

Solid Oxide Fuel Cells

Adaptive Materials Inc. has led the development of portable SOFC-based power sources. The units Amie 25 and Amie150 use a unique lightweight micro-tubular solid oxide cell construction and employ propane as the fuel. Propane is partially oxidized and processed before being admitted into the solid oxide fuel cell. The Adaptive Materials Amie 25 fuel cell system weighs 1.5 kg, and with 1 kg of propane the system is designed to provide 1700 Wh of energy. Specific energy values as high as 700 Wh/kg have been realized with a propane-fueled system. These fuel cell systems present some of the highest specific energy values reported for portable fuel cells. Protonex is also offering a SOFC-based portable generator, Valta P75 that has a 75 W output and is fueled by propane. Since SOFC systems can potentially utilize complex hydrocarbon fuels, the Department of Defense finds such systems particularly advantageous from the standpoint of utilizing logistic military fuels.

Challenges and Directions

The above examples of commercial or near-commercial devices demonstrate that the field of high-energy fuel cell based portable power sources has advanced significantly in the last decade. While several portable power products have found niche markets, widespread commercialization into mass markets such as mobile phones and laptops still face numerous technical challenges. One of the key challenges for methanol-fueled systems is increasing the power density of the fuel cell stack and the reduction of the size and mass of the balance of plant. Enhancement in power density could be achieved by hybridizing with batteries, but this solution is highly dependent on the type of load profile presented to the power source; the hybrid solution is very beneficial when the device is presented infrequent peak loads.[11] Lightweight fuel cell stack architectures using monopolar type configurations and fuel feed concepts that utilize internal system resources are likely to have a significant value in improving power density. Meeting the environmental temperature requirement of -40°C and +60°C also presents a challenge. Freezing of the fuel cell below 0°C will require hybrid batteries to support longer start-up periods. Alternately, the fuel cell system will have to be kept warm by operating at a low power level resulting in some penalty on the fuel efficiency. Also, component durability needs to be enhanced to increase reliability. However, improvements in electrocatalysis of methanol oxidation, reduction in methanol crossover, and enhancement of the voltage efficiency of the fuel cell will help realize more dramatic reductions in the size of the systems even at the 1 kW level. At environmental temperatures above 45°C, water loss from the system must be compensated and heat rejection rates must be enhanced.[12] This is usually accomplished by dilution of the fuel resulting in reduced specific energy of the system. Consequently, meeting the environmental temperature requirement of +60°C becomes a very serious challenge for small DMFC systems.

For hydrogen-fueled systems, increasing the hydrogen storage capacity of the fuel cartridge continues to be the major challenge. SOFC systems based on propane present some of the highest specific energy values in small packages. However, thermal integration issues present challenges to miniaturization for mobile devices. If the operation on logistic fuels such as liquid hydrocarbons is addressed, the use of SOFC systems in the military could grow significantly.

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