Test and Evaluation of the Smart Fuel Cell C20-MP Direct Methanol Hybrid Fuel Cell System as a Soldier Power Source

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Abstract

Recent advances in fully integrated, portable fuel cell system development have highlighted the potential benefits they might offer to military users in the near term. Soldier power (1 watt – 100 watts direct current) fuel cell applications have seen significant attention of late due to challenges in ongoing operations to meet power demands for the Warfighter's equipment. This challenge has resulted in the use of secondary (rechargeable) batteries in the field, something that was only done in training exercises prior to recent operations. Consequently, the logistics burden for dismounted Soldiers on missions longer than 24 hours has become quite arduous. As such, the growing need for lightweight, rugged, and environmentally benign soldier power systems has been targeted as an excellent entry market for portable fuel cell systems.

The U.S. Army Communications-Electronics Research, Development, and Engineering Center (CERDEC) Fuel Cell Technology Team located at Fort Belvoir, VA has been developing soldier power sources to meet such a need. In March 2005, one of the most advanced, fully integrated direct methanol fuel cell (DMFC) systems developed to date was received by CERDEC and a test and evaluation program was initiated. The Smart Fuel Cell (SFC) C20-MP is a portable DMFC hybrid power system rated for 20-watt continuous operation and was developed by Smart Fuel Cell AG of Brunnthal-Nord, Germany. Weighing approximately two (2) kilograms and fueled by hot-swappable, 500-milliliter methanol fuel cartridges, the system is fitted with an exchangeable 1.5-ampere-hour lithium polymer rechargeable battery. Two (2) SFC C20-MP systems were delivered: one was designed for moderate ambient temperature operation (1 – 35 degrees Celsius demonstrated) and operated with "neat" (high purity) methanol fuel (dubbed the Normal unit); the other was designed for high ambient temperature operation (1 - 50 degrees Celsius demonstrated) and operated on a dilute methanol-water fuel mixture (dubbed the Desert unit). CERDEC testing indicated that the Normal unit had a peak fuel efficiency of 19.1% at 19.6 watts average power output, whereas the Desert unit had a peak fuel efficiency of 19.7% at 20 watts average power output. Both systems showed improved reliability and electrical characteristics when compared with previous DMFC systems tested by CERDEC, but further developmental work is still needed in order to reach compliance with MIL-STD-705C for generator sets (U.S. Dept. of Defense 1989).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
31 OCT 2005	**Final Report**	**15-03-2005 to 31-10-2005**

4. TITLE AND SUBTITLE
Test and Evaluation of the Smart Fuel Cell C20-MP Direct Methanol Hybrid Fuel Cell System as a Soldier Power Source From the Conference Proceedings of the 2005 Annual Meeting of the American Institute of Chemical Engineers, 30 Oct. - 04 Nov. 2005

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jonathan Cristiani; Nicholas Sifer; Elizabeth Bostic; Pavel Fomin; Darwin Reckart

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army RDECOM CERDEC Fuel Cell Technology Team,10125 Gratiot Rd.,Suite 100,Fort Belvoir,VA,22060-5816

8. PERFORMING ORGANIZATION REPORT NUMBER
APD-ES-05-10-001

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army RDECOM CERDEC Fuel Cell Technology Team, 10125 Gratiot Rd., Suite 100, Fort Belvoir, VA, 22060-5816

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
AMSRD-CER-C2-AP-ES

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Recent advances in fully integrated, portable fuel cell system development have highlighted the potential benefits they might offer to military users in the near term. Soldier power (1 watt - 100 watts direct current) fuel cell applications have seen significant attention of late due to challenges in ongoing operations to meet power demands for the Warfighter’s equipment. This challenge has resulted in the use of secondary (rechargeable) batteries in the field, something that was only done in training exercises prior to recent operations. Consequently, the logistics burden for dismounted Soldiers on missions longer than 24 hours has become quite arduous. As such, the growing need for lightweight, rugged, and environmentally benign soldier power systems has been targeted as an excellent entry market for portable fuel cell systems.

15. SUBJECT TERMS
direct methanol fuel cell ; DMFC ; test and evaluation ; U.S. Army research ; soldier power ; fuel cells

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**		**16**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

During the system level test program with the SFC C20-MP, several factors were evaluated. One goal of the program was to demonstrate a technology readiness level (TRL) five (5) to six (6). Military significance was evaluated by comparing the increased or new capabilities of the SFC C20-MP with fielded power supplies of similar size. One performance factor that indicates military significance for portable power systems is mission specific energy density, which was calculated at 400 watt-hours per kilogram for the SFC C20-MP Normal system for a 20-watt continuous, 72-hour mission. Finally, technical deficiencies that remained with the SFC C20-MP systems and with DMFC technology in general were identified primarily as "growing pains" typical of any technology in development.

Although DMFC technology is largely believed to be very suitable for portable systems in the 20-watt range, some limitations remain. For example, extreme environmental conditions (especially those below freezing and above 40 degrees Celsius) can cause problems for many DMFC systems during startup and continuous operation. Other technologies such as reformed methanol fuel cells are potential competitors with DMFC technology in the portable market, due primarily to high system efficiencies and their inherent advantage of a wide range of environmental operation. Consequently, CERDEC continues to monitor the activities of the commercial sector with hopes that multiple fuel cell technologies will be successful in the portable market. CERDEC also continues its mission to develop and demonstrate a rugged 20-watt portable hybrid fuel cell system that weighs ¾ kilogram, uses packaged (safe and transportable) fuel, and is capable of 700 watt-hours per kilogram for a 72-hour, 20-watt continuous mission by 2008. If such a goal can be realized, the Warfighter will ultimately be able to perform longer (3-day) missions without the need to replace or recharge heavy batteries currently required.

Introduction

As portable electronic devices and electronic systems used by the United States military increase in numbers and capabilities, there has been a corresponding increase in their power consumption. This has presented problems for both the military and commercial portable electronics markets. Many of these devices, such as cellular telephones and global positioning systems, are currently powered by batteries, which must either be replaced or recharged periodically depending on their chemistries, capacities, and usage. Higher energy density power sources have, therefore, become a critical need for the military. Many federally funded research and development programs in alternative power sources for sensor and soldier portable applications (1W – 100W) are ongoing, and fuel cell technology has become one of the more promising near-term technologies that could potentially offer operational benefits to the Warfighter.

Fuel cell technology, although a well understood technology for space applications, has only recently begun to show advances in fully integrated, portable prototype system development. Polymer electrolyte membrane (PEM) fuel cells have been identified by many academic and industry professionals as the most appropriate fuel cell technology for portable applications. PEM fuel cells are electrochemical reactors that catalytically react a fuel (such as hydrogen) and an oxidant (such as oxygen or air), rather than combusting them, to create electricity and water as products. Direct methanol fuel cells (DMFC) are PEM fuel cells that operate with methanol fuel rather than hydrogen fuel and yield similar products (water, CO_2, and electricity). The U.S. Army Communications-Electronics Research, Development, and

Engineering Center (CERDEC) Fuel Cell Technology Team, located at Fort Belvoir, Virginia, has been investigating many different technologies for portable power applications over the past several years. Smart Fuel Cell AG (SFC) of Brunnthal-Nord, Germany has provided multiple, complete fuel cell systems in the past for test and evaluation to CERDEC. SFC specializes in commercial DMFC products for backup power applications such as the sailing and leisure market. Their newest prototype DMFC system, the SFC C20-MP, was developed for CERDEC as a soldier power source.

Background

The U.S. Army CERDEC Fuel Cell Technology Team focuses on system development, test, evaluation, demonstration, and quick transition of fuel cell technologies to the Warfighter. Three research and development focus areas have been identified as areas where fuel cell technology can be best used. These applications are soldier and sensor power (1W – 100W), forward field battery charging (100W – 500W), and auxiliary power units (500W – 10kW). Regarding the soldier power focus area, CERDEC's goal for soldier/sensor power is to develop and demonstrate a 20W fuel cell hybrid power source by 2008 with the following metrics: packaged fuel, 1.5lbs (0.75kg) dry system weight, and 700 W-hr / kg mission energy density for a 20W continuous, 72-hour (3-day) mission. Based on their past experience with PEM and DMFC systems, CERDEC has identified DMFC technology as one of the most promising technologies to meet its target goals for the soldier power program.

In 2003, under a Foreign Comparative Test (FCT) program sponsored by the U.S. Office of the Secretary of Defense, two (2) SFC A25 (a 25W DMFC) units were purchased and tested to determine the possible operational benefits to the U.S. Army. The SFC A25 units operated on "neat" (high purity) methanol fuel and performed "well under limited conditions," (Bostic et al. 2004) but were consistently unreliable when tested in extreme environmental conditions and various operational orientations. The units were bulky and heavy (21.5L volume and 7.8kg dry weight), but were not specifically designed for portable applications. In response to the size and weight disadvantage of the SFC A25 units, SFC developed a second-generation 25W system with reduced size and weight (1.8L volume and 1.7kg dry weight) referred to as the SFC C25. Three (3) SFC C25 units were leased to CERDEC through the FCT program for test and evaluation in 2004. These units did not show increased capability and reliability over the SFC A25 under normal and extreme conditions. They did, however, demonstrate slight performance improvements such as increased fuel efficiency at rated load under ambient conditions. The test and evaluation of the SFC C25 units showed that DMFC technology could potentially mature enough in the near term to be suitable for military applications if system reliability could be better demonstrated.

Leveraging the findings and results of the FCT test program, SFC developed a third generation DMFC power system under a 12-month contract with CERDEC designated as the SFC C20. A SFC C20 demonstrator system was delivered to Fort Belvoir in January 2005 for preliminary test and evaluation prior to the completion of the contract and delivery of two (2) functional units. The SFC C20 demonstrator was an "alpha" iteration of the SFC C20 system design. The SFC C20 demonstrator operated on "neat" methanol fuel, was a hybrid system, and exhibited improved performance over the previous two SFC systems tested by CERDEC. These improvements included: increased fuel efficiency (up to 16% at rated load), increased performance under extreme conditions (consistent operation for an hour or more at rated load from -25^{0}C to 40^{0}C), and improved system reliability. After testing with the SFC C20 demonstrator was complete, the system was cold soaked at –30^{0}C for four (4) hours. After thawing overnight, the system was started and operated for four (4) hours at ambient conditions and partial load. Although the system showed significantly decreased performance, the tests indicated the capability of the system to be cold-soaked, thawed, and still operate thereafter.

Figure 1 - SFC C20-MP systems with attached fuel cartridges

Two (2) SFC C20-MP prototype-DMFC systems were delivered to Fort Belvoir in March 2005, approximately twelve (12) months after the contract was awarded to SFC. Both systems can be seen with attached fuel cartridges in Figure 1. These systems use similar stack technology as their predecessors, both the SFC C25 and SFC C20 demonstrator systems. The fuel cell stack technology includes proven commercial DMFC membrane electrode assemblies (MEAs) from SFC's well-known partner, DuPont. The sand colored system (on the left in Figure 1 and herein referred to as the SFC C20-MP Desert) is designed for high temperature operation up to 50^{0}C continuously, and is fueled by a dilute methanol-water mixture. The green colored system (on the right in Figure 1 and herein referred to as the SFC C20-MP Normal) is designed for moderate temperature operation up to 35^{0}C continuous, and is fueled by neat methanol. Since the Desert unit is fueled by a dilute methanol-water mixture, higher temperature operation can be achieved continuously.

System Physical and Operational Characteristics

The SFC C20-MP units has complete packaging, hybridization, control, and user interface functions integrated into the basic system design of their immediate predecessor, the SFC C20 demonstrator. Both systems are rated for 20W continuous power (11.1 VDC nominal). According to SFC, the output voltage of the SFC C20-MP system ranges from 10 – 16 VDC. Figure 2 shows an overview diagram of the SFC C20-MP system along with numbered labels for each of the components.

The systems are activated by pressing the power button and include a standard 6-pin SC-C-179492 type military electrical connector, which allows for compatibility with devices that typically operate on military batteries (such as the BA 5590). Once activated, the system performs some short-term internal diagnostics before starting the fuel cell itself. A night vision compatible liquid crystal display, or LCD, communicates information during operation such as system output voltage, system output current, system output power, hybrid battery capacity, internal water reservoir level, and any error messages to the user. Pressing the information button once illuminates the LCD and pressing it several more times scrolls through the output information listed above.

An exchangeable, 1.5 A-hr lithium polymer battery pack provides instantaneous power (up to the rated load of 20W) as well as parasitic power during startup of the fuel cell stack. When the battery is found completely discharged upon activation of the system, it can be recharged using an external DC power supply connected to the system electrical connector via a custom SFC current limiter. Once the fuel cell stack is operational and provides power, it recharges the battery while providing the output power demanded. This hybridization is achieved through a 5-pin, System Management BUS (SMBUS) compliant interface between the fuel cell stack and the battery. The startup cycle of the SFC C20-MP systems is unique due to specific controller functions.

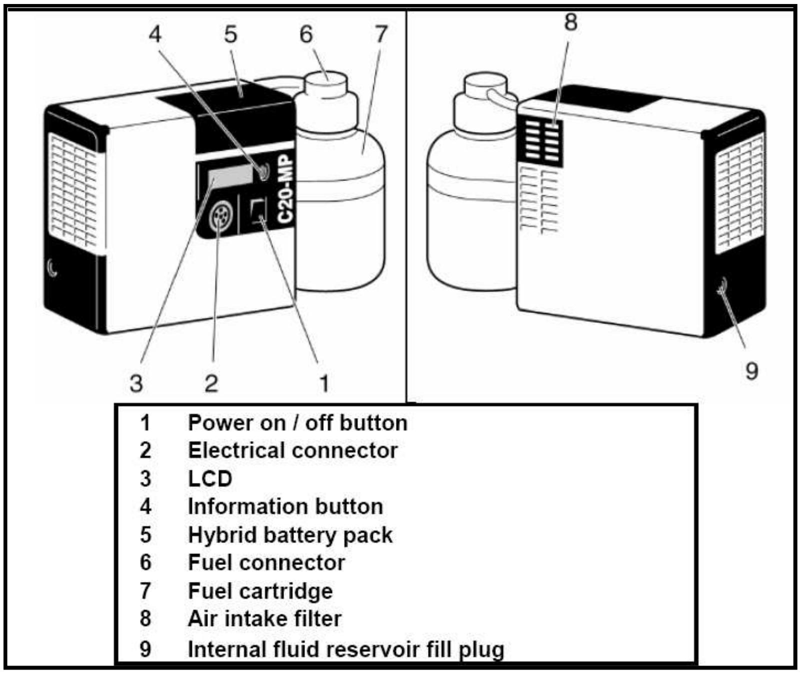

Figure 2 - SFC C20-MP component overview diagram (courtesy of Smart Fuel Cell AG)

Ambient air is drawn into the system through an air management subsystem. This includes, among other features, a particulate filter and a chemical filter, both of which are exchangeable components. The filtered air is then supplied to the fuel cell cathode. Both of these air filters are shown in Figure 3 (particulate filter on left and chemical filter inside of aperture on the right). As is standard in active DMFC systems, methanol is pumped from the fuel cartridge and diluted to a lower concentration with process medium (very low concentration methanol) stored in the internal fluid reservoir. According to the 2005 Fuel Cell Handbook, by keeping the methanol concentration low, higher efficiencies can be achieved in the fuel cell stack. Conversely, high methanol concentrations may cause faster stack performance degradation due to mechanisms such as methanol crossover and associated permanent conductivity losses in the fuel cell

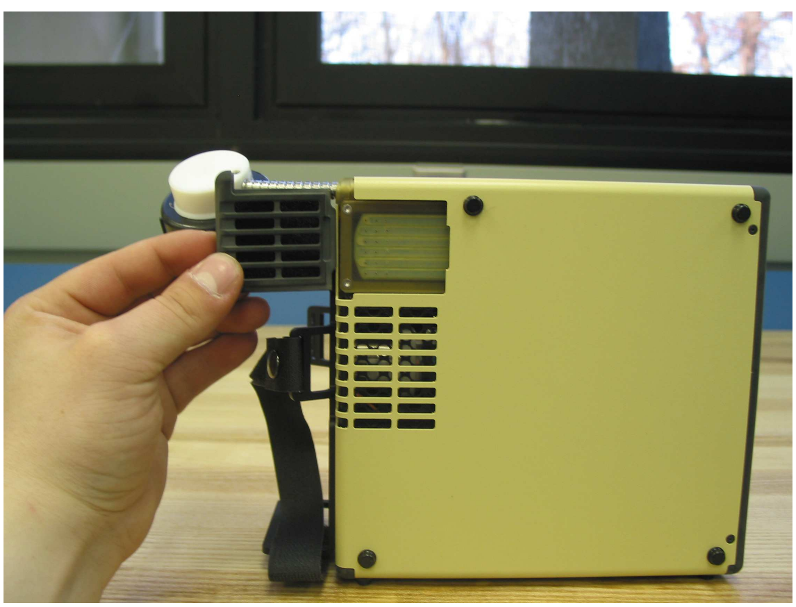

Figure 3 – SFC C20-MP air filtration system

membrane electrode assemblies (U.S. Dept. of Energy 2004). Product water on the cathode side of the fuel cell is recycled to the internal fluid reservoir. When this fluid reservoir becomes significantly depleted, it can be refilled by the user with process medium via the internal fluid reservoir fill plug.

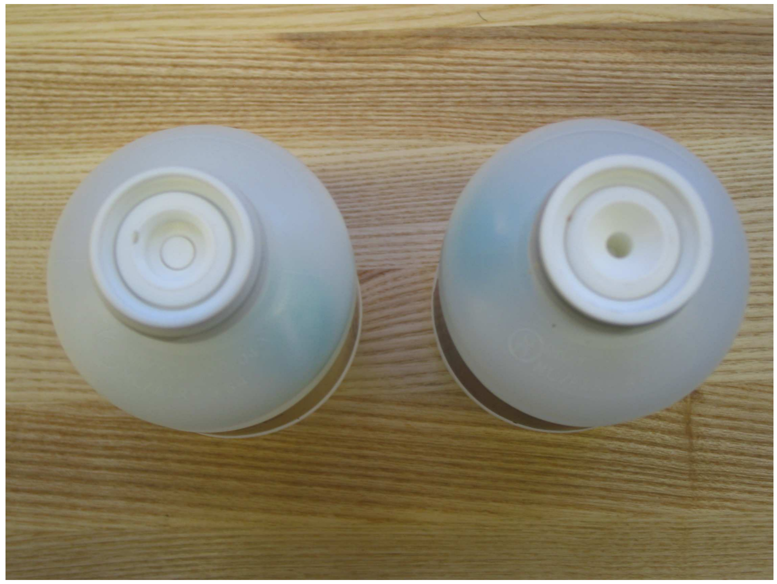

Figure 4 – SFC C20-MP Desert (left) and Normal (right) fuel adapters

Fuel cartridges for each system were designed and verified to have at least a 500mL capacity. The fuel adapter on each cartridge was designed to interface (screw-on) only with the specific fuel connector of the specific system for which that fuel cartridge was designed. This is to prevent incorrect fuel from being supplied to a system. Figure 4 displays the different adapters for the two different fuel cartridges. Figure 5 shows the specific fuel connector line on the Normal system and Desert system, which interface with the specific cartridges shown in Figure 4.

Figure 5 – SFC C20-MP Desert (left) and Normal (right) fuel connector lines

Table 1 - SFC C20-MP system dry weight calculations

Calculation	C20-MP Normal g	C20-MP Desert g
AVG	2002	1946
MAX	2031	2005
MIN	1981	1867
MEDIAN	1993	1937

Weight measurements of each system, which were conducted before and after each day of testing, are summarized in Table 1. The deviance in dry (lacking fuel cartridge) system weight was attributed to varying levels of water in the internal fluid reservoir.

Exterior size measurements were taken in all three dimensions of each system with the largest value in each

Table 2 - SFC C20-MP system exterior size measurements

Height	Length (in)	Width (in)	Volume
in. (cm)	in. (cm)	in. (cm)	ft^3 (L)
6 1/4 (16)	6 5/8 (17)	3 9/16 (9)	0.085 (2.4)

dimension being recorded. The results of the size measurement tests are included in Table 2 and do not include the volume associated with the fuel cartridge and cartridge harness.

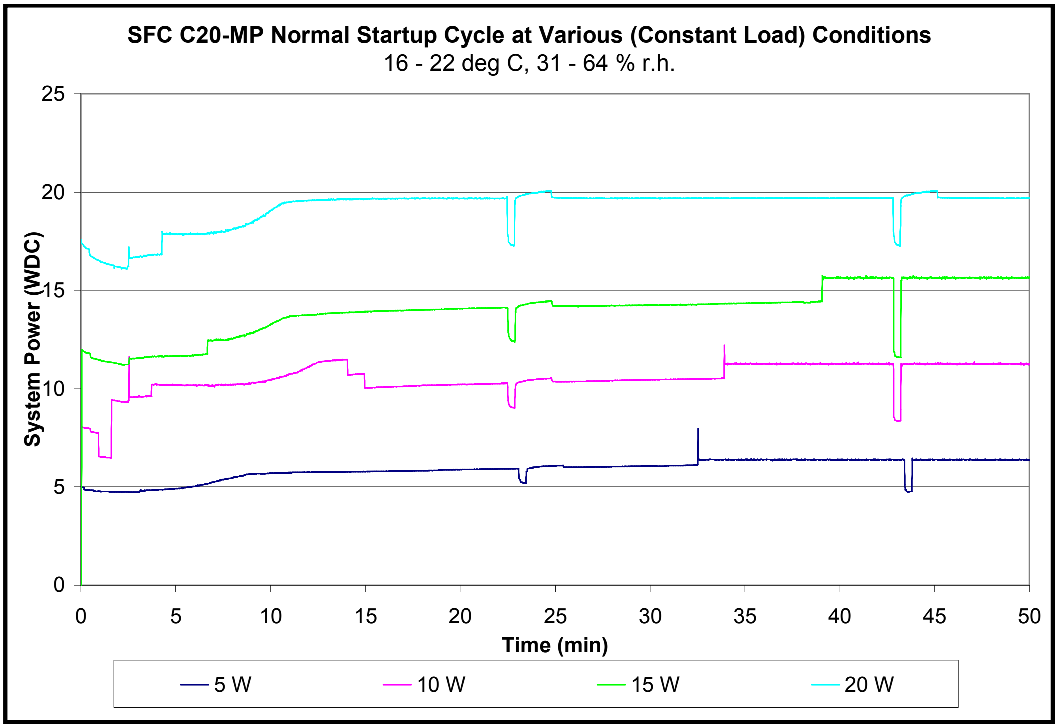

Figure 6 - SFC C20-MP startup cycle at various constant loads (power)

Start tests were conducted daily prior to other testing activities. In each case, the system was allowed to cool and aerate for 12 hours (overnight) after operation prior to being started again. The state of charge (SOC) of the battery at the end of each day of testing was kept at approximately 80% so that the following day upon startup the SOC would be similar for each startup test. Upon activation during startup testing, a varying load was immediately applied to the system and kept constant for at least 50 minutes to generate sufficient data. Figure 6 shows four (4) trials for which the SFC C20-MP provided instantaneous power over the range of its rated output capabilities. The output power fluctuated significantly during the first half hour to hour of operating the SFC C20-MP from a cold start at a constant resistive load. This is because the battery is initially being used upon system activation for the exportable power until the fuel cell reaches its operating temperature and can supply the exportable power.

Figure 7 displays the corresponding system voltage profiles for the four (4) trials shown in Figure 6. There are several points worth noting in Figure 7. First, upon activation, it is appropriate that an increasing exportable power corresponds to a decreasing initial output voltage, which can be seen in the chart. Second, it can be seen that the output voltage is increasing during stack startup until it reaches a steady state. This steady state corresponds to the optimum SOC of the hybrid battery, which was verified to be approximately 80% and represents the approximate average voltage at that specific load. Lastly, each of the four trials shows a dip in output voltage after approximately 23 and 43 minutes of operation, independent of the output power. This indicates periodic load interruption of the fuel cell, a patented method for improving the performance and achieving long lifetimes of fuel cell stacks.

SFC has claimed that methanol crossover is not necessarily a problematic mechanism for DMFC system operation. Although crossover has been widely known to cause efficiency losses and permanent degradation to the MEA, SFC asserts that methanol crossover is necessary to meet user requirements such as cold start capability, lifetime, and reliability. Dr.

Jens Müller of SFC described the process of “controlled methanol crossover” by saying that methanol crossover: “…is a way to convert methanol to water, which is helpful in certain situations such as during startup or under extreme outside conditions; …is the most elegant way to rapidly heat up the unit; …can be used to distribute the anti-freeze additive evenly across the whole stack; …is quite helpful from a system control perspective,” (Müller 2005). Active crossover control is a crucial element in SFC’s systems.

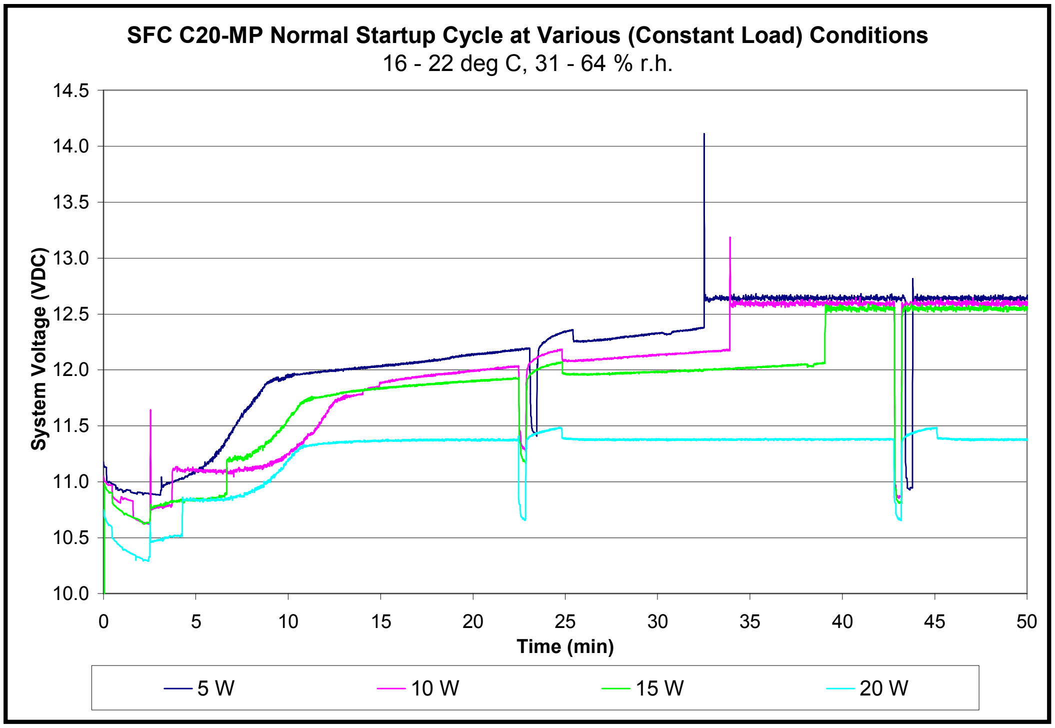

Figure 7 - SFC C20-MP startup cycle at various constant loads (voltage)

Overall the physical and operational characteristics of the SFC C20-MP are user friendly. The most highly developed features of the systems include instantaneous power, night-vision compatibility, comprehensive user interface / diagnostics, hybridization, quick startup, and exchangeable battery and air filtration components. These features as well as others make the SFC C20-MP one of the most advanced fuel cell power systems developed to date. CERDEC began a system level test program with the SFC C20-MP systems in March 2005 to evaluate the technology readiness, military significance, and remaining technical deficiencies of the systems and the technology in general. The methods and results of this test program are presented and discussed in the following sections.

Methods and Results

The CERDEC Fuel Cell Technology Team test plan applied only to system level testing of the SFC C20-MP systems with test methods covered mostly by MIL-STD-705C (U.S. Dept. of Defense 1989) and MIL-STD-810F (U.S. Dept. of Defense 2000). These military standards were written for internal combustion engine driven generator sets and environmental testing conditions, respectively. Some deviations, clarifications, and supplemental information were added to the standard test methods to correctly depict the tests that were accomplished for fuel cell systems. Testing included: size and weight measurement, start and stop, fuel consumption, voltage ripple, modified voltage dip and rise, and voltage regulation, stability, and transient response tests. All testing was conducted with calibrated equipment in CERDEC test facilities.

Fuel consumption tests were conducted on the SFC C20-MP systems for approximately 25%, 50%, 75%, and 100% of the rated load (20W) over durations of four to eight hours at each load (constant resistance). It should be noted that internal water levels, ambient temperature, and ambient relative humidity might have impacted system performance to minor extents, thus accounting for fluctuations in a system's fuel consumption at constant load.

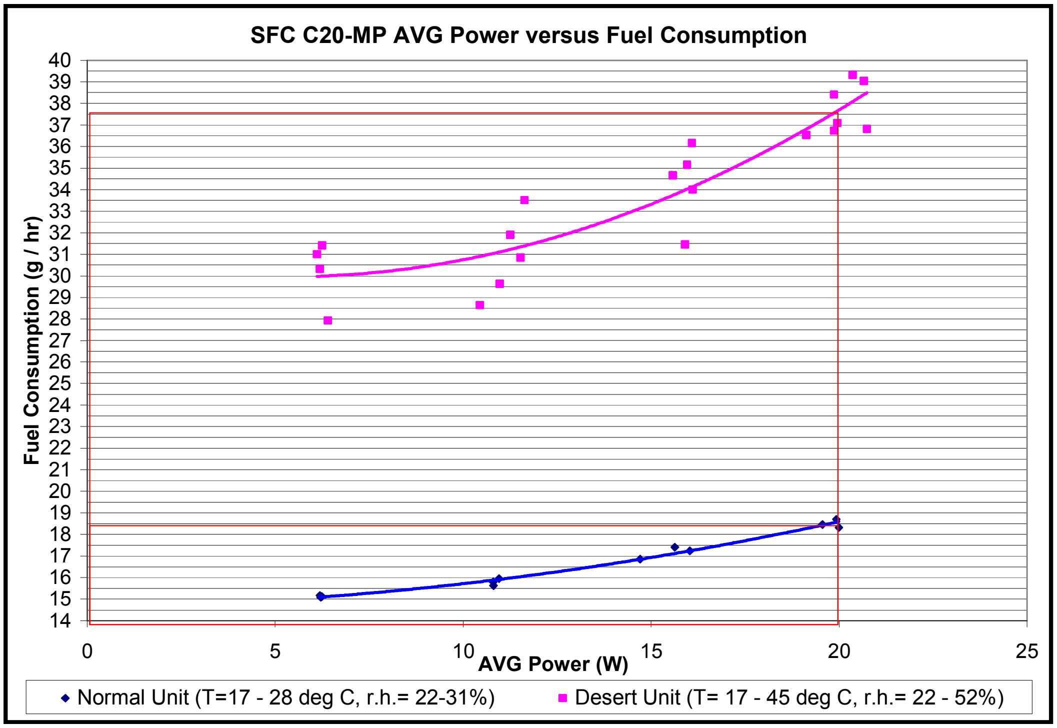

Figure 8 – SFC C20-MP average fuel consumption versus average power output

Several trials at each load condition were conducted and the average fuel consumption values from each test were compiled and used with a second-order polynomial regression to produce a best-fit relationship between output power and fuel consumption. These results are summarized in Figure 8, from which an average fuel consumption of

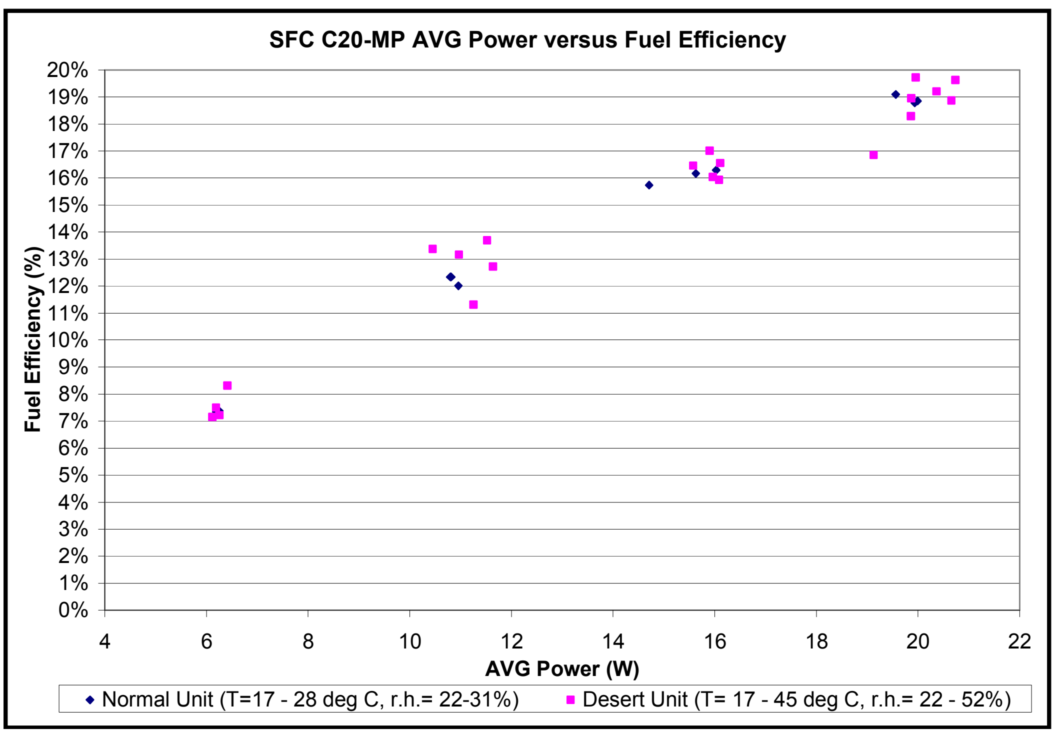

Figure 9 – SFC C20-MP fuel efficiency versus average power output

approximately 18.6 g/hr (0.02 L/hr) was interpolated for 20W average power output from the SFC C20-MP Normal system. An average fuel consumption of approximately 37.75 g/hr (0.04 L/hr) was interpolated for 20W average power output from the SFC C20-MP Desert unit.

Based on the results presented in Figure 8, efficiency values were calculated for all of the fuel consumption tests. The peak efficiency of the SFC C20-MP Normal system was calculated to be 19.1% at an average power output of 19.6W, whereas the peak efficiency of the SFC C20-MP Desert system was calculated to be 19.7% at an average power output of 20W (and at 45^{0}C). These calculations, as well as efficiency values for the remaining fuel consumption tests, are displayed in Figure 9 versus average power output. Efficiency values were calculated using recorded energy produced (in W-hr from data taken once per second) and total fuel consumed (assuming a lower heating value of 5550 W-hr / kg for pure methanol). A sample calculation of fuel efficiency can be seen in Figure 10.

$$\frac{156.6(W-hr, produced)}{1} * \frac{1}{147.8g(fuelconsumed)} * \frac{1000g}{1kg} * \frac{1kg(methanol)}{5550(W-hr)} * 100\% = 19.1\%$$

Figure 10 – Sample calculation of fuel efficiency for SFC C20-MP Normal system

Other features of the SFC C20-MP systems were verified briefly without significant testing. The systems were programmed to be orientation sensitive within specific limits using internal sensors, which shutdown the fuel cell when those limits were exceeded. The systems were tested to the approximate limits specified by SFC and verified to be functional as intended through these tests. Cartridge hot-swap capabilities were also verified (within a few seconds) during operation and at the rated load. SFC stated that the fuel cartridge hot-swap capability was programmed up to approximately 30 seconds in duration, but could be programmed up to a minute in duration. Although these system features were verified to be functional, their limits were not fully explored during testing.

To ensure that the SFC C20-MP was a fully hybridized power source, electrical tests were carried out to accurately characterize its transient response to loading, unloading, and no load conditions. Voltage regulation, stability, transient response, voltage ripple, and modified voltage dip and rise tests were conducted. In each test for varying load steps, the load was varied between a no load condition for one (1) minute and then a load condition for one (1) minute, with each step being completed three (3) times. Data was acquired at 30 Hz and analyzed for three different trials. The results of these tests are summarized in Table 3 for both

Table 3 – SFC C25, SFC C20 demonstrator, and SFC C20-MP (high/low battery SOC) electrical test results calculated by methods described in MIL-STD-705C (U.S. Dept. of Defense 1989)

Electrical Test	C25	C20 Demo	C20-MP Low Battery	C20-MP High Battery
Open Circuit Voltage (VDC)	18	16	16	16
Regulation	29%	22%	5.7%	6.1%
Steady State stability	21%	6.4%	3.0%	8.2%
Application of rated load **Recovery Time**	33% N/A	25% N/A	8.6% N/A	8.6% N/A
Rejection of rated load **Recovery Time**	34% 6.8	15% 5.73	0.6% N/A	20% N/A
Ripple Voltage	39%	30%	30 %	33%

low and high battery SOC. The same characteristics for the SFC C25 and SFC C20 demonstrator are also displayed to show improvement in electrical characteristics through hybridization and system design iterations. These values were calculated using methods described in MIL-STD-705C.

The SFC C20-MP Normal system was operated for a total of 170 hours before it needed significant repairs. On 28 April 2005, the system began to exhibit a decreased performance at the rated load (in that the SOC of the battery could not be maintained within the optimum range of ~ 80% at the rated load). The system was sent to SFC for repair on 08 June 2005 so that an error analysis could be conducted to understand the cause of the apparent degradation to the fuel cell stack. SFC reported back on 27 June 2005 that: "All balance of plant components performed in-spec. The stack showed reduced performance. It seemed to be a result of too high [of a] methanol concentration that can be reached by too many on / off cycles in a short period of time without a significant runtime in between. The hybrid battery was unbalanced (or unequally charged). As a result, the SFC C20 could not recharge the internal battery up to its full capacity and the system shut down after 40 minutes at 20W, because of the reduced performance of the stack," (Böhm 2005). As a result of this failure analysis, it was decided to proceed with the installation of a DMFC stack that included more advanced MEA technology. The SFC C20-MP Normal system was then upgraded with a similarly sized stack that included fourth generation (Gen IV) MEAs from DuPont ("DuPont" 2005) rather than the older MEAs used in the initial system design. Once this repaired and upgraded SFC C20-MP Normal system was received, a new test program began to re-characterize the system.

The SFC C20-MP Desert system was operated for a total of 149 hours. On 30 March 2005 during testing, a fluid leak was observed. This leaking continued to occur during the next several weeks of operation and had a significant effect on testing. Several orientation and internal water reservoir related errors would occur if the internal water reservoir level was not maintained above approximately 10% capacity. As a result, the system was returned to the manufacturer for repair on 16 April 2005, where it was determined that the leaking was a result of a cracked or punctured internal structure. This component was replaced and the system was updated with new firmware for the internal controller and shipped back on 25 May 2005. Testing with the Desert system was continued with only a few minor issues until testing at 50^0C ambient temperature conditions. After one full successful demonstration of operating the SFC C20-MP Desert system at 50^0C and rated load, the system failed to operate again continuously due to problems with the system battery. Upon replacement of the battery and upgrading of the system firmware, it was discovered that the new firmware was only compatible with stacks constructed from Gen IV MEAs. This being the case, the stack was also replaced in the Desert unit and a new test program began.

Overall, the SFC C20-MP demonstrated an improvement in reliability compared to previous SFC systems, but the 1000-hour goal for system lifetime was not realized. The test plan outlined for each of the systems could not be completed due to a significant change of components, therefore tests such as startup and continuous operation under extreme conditions, maximum power capabilities, aural detectability, and performance characteristics against military load profiles were not completed for the SFC C20-MP. These tests must be completed successfully in order to transition the technology to actual users for field-testing. Improvements in fuel efficiency, electrical response to load transients, and stability at constant load conditions were seen with the SFC C20-MP systems as well, but these performance factors have not yet fulfilled standards set forth in MIL-STD-705C, nor have they achieved CERDEC's goals. Despite these shortcomings, the development program with these systems was successful because the evaluation criteria set forth for the program were achieved.

Discussion

Evaluation criteria were based on three factors during this test program: military significance, technology readiness, and demonstration of DMFC tolerance to extreme conditions. One performance factor that indicated military significance for portable power systems was mission specific energy density, which was the total energy produced during the mission (typically in watt-hours) divided by the total mission weight at the beginning of the mission including all fuel and fuel cartridges, accessories needed for operation, and dry fuel cell power plant mass and in kilograms. Calculations for total mission weight in kilograms and mission specific energy density for both of the SFC C20-MP systems for a 72-hour, 20W continuous mission are provided in Table 4.

Table 4 - SFC C20-MP mission weight and mission specific energy density for a 72-hour, 20W continuous mission

System	Cartridge Size & (Cartridge Qty.)	72-hour, 20W cont. Mission Weight	72-hour, 20W cont. Mission Energy Density
	mL (# cartridges needed for mission)	*kg*	*W-hr / kg*
SFC C20-MP Normal	500 (4)	3.86	373
	1700 (1)	3.58	403
SFC C20-MP Desert	500 (7)	5.6	259
	3100 (1)	5.1	282

These values were calculated by first using the interpolated value of 18.6 g/hr for the SFC C20-MP Normal system at 20W continuous operation (Figure 8) to calculate the exact amount of fuel for a 72-hour mission. For the 500mL fuel cartridge calculation, the total exact fuel requirement was divided by 500mL and rounded up, yielding the total number of 500mL cartridges needed for the mission. For a mission "optimized" fuel cartridge, the average fuel weight to average full fuel cartridge weight ratio was used to calculate an optimized cartridge weight, assuming similar packaging efficiency for an optimized cartridge as for the 500mL cartridges. The sum of the weight of this optimized cartridge and the dry system weight equaled the total mission weight. Sample calculations of these principles for the SFC C20-MP Normal system are provided in Table 5 for

Table 5 – Sample calculation of mission specific energy density for SFC C20-MP Normal using 500mL fuel cartridges on a 72-hour, 20W continuous mission

Step 1:	$72 hours * \frac{18.6g}{hr} = 1339 g(fuel)$
Step 2:	$\frac{1339 g(fuel)}{mission} * \frac{mL(fuel)}{0.791 gMeOH} * \frac{1 cartridge}{500 mL(fuel)} = 4 cartridges$ $\frac{465 g(AVG)}{cartridge} * \frac{4 cartridges}{mission} = 1860 g(fuel)$ $1860 g(fuel) + 2000 g(system) = 3860 g(mission)$
Step 3:	$\frac{20W}{1} * \frac{72 hours}{1} * \frac{1}{3860 gmission} * \frac{1000g}{1kg} = 373 \frac{W-hr}{kg}$

500mL fuel cartridges and in Table 6 for an optimized fuel cartridge. Similar methods were used to calculate the mission specific energy density values for the SFC C20-MP Desert system in Table 4.

Table 6 – Sample calculation of mission specific energy density for SFC C20-MP Normal using an optimized fuel cartridge on a 72-hour, 20W continuous mission

Step 1:	$72hours * \frac{18.6g}{hr} = 1339g(fuel)$
Step 2:	$\frac{396g(AVGfuel)}{465g(AVGfull500mLcrtdg)} = \frac{1339g(fuel)}{x}$ x = 1576 g optimized full canister of fuel $1576g(fuel) + 2000g(system) = 3576g(mission)$
Step 3:	$\frac{20W}{1} * \frac{72hours}{1} * \frac{1}{3576g(mission)} * \frac{1000g}{1kg} = 403\frac{W-hr}{kg}$

Military significance was also evaluated based on whether or not a technology offered enhanced or new capabilities over existing technologies that are already fielded. The most commonly used military batteries are the BA 5590 (lithium sulfur-dioxide primary), the BA 5390 (lithium manganese-dioxide primary), and the BB 2590 (lithium ion secondary). Of these batteries, the BA 5390, manufactured by Ultralife Inc, has the greatest (per cycle) specific energy density. Newer battery technologies are being fielded, as well, for niche applications that require higher power over longer periods of time than lithium batteries can currently provide. The 8180 is a zinc-air primary battery developed by Electric Fuel Corp. Their third-generation 8180 batteries are currently being tested and fielded, and their fourth-generation 8180 batteries are in development. Mission weight versus mission length values were generated to show if the SFC C20-MP Normal system offered any increased capabilities (decreased mission weight for same power) over other portable power technologies. These values are shown in Figure 11 for a continuous 20W

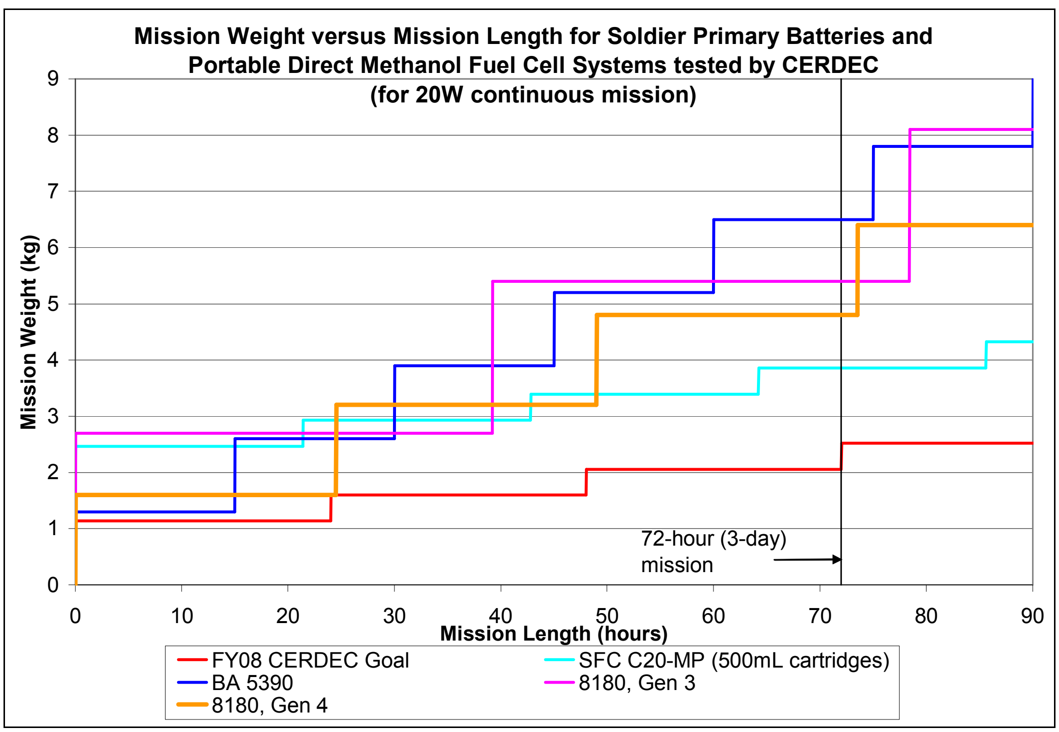

Figure 11 – Mission weight versus mission length for various portable power systems

mission. CERDEC's 2008 goal for the soldier power fuel cell hybrid power source is also shown.

Technology readiness was evaluated in terms of predefined levels, which range from 1 to 9 and were de-fined by the U.S. National Aeronautics and Space Administration (NASA). The goal of the development and test program with the SFC C20-MP hybrid fuel cell power system was to demonstrate a technology readiness level (TRL) of five (5) to six (6). This level is generally defined as the point in technical maturity where a component / breadboard / prototype system demonstrating the technology in question has been validated in a relevant (military) environment. The SFC C20-MP certainly met the criteria as a component / breadboard / prototype system due to its highly advanced user interface, complete packaging, and control functions (among other reasons). A "relevant" or military environment in this case was defined as a simulated atmosphere created in a laboratory. The variables being simulated in this test program included ambient conditions (temperature and relative humidity), load conditions, load profiles, and orientations. The SFC C20-MP systems were tested against these variables during the system level test program. Although the test program was not completed, many of these variables were still validated by testing (for example, operation in a range of ambient conditions, operation over its specified load range, and orientation sensitivity to specified levels were all verified). Overall, CERDEC personnel feel comfortable in assigning a TRL 5 – 6 to the SFC C20-MP system, pending completion of the entire test plan.

Operation of the SFC C20-MP in extreme environmental conditions was demonstrated at least once with each of the systems. The SFC C20-MP Normal system was operated for short periods of time (after startup) in the range from 1 degree Celsius to 35^0C without any significant problems. Similarly, the SFC C20-MP Desert system was operated for short periods of time (after startup) in the range from 1^0C to 30^0C, and for longer periods of time (after startup) in the range from 30^0C to 50^0C. The target ambient temperature of 50^0C was successfully demonstrated without causing degradation to the fuel cell stack itself (although the system battery did suffer some malfunctions). Furthermore, ambient conditions lower than freezing (less than 1^0C) were not specifically demonstrated with the SFC C20-MP, but were successfully demonstrated down to – 25^0C with the SFC C20 demonstrator, which included the same basic components as its successor. Cold-soak – thaw – operate capabilities were also shown with the demonstrator system. The net conclusion that can be drawn from these exhibitions is that active DMFC system technology, despite a few inconsistencies experienced with the SFC C20 systems, could be properly engineered to tolerate many extreme conditions that Soldiers are expected to endure.

Conclusion

Several malfunctions occurred with the SFC C20-MP systems, which required maintenance by SFC. These types of failures are intrinsic to nearly any technical system development program. The first malfunction occurred with a cracked internal structure in the SFC C20-MP Desert unit. This malfunction was most likely due to a faulty component that was originally installed in the system. The second malfunction was the stack degradation seen in the SFC C20-MP Normal system. SFC stated that excessive on / off cycling was the likely cause of too high of a methanol concentration entering the fuel cell stack and therefore the reason that the stack showed decreased performance. This being the case, CERDEC has concluded that SFC's use of "active crossover control," as described previously, might have been the probable cause of this stack degradation. This indicates that with better internal diagnostics and crossover control, DMFC hybrid systems of the future could potentially avoid these problems with the same number of system on / off cycles. SFC has been developing and updating firmware for their SFC C20-MP systems throughout their development. These “teething” problems, therefore, do not likely indicate the inability of DMFC technology to be frequently cycled, but rather the need for more careful control during fuel cell startup. By replacing the MEAs in the stack with newer technology, the refurbished SFC C20-MP prototype systems could potentially show an “increase in power density and well over two times improvement in durability and reliability,” (“DuPont” 2005). The final malfunction that occurred was with the system battery of the SFC C20-MP Desert unit. The likely cause of the failure of this battery was due to the battery becoming overheated during the high temperature operation of the system at 50^0C. Better battery heat rejection through design and safety monitoring might avoid problems like this in the future. Overall these major malfunctions represent “growing pains” inherent to any technological system development.

DMFC technology is largely believed to be one of the most suitable technologies for portable systems in the 20W range; however, there are still many limitations with it today, some of which were seen with the SFC C20-MP. These issues are due, in many cases, to the internal water management subsystems of DMFC systems. Other technologies such as reformed methanol fuel cells show great potential as competitors with DMFC technology in the portable market. This is due to advantages including high system efficiencies and a wide range of environmental operation, which results from having a higher internal operating temperature. Furthermore, many of these systems do not have as significant water management subsystems as DMFC systems. Consequently, CERDEC continues to monitor the activities of the commercial sector with hopes that multiple fuel cell technologies will be successful in the portable market. Overall, CERDEC would like to develop and demonstrate a rugged 20W portable hybrid fuel cell system that has a dry weight of (1.5lbs) 0.75kg, uses packaged (safe and transportable) fuel, and is capable of 700 W-hr / kg for a 72hr, 20W continuous mission by 2008. If such a goal can be achieved, the American Soldier will ultimately be able to perform very long (3-day) missions without the need to replace or recharge the excess of heavy batteries that are currently fielded.

Major success of this development program is dependent upon demonstrating key performance parameters for the SFC C20-MP systems. The system (as shown in Figure 11) could potentially provide mission weight benefits over currently fielded technologies for similar power output in the two (2) to three (3) day mission timeframe. Although the evaluation testing was not completed, the units did demonstrate more reliable performance for a longer period of time than any other fuel cell soldier power source tested to date by CERDEC. The testing of the system indicated a TRL 5 – 6 for portable DMFC power system development, showed higher fuel efficiency and better response to loading and unloading (for SFC systems), and demonstrated tolerance to extreme ambient conditions. Furthermore, the demonstrations with the SFC C20-MP proved that with more development and better-proven reliability, DMFC technology shows great potential to replace soldier batteries for missions longer than 24 hours.

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