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Emerging Power/Energy Technologies for Portable Electronics for SOCOM

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1. Executive Summary

SOCOM is seeking more capability for SOF teams to operate advanced portable electronics over 72-h missions, but is limited by the energy of present battery systems. In 2007, Windermere Corporation was funded to research new options in portable power. This report studies the Windermere results, and compares them to present and future systems.

The following conclusions are made:

- The BA5590 battery is the present standard portable power solution for SOCOM. Batteries with only modest improvements in specific energy over the BA5590 have only a small impact on 72-hour missions at 20 W. An improved battery, the BA5390 UHC, will become available in 2008. It will provide about 40% more endurance at 20 W over 72 h, and thus should be adopted should it meet military standards.
- SOCOM should try to cut the power demand for each mission to 10 W or less through improved power/energy management for each soldier and operator.
- Many different types of fuel cell systems are in development, and many show significant weight savings over BA5590 batteries when compared over 72-hour missions at 20 W. The fuel cell systems do not yet perform consistently in independent tests, and more time and investment in engineering is needed before they will be mature enough to be fielded. As battery technology improves, such as the case of the BA5390 UHC batteries, they will compete with proposed fuel cell and other fuel conversion technologies.

2. Introduction

The military has always been quick to adapt new opportunities in power and energy, with the recognition that it gave them more capabilities. Naval warfare emerged from power under sail and human powered (rowing) to steam engines and then turbines. The Cavalry were delighted to move off of horses and camels to automobiles, trucks and tanks. Air Power has only existed in the 20th century, in parallel with the development of effective internal combustion engines and ultimately turbine technology. The proliferation of high performance portable electronic devices (laptops, mobile phones, GPS locators) throughout the civilian and military markets, has been closely tied to the advent of modern lithium batteries.

SOCOM's objective is to have a portable power/energy source capable of providing sufficient power and energy for complex missions at a minimal weight penalty. *Power* is defined with the usual unit for electrical power, Watts (W), although the terms horse power (HP) and Joules/s are used for engines and electronics, respectively. The units are mathematically interchangeable. The *energy* of a system equates to $power \times time$, and can be compared in Watt-hours (Wh). Other units for energy include Joules, BTUs, and calories. Common units for specific energy and specific power (where specific correlates to unit weight) are Wh/kg and W/kg, respectively. The energy density and power density of a system are related to the values per unit volume as Wh/L and W/L. This report focuses on the specific energy of systems, as it defines the weight of the power/energy system that must be carried by the soldier.

This report analyzes the data measured by Windermere as part of their 2007 study for SOCOM through SPAWAR Charleston.¹ Windermere's data were provided to the Naval Research Laboratory (NRL) to be included as part of this report. Windermere also shared with NRL their testing methods, and the results are deemed by NRL to be credible and accurate. The Windermere study experimentally evaluated the performance of various commercial power sources including batteries and fuel cells under ambient conditions, and did not probe long-term stability and operation or temperature sensitivity. The Windermere study can serve as an important independent metric for the selection of a power source, with the understanding that more rigorous parameters would be needed to validate the new system for military acceptance.

3. Comparison of BA5590, BA5390 HC, and new BA5390 UHC batteries (Windermere Study)

The military standard battery is the BA5590, weighing 1 kg with a specific energy of approximately 195 Wh/kg when fully packaged, and thus having a capacity of 195 Wh. The chemistry of these batteries is lithium metal vs. sulfur dioxide, and they are primary systems (not rechargeable). This chapter compares standard BA5590 batteries to a new BA5390 HC (high capacity) battery available in 2007, and a BA5390 UHC (ultrahigh capacity) battery available in 2008.

Table I shows the weight of BA5590 batteries needed over missions ranging from 8 h to 10 days. The “practical specific energy” of the batteries is normalized to the number of batteries needed – a soldier cannot bring half of a battery, so the full battery must be counted even if only part of it is used. Table II reports the same metrics for the new BA5390 HC batteries from Ultralife, newly available in 2007. These batteries weigh 1.39 kg each and have a specific energy of 237 Wh/kg. The purpose of analyzing the data in this way is to show how many batteries are actually needed for a mission, reflecting the weights of the batteries, e.g. 1 kg vs 1.39 kg for the BA5590 and BA5390.

Table I: Total system weight and practical specific energy of 1 kg BA5590 (195 Wh; 195 Wh/kg) batteries needed for 8, 24, 48, 72, 168, and 240 h at 20 W average power.

Mission length (h)	Power (W)	Energy for Mission (Wh)	Battery Capacity (Wh)	Battery Weight (kg)	Battery Specific Energy (Wh/kg)	Number of batteries	Total battery weight (kg)	Practical Specific Energy (Wh/kg)
8	20	160	195	1	195	1	1	160
24	20	480	195	1	195	3	3	160
48	20	960	195	1	195	5	5	192
72	20	1440	195	1	195	8	8	180
168	20	3360	195	1	195	18	18	187
240	20	4800	195	1	195	25	25	192

Table II: Total system weight and practical specific energy of 1.39 kg BA5390 HC (350 Wh; 237 Wh/kg) batteries needed for 8, 24, 48, 72, 168, and 240 h at 20 W average power.

Mission length (h)	Power (W)	Energy for Mission (Wh)	Battery Capacity (Wh)	Battery Weight (kg)	Battery Specific Energy (Wh/kg)	Number of batteries	Total battery weight (kg)	Practical Specific Energy (Wh/kg)
8	20	160	330	1.39	237	1	1.39	115
24	20	480	330	1.39	237	2	2.78	173
48	20	960	330	1.39	237	3	4.17	230
72	20	1440	330	1.39	237	5	6.95	207
168	20	3360	330	1.39	237	11	15.29	220
240	20	4800	330	1.39	237	15	20.85	230

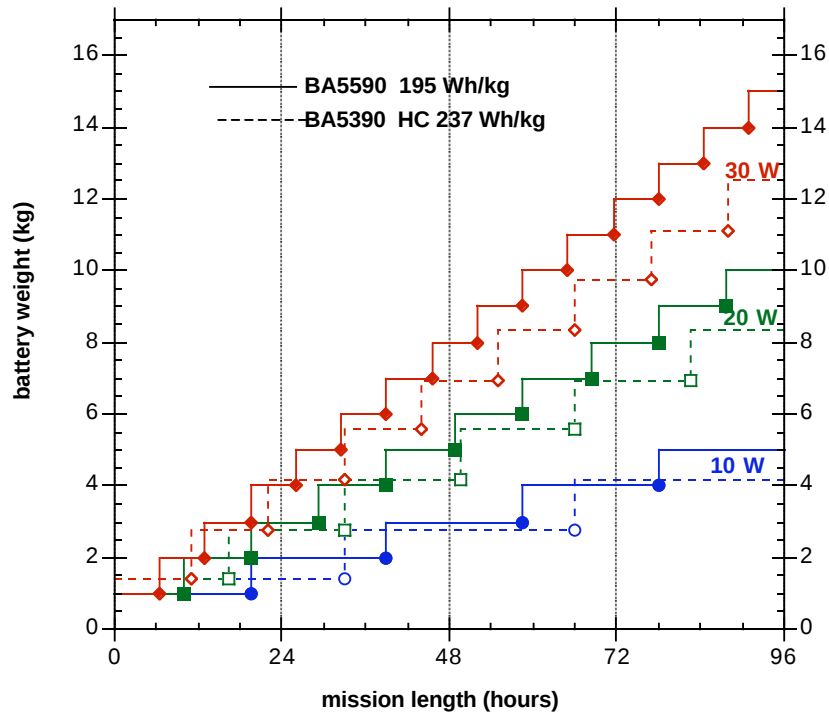


Figure 1. Weight comparison of BA5590 and BA5390 HC batteries as a function of missions of up to 4 days at average power demands of 10, 20 and 30 W.

Figure 1 shows a more detailed description of the data in Tables I and II, showing the projected weight of the batteries used for 10, 20 and 30-W missions up to 96 h. The plot shows the data “stepwise”, again as you can only bring full batteries, thus reflecting the practical specific energy. The analysis assumes that the battery performance is the comparable when used at 10, 20 and 30 W, although it may decrease with increasing current depending on the I^2R losses (heat generation) that will increase with increasing power draw.

Although the BA5390 HC has a specific energy of 237 Wh/kg vs. the 195 Wh/kg of the BA5590 which should lead to a 22% increase in capacity, the practical specific energies of the systems are 180 and 207 Wh/kg at 72 h at 20 W continuous operation, so only a 15% increase in capacity is realized. Figure 1 shows additional data not reported in Tables I and II, and shows that at a higher average power load, 30 W, the BA5390 HC batteries also only have a small (13%) benefit over BA5590 systems for a 72 h mission (9.73 kg of BA5390 HCs vs 11 kg for BA5590s). These small benefits suggest that it is not worthwhile to implement the new BA5390 HCs over the trusted BA5590 technologies for 20 and 30-W missions. Likewise, there is also no benefit for using the BA5390 HC batteries for missions less than 2 days.

Note that at 10 W average power over 72 hours, it is more beneficial to use the BA5590s weighing 4 kg vs 4.17 kg for the BA 5390 HC batteries.

The analysis above does not take into account a “safety margin” for the mission, though, and the analysis does change if the soldier chooses to bring an extra battery. When this is taken into account the analysis changes slightly. The results for an analysis of 10, 20 and 30 W missions for up to 96 hours are shown in Figure 2, for the case when the soldier brings one extra battery. With this safety margin, the benefit of the BA5390 HC shrinks further compared to the BA5590. At 10, 20 and 30 W in 72 h, the BA5590s weighs 5, 9, and 13 kg, while the BA5390 weighs 5.56, 8.4 and 11.12 kg, thus representing a 11% weight increase at 10 W, and only a 7 and 14% weight decrease at 20 and 30 W respectively. This analysis shows that it is not worthwhile for SOCOM to change from the standard BA5590 to the BA5390 HC technology, unless there is another driver such as better temperature performance or shelf life of the new batteries.

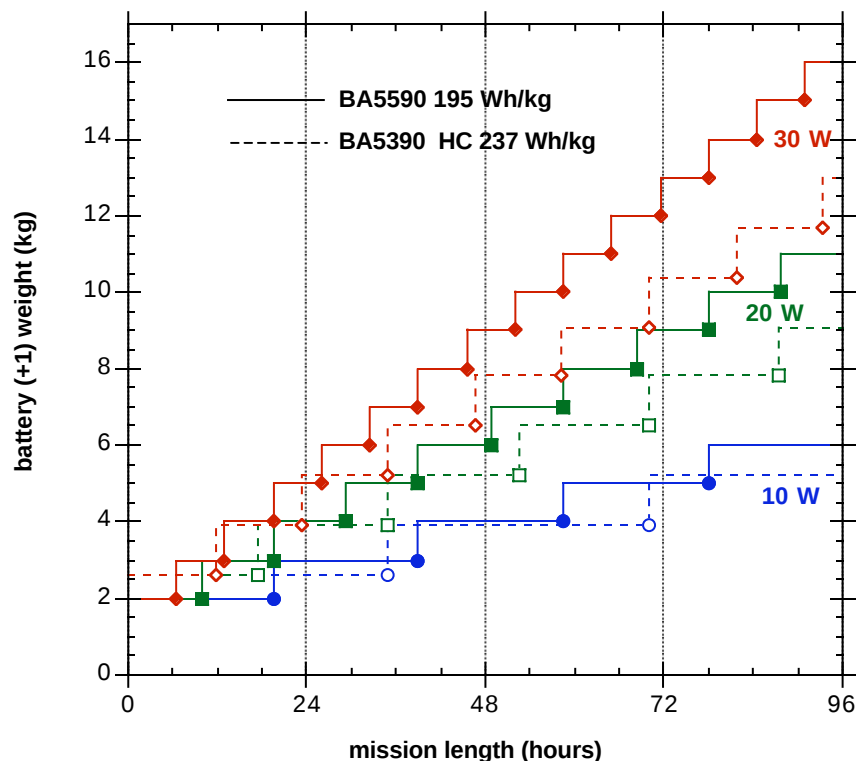


Figure 2. Weight comparison of BA5590 and BA5390 HC batteries as a function of missions of up to 4 days at average power demands of 10, 20 and 30 W. Similar to Figure 1, but soldier carries one extra battery.

A modified version of the BA5390 HC, the “ultra high capacity” (UHC) cell was developed with funding under this Windermere program.¹ Windermere measured a specific energy of 329 Wh/kg for this 1.26 kg BA5390 UHC battery. This performance suggests almost a 70% increase in specific capacity over the BA5590. The status of the batteries in terms of shelf life, temperature stability, flammability, etc. has not yet been reported.

The three batteries, BA5590, BA5390 HC and BA5390 UHC are compared for 20 W missions in Fig. 3, and tabulated for the 10, 20 and 30 W missions for 72 h in Table III. At 72 h for the 20 W mission, the BA5390 UHC weighs 5.04 kg vs. the 8 and 6.95 kg needed for the BA5590 and BA5390 HC batteries. Although 5 kg is still a formidable amount of battery weight to carry, it is a significant weight savings of almost 40% over the BA5590 standard. The weight savings is also significant for the 10 and 30 W missions, as shown in Table III.

These results suggest that while the BA5390 HC only had a moderate increase in capacity over the BA5590, the BA5390 UHC is valuable because of the weight per unit package (1.26 kg) in combination with its high specific energy (329 Wh/kg), gives it a high practical specific energy.

Table III. Weights of BA5590, BA5390 HC and BA5390 UHC batteries for 72 h missions at average power demands of 10, 20 and 30 W.

Average Power (W)	Battery Weight (kg)		
	BA5590	BA5390 HC	BA 5390 UHC
10	4	4.17	2.52
20	8	6.95	5.04
30	12	9.73	7.56

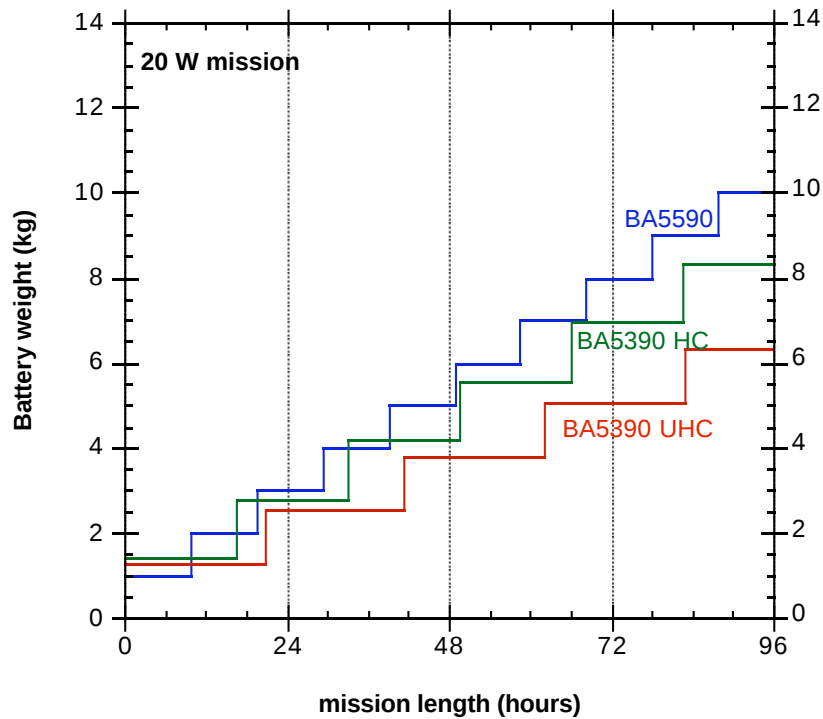


Figure 3. Weight comparison of BA5590 and BA5390 HC batteries to new BA 5390 UHC battery for missions from 24 to 96 hours at 20 W average power.

From the analysis above, the following conclusion is made.

- The BA5590 battery is the present standard portable power solution for SOCOM. Batteries with only modest improvements in specific energy over the BA5590 have only a small impact on 72 hour missions at 20 W. An improved battery, the BA5390 UHC, will become available in 2008. It will provide about 40% more endurance at 20 W over 72 h, and thus should be adopted should it meet military standards.

4. Power management

The results shown in Figure 1 also highlight an important alternative for SOCOM – ***to cut the power usage for the soldier***. There is a 50% decrease in battery weight for the soldier to operate at 10 W vs 20 W over 72 h using BA5590s, and there is little benefit to advanced battery chemistry.

The need for cutting the power usage for the soldier has been noted before. The 2004 NRC study on “Meeting the Energy Needs of Future Warriors”² recommended to the Army, “[it] should make energy efficiency a first order design parameter whenever specifying system performance parameters in its contract. It should provide monetary incentives as needed to reduce power demand in all procurements for soldier electronics, especially for communications.” The purpose of this recommendation was to avoid the continued development of electronics systems for soldiers that are ultimately unusable by the soldier because of their large battery demand.

Unfortunately, such advice still seems to be going unheeded, and Concurrent Technologies reports high power demand for a three-component system that has been recently developed for SOF.³ The power demand for each components #1, #2 and #3 is, on average, 38, 21 and 113 W, respectively (taken from the average of the manufacturer’s specification and the actual operation power measured by Concurrent Technologies), for a total of 172 W.

Figure 4 shows the battery usage for each component from one to 4 days, for both the BA5590 (195 Wh/kg) and the BA5390 UHC (329 Wh/kg). This analysis is only an estimate of the amount of batteries needed, as there will likely be a reserve, and the higher power component #3 (~113 W) would need to operate on a pack of 6 batteries, as the BA5590s are designed for operation at 20 W. Even this top-level summary is discouraging. Component #3 requires about 42 kg – or nearly 100 lbs of BA5590s to operate for 72 h. By using the high energy BA5390 UHCs, the battery weight is cut to 25.2 kg, or about 55 lbs. Clearly this system is difficult to use as a manpackable unit. The 38 W component #1 requires about 15 to 8.82 kg of BA5590 and BA5390 UHC batteries, respectively, for 72 h; component #2, that works at only an average of 21 W, requires 8 to 5.04 kg of the BA5590 and BA5390 UHC batteries. The total weight of batteries needed to operate the suite of equipment at an average power draw of 172 W is 65 kg (143 lbs) when using BA5590s and 39 kg (86 lbs) for the BA5290 UHC batteries. This analysis also does not include provisions for reserve batteries, as noted will be necessary in the Concurrent Technologies study.³

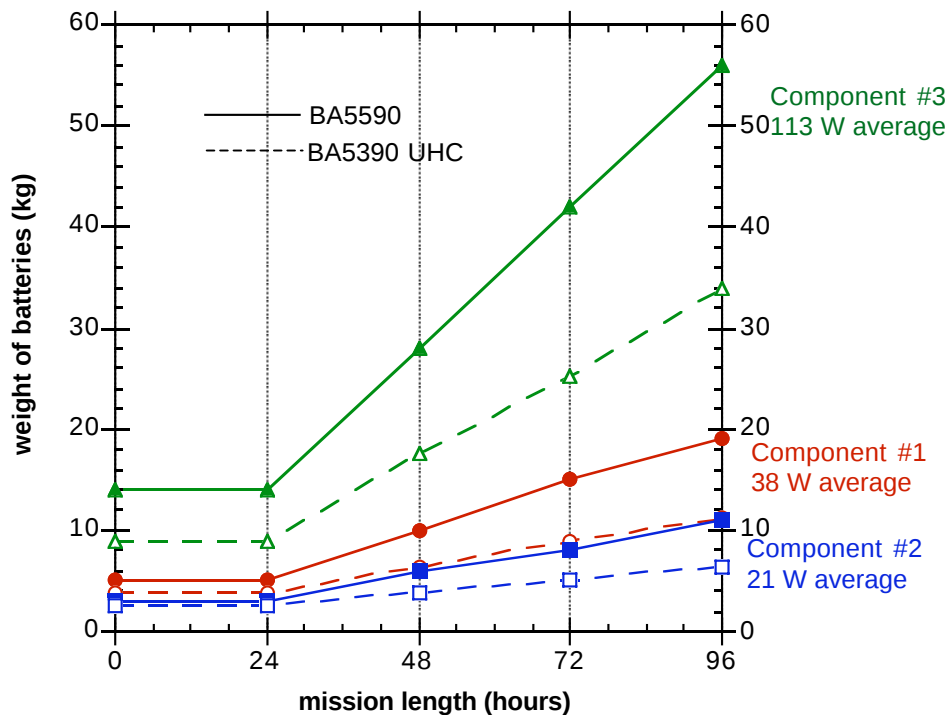


Figure 4. Weight BA5590 and BA5390 UHC batteries needed to provide power to new SOF electronics systems for 1 to 4 day missions.

The military is not keeping in step with modern electronics development. Most developers of portable electronics are aggressively developing code and devices to turn off when not in use, or going through duty cycles to reduce sampling time without sacrificing performance. The military is notoriously unsophisticated in this arena, because power management, or power-conserving chip development, can be costly. However an investment of \$1 million in chip development is made back with 10,000 batteries (assuming \$100 per battery), plus would result in a lighter load for the soldier. Another option is to move to lower power computer operating systems such as Linux, assuming that the systems can be made secure.

Note that one type of power usage is difficult to cut - the power cost for communications, which is proportional to the square of the distance for the data transmission. The power for data transmission has been cut for cell phone users by adding more cell phone towers, and thus decreasing the average communication distance – an option obviously not available to SOF teams. However, hybrid systems might be developed with appropriate duty cycles with capacitors to transmit data intermittently at higher power, while reserving a low average power for the battery.

The conclusion for this section is:

- **SOCOM should try to cut the power demand for each mission to 10 W or less through improved power/energy management for each soldier and operator.**

5. Energy conversion systems – comparisons

The US government has invested significant funds in portable energy conversion systems. In the 1990s, there were DARPA programs in hydrogen fuel cells (notably, SNORKLER), and then much work on direct methanol fuel cells, stemming from some original work at Los Alamos National Laboratory and the Jet Propulsion Laboratory. In 2000, the ~\$60M DARPA Palm Power program began with the ambitious goal of developing man-portable (20 W) energy conversion devices fueled by JP-8, in compliance with the Army's goal of one fuel forward. JP-8 is an ideal logistics fuel because it is very high energy, but has very low flammability and is extremely stable. However, the same properties which make JP-8 a safe and viable fuel for large engines and turbines, make it very difficult to cleanly burn and/or combust in small systems. Thus, several DARPA contractors switched to propane with the argument that propane is available world wide, and its use would not compromise the logistics tail. Methanol is also an easily combustible fuel, and some have pursued "reformed methanol fuel cells", which are a high temperature derivative of direct methanol fuel cells. The Army has since worked to certify methanol as a battlefield fuel, despite its high flammability.

Several government facilities and contractors have done independent evaluations of the portable fuel cells and engines that have been developed over the last decade. Naval Surface Warfare Center (NSWC) Crane recently reported a comparison of various portable power systems.⁴ A summary of the findings is shown below in Fig. 5. The data were reported in Amp hours at 12 V operation, as many of the units being tested were optimized for different power ranges (e.g. 20 to 50 W). They are normalized here to 20 W, for comparison to the figures above.

The Crane study compares the following systems to BA5590s in their projected operation to 420 h (17.5 days): Adaptive Materials Inc 20 W propane-fueled solid oxide fuel cell (AMI 20); Protonex 30 W hydride-fueled polymer fuel cell (Protonex 30); UltraCell 45 W reformed methanol fuel cell (UltraCell alpha); Smart Fuel Cells 20 W direct methanol fuel cell (Smart C-20-MP); Smart Fuel Cells 50 W direct methanol fuel cell (Smart A-50), Giner 120 W direct methanol fuel cell (Giner 120), and Electric Fuel Zinc-air battery (BA-8180). Only the AMI, Protonex and Giner systems were tested by Crane – the remainder of the data was provided by the manufacturer.

The lightest system for long term use is the AMI 20-W solid oxide fuel cell/propane system. Two of the systems, the Giner and Smart 50 are so heavy to start (~10 kg), that they have no benefit over batteries to well beyond 120 hours (~10 days). The best performing system at 72 hours is more difficult to discern. The fuel cells all weigh approximately 2.5 to 4.5 kg, while the BA5590s weigh 8 kg at 72 h.

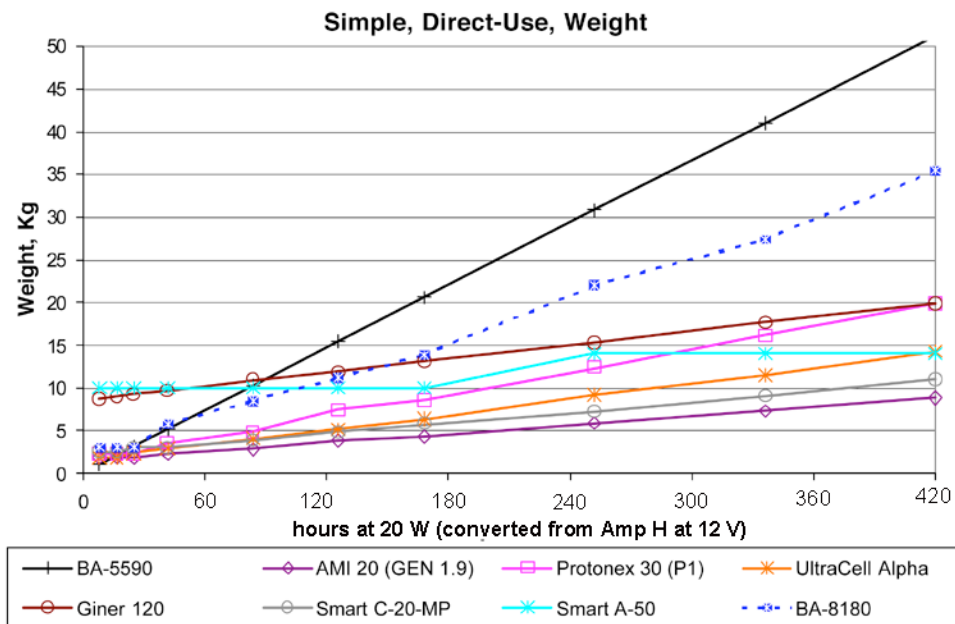


Figure 5. Comparison of several battery and fuel cell systems to 420 hours (NSWC Crane), adapted from reference 4.

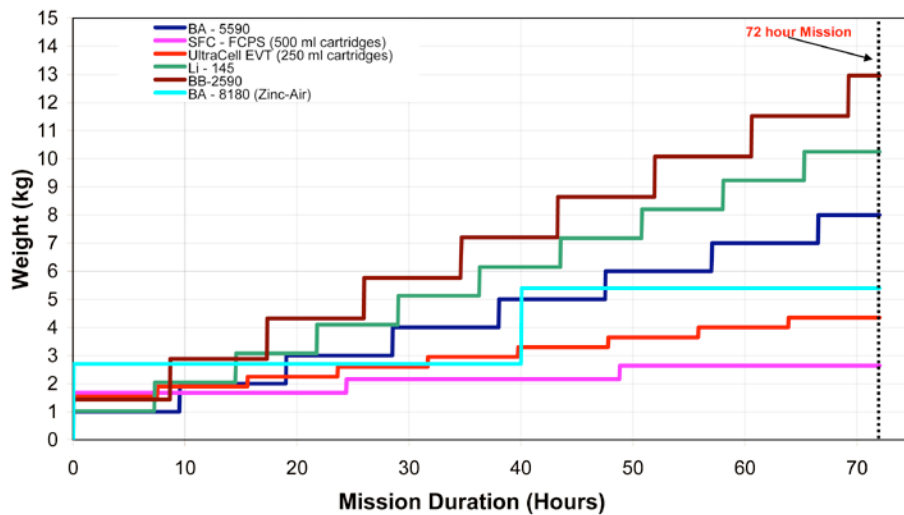


Figure 6. Comparison of BA-5590 to various 20 W fuel cells systems (CERDEC), from reference 5.

CERDEC has also compared the performance of various 20-W fuel cell systems, as shown in Figure 6, adapted from reference 5. This compares the BA5590 to a 20 W reformed methanol fuel cell system from UltraCell (UltraCell EVT), a Smart Fuel Cell 20-W direct methanol fuel cell system (SFC – FCPS), an Ultralife rechargeable Lithium-ion battery (Li-145), a Bren-tronics rechargeable Lithium-ion battery (BB-2590), and a BA-8180.

The Lithium ion batteries (Li-145 and BB-2590) are the heaviest by far, but this comparison is somewhat meaningless, as the rechargeable batteries are not energy sources, but rather energy storage devices, and should be coupled with an energy source such as a solar cell or engine for charging when doing a full system analysis.

Figure 6 also shows a Zinc-air (BA8180) battery that lasts for 40 hours. The higher energy of the BA8180 batteries provides a weight benefit to BA5590s beyond about 20 hours, as three BA5590s weigh 3 kg, but a single BA8180 weighs 2.9 kg. At around 40 hours, though, five BA5590s at 5 kg is lighter than two BA8180s weighing 5.8 kg, thus showing again how the benefit of various power sources changes with the mission. This analysis would also change if the soldier opted to carry a spare battery.

According to the CERDEC analysis, the SFC – FCPS and UltraCell systems appear to be the best choices for the Army with the SFC – FCPS providing a weight benefit to the BA5590 after only ~10 hours. The UltraCell system offers a weight reduction benefit at around 20 hours. At 72 hours, the SFC and UltraCell systems weigh about 2.8 and 4.3 kg, respectively, vs the 8 kg of BA5590s needed for that mission, thus offering weight reductions of 65 and 46%.

Figure 7 is a modified version of Figure 6, showing how the weight vs mission duration for several fuel cell systems and BA8180 batteries measured with a 20 W load by Windermere¹ compared to the CERDEC data.⁵ Windermere's BA5590 data are identical to that of CERDEC, with each 1 kg unit having a run time of about 9 h and 46 min per battery. Likewise, both Windermere and CERDEC report the same results for the BB2590, with a weight of 1.44 kg and a discharge time of around 9 hours (see Fig. 6). The result for the Windermere evaluation of the BA8180 Zn-air batteries differs significantly from that of the CERDEC study. CERDEC reports a discharge time of 40 hours for each 2.9 kg BA8180 unit, while Windermere only measured a discharge time of around 21 hours. So while CERDEC reports a specific energy of 275 Wh/kg, Windermere only measures 145 Wh/kg, which is significantly worse than the BA5590 at 195 W/kg. As shown in Figure 7, there is no benefit to the BA8180 batteries over the BA5590s if their discharge time is only 21 hours.

The other battery system that has a 21-hour discharge time is the BA5390 UHC, discussed above in Sections 3, 4 and 5. This new battery only weighs 1.26 kg compared to the 2.9 kg for each BA8180. The BA5390 UHC batteries are still lighter than the BA8180s which achieve 40 h discharge times. If the performance, reliability and ruggedness of the BA5390 UHC can be verified, they should be strongly considered by the Army, SOCOM and USMC seriously for replacement of BA8180 systems.

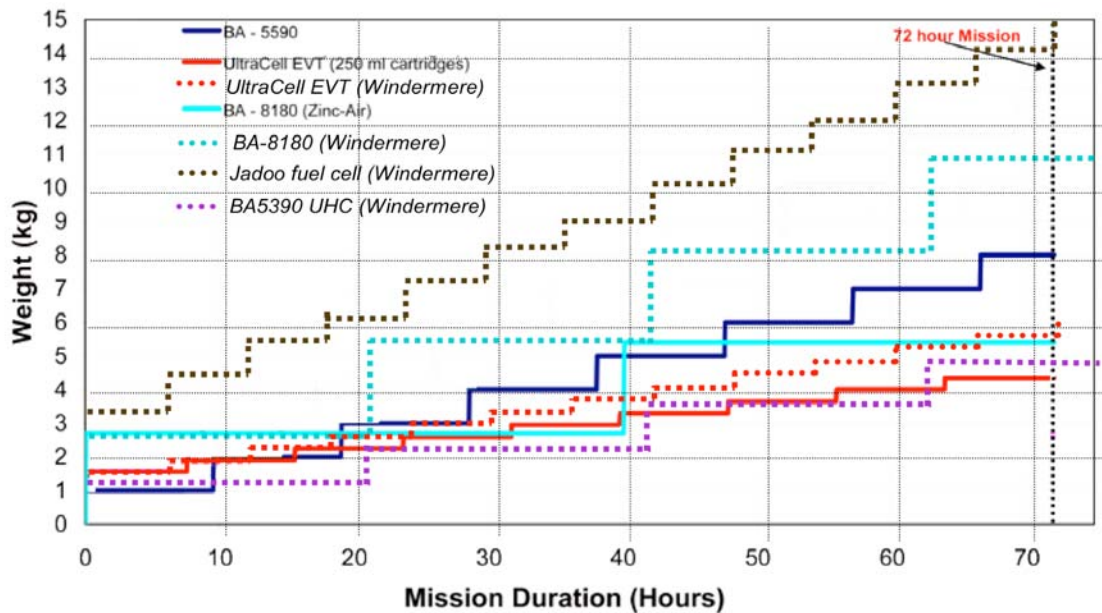


Figure 7. Comparison of mission duration vs. weight for a BA5590, BA5390 UHC, UltraCell EVT reformed methanol fuel cell, BA8180 Zinc-air battery, and Jadoo fuel cell. Data from CERDEC⁵ and Windermere.¹ All systems operated at 20 W.

The results for the Windermere and CERDEC evaluation of the UltraCell EVT systems are also different. CERDEC shows that each 0.345 kg methanol cartridge lasts about 8 h, while Windermere measured only 6 h and 6 min for each fuel cartridge. While CERDEC indicated 9 fuel cartridges are needed over 72 hours, the Windermere data suggest that 12 are needed for a weight difference of 1.04 kg. Still when operated to 72 h, the UltraCell EVT with 12 fuel cartridges weighs 5.74 kg vs. the 8 kg of BA5590s, or offers a moderate 28% weight savings. The competitor to this fuel cell technology is the BA5390 UHCs which only weigh 5.04 kg for the 72 h/20-W mission.

The Jadoo fuel cell system, which is sold commercially, appears to have no benefit over any of the systems studied, weighing almost twice as much as the BA5590s over 72 h. The only advantage of using the Jadoo system would be in cases where its hydrogen filling/recharging system is an overall logistics savings.

Windermere and CERDEC report identical results for BA5590 and BB2590 batteries when discharged at 20 W, but have a large discrepancy for the BA8180s and a modest difference in the UltraCell EVT results. The most likely explanation for the observations is due to the maturity of the technologies. The BA5590s and BB2590 systems are mature, and are presently fielded, having undergone extensive military testing and qualification. The BA8180, although having undergone testing, is less mature than its battery competitors. Because the BA8180 is air breathing, it is also likely to be more affected by

its test environment. The UltraCell EVT is considered still to be in development, with investment needed for military ruggedization, which can explain the ~20% difference between the fuel cartridge lifetime measured by CERDEC and Windermere.

These results highlight that fuel cell systems are at a lower maturity level than batteries. The same is true of portable engines (e.g. Stirling), and their lower “technology readiness level” can explain inconsistencies between tests. The discrepancies here were measured between different laboratories, with testing carried out by engineers in controlled environments – the actual performance of the systems in the field by operators who are under pressure is not known. SOCOM can take a lead in evaluating new power source technologies in the field to provide this valuable feedback to systems developers.

Fortunately, the Army and DARPA continue to invest in portable fuel cells and engines with the recognition that many of the issues with reliability are related to systems and controls issues, and can be resolved through continued engineering and investment. Yet, it will be hard to predict when the fuel cell systems will be ready to be fielded. In the meantime, the clear choice for SOCOM operations in 2008 is to continue to use batteries.

- **Many different types of fuel cell systems are in development, and many show significant weight savings over BA5590 batteries when compared over 20W/72 hour missions. The fuel cell systems do not yet perform consistently in independently tests, and more time and investment in engineering is needed before they will be mature enough to be fielded. As battery technology improves, such as the case of the BA5390 UHC batteries, they will compete with proposed fuel cell and other fuel conversion technologies.**

6. Acknowledgements

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7. References

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