Power Technology Branch
Army Power Division
US Army RDECOM CERDEC C2D
Aberdeen Proving Ground, MD

APPT-TR-08-02

The Current Status of Fuel Cell Technologies for Portable Military Applications

Presentation to the 25th International Battery Seminar and Exhibit
17-20 March 2008, Fort Lauderdale, FL

Jonathan M. Cristiani

AMSRD-CER-C2-AP-PT

APPT-TR-08-02 The Current Status of Fuel Cell Technologies for Portable Military Applications

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The US Army CERDEC has the mission to develop, demonstrate, and transition portable power technologies into Army programs of record. This presentation details progress in the development of battery and fuel cell systems for portable military applications.

15. SUBJECT TERMS
battery, fuel cell, soldier power

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RDECOM

CERDEC
US ARMY – RDECOM

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

The Current Status of Fuel Cell Technologies for Portable Military Applications

25th International Battery Seminar and Exhibit
17 – 20 March 2008, Fort Lauderdale, FL

Jonathan M. Cristiani, Chemical Engineer, US Army CERDEC C2D Army Power Div.

Outline

- US Army CERDEC C2D Power Division
  - Technology Gaps
  - Mission and Products
  - Customers and Partners
- Soldier Power and Battery Update
  - Challenges and Mission Assessment
  - Battery Improvements and Developments
- Fuel Cell Update
  - Focus Areas and Contractors
  - PEMFC, DMFC and RMFC
  - SOFC, Comparisons, and Conclusions

Technology Gap Summary

General Thrust Areas – Non-system Specific

- **Power and energy density improvements**
  - Dramatic improvements in power & energy densities required
  - Applicable to engines, batteries, fuel cells, generators
  - Offers dramatic improvements in operational performance and logistics reduction
- **Fuel efficiency improvements**
  - Reduces logistical burden and costs
  - Applicable to internal combustion, turbine, fuel cells, Stirling
- **Renewable energies and fuels**
  - Alternative fuels to reduce energy dependency
  - Includes: solar, alternative (bio-diesel, trash-to-waste)

Technology Gap Summary

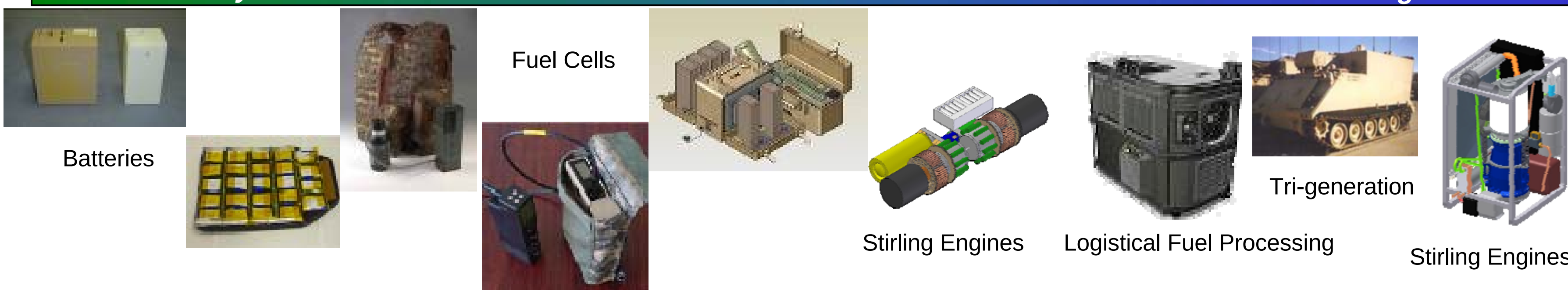
General Thrust Areas – Non-system Specific

- **Thermal management and Co-generation**
  - Improved, lightweight, efficient thermal management techniques to reduce parasitic energy losses
  - Development of co-generation power sources to improve efficiency
- **Power demand / fuel consumption reductions**
  - Materials, techniques, and products designed to reduce power consumption in militarily relevant products
- **Improved power management and distribution**
  - Materials, techniques, software, and products that provide improved grid diagnostics, load-balancing, efficiency, redundancy

Army Power Division
Mission and Products

RDECOM | CERDEC US ARMY – RDECOM

Soldier Power- Batteries/ Hybrid — ***Watts*** ⟷ ***Kilowatts*** — ***Tactical Power- Logistics Fuel***



ATO D.CER.2008.08
Power for Dismounted Soldier

- Half-Sized BA5590 Li/CFx Battery
- Half-Sized BA5590 Li-Air Battery
- Soldier Conformal Rechargeable Battery
- Soldier Hybrid Direct Methanol Fuel Cell Power Source
- Soldier Hybrid Fuel Cell Power Source
- Portable Hybrid Power Sources & Chargers, JP-8 fueled

ATO R.LG.2009.01
Mobile Power

- Transitional Hybrid Power Source, Log-fueled
- Universal Tactical Auxiliary Power Unit
- Co-generation and Tri-generation System

Technical Objectives

- ***Power for Dismounted Soldier***

• 1.1lbs	400Whr/kg	TRL 4/6
• 1.1lbs	600Whr/kg	TRL 3/5
• 3lbs, flat	140Whr/kg	TRL 4/6
• 25W	1.5lbs	TRL 4/6
• 50-100W	3.5lbs	TRL 4/5
• 150-250W	25lbs	TRL 4/6

- ***Mobile Power:***

• 250W-2kW	50W/kg	TRL 3/5
• 3-5kW	90W/kg	TRL 3/6
• 3kW/18BTUh	205kg	TRL 3/5

Army Power Division Mission: *Conduct research, development and system engineering leading to the most cost-effective power, energy, and environmental technologies to support Army's soldier, portable, and mobile applications.*

Army Power Division
Transition and Support

Customers

Partners

Soldier Power *Challenges*

- Too many battery types
  - – Need effective standardization policy
  - – Equipment development community needs to utilize common battery form factors, connectors, voltages, etc.
- Too many batteries required to complete long missions
  - – Need to develop hybrid power source solutions – fuel cells
- Batteries are too large
  - – Need to develop smaller, lighter, higher capacity battery chemistries
- Future power demands are increasing
  - – Need to make equipment developers accountable for system power draw. Power should be a critical design parameter in the hardware development process.

Soldier Power
Contributing Factor

Capability Driven Requirements for Systems -

More is Better…

…Creates Complexity and Increased: Size, Weight, Volume, and Power Needs

Seen as a Power Source Problem-

"Power Sources Are Too Heavy and Don't Last Long Enough, too Costly"

Reality - Army Soldier Power Sources for C4ISR are Improved - Rechargeable Batteries providing 2-3X the energy density over 10 Years Ago…However, Power Demand increasing >3 fold. (i.e. SINCGARS 10-20 W to JTRS 30- 40W - 80W transmit)

Infantry Battery Requirements

Typical Battery Requirements for the Platoon Leader

8 Different Types!

As a rule of thumb, an Infantry Soldier requires (1) AA battery every hour in combat

Mission Based Assessment

- For mission durations < 24 hours:

Development of higher capacity batteries can **reduce battery weight** carried by Soldiers by enabling the use of smaller lighter batteries to complete the same mission.

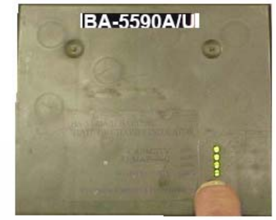
Example: Li/SO2 (175Wh/kg) ⟶ Li/MnO2 (205 Wh/kg) ⟶ Li/CFx (350Wh/kg) ⟶ Li-Air (700Wh/kg)

- For mission durations > 48 hours:

Development of hybrid systems that integrate a high power rechargeable battery with a high energy packaged fuel system will enable longer runtimes with **less weight.**

Example: 140 Wh/kg Li-ion Battery with a 20W Fuel Cell using logistical packaged methanol (volume x cc)

Power Strategies to Maintain or Reduce Power Consumption

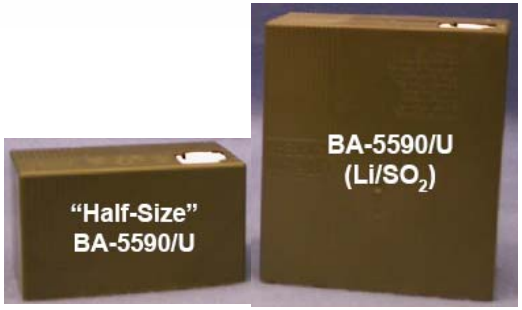


- Near Term (FY 07-10)
  - ➢ Use existing military and commercial standard batteries
    - Limit the quantity of commercial batteries (cells) per pack
    - Promote the use of standard batteries and Power Management on present/future system improvements
    - Promote the use of battery alternatives when feasible
    - Assist units in the development of rechargeable batteries logistics charging issues

Power Strategies to Maintain or Reduce Power Consumption

Mid-Term (FY 10-14)

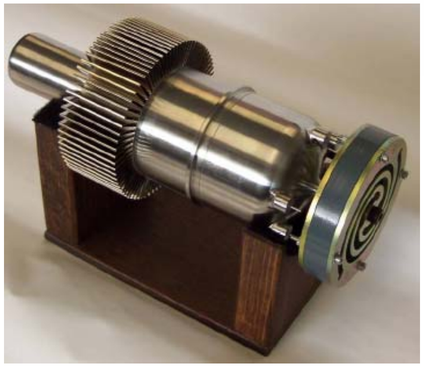
- ➢ Hybrid Power Systems
- ➢ Higher capacity military standard batteries
  - Technology driven
- ➢ One battery or power source type to power all future systems the warfighter carries
- ➢ Power Management



Power Strategies to Maintain or Reduce Power Consumption

Long Term (FY 14+)

- Portable Stirling engines
- Fuel Cells
- One Power Source to operate all soldier C4ISR equipment
  - Power distribution box
- Power Management



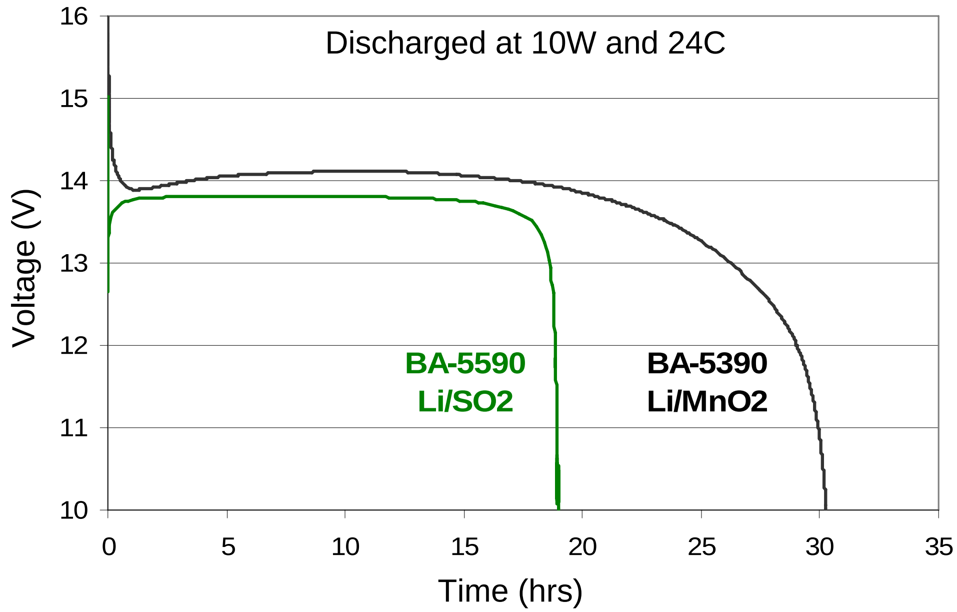
Army Standard Batteries

Specifications - Rechargeables:

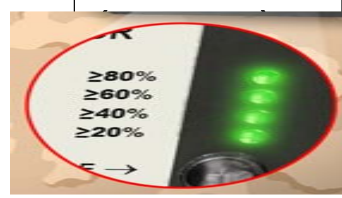
- 140W/kg (Li-Ion)
- Long Cycle Life : >500 Cycles, 100% DOD
- Capacity Retention : >80% @ 500 Cycles
- Rapid recharge : 100% in < 30 min
- High Rate : 10C on BB-2590
- Thermal Storage : 30 days @ 70C, <5% loss
- Temperature range -40C to 55C
- 5-Segment State on Charge Indicator

Designation Chemistry	V nominal	Ah @ C-rate
BB-516 NiCD	24	0.22 @ 0.3A
BB-503 NiCd	4.8	4.0
BB-2847 Li-Ion	8	3.6
BB-388 NiMH	13.2	1.5
BB-390 NiMH	12/24	3.6 @ 24V
BB-2590 Li-Ion	12/24	6.2 @ 24V
BB-2800 Li-Ion	7.2	3.7
BB-2600 Li-Ion	7.2	5.2
BB-2557 Li-Ion	12/24	2.2 @ 24V

Army Primary Battery Improvements

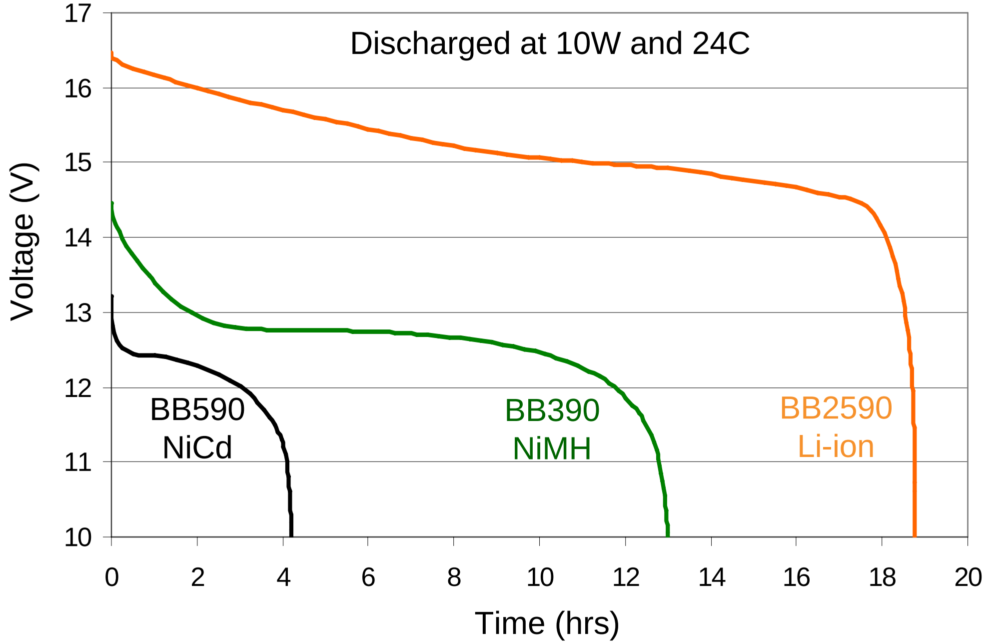


Battery	BA-5590	BA-5390
Chemistry	Li/SO2	Li/MnO2
Capacity, Ah	7	13
Energy, Wh	175	280
Weight, lbs	2.24	3.0
Cost, $	$75	$90



- ***Introduced higher energy Li/MnO2 chemistry.***
- ***Introduced fuel gauge to enable full consumption of capacity***

Army Rechargeable Battery Improvements



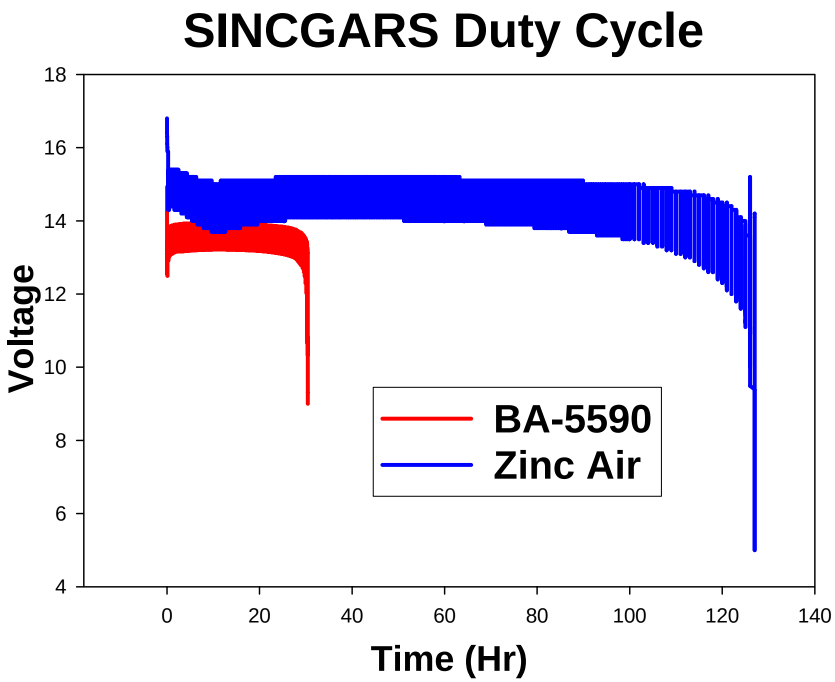
Battery	BB-390	BB-2590
Chemistry	NiMH	Li-ion
Capacity, Ah	4.9	6.2
Energy, Wh	118	180
Weight, lbs	4	3.2
Cost, $ (contract)	$190	$226


Li-Ion Rechargeable Batteries

- ***Conversion from NiMH to Li-ion batteries has resulted in longer runtimes, lower weights, lower self discharge, and easier charging logistics.***


Military Standard Chargers

Mission Extender Battery – Zinc Air



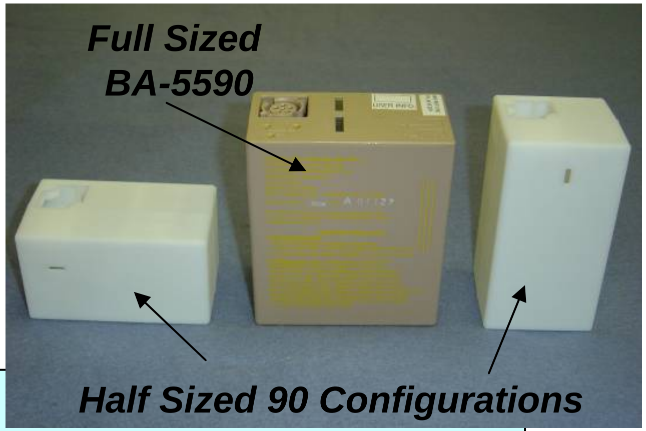
System	BA-5590/U	BA-8180/U
SINCGARS	18-24 Hours	5-9 Days
SATCOM/HF	24 Hours	4-6 Days
Javelin CLU	4 Hours	18-20 Hours
RHC or Toughbook	N/A	30-40 Hours
M-22 ACADA	8 Hours	2 Days

- ***Family of batteries based on lightweight, low cost, environmentally safe Zn-air chemistry***
- ***280Wh/kg, 255Wh/l***
- ***BA-8180 Powers ASIP radio for 5-9 days***
- ***BA-8140 Powers MBITR radio for 5-9 days***

Reduced Cost Option Primary for Extended Missions

Half-Sized 90 Battery

- Higher energy density (Wh/kg) Chemistries (Li/CF_x & Li-Air) enabling development of a Half-Sized BA-5590 with **half the weight and Volume and 1.5X More Energy.**



Program Goals

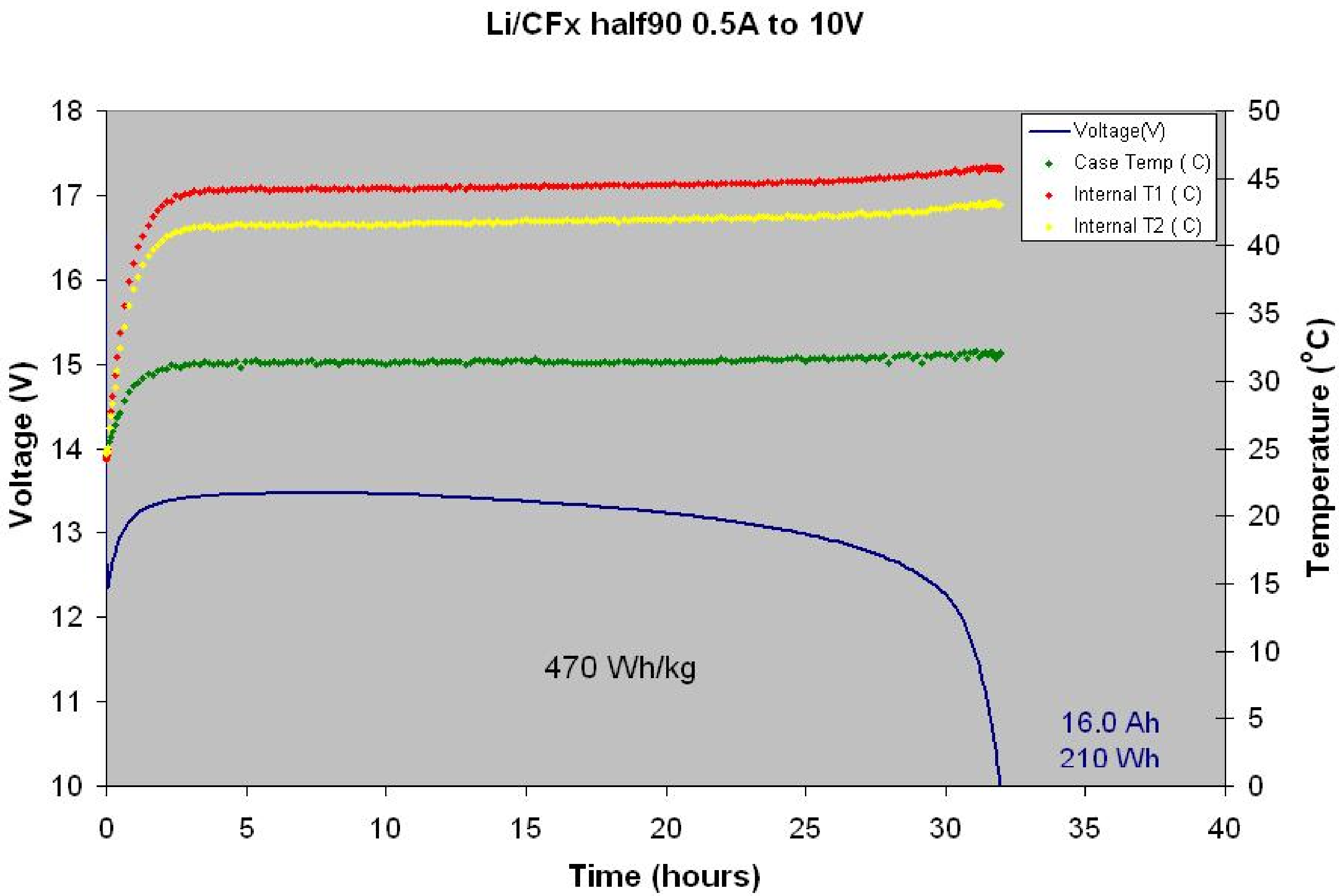
Battery Type	Primary	Rechargeable
Nomenclature	BA-HALF90	BB-HALF90
Threshold Specific Energy	350 Wh/kg	190 Wh/kg
Objective Specific Energy	700 Wh/kg	250 Wh/kg
Maximum Voltage	16.8 Volts	
Minimum Voltage	10 Volts	
Minimum Required Current	2 Amps	6 Amps
Fuel Gauge / SMBus	Yes	
Maximum Recharge Time	na	3 hours
Operational Temperature	-30C to 55C	
Storage Temperature	-40C to 70C	

Full Sized versus Half Sized 90 Batteries Comparison

Disposable Battery	Chemistry	Weight (lbs)	Energy (Wh)
BA-5590	Li/SO_2	2.2	175
BA-5390	Li/MnO_2	3.0	280
Half - BA-5590	Li/CF_x	**1.1**	**210**
Half - BA-5390	Li-Air	**1.1**	**350**

Half the Weight and Size & More Energy Than Full Sized BA-5590

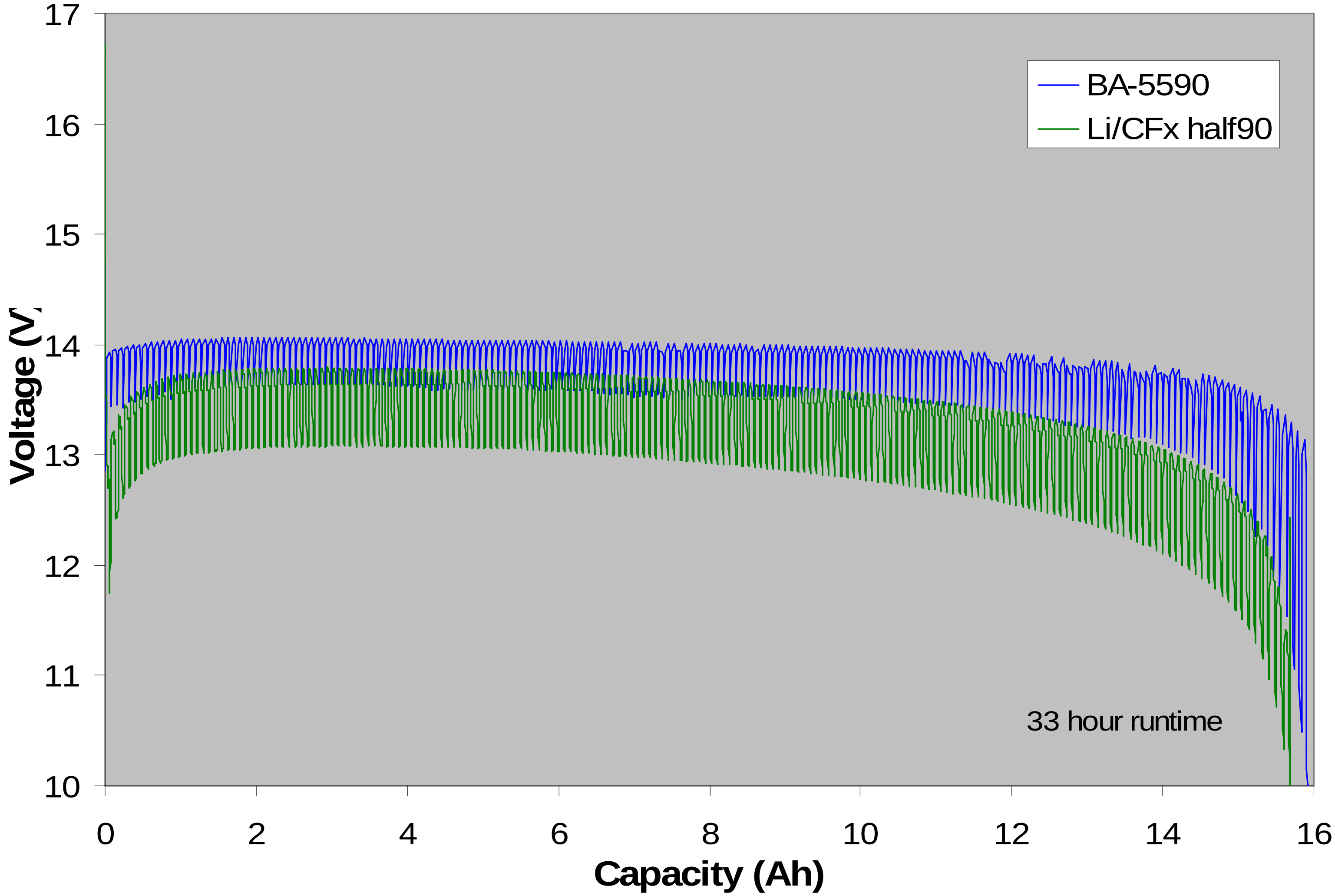
Prototype Li/CFx Half-Sized 90



TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Prototype Li/CFx Half-Sized 90

Sincgars Radio Duty Cycle: 4.6W:6.0W:20W (6:3:1 min) at 35C



Future

BATTERY CHEMISTRIES

Disposable

- **Li/MnO2 Pouch** 250 Wh/kg TRL 7
  - **Issues: low temp performance, fabrication costs, transportation**
- **Li/CFx** 350 Wh/kg TRL 5
  - **Issues: thermal management, material cost and supplier reliability**
- **Li/Air** 700 Wh/kg TRL 2
  - **Issues: low power density and safety**

Rechargeable

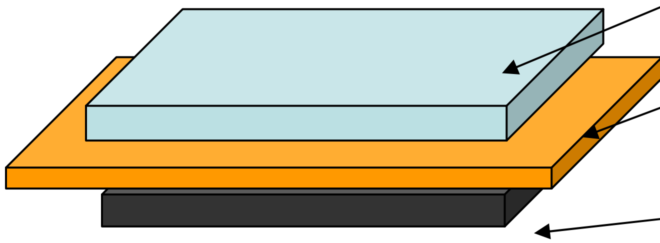
- **Li-ion Polymer** 160 Wh/kg TRL 8
  - **Note: Led by commercial market improvements**
- **Li Polymer** 300 Wh/kg TRL 3
  - **Issues - Safety and packaging**

BATTERY ELECTRONICS

Smart Batteries – adopting commercial open system architecture of Smart Management Bus (SMBus) for fuel gauging and battery to system and battery to charger communication.

Future - Lithium Air Battery

Lithium Air Cell



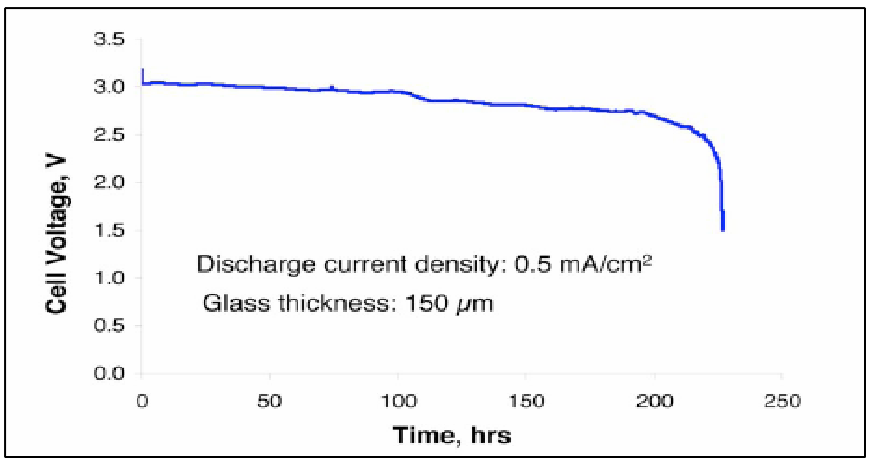
Lithium electrode

LISICON Glass $LiM_2(PO_4)_3$, 1-5 X10-4 S/cm & 1M LiOH electrolyte

Carbon Air electrode

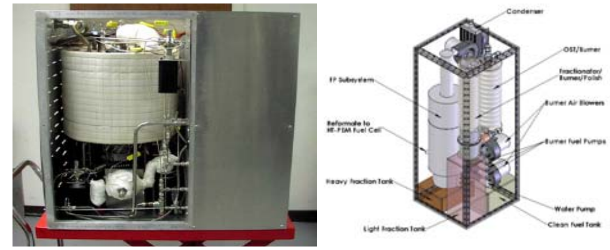
Cell Reaction: $2Li^+ + O_2 = 2Li_2O_2$, $E_0 = 2.96$ V

Observed (cathode):
1,152 – 1,958 mAh/g @ 2.75V@ 0.05 mA/cm2 → **3,168 - 5,385 Wh/kg**



Projected Practical Energy Density Approaching 1,000 Wh/kg

Fuel Cell R&D
Mission Focus Areas



Soldier & Sensor Power (1W-100W)	Man-Portable Power (100W-500W)	Auxiliary Power Units (500W-10kW)

Mission: Rapidly develop and transition suitable fuel cell technologies to applications where they are most needed.

Fuel Cell Industry & Academic Partners

AMI
Adaptive Materials Inc.

UltraCell™
HIGH POWER MICRO FUEL CELLS

SFC
SMART FUEL CELL

jadoo
POWER

GENERAL ATOMICS

EBA&D
Ensign-Bickford Aerospace & Defense Company

LYNNTECH

ULTRALIFE® Batteries

Giner Electrochemical Systems, LLC

Protonex™

ASPEN PRODUCTS GROUP, INC.

IdaTech®

CGFCC
INNOVATION MADE SIMPLE

NanoDynamics Inc

Tennessee Tech UNIVERSITY

RADIAN
ENGINEERING LOGISTICS SECURITY

Altex Technologies Corporation

ESSI
Engineered Support Systems, Inc.

Precision Combustion, Inc.

THE UNIVERSITY OF TOLEDO
1872

Ultracell EVT

Developed Jointly with CERDEC and DARPA
Rated 20W continuous
Reformed Methanol Fuel Cell (RMFC)
Fuel: 67% Methanol / 33% Water

Dimensions:	9.30" X 5.38" X 1.80"
Start Up Time:	23 min. AVG

System Dry Weight:	1.2 kg
Fuel Cartridge Weight:	0.35 kg (250 mL)

20W Mission Energy Density:

24 hr	210 W-hours/kg
72-hr	360 W-hours/kg

Orientation independent except upside down

Started and operated continuous from -5 ^{o}C to 45^{o}C

Ultracell Rev. A

In Development with CERDEC and DARPA
Rated 25W continuous
Reformed Methanol Fuel Cell (RMFC)
Fuel: 67% Methanol / 33% Water

Dimensions:	9.30" X 5.38" X 1.80"
Start Up Time:	20 min.

System Dry Weight:	1.2 kg
Fuel Cartridge Weight:	0.35 kg (250 mL)

25W Mission Energy Density:

24 hr	270 W-hours/kg
72-hr	410 W-hours/kg

Orientation independent except upside down

Ultracell Rev. A at Ft Polk JRTC

- **10 Rev. A units were taken to the Joint Readiness Training Center in Ft. Polk, LA and soldiers were trained on the use of the fuel cell power system**

- **The JRTC Science and Technology team keeps soldiers who will soon be deployed informed on new technologies that will be fielded in the near future**

Ultracell Rev. A at Ft Polk JRTC

- **Soldiers were very pleased with the lighter weight compared to batteries and showed acceptance of the system for certain missions (OP)**

- **Major issues expressed by soldiers were:**
  - **Safety**
  - **High Temp. Operation**
  - **Integration with Applications**

Smart Fuel Cell

In Development with PM Soldier Warrior and CERDEC
Rated 20W continuous
Direct Methanol Fuel Cell
Fuel: 100% Methanol

Dimensions: 2.31'' X 3.06 '' X 9.75''
Start Up Time: Instant

System Weight: 1.18kg
Fuel Cartridge Weight: 0.47 kg (500 mL)

20W Mission Energy Density:
24 hr 291 W-hours/kg
72-hr 556 W-hours/kg

Orientation dependent

Protonex

In Development with CERDEC and AFRL
Rated 30W continuous
PEM Fuel Cell
Fuel: Sodium Borohydride ($NaBH_4$)

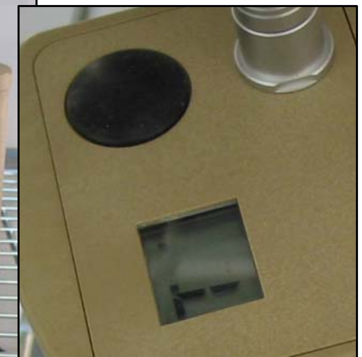
Dimensions: 7.2'' X 7.2'' X 3.6''
Start Up Time: <1 min.

System Dry Weight: 0.96 kg
Fuel Cartridge Weight: 1.32 kg (hydrated)

20W Mission Energy Density:
24 hr 200 W-hours/kg
72-hr 350 W-hours/kg

Orientation independent

Operated continuous from -5 ^{o}C to 45 ^{o}C



Jadoo Power Systems

In Development with CERDEC and SOCOM
Rated 45-55W continuous (user selectable 24/12 VDC)
PEM Fuel Cell
Fuel: Metal Hydride

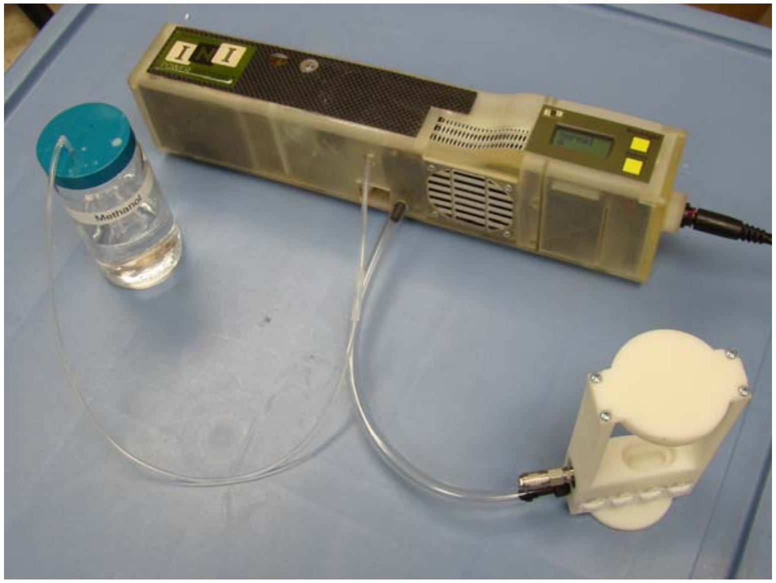
Dimensions:	11'' X 6.4'' X 3.5''
Start Up Time:	immediate

System Dry Weight:	2.86 kg
Fuel Cartridge Weight:	2.30 kg
System + Fuel Weight:	5.16 kg

Metal hydride is used to fuel this technology demonstrator and is not the final fueling solution

Started and operated from 0 ^{o}C to 40 ^{o}C

INI Power



Tested at CERDEC Labs
Rated 15W continuous
Direct Methanol Laminar Flow Fuel Cell
Fuel: 100% Methanol

Start Up Time: instant

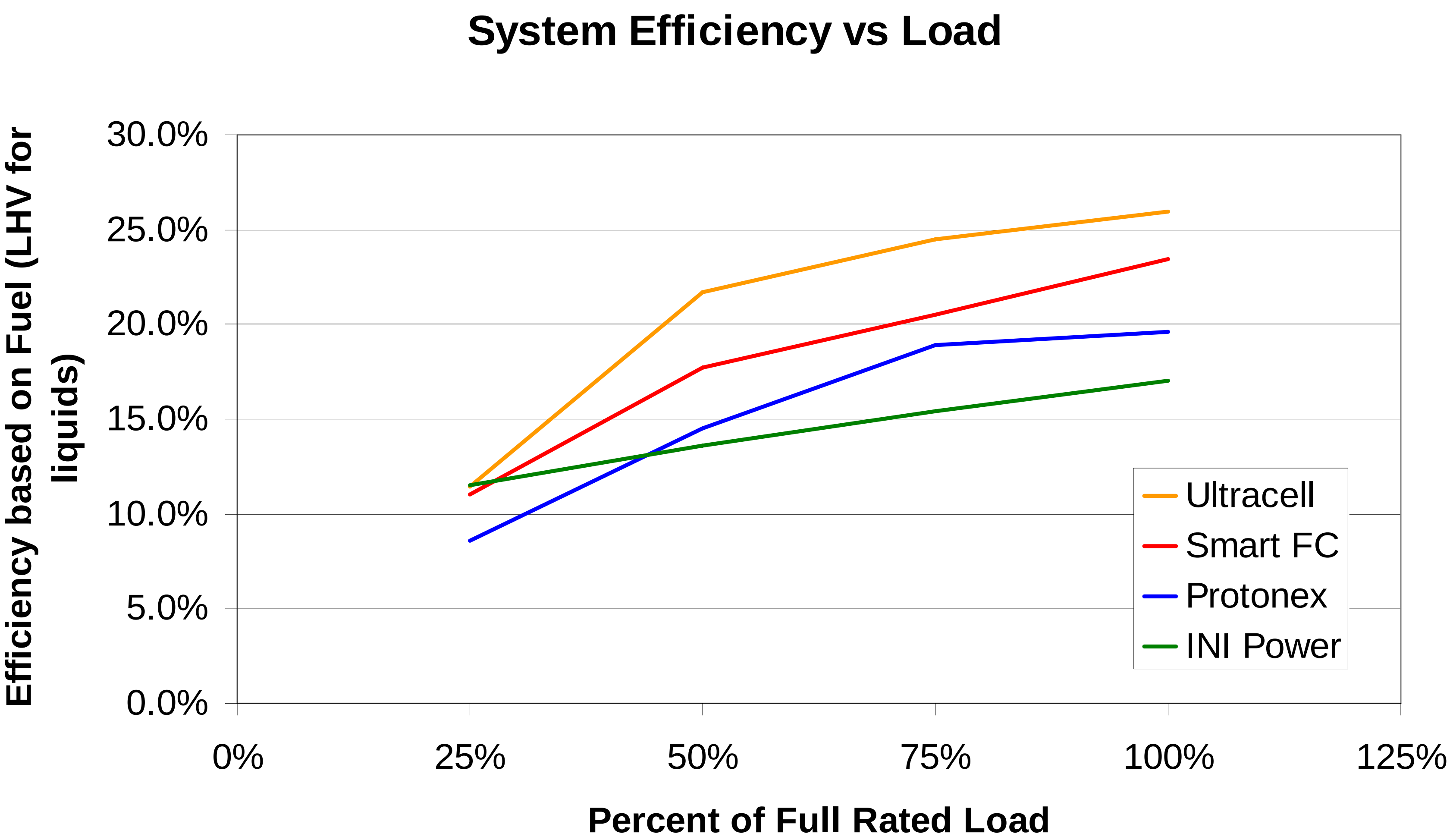
System Dry Weight: 1.8 kg

15W Mission Energy Density:

24 hr	160 W-hours/kg
72-hr	350 W-hours/kg

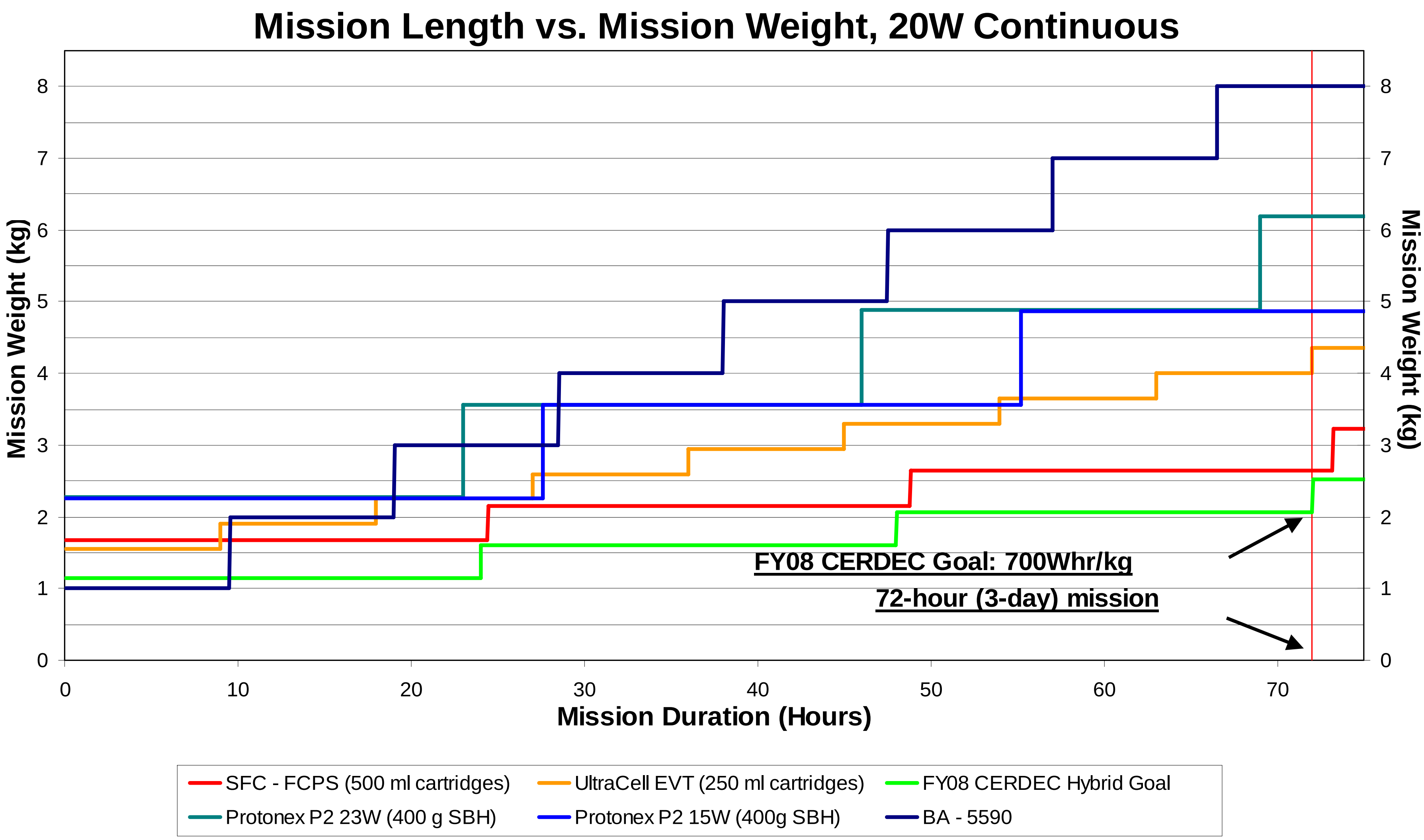
(cartridge weight not included)

Comparisons



Efficiency is not the whole story…

Comparisons



Fuel Cell Issues

Unit	Pros	Cons / Issues
INI Power	Potentially lighter weight	Orientation, Shock/vibration, Technical Maturity
Jadoo	Reliability, Durability, Orientation	Currently heavy, Supportability
Protonex	Durability, Orientation	Supportability, Reliability
Smart Fuel Cell	Size, Weight	Orientation, Supportability, Reliability
Ultracell	Supportability, Durability	Orientation, Emissions, Reliability

Issues for all: Safety (disruptive technology), High Temp Operation

Solid Oxide Fuel Cells

Both currently undergoing test plan at CERDEC

Adaptive Materials Inc. (AMI)

- 50 Watts
- System Weight: 2.3 kg
- Cartridge Weight: 0.4-0.9 kg

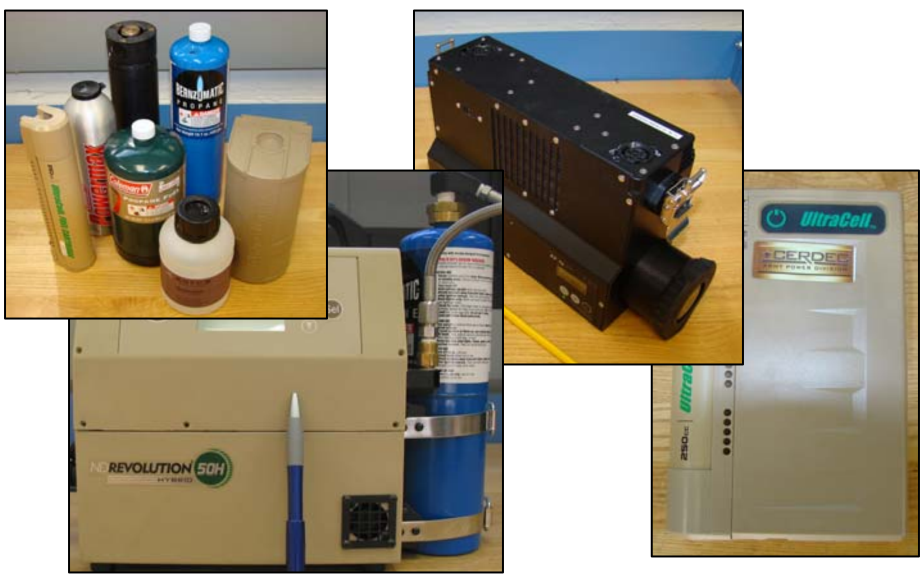
Nanodynamics

- 50 Watts
- System Weight: 4.5 kg
- Cartridge Weight: 0.8 kg

Fuel Cells vs. Batteries

Advantages

- Higher efficiency
- Potential cost benefits
- Long, continuous run times
- Lighter weight for longer missions (especially over 72 hours)



Drawbacks

- Air-breathing
- More complex
- *Cost
- *Reliability
- *Robustness

* High potential for improvement

Conclusions

- All current development programs are geared towards reducing logistics footprint of power sources, as cited in summary of technology gaps
- Capability-driven requirements for systems results in an ever-increasing demand for power: capabilities are lagging demand
- Advanced battery chemistries and fuel cells are promising but significant technical challenges require resolution prior to transitioning from the lab to the battlefield
- There is not yet a clear technology, fuel strategy, or power level that is most suitable for soldier power applications
- Fuel cells and advanced battery chemistries will only be used where appropriate when the technologies are sufficiently developed and commercially viable