

## 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 25<sup>th</sup> International Battery Seminar and Exhibit  
17-20 March 2008, Fort Lauderdale, FL

Jonathan M. Cristiani

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| 1. REPORT DATE<br><b>17 MAR 2008</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                    | 2. REPORT TYPE<br><b>Final Presentation</b> |                                                           | 3. DATES COVERED<br><b>17-03-2008 to 20-03-2008</b>              |                                 |
| 4. TITLE AND SUBTITLE<br><b>The Current Status of Fuel Cell Technologies for Portable Military Applications Presentation to the 25th International Battery Seminar and Exhibit</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                    |                                             |                                                           | 5a. CONTRACT NUMBER                                              |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                             |                                                           | 5b. GRANT NUMBER                                                 |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                             |                                                           | 5c. PROGRAM ELEMENT NUMBER                                       |                                 |
| 6. AUTHOR(S)<br><b>Jonathan Cristiani</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                    |                                             |                                                           | 5d. PROJECT NUMBER                                               |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                             |                                                           | 5e. TASK NUMBER                                                  |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                             |                                                           | 5f. WORK UNIT NUMBER                                             |                                 |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><b>U.S. ARMY COMMUNICATIONS-ELECTRONICS RESEARCH DEVELOPMENT AND ENGINEERING CENTER,328 Hopkins Rd.,Bldg 1105,Aberdeen Proving Ground,MD,21005</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                    |                                             |                                                           | 8. PERFORMING ORGANIZATION REPORT NUMBER<br><b>APPT-TR-08-02</b> |                                 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><b>U.S. ARMY COMMUNICATIONS-ELECTRONICS RESEARCH DEVELOPMENT AND ENGINEERING CENTER, 328 Hopkins Rd., Bldg 1105, Aberdeen Proving Ground, MD, 21005</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                    |                                             |                                                           | 10. SPONSOR/MONITOR'S ACRONYM(S)<br><b>AMSRD-CER-C2-AP</b>       |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                             |                                                           | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)<br><b>APPT-TR-08-02</b>   |                                 |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><b>Approved for public release; distribution unlimited</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                    |                                             |                                                           |                                                                  |                                 |
| 13. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                    |                                             |                                                           |                                                                  |                                 |
| 14. ABSTRACT<br><b>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.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                    |                                             |                                                           |                                                                  |                                 |
| 15. SUBJECT TERMS<br><b>battery, fuel cell, soldier power</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                    |                                             |                                                           |                                                                  |                                 |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                             | 17. LIMITATION OF ABSTRACT<br><b>Same as Report (SAR)</b> | 18. NUMBER OF PAGES<br><b>40</b>                                 | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT<br><b>unclassified</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | b. ABSTRACT<br><b>unclassified</b> | c. THIS PAGE<br><b>unclassified</b>         |                                                           |                                                                  |                                 |



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The Current Status of Fuel Cell Technologies for  
Portable Military Applications

25<sup>th</sup> International Battery Seminar and Exhibit  
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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

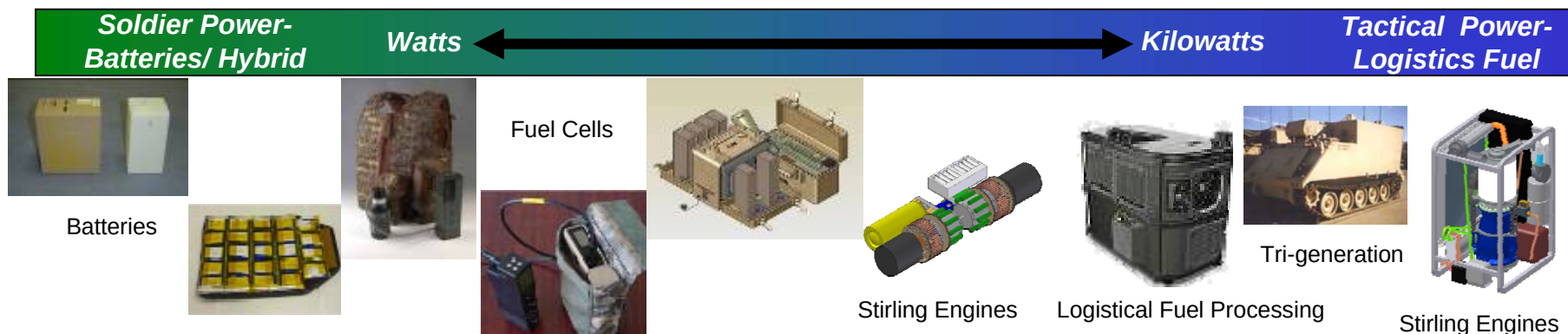


## General Thrust Areas – Non-system Specific

- **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*



| <b>ATO D.CER.2008.08<br/>Power for Dismounted Soldier</b>                                                                                                                                                                                                                                                                                                          | <b>Technical Objectives</b>                                                                                                                                                                                                                                                                       |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>• Half-Sized BA5590 Li/CFx Battery</li><li>• Half-Sized BA5590 Li-Air Battery</li><li>• Soldier Conformal Rechargeable Battery</li><li>• Soldier Hybrid Direct Methanol Fuel Cell Power Source</li><li>• Soldier Hybrid Fuel Cell Power Source</li><li>• Portable Hybrid Power Sources &amp; Chargers, JP-8 fueled</li></ul> | <ul style="list-style-type: none"><li>• <b>Power for Dismounted Soldier</b></li><li>• 1.1lbs 400Whr/kg TRL 4/6</li><li>• 1.1lbs 600Whr/kg TRL 3/5</li><li>• 3lbs, flat 140Whr/kg TRL 4/6</li><li>• 25W 1.5lbs TRL 4/6</li><li>• 50-100W 3.5lbs TRL 4/5</li><li>• 150-250W 25lbs TRL 4/6</li></ul> |
| <b>ATO R.LG.2009.01<br/>Mobile Power</b>                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                   |
| <ul style="list-style-type: none"><li>• Transitional Hybrid Power Source, Log-fueled</li><li>• Universal Tactical Auxiliary Power Unit</li><li>• Co-generation and Tri-generation System</li></ul>                                                                                                                                                                 | <ul style="list-style-type: none"><li>• <b>Mobile Power:</b></li><li>• 250W-2kW 50W/kg TRL 3/5</li><li>• 3-5kW 90W/kg TRL 3/6</li><li>• 3kW/18BTUh 205kg TRL 3/5</li></ul>                                                                                                                        |

**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.

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# Army Power Division *Transition and Support*



## Customers



## Partners



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# 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/SO<sub>2</sub> → Li/MnO<sub>2</sub> → Li/CF<sub>x</sub> → Li-Air  
(175Wh/kg)      (205 Wh/kg)      (350Wh/kg)      (700Wh/kg)

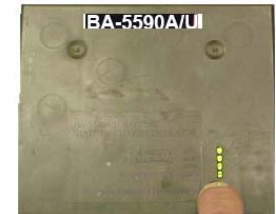
- For mission durations > 48 hours:

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



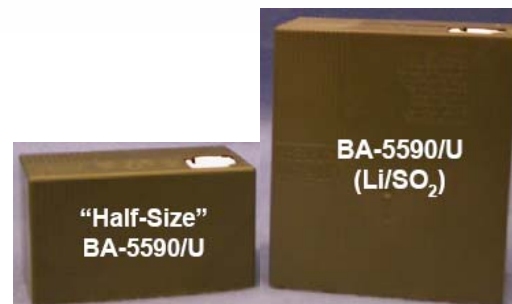


# Power Strategies to Maintain or Reduce Power Consumption



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



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# 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



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# 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

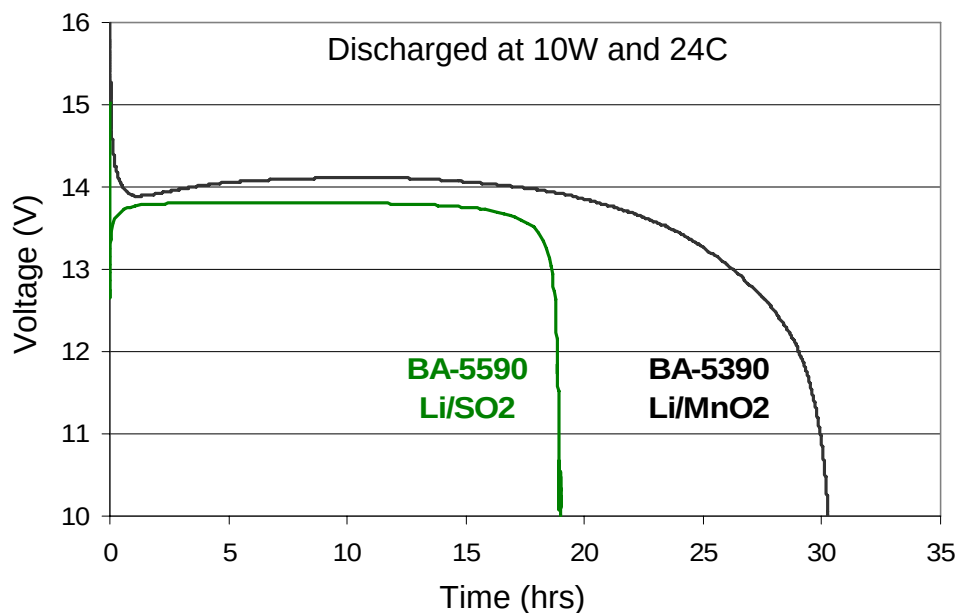


| Designation<br>Chemistry | V nominal | Ah<br>@ C-rate |
|--------------------------|-----------|----------------|
| BB-516<br>NiCD           | 24        | 0.22 @<br>0.3A |
| BB-503<br>NiCd           | 4.8       | 4.0            |
| BB-2847<br>Li-Ion        | 8         | 3.6            |
| BB-388<br>NiMH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

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# 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    |

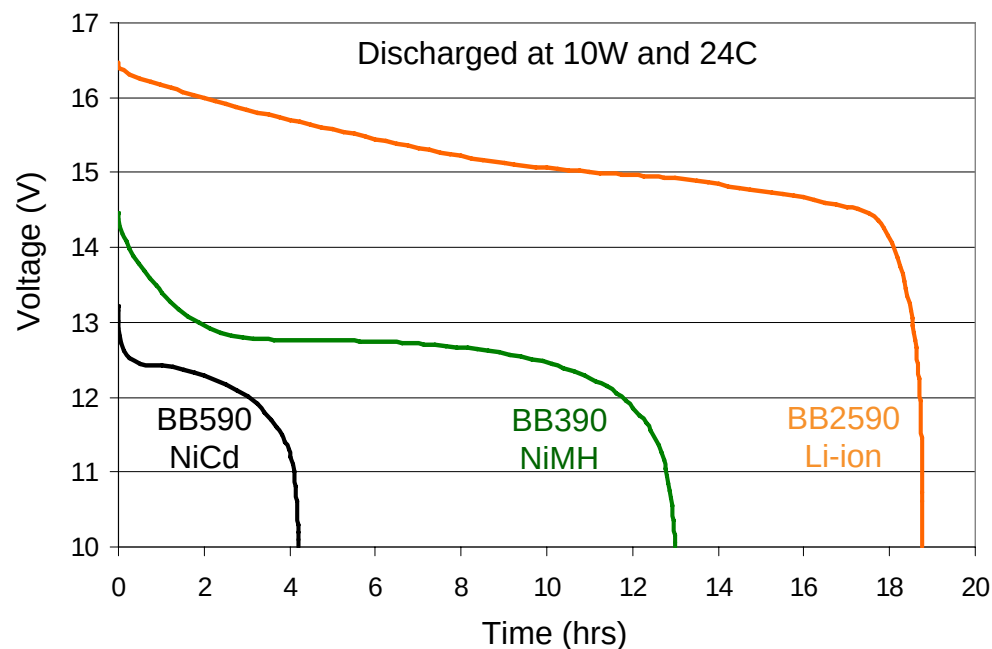


- Introduced higher energy Li/MnO2 chemistry.
- Introduced fuel gauge to enable full consumption of capacity

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# 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   |

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



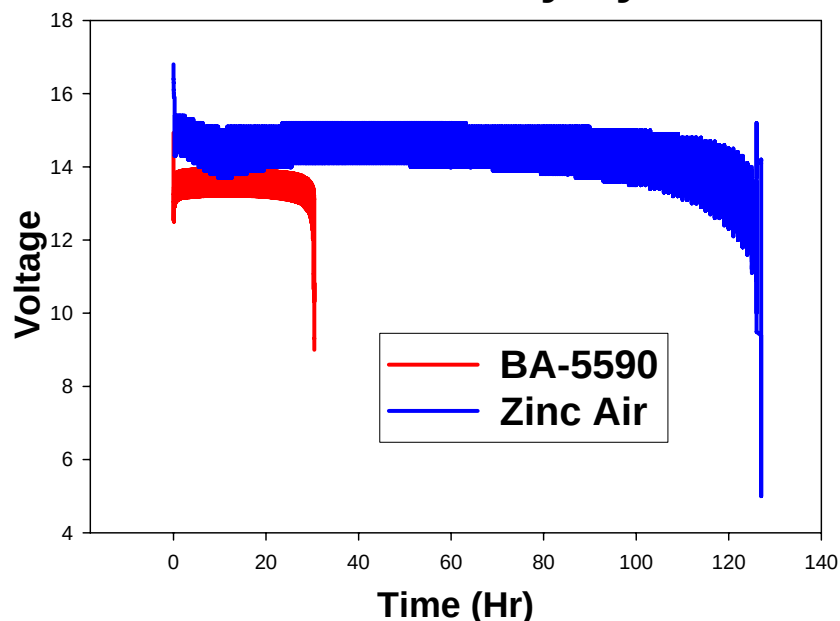
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# Mission Extender Battery – Zinc Air



**SINCGARS Duty Cycle**



| 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**

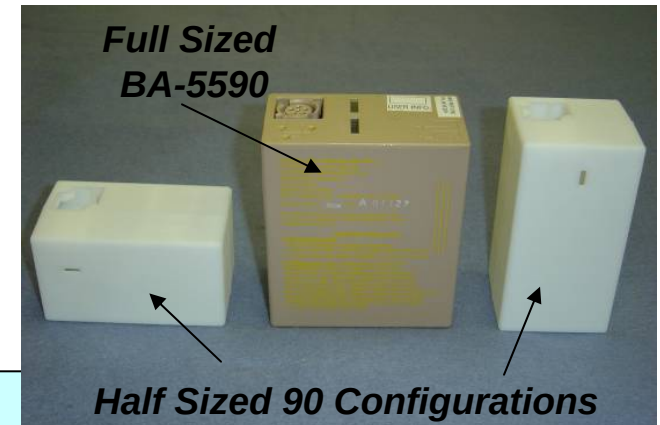




# Half-Sized 90 Battery



- Higher energy density (Wh/kg) Chemistries (Li/CF<sub>x</sub> & 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 |              |

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# Full Sized versus Half Sized 90 Batteries Comparison

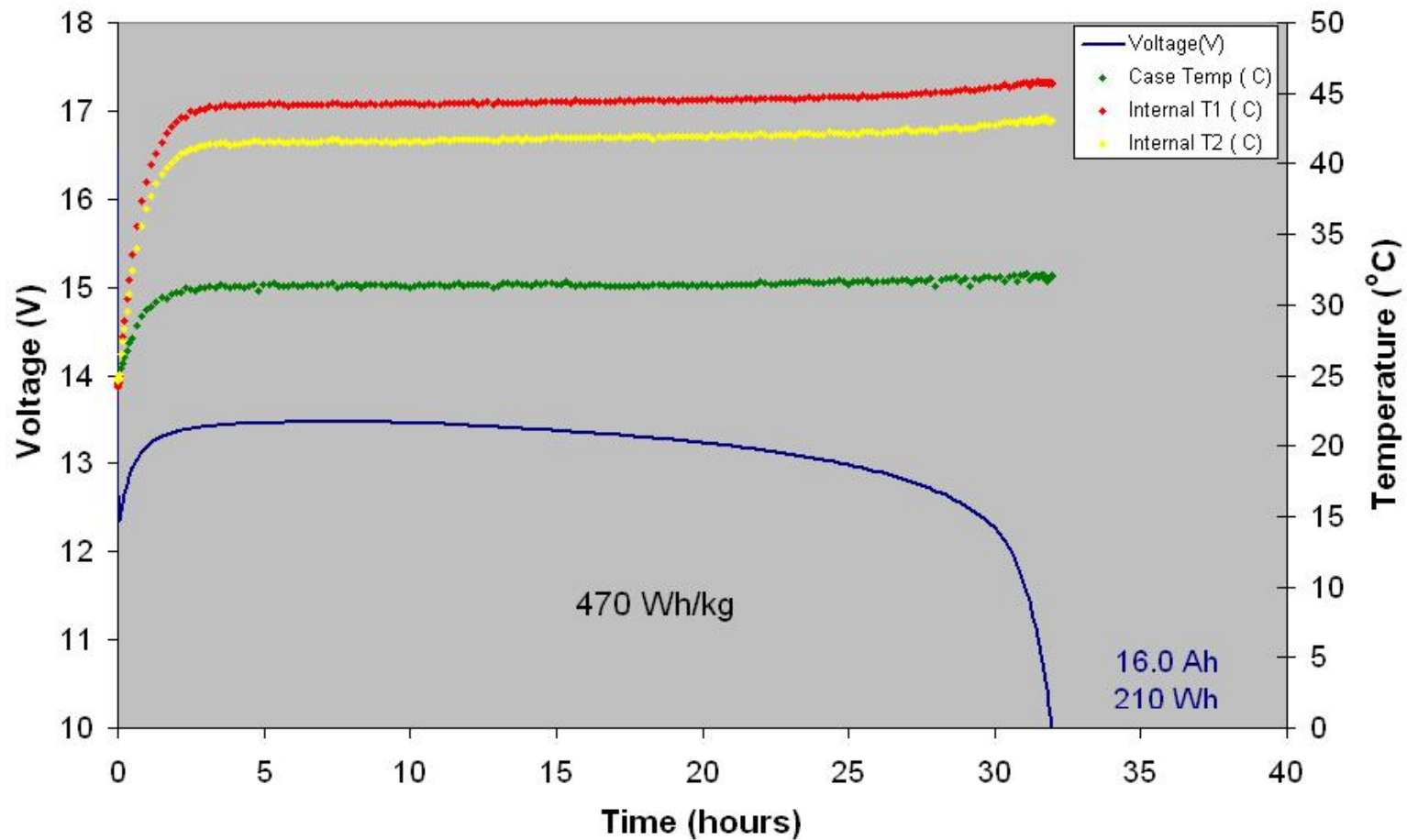


| Disposable Battery | Chemistry           | Weight (lbs) | Energy (Wh) |
|--------------------|---------------------|--------------|-------------|
| BA-5590            | Li/SO <sub>2</sub>  | 2.2          | 175         |
| BA-5390            | Li/MnO <sub>2</sub> | 3.0          | 280         |
| Half - BA-5590     | Li/CF <sub>x</sub>  | <b>1.1</b>   | <b>210</b>  |
| Half - BA-5390     | Li-Air              | <b>1.1</b>   | <b>350</b>  |

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

# Prototype Li/CFx Half-Sized 90

Li/CFx half90 0.5A to 10V

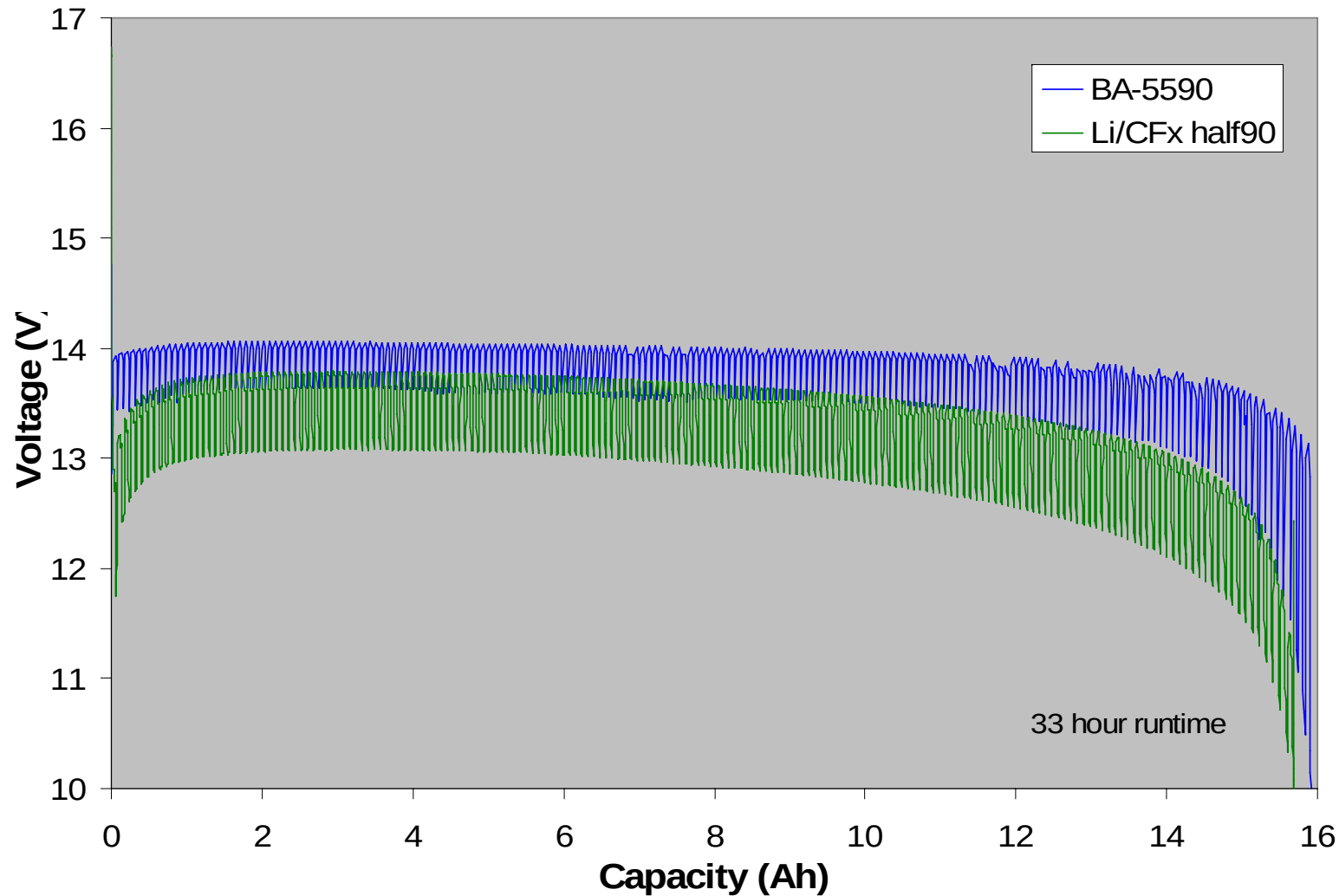




# Prototype Li/CFx Half-Sized 90



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



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## BATTERY CHEMISTRIES

### Disposable

- **Li/MnO<sub>2</sub> Pouch**      250 Wh/kg  
TRL 7
  - Issues: low temp performance, fabrication costs, transportation
- **Li/CF<sub>x</sub>**      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

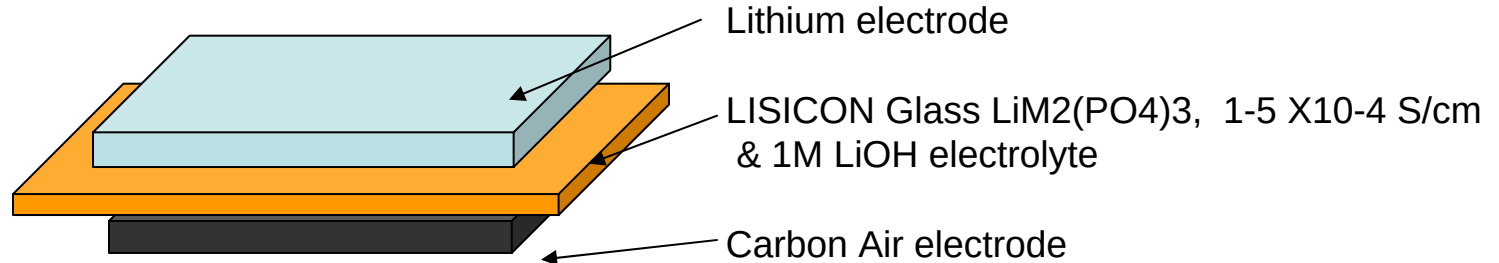
### Rechargeable

- **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.

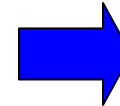
## Lithium Air Cell



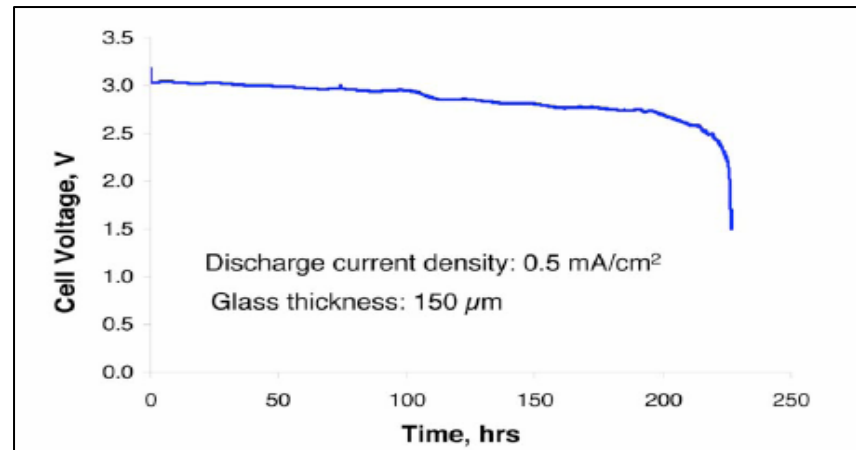
Cell Reaction:  $2\text{Li} + \text{O}_2 = 2\text{Li}_2\text{O}_2$  ,  $E^0 = 2.96 \text{ V}$

Observed (cathode):

1,152 – 1,958 mAh/g @ 2.75V @ 0.05 mA/cm<sup>2</sup>



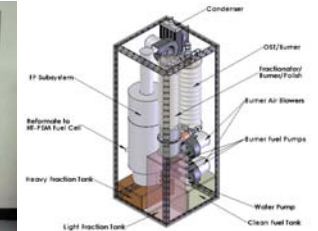
3,168 - 5,385 Wh/kg



**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.**

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# Fuel Cell Industry & Academic Partners



Giner Electrochemical Systems, LLC



Precision Combustion, Inc.



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# 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 °C to 45°C

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**



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- 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



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In Development with CERDEC and AFRL  
 Rated 30W continuous  
 PEM Fuel Cell  
 Fuel: Sodium Borohydride ( $\text{NaBH}_4$ )

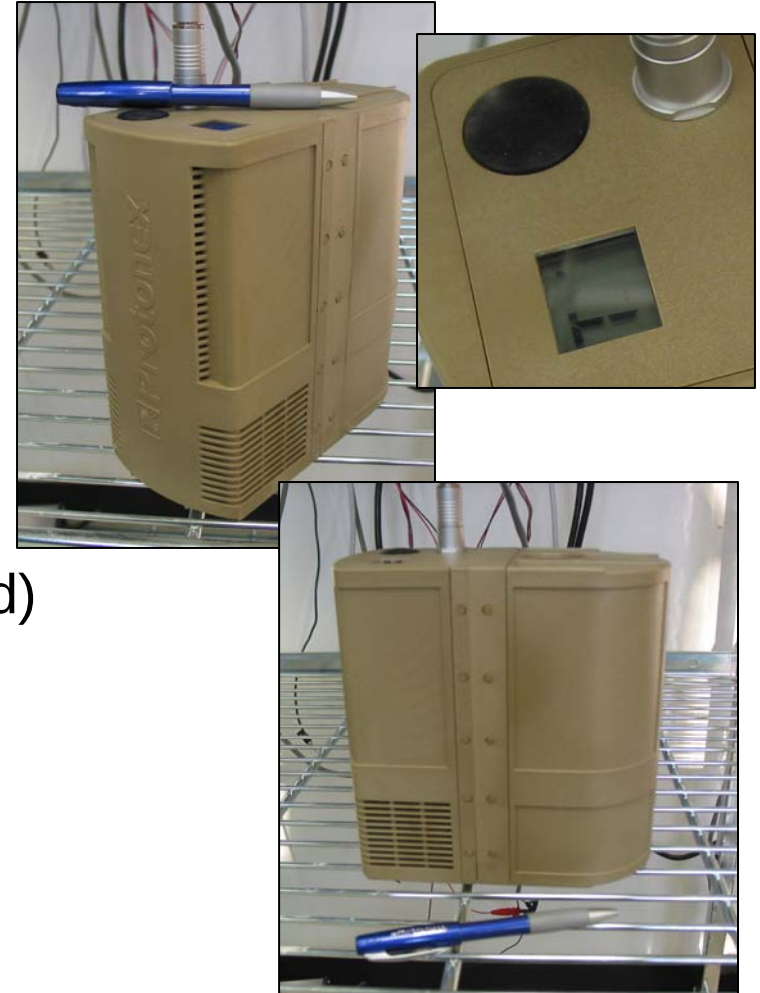
Dimensions: 7.2" X 7.2" X 3.6"  
 Start Up Time: <1 min.

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 °C to 45 °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

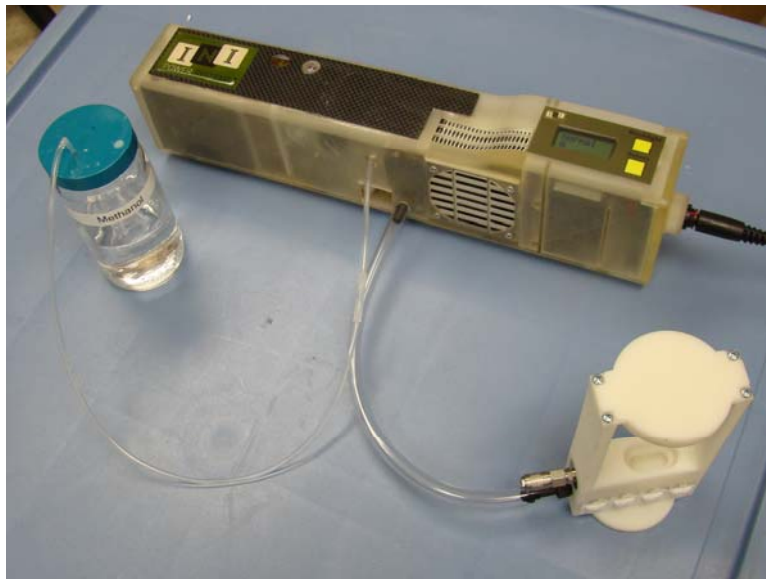
Fuel Cartridge Weight: 2.30 kg

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 °C to 40 °C

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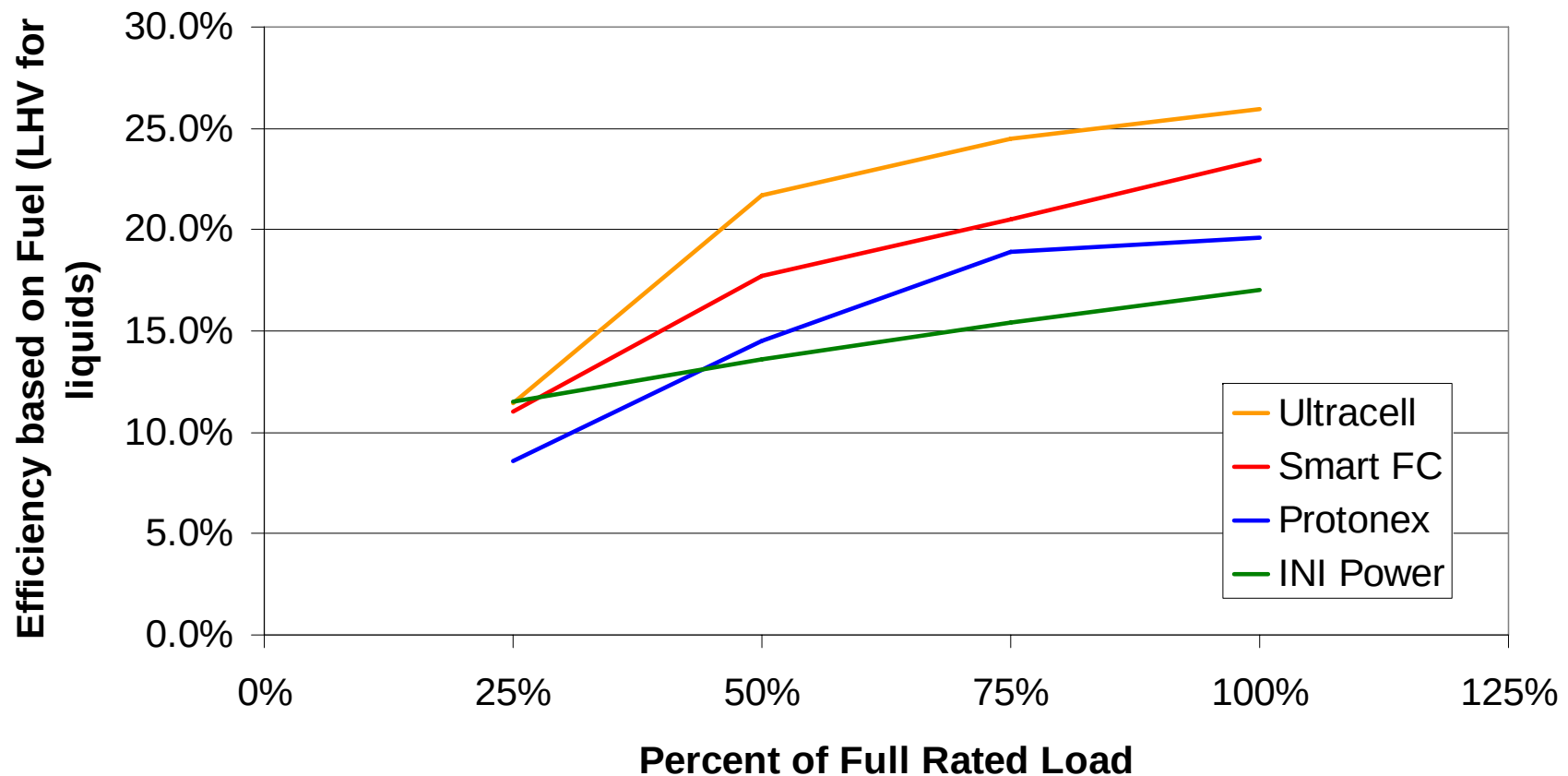
Tested at CERDEC Labs  
 Rated 15W continuous  
 Direct Methanol Laminar Flow Fuel Cell  
 Fuel: 100% Methanol

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)

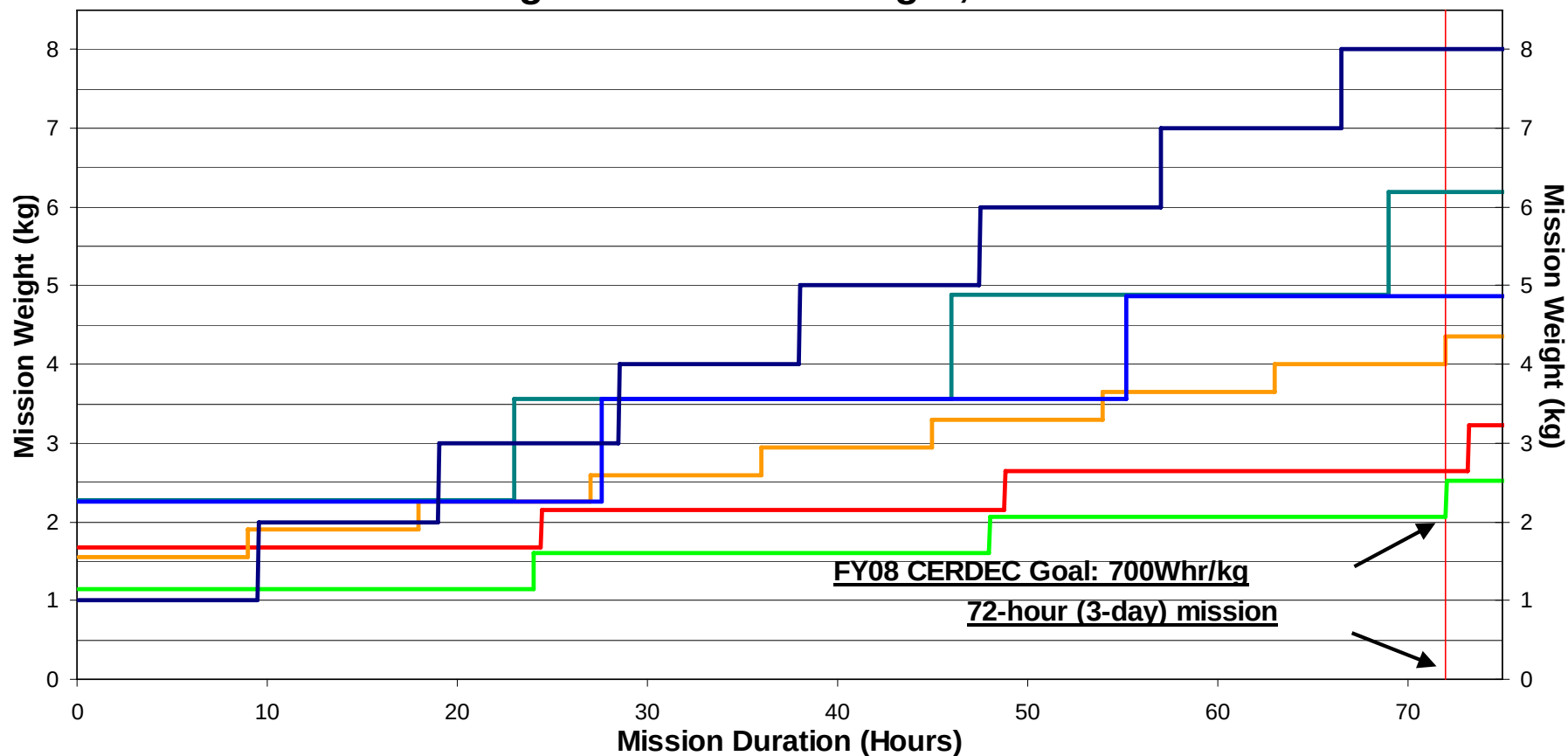
## System Efficiency vs Load



**Efficiency is not the whole story...**

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## Mission Length vs. Mission Weight, 20W Continuous



SFC - FCPS (500 ml cartridges)    UltraCell EVT (250 ml cartridges)    FY08 CERDEC Hybrid Goal  
 Protonex P2 23W (400 g SBH)    Protonex P2 15W (400g SBH)    BA - 5590





# 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

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



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## 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

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# 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**