TARDEC Collaboration – *Energy Storage*

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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Energy Storage Goals and Mission

Energy Storage Goals

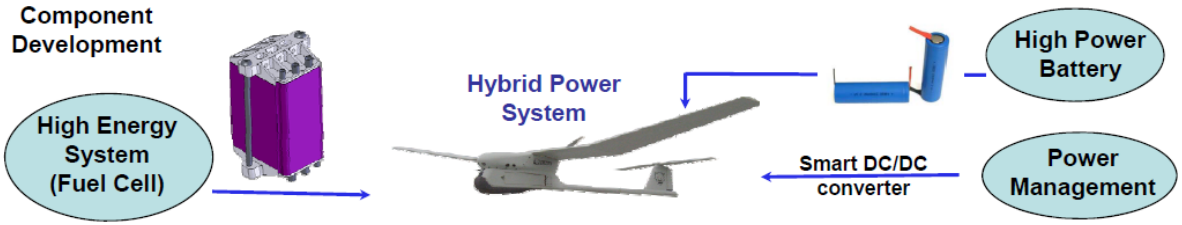
- Develop **safe and cost** effective energy storage systems
- Reduce **battery weight & volume burden** (Increase Energy & Power Density)
- Reduce logistics and fuel burdens
- Extend **calendar and cycle life**
- Enhance performance and increase operating time (silent watch, etc)

Energy Storage Mission

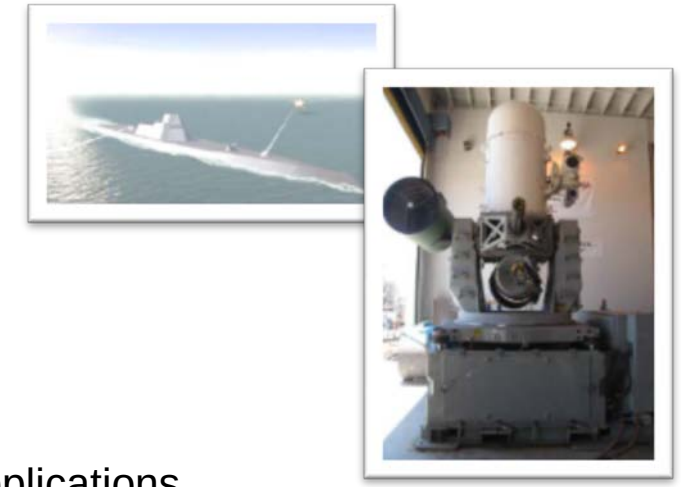
- **Develop** and **mature** advanced ES technologies for transfer to vehicle platforms
- Test & evaluate ES technologies for prequalification and to assess their TRL
- Identify **technology barriers** and develop technical solutions
- Provide technical support to customers, other teams and government agencies for all ES requirements
- Provide **cradle-to-grave** support for all Army ES systems

DOD Applications & Approach

- **Air Force: (mass restrictions)**
  - Major Applications:
    - Aircraft Emergency Power
    - Small Unmanned Aerial Vehicle (UAV)
    - Long Endurance UAV / Persistent Munitions
  - Approach
    - High Energy component
    - High Power component
    - Power Management



- **Navy: (volume restrictions)**
  - Major Applications:
    - Unmanned Underwater Vehicles (UUV)
    - Shallow Water Combat Submersible (SWCS)
    - Submarine Small Distributed Power Systems
    - Surface Ship Fuel Economy
    - Surface Ship Pulsed and High Power
  - Approach
    - Modular, scalable approach to support multiple applications



DOD Applications & Approach (Cont.)

- **Army Applications/Drivers:**

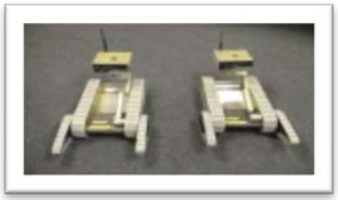
CERDEC - Soldier

– Major Applications
  - Soldier Power – *(Soldiers carry as much as 30lbs of batteries to support Mission Essential Equipment)*
  - Advanced C4ISR Systems

– Approach
  - Standard Form Factor (BB2590)
  - Fuel-Cell/Battery Hybrid Power Sources

Communications

TARDEC - Ground



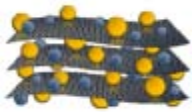
– Major Applications
  - Robotics
  - Survivability
  - Weapons Systems
  - Electromagnetic Armor (EM Armor)
  - Silent Watch
  - Starting, Lighting and Ignition (SLI)
  - Hybrid Vehicle Acceleration and Regenerative Breaking

Hit Avoidance

Targeting Systems

– Approach
  - Standard Form Factor (6T)
  - Ultra-capacitor/Battery Hybrid Power Sources

Energy Storage Functional Breakdown



Basic Research

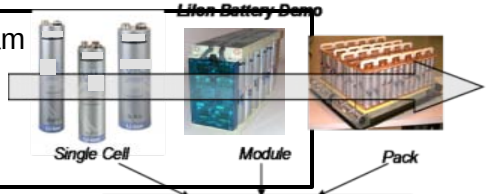
- Lithium plating phenomenon in Li-ion batteries
- **Study on the mechanism of thermal runaway in VRLA Batteries and Methods of Suppression**
- Study of electrode/current collector interface & safe separator for Li-ion batteries
- Development of high energy density anode materials for improved Li-ion batteries
- Alternative electrolyte for use in lithium-ion batteries (higher voltage, improved performance)

Applied / Applications Research

- Electromagnetic Armor Power Maturation
- Nickel-Zinc 6T Battery Development
- **Development of 6T battery for SLI and silent watch using lithium-iron phospha**
- Absorbed Glass Matt lead acid battery for 24V military 4HN battery

Manufacturing

- High Power, High Energy Density Li-Ion Battery Manufacturing Program
- **Lithium-Ion Battery Pack Manufacturing**
- Advanced battery material scale-up facility



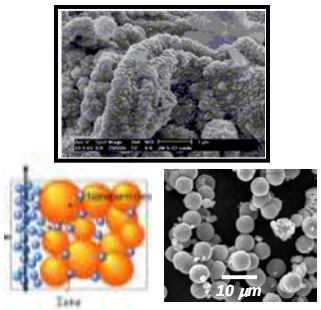
Battery Management / Safety

- **In-House BMS evaluation for PM HBCT & new laboratory**
- Universal BMS using novel algorithms for battery health
- Ballistic and abuse tolerance studies on cells, module and packs
- Development of advanced diagnostic tools for cycled cells

Alternative Systems

- Hybrid Power Module
- Lithium-Titanate Hybrid Vehicle Pack Integration
- **Characterization of ultra-capacitors for SLI and high power applications**

Argonne National Lab – Advanced Battery Materials/Manufacturing



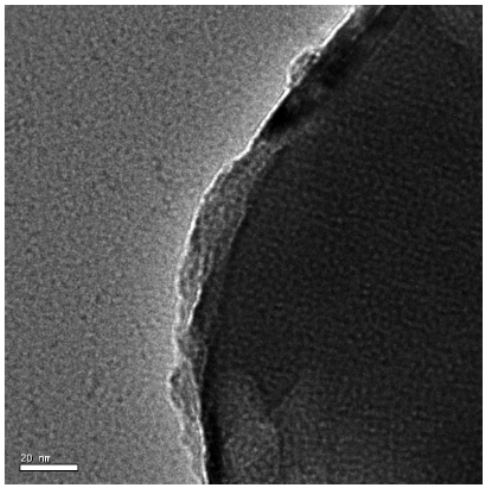
Advanced Battery Materials

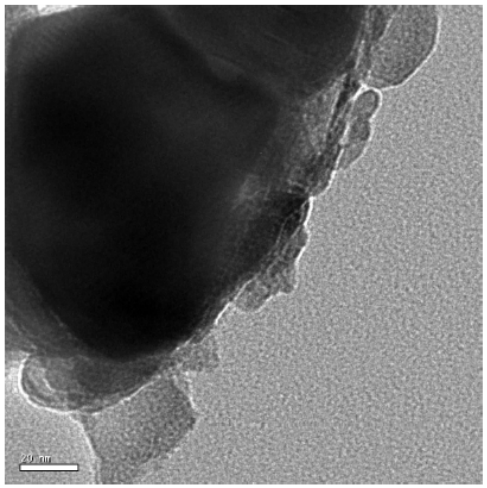
Cells

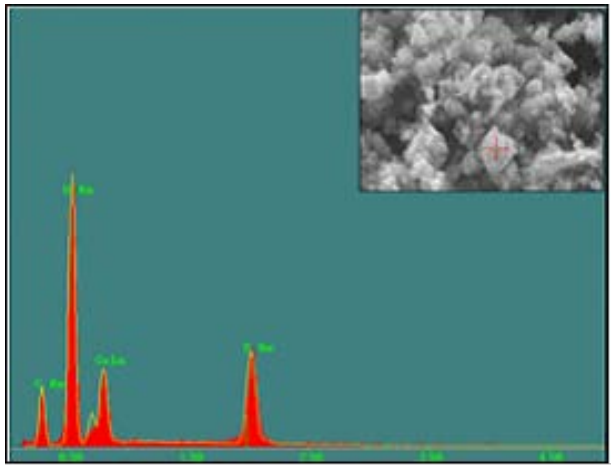
Modules

- Scale-up facility at Argonne National Laboratory (ANL).
  - Prepare scaled-up quantities of advanced materials prepared at Argonne. Initial focus is on high energy cathode materials and advanced electrolyte/electrolyte additives.
  - Process design and engineering for scale-up
  - Bulk materials production for evaluation (e.g., 1-100 kg batches or continuous)
  - Deliveries include materials to Army Labs and to battery vendors for evaluation
- Enhancing Argonne's battery post-test laboratory capabilities.
  - Develop "closed loop" feedback into materials development programs at ANL.
- Both will be user facilities.

Cathode Material Development







- Research is being carried out to improve energy density by developing advanced high voltage cathode materials.
  - 2 Phase I Small Business Innovative Research (SBIR) projects
- **Project #1:**
  - Core shell structured cathode material: shell coating to enhance stability at high voltage (to 5V)
- **Project #2:**
  - Develop/optimize high voltage, high capacity cathode materials.
    - Phospho-olivine LiMPO4 (M = Mn, Co, & Ni) with high voltage electrolytes
    - Particle size, doping and carbon coating

Industry
Lithium Plating Phenomenon

TARDEC and Industry have an ongoing project studying lithium plating in lithium ion batteries

- Lithium plating results in loss of capacity and eventually shorts between battery electrodes
- Plating can occurs when the battery is charged at a rate higher than the anode can accept charge (regenerative breaking)
- Observe lithium intercalation and plating in-situ with specially designed cell
- Investigation of strategies for avoiding plating while still capturing as much energy in the battery as possible for a given set of conditions

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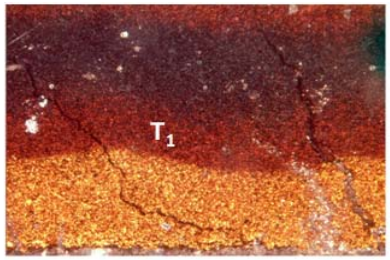

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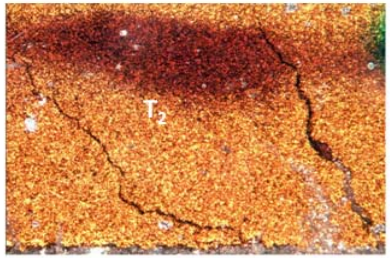

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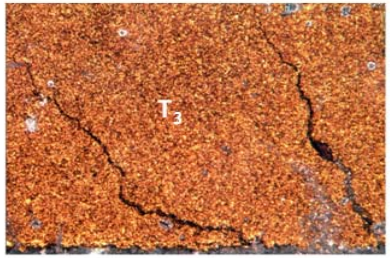


Silicon Anode Materials

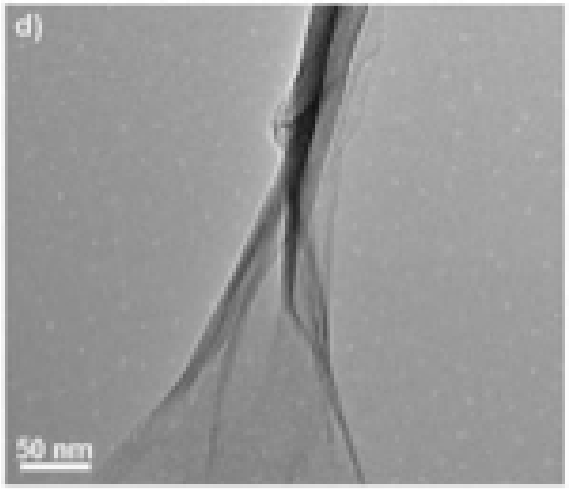
Recently TARDEC completed a Phase I Small Business Innovative Research (SBIR) project

- Silicon has the potential for significantly higher capacity than graphitic anode materials (~4200 mAh/g theoretical)
- However, silicon anode materials have suffered from short cycle life/rapid capacity loss due to expansion and contraction of the material during cycling
- SBIR project objectives:
  - Capacity: >1500 mAh/g
  - Cycle life: >500 cycles
- Portions of this effort including lab scale cell cycling and material analysis was carried out at an industry laboratory

University Projects

Anode Materials

- Research study on novel carbonaceous anode materials
- First principals modeling of materials identified graphene edges as favorable for lithium intercalation
- Graphene Nano-ribbons (GNR)



Electrolytes

- Ionic Liquid Electrolytes
- High throughput examination of Li-Air Catalysts
- Graphene Electrodes
- In-Situ observation of battery Cycling
- Polymer and Solid State Electrolytes

Battery Monitoring Systems

- **Lead-Acid Battery Monitoring Systems**
  - Relationships with several commercial lead-acid BMS vendors.
  - CRADAs: Evaluate the commercial BMS for accuracy of vendor claims and suggestions for design improvements.
  - PEO-GCS Battery Monitoring System Specification
  - Stryker BMS source selection: 3 BMS were tested and evaluated against specification focused on 95% accuracy for SoC and SoH.
- **Lithium-Ion Battery Management Systems**
  - Li-ion Battery OEMs produce BMS for their own battery systems.
  - SBIR Advanced Battery Management Systems: Looking at developing algorithms for improved SoC, SoH, and SoL accuracy.
  - BMS Laboratory capability to evaluate BMS technology readiness level independent of the battery system.

Battery Management Systems Lab

- **Battery management system & architecture design and test capability**
- **Develop in-house advanced battery test capability to assess performance and TRL of BMS technologies/systems independent of the battery pack; and standard architecture and interface for advanced ground vehicle battery packs**
- **Support battery system standardization and open pack architecture definition to support improved commonality in Army ground vehicles.**
- **Major Lab Components**
  - **Automated test control and data processing system**
  - **Hardware-in-loop (HIL) Simulator w/ Battery Models**
  - **Thermal testing via Environmental Chambers**
  - **Failure Analysis**

DOD Lithium-Ion Specification

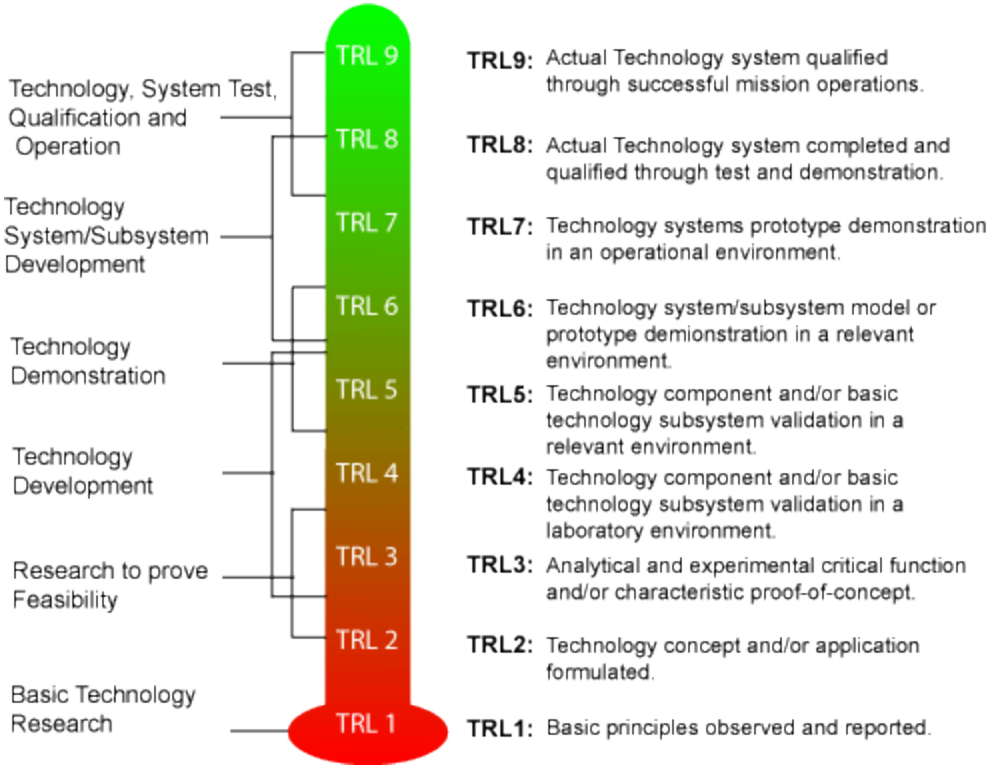
- **Purpose: Create a single Li-ion rechargeable specification applicable to all DOD components. Results will be:**
  - Standardization of test and performance requirements
  - Reducing test duplication with in DOD
  - Cost benefits include a decrease in qualification testing as well as potential replacement of multiple current chemistries with standardized Li-ion systems.
- **Participants: Under the auspices of the Power Sources Technical Working Group (PSTWG).**
  - US ARMY TARDEC
  - US Army CERDEC
  - NAVAIR
  - NAVSEA
  - Air Force
  - Marines
  - Defense Logistics Agency

- **Status: The specification outline is created and merging of two existing specifications is complete.**
- **Expected Completion: Approximately 1 year to complete adding other services requirements and obtain services and vendor consensus.**

TARDEC Technology Readiness Level (TRL) Certification

- **TRL Certification process developed for Energy Storage Systems (ESS's)**
- **Process provides both Government & Industry with a standard to make quantifiable measurements and evaluations of technical maturity**
- **ESS Process is a detailed set of requirements / tests for each of the TRL levels for specific ESS technologies tailored to the specific chemistry**

- **Tests include:**
  - BMS checkout
  - Rate characterization
  - Charge retention / stand
  - Altitude
  - Vibration
  - Impact
  - Short circuit
  - Extreme temperature
  - Overcharge / thermal runaway



Current 6T Lead Acid Baseline

Characteristic:	Units	Pack 6T Size
Nominal Voltage	*V*	12.0
Capacity	*Ah*	127.0
Total Installed Energy	*Wh*	1524.0
Cell Mass	*kg*	40.0
Cell Volume	*L*	13.9
Cold Crank Amps (30sec, -18°C)	*A*	1100
Energy Density	*Wh/L*	109.6
Estimated Specific Energy	*Wh/kg*	38.1
Battery Height	*mm*	209.0
Battery Width	*mm*	265.0
Battery Depth	*mm*	253.0

Approximate cost for 6T Lead Acid battery: $250-300/battery

12V - USMC "Improved Battery System (IBS)" Posted Date: 4/6/10, Solicitation Number: M6785410R5068

- **USMC intention is to develop "drop-in" replacement for NATO 6T batteries**
- **Initial purchase of 4 batteries with option to purchase a maximum of 2000 batteries.**
- **Solicitation specifies two types of batteries: High Energy and High Power**
- **Requirements:**
  - Both types: same dimensions and design as NATO 6T format
  - Key performance characteristics:

	High Energy IBS (HEIBS)	High Power IBS (HPIBS)
Voltage	12V	12V
Capacity	160 Ah	60 Ah
Cold Cranking Amps (30 sec, -19°C, >7.2V)	900A	2000A
Cold Cranking Amps (30 sec, -40°C, >7.2V)	400A	1000A

Discussion

- **A 28V 6T size Li-ion Battery provides greatest flexibility:**
  - A single 6T size Li-ion battery could in replace 2- 6T size lead acid batteries
    - Reduction of logistical footprint and minimize costs penalty
      - Initial Li-ion batteries are going to cost ~$15k to $20k each (~$0.20/Wh L.A. to >$5-6/Wh for Li-ion)
  - Silent watch kit: Single 28V 6T Li-ion units could be added in parallel for Silent watch capability.
  - More cost effective/efficient module size if we were to develop a hybrid system based on this modular design.
  - Would require a 12V supply for most applications
    - Providing a 12V is a concern in the current configuration (tapping into a single battery within a string
- **Recommendation would be to develop a specification similar to the anticipated characteristics estimated for the 28V prismatic cell 6T size Li-ion battery**
  - 25.2V nominal, >90Ah battery in a 6T size format

Summary

- **Army has a diversified energy storage portfolio supporting a wide-range of customers**
- **Army has and is actively seeking collaboration with other Government Agencies, and Commercial & Military OEM's**
- **Army has projects supporting several different functional areas in Energy Storage including: basic research, applied research & applications, manufacturing, battery management & safety, and alternative systems**
- **Army labs currently perform a wide variety of testing activities and has an established program for technology maturation and technology readiness level verification**
- **Army is actively involved in the development of battery standards and standard vehicle battery products**

Thank You