U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

Energy & Power Update

The National Academies of Sciences Engineering Medicine

Board on Army Research and Development (BOARD): "Powering The Army" Study

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FCDD-RLS-R

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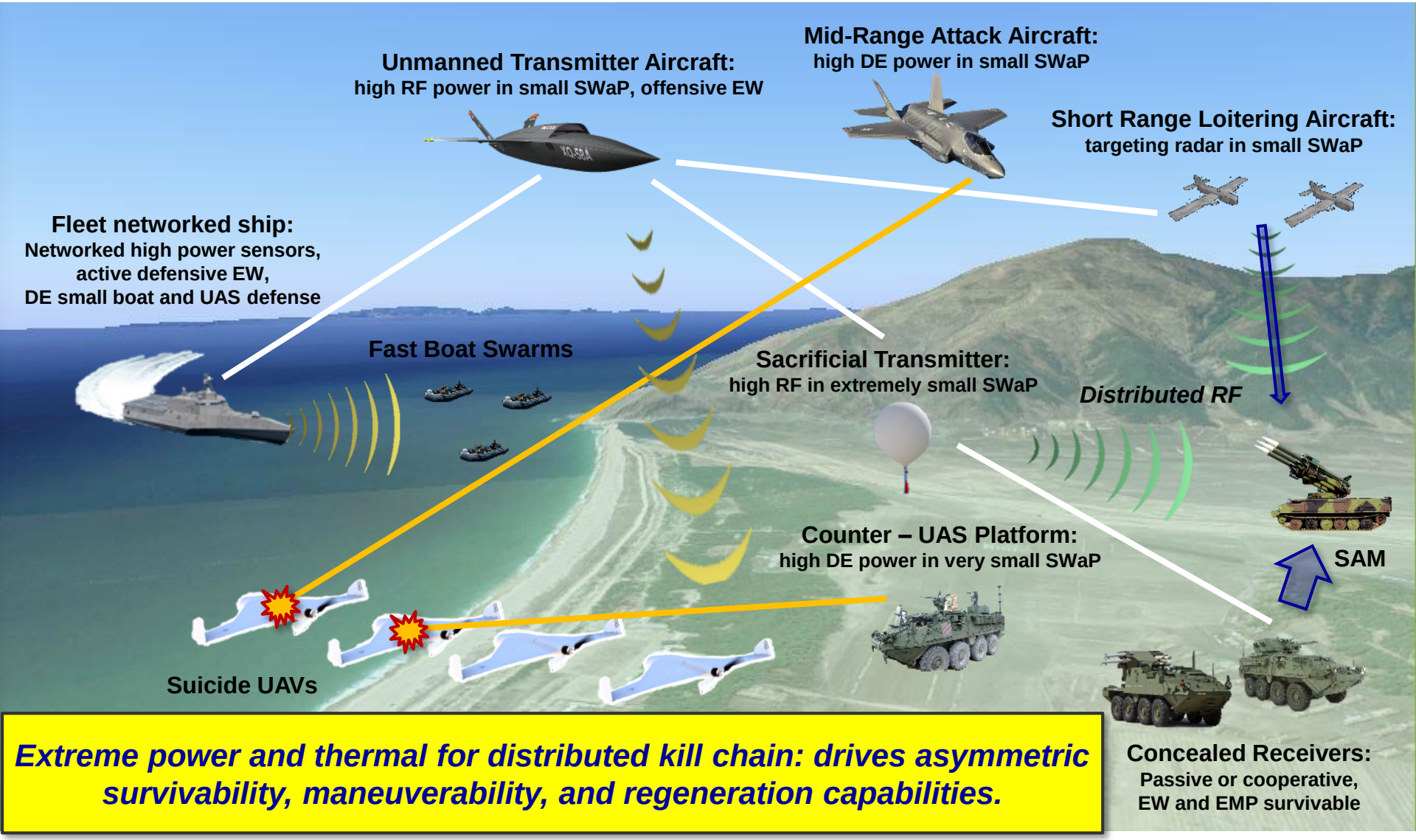
ENERGY & POWER: KEY ENABLER TO MULTI-DOMAIN OPERATIONS



Extreme power and thermal for distributed kill chain: drives asymmetric survivability, maneuverability, and regeneration capabilities.

ARMY ENERGY & POWER S&T PERSPECTIVE

What's driving E&P S&T?

- Greater electric power requirements for advanced weapons and C4ISR over longer stand-off distances & extended operations
- Unique military systems require dedicated DoD S&T; DoD S&T essential to leverage emerging commercial/OGA R&D
- Demand signals - increase operational reach, reduce operational risk via more effective and efficient use of energy

Enduring S&T Gaps

- Thermal limitations on capabilities, efficiencies, power densities
- High voltage, high frequency, high rate pulse power
- Energy densities to extend operational reach/ range, reduce energy resupply
- Power distribution agility, asynchronous modes
- Energy self-sufficiency/ sustainment

Current challenges to Army E&P S&T:

- Inconsistent prioritization of energy and power technologies needed to support and sustain current and future modernization efforts
- Resources (facilities, personnel, etc.) for platform energy and power systems integration
- Sourcing & retaining core competencies /institutional knowledge
- Balancing innovation space opportunities (in-house and out-of-house focus and capabilities)
- Scale up, technology insertion, supply chain dynamics

ENERGY & POWER: FOCUS FOR DOD/ARMY CAPABILITIES

DoD Energy & Power Community of Interest (DoD Reliance 21) Purpose:

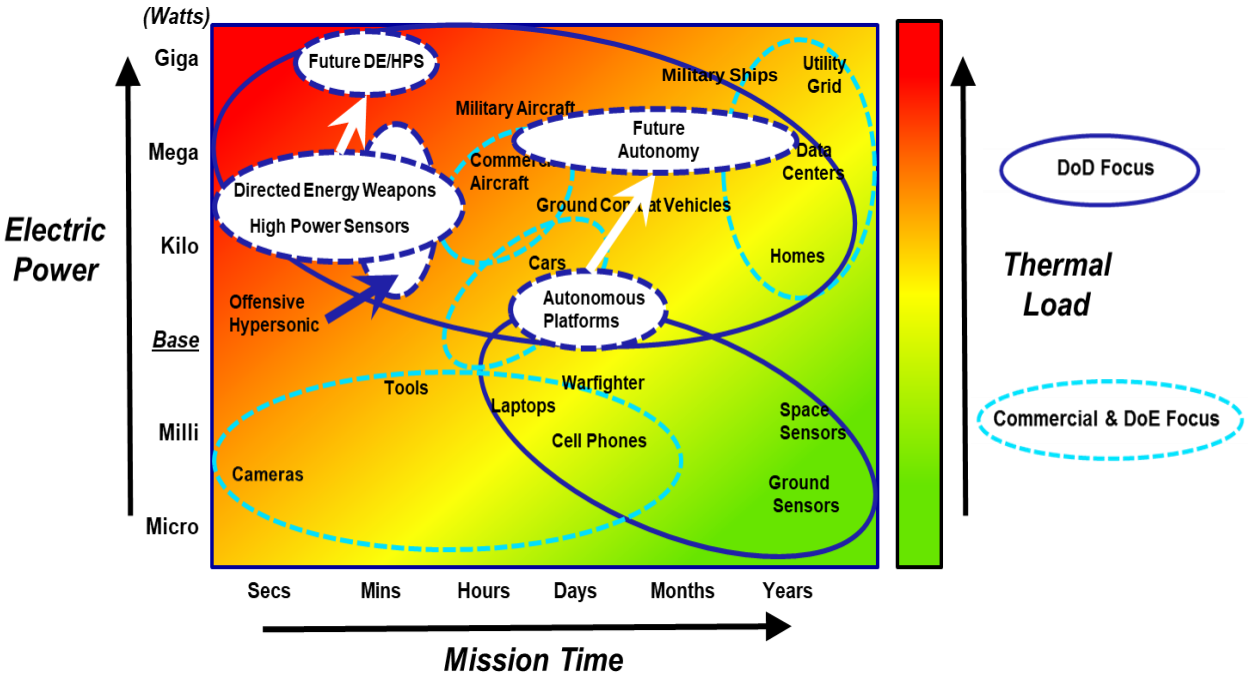
"Provide energy and power technologies to enhance operational capability and effectiveness of both manned and unmanned platforms and systems."

Warfighter Opportunity Areas (WOA)*

High Power Weapons and C4ISR
Energy Optimized Warfighting
Autonomous Systems Power
Resilient & Adaptive Power Architectures
(Emerging) **Multi-Domain Tactical Energy Independence**
(Emerging) **Hypersonic Power & Thermal Management**

Energy & Power CoI Technology Taxonomy

Power Generation/Energy Conversion
Energy Storage
Power Control and Distribution
Thermal Transport and Control
Electromechanical Conversion



Warfighter capabilities demand DoD-unique S&T focus

WARFIGHTER OPPORTUNITY AREA: HIGH POWER WEAPONS AND C4ISR

Objectives:

- Minimize size, weight, and thermal management systems of high pulsed power
- Develop power and thermal technologies with:
  - Higher baseline continuous power availability,
  - Longer high power pulse times,
  - Faster repetition rates, and
  - Longer lifecycles





Asymmetric capabilities for overmatch

Capability Opportunities:

- Greater operational reach of high power weapons and C4ISR
- Higher power sensors (e.g., radar) with both continuous and pulsed operations
- Stand-alone power and thermal management systems for legacy platforms
- Enable asymmetric capabilities on multi-domain, longer-range, and distributed platforms to:
  - penetrate and neutralize adversary A2AD
  - extend resilient, distributed ISR networks

Technical Challenges:

- Very high density power sources, energy storage, and devices for high rate pulsed power
- On-demand, high pulsed power M&S and controls
- Electric power & thermal management platform architectures for stochastic, high rate pulsed power demands
- Safety, repeatability, containment, and signatures of pulsed power systems

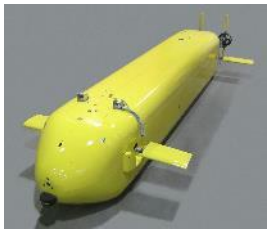
WARFIGHTER OPPORTUNITY AREA: AUTONOMOUS SYSTEMS POWER

Objectives:

- Enable next-generation autonomous systems across all domains with increased electrification:
  - High power mission capabilities
  - Extended operational reach
  - High reliability
- Low power system total ownership cost
- Energy self-sufficiency







Autonomous, distributed capabilities in contested environments

Capability Opportunities:

- Support autonomous capabilities across long stand-off distances
- Improve maneuverability beyond supply chains
- Provide cost effective, safe, and reliable distributed mission capabilities
- Enable distributed high power effects

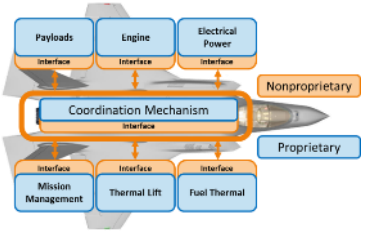
Technical Challenges:

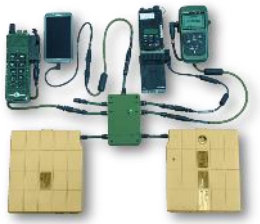
- High density, compact power and propulsion for long endurance in extreme environments
- On-demand, mission adaptable power
- Autonomous energy & power optimization
- High density, compact and rechargeable energy storage
- High reliability power systems

WARFIGHTER OPPORTUNITY AREA: RESILIENT & ADAPTIVE POWER ARCHITECTURES

Objectives:

- Intelligent power distribution and management
  - Self-aware power networks
  - Real-time adaptive control architectures
  - Power source flexibility
  - Architecture and systems interoperability
- Rapid recovery from degraded operations
- Maintainability





Increased survivability within rapidly changing missions

Capability Opportunities:

- Improved survivability while degraded
- Dynamic, on-demand reconfigurability
- Extended mission durations through optimal energy utilization

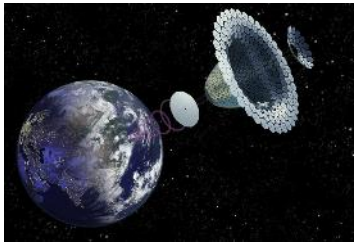
Technical Challenges:

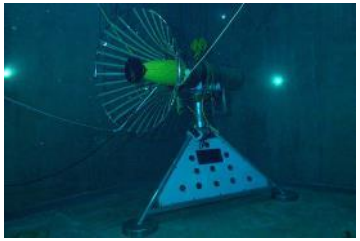
- Software, firmware, and hardware integration and interfaces
- Networked, intelligent energy control architectures
- Energy and operating environment situation awareness
- Electric network reconfigurability, scalability, and modularity

WARFIGHTER OPPORTUNITY AREA: MULTI-DOMAIN TACTICAL ENERGY INTEROPERABILITY

Objectives:

- Energy source flexibility
- Energy interoperability between systems and partners, manned and unmanned
- Distributed multi-domain energy awareness and management





Distributed and resilient multi-domain operations

Desired Capabilities:

- Extended missions through dynamic energy transfer
- Reduced logistics tethers by leveraging all energy sources across platforms/systems
- Universal, mobile energy sources

New research needed to achieve seamless energy in MDO

Expected Technical Challenges:

- Efficient and resilient power transfer
- Controls for cooperative autonomous energy behaviors
- Intelligent power systems for supply/demand management
- Cyber security and resiliency of data, controls, and interfaces

E&P: CRITICAL CROSS-CUTTING S&T FOR ARMY CFT OBJECTIVES

	E&P Gaps in CFT Objectives	Crosscutting E&P S&T
Long Range Precision Fires 	• Non-explosive, EMP-based effects • Long endurance for loitering munitions • High density energy for munitions • EM propelled munitions	• Advanced energy release and power circuits for high current, voltage and frequency requirements • High voltage WBG materials for power electronics • Thermal packaging and modeling
Next Gen Combat Vehicle 	• Future combat platforms need compact, high voltage, very robust power systems • Need to fully enable onboard DE, radars, active EW, and protection • Current powertrain/ 6T batteries insufficient to realize “silent watch”	• High voltage, rapidly rechargeable Li-ion batteries • Multi-fuel 300W SOFC for UGVs • High voltage WBG materials for high power electronics • AI/ML Power Control • Thermal packaging and modeling
Future Vertical Lift 	• Extend sUAS range through use of hybrid and fueled power sources (non-engine) • Improved battery safety • High power loads (DE/EW, electric/hybrid mobility)	• Multi-fuel 350W SOFC and TPV power sources • Non-flammable aqueous & high voltage Li-ion batteries • High voltage WBG materials for power electronics • Thermal packaging and modeling
Network APNT 	• Power hungry C5ISR/ electronics • Inefficient, bulky power conversion & distribution • “Always-on” power systems • Energy sharing across systems, domains	• AI/ML Power Control • Power sharing and offloading techniques • Wireless power transfer • Energy efficient electronics methods
Air & Missile Defense 	• Insufficient pulse power for high output DE • Power instability under fast transients • Thermally limited DE / Radars / Active EW • Slow recharge, limited energy storage	• Higher power, higher voltage architectures with fast conversion and switching • Ultra-high density energy and power and storage • WBG and UWBG materials for both power and front end • Adaptive optimal control for power and thermal mngmt
Soldier Lethality/ Training 	• No 24+ hour compact wearable power • No lightweight 24+ hour squad generation • Continuing multi-battery, power hungry Soldier Tactical Power systems	• Efficient Compact Portable Power: Multi-fuel TPV; Multi-fuel 300W SOFC • Aqueous, High Voltage & Rapidly rechargeable Li-ion batteries • Low Power Electronics

EMERGING RESEARCH POTENTIAL: ENERGY & POWER FOR ARMY CAPABILITIES

Future capabilities being considered require new perspectives and different focus for the E&P S&T Community

- **More robust power & thermal materials, components, systems: increased platform, weapon, and C5ISR design flexibility**
- **Ultra Wide Bandgap power materials/ devices: higher power/voltages; reduced SWaP; higher efficiency weapons, DE/EW, sensors**
- **Novel power architectures, distribution, & energy sharing: enable distributed, convergent, cumulative effects, sensors & mobility for multi-domain operation platforms; adapt to operational/environmental conditions**
- **Hybrid energy and power dense components; structurally integrated approaches: extend operational reach (range/duration); support multi-mode maneuver; reduce SWaP/ lightweighting**
- **AI/ML, autonomous energy & power: energy independent manned/ unmanned capabilities; robust M-M, M-U, U-U energy sharing**

Out-year Army Modernization enhanced by energy & power innovation

ARL ESSENTIAL RESEARCH PROGRAMS (ERP)

ARL core competencies aligned to Army's Modernization Priorities via Essential Research Programs

Human Autonomy Teaming
Next Gen Combat Vehicle

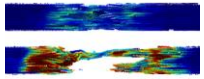
Quantum PNT
Network/C3I
APNT

Foundational Research in Electronic Warfare for Multi-Domain Operations
Network/C3I

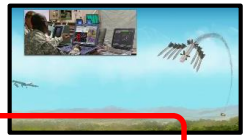
Convergence of Lethality, Protection, and Autonomy to Dominate Ground Combat
Soldier Lethality
Long Range Precision Fires

AI for Maneuver and Mobility
Next Gen Combat Vehicle

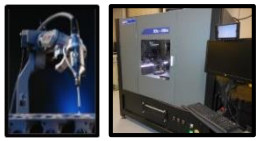
Physics of Soldier Protection to Defeat Evolving Threats
Next Gen Combat Vehicle
Soldier Lethality



Long Range Distributed & Cooperative Engagements
Long Range Precision Fires

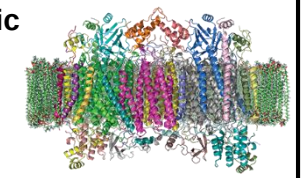


Manufacturing for Next Generation Munitions
Next Gen Combat Vehicle



Versatile Tactical Power and Propulsion
Next Gen Combat Vehicle
Future Vertical Lift

Transformational Synthetic Biology for Military Environments
Next Gen Combat Vehicle

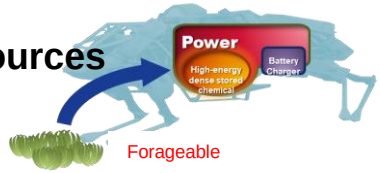


Discovery

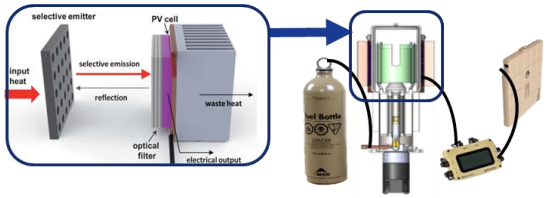
ARL ENERGY AND POWER FOCUS AREAS

Power Generation & Conversion

- Efficient Compact Portable Power: Multi-fuel TPV; Multi-fuel 350W SOFC
- Fuel synthesis from local resources or sunlight



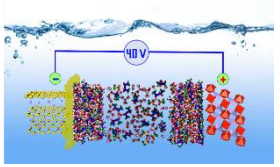
Foragable Raw Material



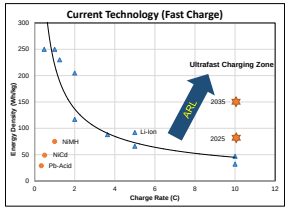
ARL Thermophotovoltaic multi-fuel portable power generator

Energy Storage

- Aqueous Li-ion battery that is safe, non-flammable, truly flexible
- High voltage (5V) Li-ion cathodes for 40% better rechargeable batteries
- Rapid recharge



4V Aqueous Li-ion

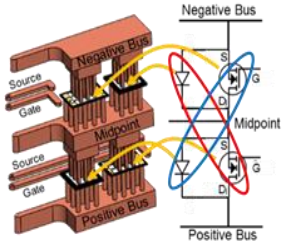


Rapid recharge battery objectives

Power Control, Distribution, and Thermal Mngmt

- Energy efficient electronics for low-power demand radios/devices
- Compact, thermally robust power electronics (ARL's ParaPower design tool)

ARL WBG Power Electronics



ARL ParaPower

Novel Energy

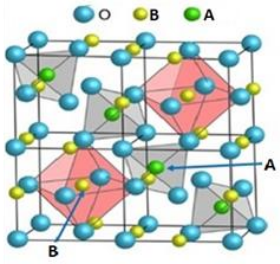
- Pulse power
- Wireless Power Transfer
- Advanced energy release and power circuits for high current, voltage and frequency requirements
- Energy scavenging
- Nuclide Power

ARL Compact High Energy Pulser

ARL: foundational research focused toward future Army capabilities.

ARL BATTERY RESEARCH

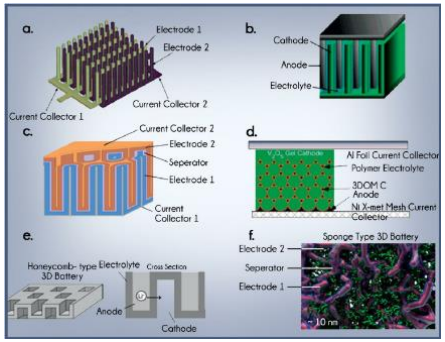
Electrochemical Storage



Spinel Electrolytes

Focus:

- (a) Fast charge energy storage;
- (b) Solid state lithium batteries
- (c) Higher voltage and energy density Li-ion batteries;
- (d) Li-ion capacitors;
- (e) Improved thermal and liquid reserve batteries for long shelf life applications.

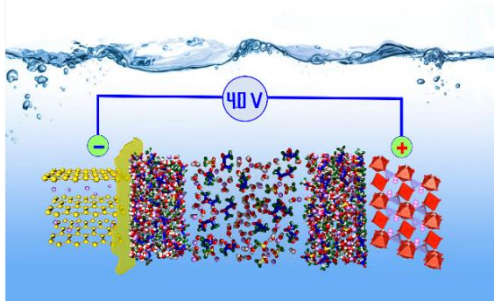


Designing 3D battery electrodes for improved energy density

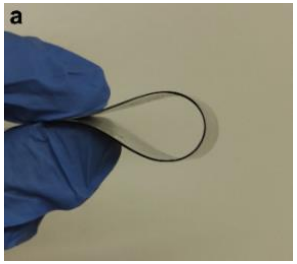
Aqueous Electrolytes

Focus:

- (a) Aqueous electrolytes;
- (b) Non-aqueous electrolytes;
- (c) Fundamental electrochemistries



ARL 4V non-flammable aqueous electrolyte for Li-ion rechargeable cells



Long-lasting power for Soldier, NGCV, autonomous systems, pulse power

AQUEOUS BATTERIES

Conformal to Soldier Gear

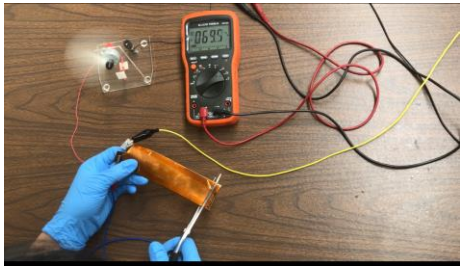
- Utility belt
- Combat armor
- Helmet conformal
- Boot

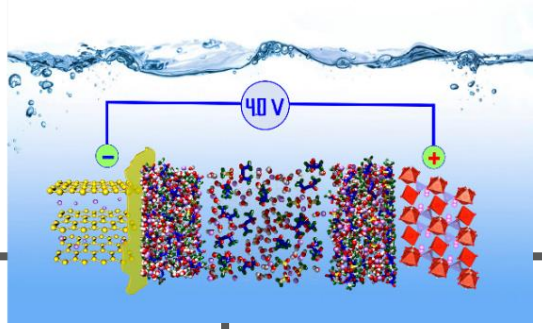
Integrated Helmet Battery

- Gel-based flex battery allows safe helmet energy storage for NVGs

Improved Safety

- Non-flammable
- Works while damaged
- Works under water
- Low/non-toxic components



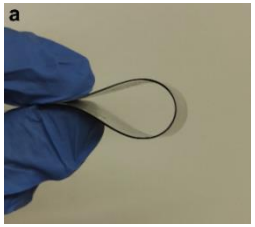


Integrated in platform structure

- Pouch cells form fit to vehicle frame
- Non-standard shapes
- Possibility of 3D printing & manufacturing at point of need

Aqueous Electrolytes

- Solves Li-ion battery flammability
- Poised for accelerated transition
- Addresses Army concerns: fast recharge while safe and energy dense



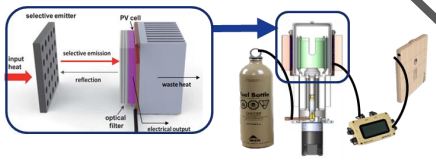
Long-lasting power for Soldier, NGCV, autonomous systems, pulse power

ARL ENERGY CONVERSION RESEARCH

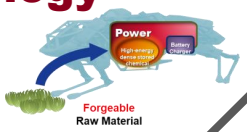
Compact Power

Focus: TPV;
Multi-fuel microreactor;
Energy conversion

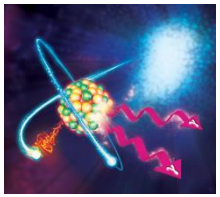
ARL Thermophotovoltaic multi-fuel portable power generator



Energy Foraging Technology

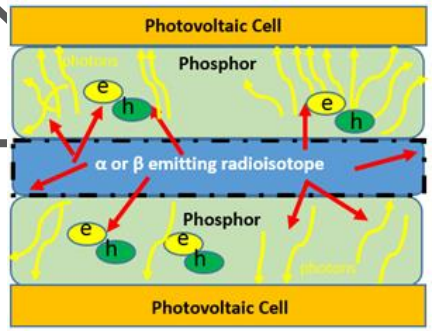


Focus: Catalysts for artificial muscle, combustion and energy foraging



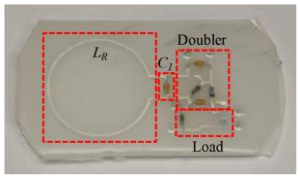
Energy Dense Materials

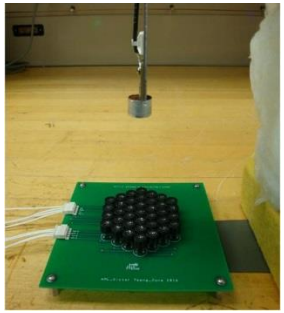
Focus: Long-lived & light weight power from radionuclides/isomers

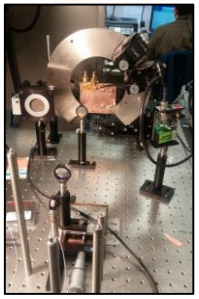


Microsystem Power

Focus:
(a) Very efficient power conversion;
(b) Wireless power transfer



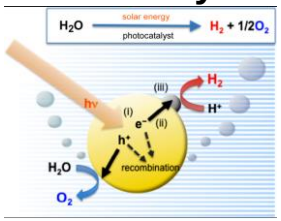




First Laser-to-Pyroelectric Power Transfer Experiment

Energy Conversion Technology

Focus:
(a) H_2 via Photoelectolysis
(b) Hydrocarbons via CO_2 Reduction
(c) Fuel cell materials, components and system designs



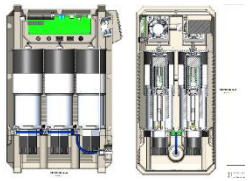
Fuel Cell powered Stalker UAS

Developing disruptive power science technologies to win the future wars without fuel resupply

SEAMLESS POWER OFFLOADING

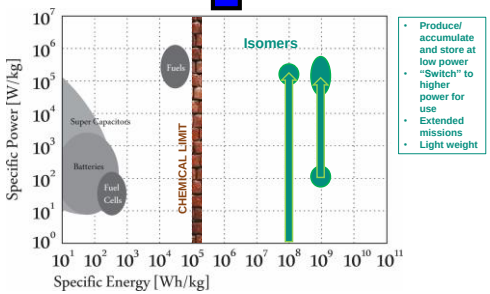
Cooperative Power Redistribution Seamlessly Among Heterogeneous Mixes of Manned and Unmanned Systems and Dismounts

Fuel-fired thermophotovoltaic (TPV)



Energy storage

Heat to electricity



Isomer power

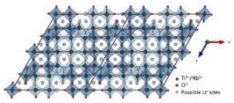
Position insensitive on platform wireless power transfer

Fast charge battery onboard

Representative SMET Platform

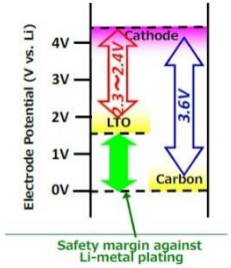
Cooperative Power Redistribution

Fast charging energy storage



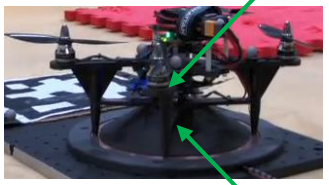
Structure of $TiNb_2O_7$

New anode materials



Potential window for oxide anode

Receiver



Transmitter

Through metal acoustic energy transfer or maximum power point tracking for inductively coupled wireless power

ARL: POWER INTEGRATION & ARCHITECTURE

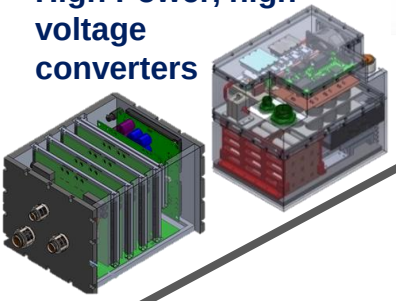
Extreme Power Switching

Focus:

- (a) Electrical power control, prediction and monitoring
- (b) Advanced energy release and power circuits for high current, voltage and frequency requirements

1 GW Marx Bank

High Power, high voltage converters

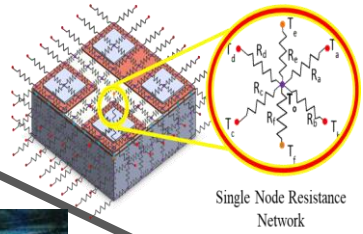


Power Distribution and Packaging

Focus:

- (a) Advanced evaluation, analysis, modeling and fabrication methods for power electronics modules
- (b) Thermal packaging and modeling

Co-Design / Co-Engineered Power Electronic Devices



Single Node Resistance Network

HEMP Effects

Focus: Joint E&P and E&RF effort for HEMP evaluation, analysis and upgrades for Army customers ensuring long haul communications systems are HEMP survivable.

HPS Generator

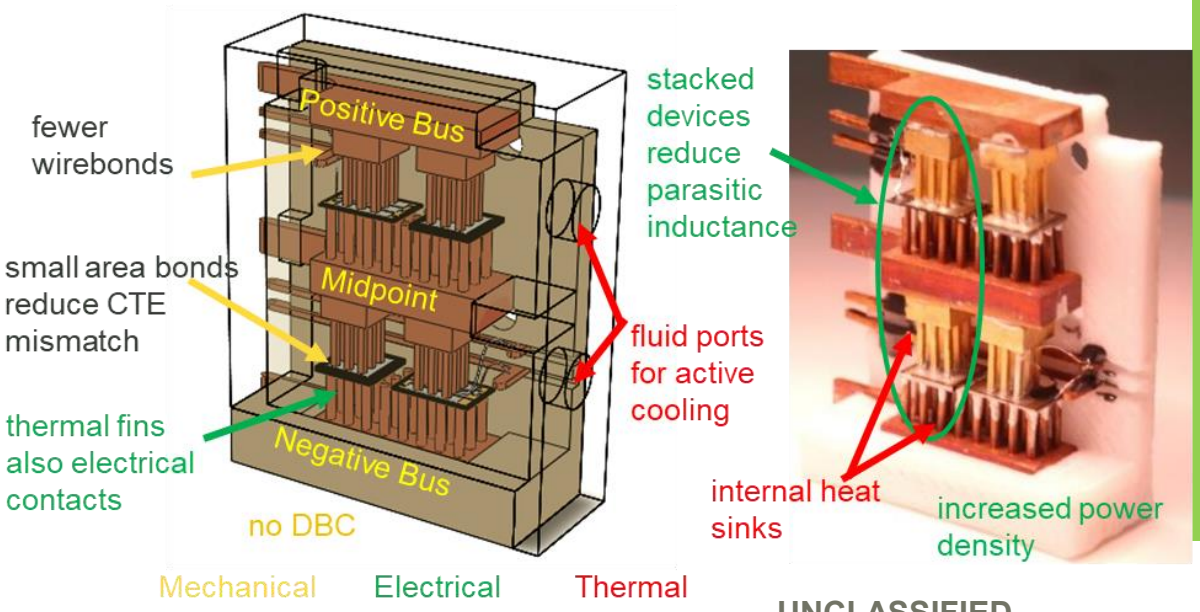
Mission effective electrical power for tomorrow's battlefield

POWER / THERMAL COMPONENTS

Packaging limits performance: Co-Design/Co-Engineering (eliminate single function components)

- **Transient Thermal Mitigation**
  - Designing for steady state leads to overdesign
  - Metallic PCM in direct contact w heated surface
  - CMs incorporated into ARLs ParaPower tool
- **High Voltage Design and Packaging**
  - New high voltage devices create the need for advanced packaging
- **Additive Manufacturing**
  - Custom power modules

Single-Half Bridge:



ARL's ParaPower Tool

- Compact 3D thermal resistance & stress network model
- Quickly analyze **large multi-disciplinary parameter** space
- >100X faster solution time with reasonable accuracy
- Simple node temperature and stress output

EXTREME POWER: ULTRAWIDE BANDGAP MATERIALS

High device breakdown strength (6x vs SiC):

- Highly dense (weight/volume), high voltage power
- High efficiency switch-mode power electronics:
  - >95% efficient DC/DC power conversion
  - Up to 8x higher density RF power amplifiers

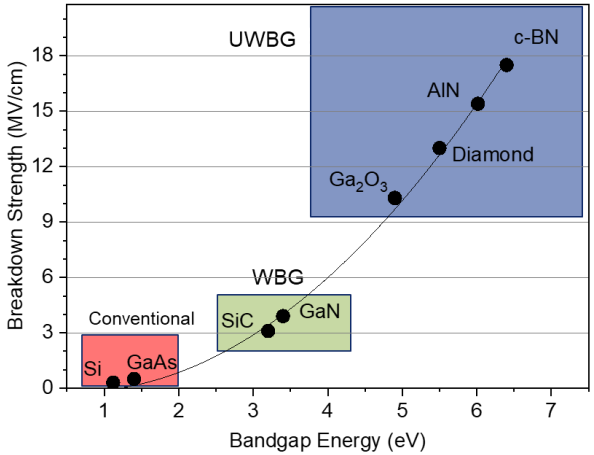
Faster switching / higher frequencies:

- Elimination of transformer magnetic materials & associated size and weight
- High speed, high power circuit protection

Higher maximum operating temperatures:

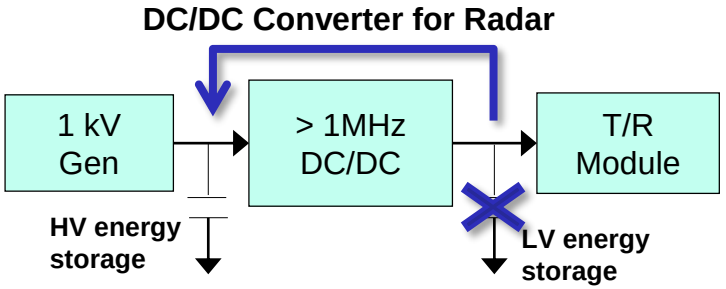
- Reduced system cooling needs (size & weight)
- Smaller thermal gradients = higher reliability

UWBG expands the Size-Weight-Power trade space to enable more capability in smaller platforms.



UWBG materials enable smaller size, efficient point-of-load power converters

- High voltage and high frequency power converter components reduce size and increase efficiency
- Elimination or reduction of passive components



Fast, UWBG Point-of-Load switch allows >100X smaller high voltage capacitor at source

ARL ENERGY & POWER: SUMMARY

1) ***ARL addresses opportunities beyond near-term needs (i.e., CFTs and PEOs)***

- **Develop new materials/ performance regimes vs. industry (driven by commercial viability)**
- **Army focused research enterprise – academics only do funded projects at the very basic level**
- **Technology thought leadership beyond Army current modernization focus (2028+)**

2) ***Army unique E&P requirements not being met commercially or from OGAs***

- **High power and high thermal systems necessary for DE, Active-EW, and high power radars are not yet sufficient to provide onboard, compact configuration**
- **Army (Soldiers and platforms) needs very safe, non-flammable, long-lived batteries; Army platforms need greatly reduce resupply and recharge to enhance mission duration for MDO.**
- **ARL focused on very high energy/power density generation, storage, distribution for constrained Soldier/platform volume/weight spaces**

3) ***E&P research enables more electrification → reduced SWaP-C, signature reduction, future capabilities***

- **Reduced fuel/energy logistics via energy efficiencies; holistic energy sharing among units**
- **Platform electrification enables enhanced mobility, lethality, protection, new mission packages**
- **Reduced thermal, acoustic, mechanical signatures**
- **Higher voltage/power architectures – less space/weight, enables pulse/high power effects**

ARL is the ONLY organization researching needed energy and power material, device, and component based solutions for future Army systems and capabilities.