Army Power & Energy: S&T Focus

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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Outline

- Army Power & Energy Trends
- TRADOC Warfighter Outcomes
- Power & Energy TFT Taxonomy
- Power Regimes: Definition
- Underlying Technologies
- Power Regimes
    - Soldier Power – attributes, technologies
    - Mobile Power – attributes, technologies
    - Platform Power – attributes, technologies
- Summary

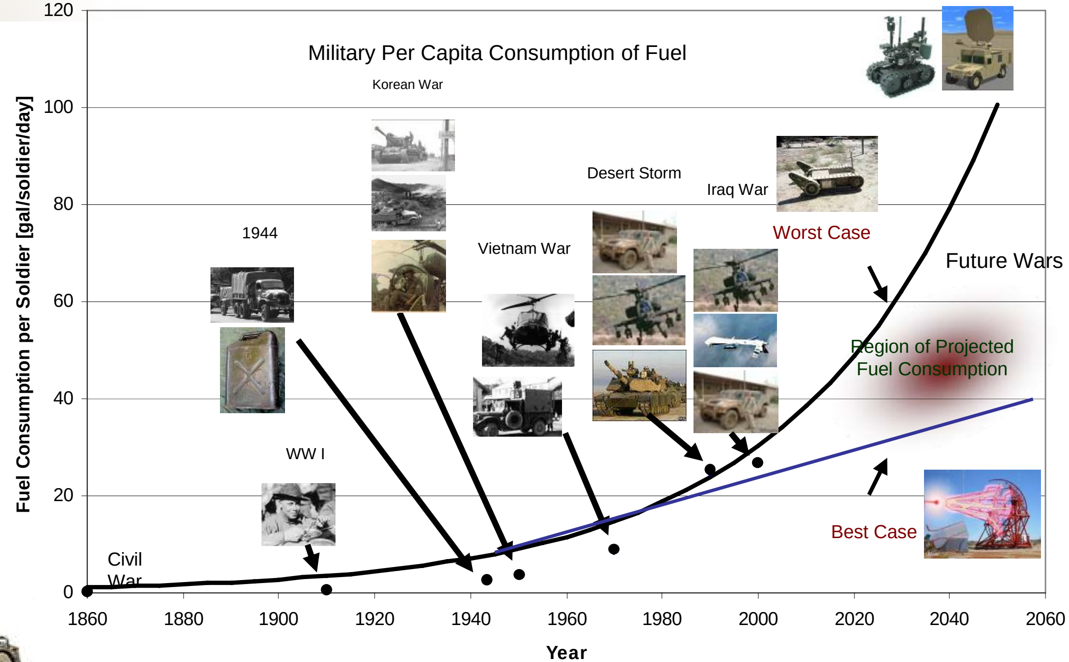
The Challenges

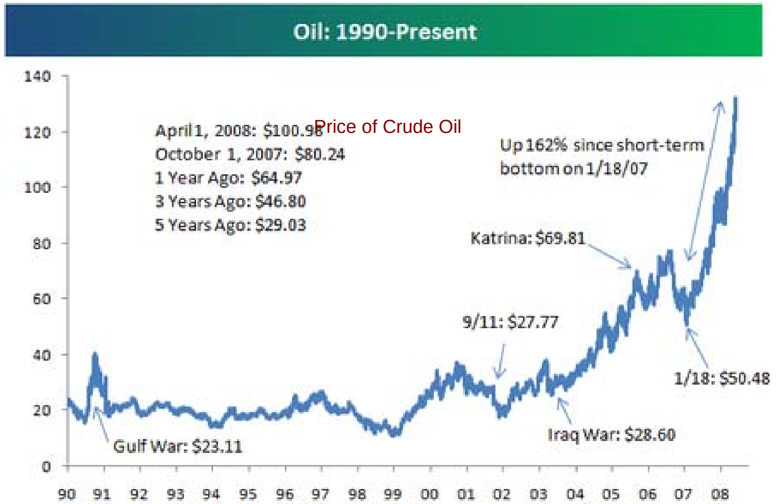
Battlefield consumption of energy increasing
- New C4ISR technologies
- IED Defeat Systems
- New weapons (EM guns, lasers)

Energy security problematic
- Cost of fuel skyrocketing
- Alternative sources sought – wind, solar, bio-mass, waste to energy

Operational issues
- Battery usage & limitations – energy & power density
- Demand for auxiliary power on-board vehicles
- Emphasis on silent ("quiet") watch
- Unmanned vehicles (air/ground)
- Unattended sensors
- Inefficient management/ distribution of power
- Demand for soldier-wearable power

Increased emphasis on system power metrics
(KPPs, low consumption components)





TRADOC - Alignment of Big 5 Integrated Warfighter Outcomes

S&T TOPIC AREA AND INTEGRATED WARFIGHTER OUTCOME STATEMENT		**From FY09 Warfighter Outcome Workbook (Dec 07)**		
		Force Operating Capability (FOC)	**Priority Within FOC**	**Warfighter Outcome Title**
Power & Energy * ** ***	Provide enhanced agility to operate worldwide by **reducing by half, the weight and volume of fuel** associated with powering the force. Combat platforms require **up to 30 MJ of pulsed power for lethality and 20 percent increase in continuous power** to enable superior tactical mobility, speed and **an excess capacity for on/off board electrical power use while increasing fuel economy by 40 percent.** Emerging electrical components and systems require **dismounted Soldiers to possess a fourfold increase of available power, above current 12.3 Watts/Hr, at half the tactical weight.**	Mounted/ Dismounted Maneuver	4	**Alternative Power for Dismounted Soldiers** ***
			5	**Alternative Power for Platforms** **
		Maneuver Sustainment	10	**Increased Fuel Efficiency** *

Power & Energy Technology Focus Team Current Scope

DEFINITION: Power & Energy includes systems/technologies that generate, store, distribute, condition electrical energy, or produce/distribute non-propulsion power.

Focus Areas

- Energy Storage
- Power Generation & Conversion
- Power components for DE Weapons
- Power Control & Distribution
- Thermal Management

Air Systems
Rotorcraft & UAS

Ground Systems
GCS &TWV, UGV, Water Gen

Soldier Systems
Dismounted, Portable P&E

Effects
DE P&E – Lethal. Non-Lethal

C4ISR
Sensor, Network, Distributed P&E

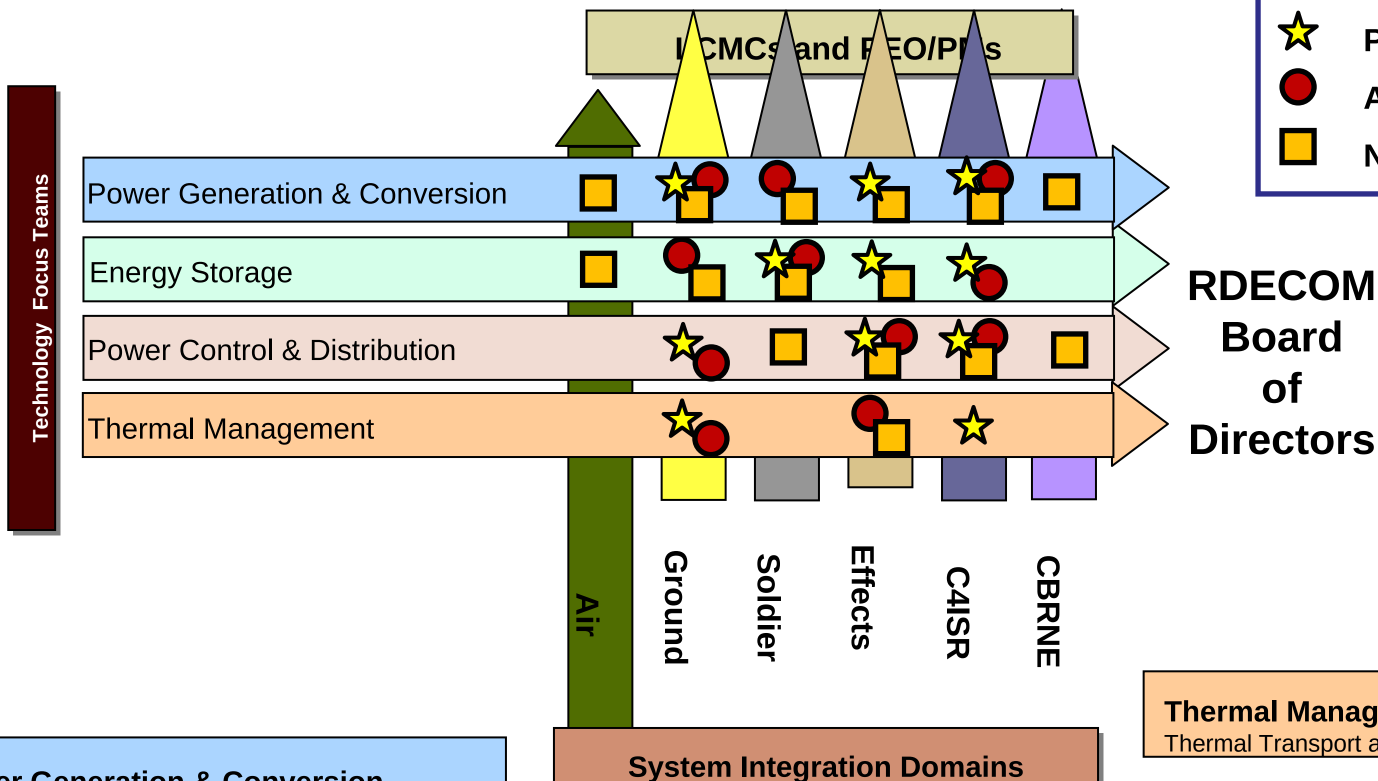
CBRNE
Environmental, Sensor P&E

Related Areas

- Explosives/ propellants for Munitions (Lethality TFT)
- Non-Electic Propulsion (Mobility & Logistcs TFT)
- Fixed & Grid-Based Power (COE)
- Directed Energy Weapons (HEL, RFDE, EMGun) (Lethality, Protection TFT)
- Bulk Class III Fuels (Mobility & Logistcs TFT)

Multiple Technologies, Multiple Applications

Power & Energy
Technology Integration Taxonomy



★ **Proposed ATOs**
● **Active ATOs**
■ **Non-ATO Programs**

Synchronized and Aligned Command Technology Solutions

Thermal Management
Thermal Transport and Control

Power Generation & Conversion
Fuel Cells and Reforming
Generators (engines, Stirling, alternators)
In Situ Energy Conversion (PV, wind, Waste to Energy)
Power MEMS
Others (actuators, motors, non-propulsion, energy efficiency)

Energy Storage
Primary Batteries
Rechargeable Batteries
Thermal/Reserve Batteries
Capacitors (Pulse, Continuous, Ultracaps)
Packaged Fuels and Fuel Processing

Power Control & Distribution
Power Switches and Electronics (pulsed/continuous)
Power Converters & Inverters
Power Distribution
Intelligent Power Management
Magnetics/Other (Superconducting Storage, Magnetic Materials, Inductors)

Underlying Technology Example
Power Generation: Fuel Cells

Soldier Power

On-soldier & Battery Charger Applications

- Competing approaches
- Direct Methanol & Reformed Methanol Fuel Cells
- Hybrid solutions

Reformed Methanol

25W Ultracell

IdaTech 250W

20W Smart Fuel Cells (SFC)

Direct Methanol

Giner DMFC for Battery Charger

Solid Oxide Fuel Cells

ADVANTAGES
- Sulfur/CO resistant
- Fuel flexibility
- Co-generation potential

DISADVANTAGES
- Ruggedness -- fragility
- Slow startup times
- High temperatures

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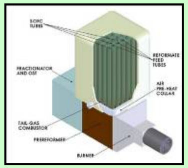
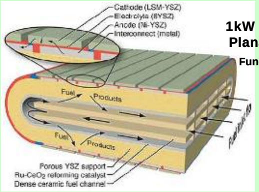


50W Microtubular Propane SOFC
NanoDynamics
(BAA, "On-the-Move" Demo, 2006)



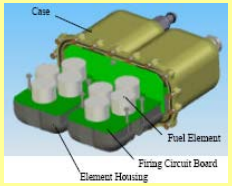
1kW Logistic-fueled Planar Segmented
Functional Coating Technology

Alternative Fuel & Storage (H2)

Exploring novel alternative fuels & storage.

***Technology Areas of Interest*:**
- **Boranes**
- **Hydride storage**
- **Nanotubes**
- **Acid- Alkaline Membranes**

30 W Protonex Sodium Borohydride



Ensign Bickford Ammonia Borane Fuel Cartridge (10g H2, 12hrs @ 11 W)

General Atomics
Ammonia Borane PEMFC

Hydrogen Storage Cartridge

Fuel Cell System

Pellets

Logistic Fuel Reformation (JP8)

5kW Logistics Fuel Reformer
(Regenerable S removable & CPOx reformer)
GD / Aspen

Issues
- **JP8 complexity**
- **ATR/POX/SCW**
- **Infant technology**
- **Little commercial interest**

Supercritical Water Reformer JP8)
Radian, Inc
(w/U. Missouri)

Underlying Technology Example
Energy Storage: Batteries

Low ⟷ High

Investment Priority: High ⟷ Low

Commercial Market

Lead Acid Rechgble (SLI) O
Vehicle, critical backup

Lead Acid Rechgble (HEV) C
Vehicle, deep cycle applications, low cost electrical storage

Alkaline Primary S
Non-critical applications

Ni-MH Rechargeable S
Soldier power, HEV

Li-MnO_2 Primary S
Soldier power, sensors

Zinc-air Primary S
Soldier power, sensors

Li-FeS2 Primary S
Soldier power, sensors, long shelf life applications

Commercial Chemistry requiring Military Adaptation

Hi Power Li-Ion Rechargeable for HEV O,C
SLI, HEV, critical backup

High Energy Li-Ion Rechargeable S
Soldier power, persistent surveillance, sensors

Li-(CF)x Primary S
Soldier power, sensors

Ni-Zn Rechargeable O,C
SLI, HEV, critical backup

Military Unique Chemistries

Li-Air Primary S
Soldier power, persistent surveillance, sensors

Liquid Reserve
•Electric fuzes for artillery, mortar, missiles, submunitions

Thermal Reserve
Electric fuzes for artillery, missiles

Pulse Power Li-Ion Rechargeable P
Weapons, FCS, 600V battery pack

Li-SO2 Primary S
Soldier power, sensors

S: Soldier/portable; C: Veh Continuous; P: Pulse; O: OBVP/Export

Power & Energy Strategy

SOLDIER

Requirement:
72 Hour Missions

Technologies: High Energy Batteries, Hybrid Power Sources, Photovltaics

MOBILE

Requirement:
Silent Power

Technologies: Fuel Cell APUs, Reforming, Power MEMS

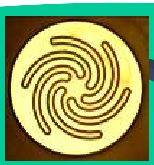
PLATFORM & WEAPONS

Requirement: Platform Surge Power , Weapon Pulse Power

Technologies: High Power Switching & Conditioning; Intelligent Power Management, Integrated Thermal Management

DOMAINS:	Soldier, C4ISR	C4ISR, Air, Ground	Ground, Effects
	MicroWatts to 10s of Watts	100s of Watts to 100s of kW	Up to 1000s of MW

Soldier Power Regime: Attributes & Technologies (Soldier, C4ISR, Effects, CBRNE SIDs)



Near Term (2011)

Attributes

- Fuel Cells: 30 W/kg, 1000 Whr/kg
- Packaged fuels
- Primary Li: 200 Wh/kg, 40 W/kg, -30o to 70oC
- Metal/air: 300 Wh/kg, 10 W/kg, 10o to 70oC
- Rechargeable Li-ion: 150 Wh/kg, recharge in hours

Technologies

- DMFC, RMFC
- Primary Li/MnO2
- Zn/air primaries
- Li-ion cells with carbon anodes

Mid Term (2017)

Attributes

- Fuel Cells: 80 W/kg 40% efficient, packaged/processed fuels
- 100 W/cc (1kW/kg) engine, 30% efficient
- Primary Li: 400Wh/kg, 20 W/kg, -10o to 70oC
- Metal/air: 300 Wh/kg, 10 W/kg, 10o to 70oC
- Rechargeable Li-ion: 120Wh/kg, recharge in minutes

Technologies

- DMFC, RMFC, fuel reforming
- Fuel atomization
- Primary Li/(CF)x, Li/air primaries
- Li-ion cells w/ rapid-recharge anodes

Far Term (2027)

Attributes

- Fuel Cells: 120 W/kg 50% efficient
- Multiple fuels
- Micro Power generation
- Primary Li: 500 Wh/kg, 40 W/kg, -30o to 70oC
- Metal/air: >700 Wh/kg, 20 W/kg, -10o to 70oC
- Rechargeable Li-ion: 200Wh/kg, recharge in minutes

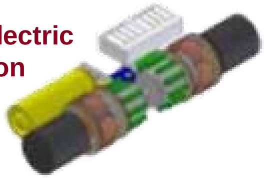
Technologies

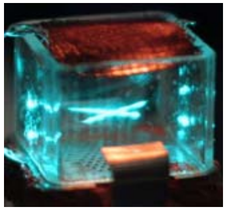
- DMFC, RMFC, Alkaline FC
- Micro fuel cells, PZT MEMS, Direct conversion, MEMS fuel control
- Multi-fuel FCs and engine systems
- Primary Li with doped fluorocarbons
- Li/air primaries, Li-ion cells with rapid recharge

Soldier Power Regime: Micro Power

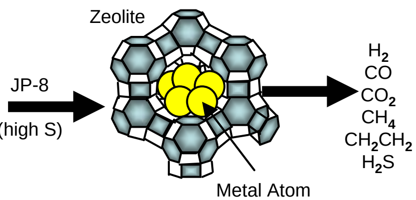
Fuel Atomization

Thermal-to-Electric Conversion

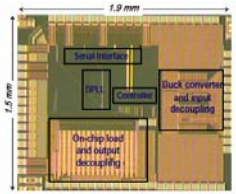




Efficient Combustion



Catalyst Materials



Power Management

Payoff: *Near term*

- **Efficient MEMS-based burners for integration with Stirling engine squad battery charger (150-250W)**
- **Miniature power converters for efficient hybrid system**

Payoff: Far term:

- **Long-lifetime catalytic micro-combustors with integrated thermoelectric generators**
- **Advanced power management of autonomous systems**

Objectives:

- **Provide Warfighter with small, light weight power sources maximizing specific energy for Soldiers, Soldier systems & sensors.**

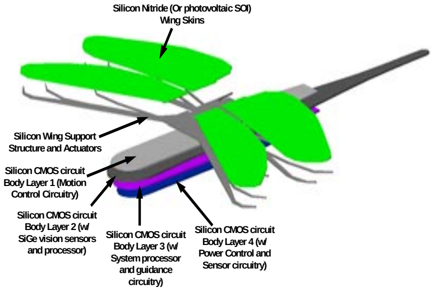
Accomplishments:

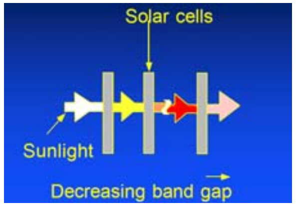
- **Demonstrated low power, microfabricated fuel atomizers from 1 - 200 mL/hr (<500 W_{elec} range)**
- **Integrated atomizer / catalytic micro-combustor operating at 270 MW/m^3**

Technical Approach:

- ***Leverage MEMS expertise to develop efficient power generation & management components***
  - ***Micro-fuel / air control – efficient fuel atomization and mixing is required for miniature combustors***
  - ***Catalytic combustion – heavy fuels (i.e. JP-8) require new sulfur tolerant catalyst materials for long life***
  - ***Power management – intelligent power conversion & management of hybrid systems improves efficiency***

Soldier Power Regime: PhotoVoltaics





Payoff: Near Term

- Less costly, more efficient Solar panels to the field
- Lower Weight and Volume
- Under one sun illumination, power densities ~ 200W/m2

Payoff: Far Term

- Under one sun, illumination up to 400W/m^2
- Creating "Smart Skins" for Army systems consisting of monolithically integrated thin photovoltaics with power conditioning circuits and thin film batteries
- Potential efficiencies >30%

Objectives:

- High efficiency PV and TPV, crystalline and flexible, for remote power, expeditionary forces, Soldier aux power, un-attended/ autonomous sensors & systems
- Novel micro PV structures integrated with batteries and interconnect schemes for micro devices

Accomplishments:

- Fabricated (5 x 5) 1mm^2 solar cell arrays, yielding 4 volts at 5 ma/cm^2 current
- Initial un-optimized efficiencies of 14%.

Technical Approach:

- Develop substrate removed muli-color tandem photovoltaic arrays with novel interconnects to develop high voltages or currents

One Color Inverted GaAs PV that is 20% efficient on a flexible Substrate Offers 5-times higher power than existing Army PV power systems

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DoD Wearable Power Prize (WPP) Competition

Grand Challenge Goals:

- Wearable Power System that provides 20 watts of average power with 200 watt peaks for 96 hours weighing 4kg or less (480wh/kg)
  - Inspire students, academia, private inventors, and industry to leverage resources and compete using innovative ideas and approaches
  - Reach non-traditional DoD performers by lowering barriers for participation

Capstone Event 22 Sep – 4 Oct 2008

Marine Corps Air Ground Combat Center (Twentynine Palms, CA)

DoD Prize Execution Team

DDR&E DUSD(LABS) –Sponsor
Army (ARL Lead), Navy, and Air Force

Competition Funding ($5.7 M)

$1,750,000	Prize Purse
$2,550,000	Prize Execution
$1,415,000	Service Cost Share

Wearable Power Prize Results

- **Competition metrics were met by 5 Teams:**
  - **1st Dupont/Smart Fuel Cell, $1M Prize**
  - **2nd AMI, $500K Prize**
  - **3rd Jenny 600S, $250K Prize**
  - **4th Ultralife 5th Ultracell**
- **7 Teams demonstrated energy densities > 480 Watt-hour/kg**
- **169 Teams entered, 108 Teams submitted Fuel Plans, 55 Team submitted System Descriptions and 20 Teams competed at Twenty Nine Palms**


DuPont/SFC

AMI



Jenny 600S

DoD Wearable Power Prize Competition Outcomes and Way Ahead

- Uniquely demonstrated highest energy density wearable power systems using realistic Warfighter multi-day load profiles
  - Goal: 480 Whr/kg at < 4 kg   Demo: up to 790 Whr/kg at 2.4 kg

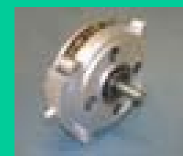
- Significant industrial investment - multiple teams spending $1M plus
  - New technologies revealed including materials, devices and system concepts
  - Material approaches from non traditional players (Russia)
  - Wide variety of proposed fuels

- Value to OSD, Services, and Army
  - New interest in S&T challenge prizes and P&E technology
  - Collaboration, joint-service engagement and assessment by the DoD P&E community
  - Raised awareness at Service and National leadership levels
  - Outreach component - exposure to DoD Science and Engineering

- Value to Competitors
  - DoD funded, independent laboratory grade test and evaluation in field-like environment
  - Access to DoD Professionals (Civilians and Warfighters) –
    - Direct feedback and real-time technical assessment from key service SMEs in P&E
  - Exposure to other teams – collaboration and networking opportunities
  - National and international publicity

  - Initial Follow-on Actions:
    - Review S&T portfolios for adequacy, opportunities in underlying technologies
    - Assess DoD, Army interest in packaged fuels, qualification
    - Outreach to non-traditional players, new approaches

Mobile Power Regime: Attributes and Technologies (C4ISR, Ground, Air SIDs)



Near Term

Attributes

- High power density (50W/L), quiet power generation (<50 dBA @ 7m)
- Packaged / processed fuels
- Fuel Cells, 40 W/kg 35% efficient
- Hybrid energy storage

Technologies

- Modified COTS engine generators
- Solid oxide fuel cells
- ATR, CPOX, Steam Reforming, Plasma
- Hybridized primary/ rechargeable batteries

Mid Term

Attributes

- Silent power generation (silent @ 10m)
- 100 W/cc (1kW/kg) Power Density, 30% efficient
- Fuel Cells 80 W/kg 40% efficient
- Rapid charge/discharge

Technologies

- Novel, very high power density engine generators
- Compact small engine/generators
- Reformer based fuel cells (SOFC) generators, ATR, CPOX, Steam Reforming, Plasma
- Rapid recharge Li-ion anodes for hybrid sources

Far Term

Attributes

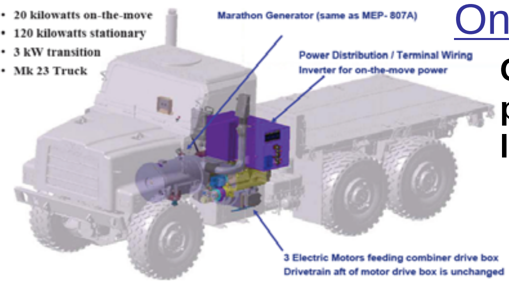
- Silent power generation (silent @ 50m)
- Fuel Cells 120 W/kg 50% efficient
- Advanced air cooling

Technologies

- Multi-fuel fuel cells (SOFC, PEM) and engine systems
- Compact high power generators/alternators
- Advanced magnetics for generators/ alternators
- Micro air coolers with laminar flow

Mobile Power Regime: OBVP/Under-Armor APU

On Board Vehicle Power



OBVP: additional platform power - increased mission loads (eg idle, low speeds)

Auxiliary Power Units

APUs: Power for sustained engine-off missions

Pay Off: Near Term

- **Abrams UAAPU: extended engine-off mission capability**
  - **Reduce fuel consumption by 4,300 gallons* per day per brigade**
  - **Save over $86,000 per day ($20/gallon JP-8) or 18 miles range.**
- **High power alternator upgrade kits**
  - **Increased power at idle and low speeds**
- **OBVP Demonstrators**
  - **USMC / ONR - 120kW MTVR (MAY 2008)**
  - **PM Stryker / TARDEC – 70 kW CMPS Stryker (AUG 2008)**

Pay Off: Far Term

- **Family of common APUs for ground vehicle fleet**
- **JP-8 fuel cell generation system - silent power demo**

***M1A2 System Spec defined battlefield day (12 hours engine-off)**

Objectives:

- **Enhance OBVP for operational platforms**
- **OBVP for fleets - reduce idling and fuel consumption**
- **Under-Armor APUs: engine-off, silent watch**

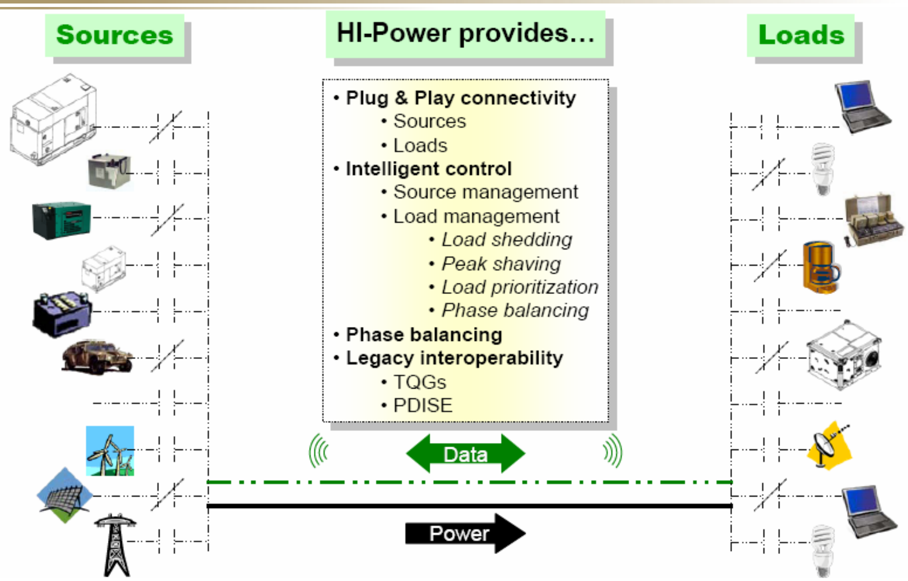
Accomplishments:

- **Fielded OBVP alternator upgrade kits (HMMWV/RG-31)**
- **Gen III rotary APU for Abrams - May 2009 (on-vehicle demonstration and user assessment)**
- **Advanced power generation system for MRAP block upgrade for FUE 4th QTR FY09**
- **Phase I demonstration of idle reduction APU for HTV**

Technical Approach:

- Small engine/ generator development
- CPOX fuel reforming, sulfur removal
- Fuel and combustion control
- Advanced magnetics, structural materials
- Idle reduction techniques
- Intelligent power management

Mobile Power: HI-Power (Hybrid Intelligent Power)



Pay Off: Near Term

- Potential "spin-off" of controls and electronics
- Potential integration into Net-Zero Plus JCTD
- Standard protocols for power distribution systems

Pay Off: Far Term:

- Reduce fuel consumption by up to 40%.
- Increased Force Protection via reduced fuel convoys
- Reduce generator maintenance
- Improved tactical grid reliability
- Energy sharing between soldier, generators, vehicles, forward operation bases

Objectives:

- Seamlessly integrate generators into electric grid
- Reduce fuel consumption by up to 40%.

Accomplishments:

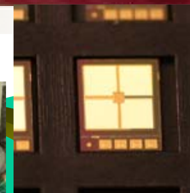
- Leveraged previous RDECOM/CERL SBIRs
- Three technology development contracts (FY08) (deliverables FY09)
- Issued revised BAA for FY09
- Established test bed and support equipment

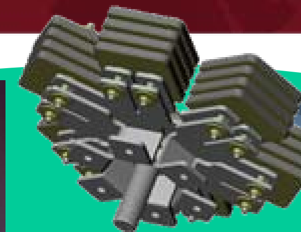
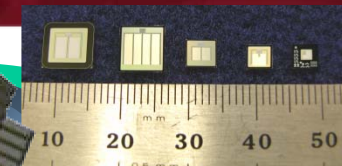
Technical Approach:

- CERDEC Technical Lead; PM-Mobile Electric Power POR; Joint IPT Established
- Integrate competing component technologies
- establish protocols and standards; performance specifications
- Bridge architecture gaps
- competitive down select (FY10-13); final development, qualification; fielding after FY14

Platform & Weapons Power Regime (Ground, Effects SIDs)



Near Term

Attributes

- Power Electronics w/ 80o C coolant, 1200 V continuous
- Room temp, 10 kV pulsed
- Power Density: DC/DC: 5 kW/l; AC/DC: 40 kW/l
- Rechargeable Li-ion: 150 Wh/kg, recharge in hours
- 80oC Water/Ethylene Glycol, 200 oC air cooling

Technologies

- Silicon, SiC switches
- Nanocrystalline magnetics
- Li-ion cells w/ carbon anodes
- Capacitors w/ metallized polypropylene film, 125o C

Mid Term

Attributes

- Power Electronics w/ 100o C coolant, 1200 V continuous
- 80o C, 10 kV pulsed
- Power Density: DC/DC:8 kW/l; AC/DC: 50 kW/l
- Rechargeable Li-ion: 120Wh/kg, recharge in minutes
- Capacitors: msec discharge, 10J/cc, T<100o C
- 110oC Water/Ethylene Glycol; 250 oC Air cooling

Technologies

- SiC high current devices pulsed and continuous
- Nano-particle magnetics
- Li-ion cells with rapid-recharge anodes, high temp capacitor films
- Micro Channel designs

Far Term

Attributes

- 150 oC coolant, 1200 V continuous
- 120 oC, 10 kV pulsed
- Power Density: DC/DC:10 kW/l; AC/DC: 60 kW/l
- Rechargeable Li-ion: 200Wh/kg, recharge in minutes
- 150oC Oil cooling 300 oC Air Cooling

Technologies

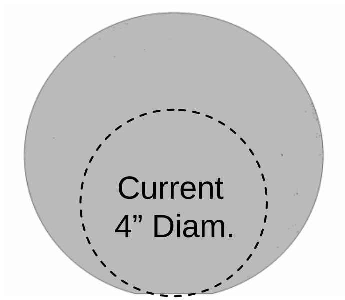
- Next gen devices (GaN, diamond)
- Bulk nano-lattice magnetics
- Bulk ceramic capacitors
- Bi-directional solid state/MEMS breakers
- Li-ion cells with rapid recharge, high voltage anodes and cathodes
- Double sided micro channels, MEM based spray cooling, micro air coolers

Platform & Weapons Power: Power Switches

EM Gun

HPM/DE Systems

Mobility Systems



6” Diam. SiC Wafers

SiC Ultra-High Power Large-Area Switches

Payoff: Near term

High temp. compact converters that will enable reliable operation at 80-90 C within weight/size and cost constraints

Payoff: Far-term

- **Advanced platform capability with reliable operation at 100-120 C**
- **Advanced capabilities at reduced power and cooling system size and cost**
- **Limp home capability**

Objective:

Provide high-temperature high-power SiC devices for high-power density high-efficiency power converters for platform mobility, survivability, and lethality systems.

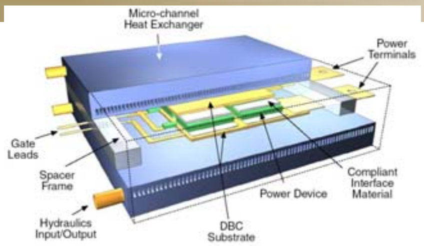
Accomplishments:

- **Demonstrated SiC 10 A switches in 10/20 kW TRL-4 inverter at 110-150C.**
- **Demonstrated SiC 20 A switches in 60/80 kW inverter at 80 – 120 C, TRL-4.**
- **Operated paired SiC MOSFETs and diodes up to 80 A rms (200 A peak) for 20 hours at 150-190 C junction temp.**

Technical Approach:

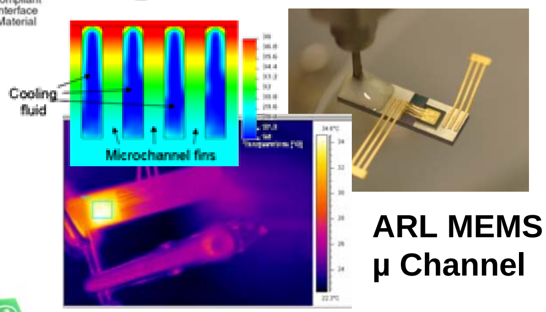
- **Develop larger diameter material (current 4”, future 6”)**
  - **Ultra large area SiC devices**
- **Decrease defects in starting material & in processed MOS gating structures**
- **Develop ultra-large area device designs & processes**
- **Enhance identification of process- and stress-induced defects in SiC devices**
  - **Focus: MOS gating, device termination structures**
- **Screening, burn-in, and high-temperature accelerated reliability determination methods.**
- **Investigate next generation semiconductor materials (GaN)**

Platform Power: Component Thermal Management



Advanced Modules

ARL Wide Gap Off-set Channel



ARL MEMS μ Channel

Thermal Management

Payoff: Near term

- 2-5X module volume reduction
- 2X thermal resistivity improvement
- 2X system power density improvement
- System operation above 100 °C

Payoff: Far term:

- 5-10X module volume reduction
- 6-7X thermal resistivity improvement
- 2X system power density improvement
- System operation above 115 °C

Objective:

Increased power efficiency to reduce power train cooling burden.

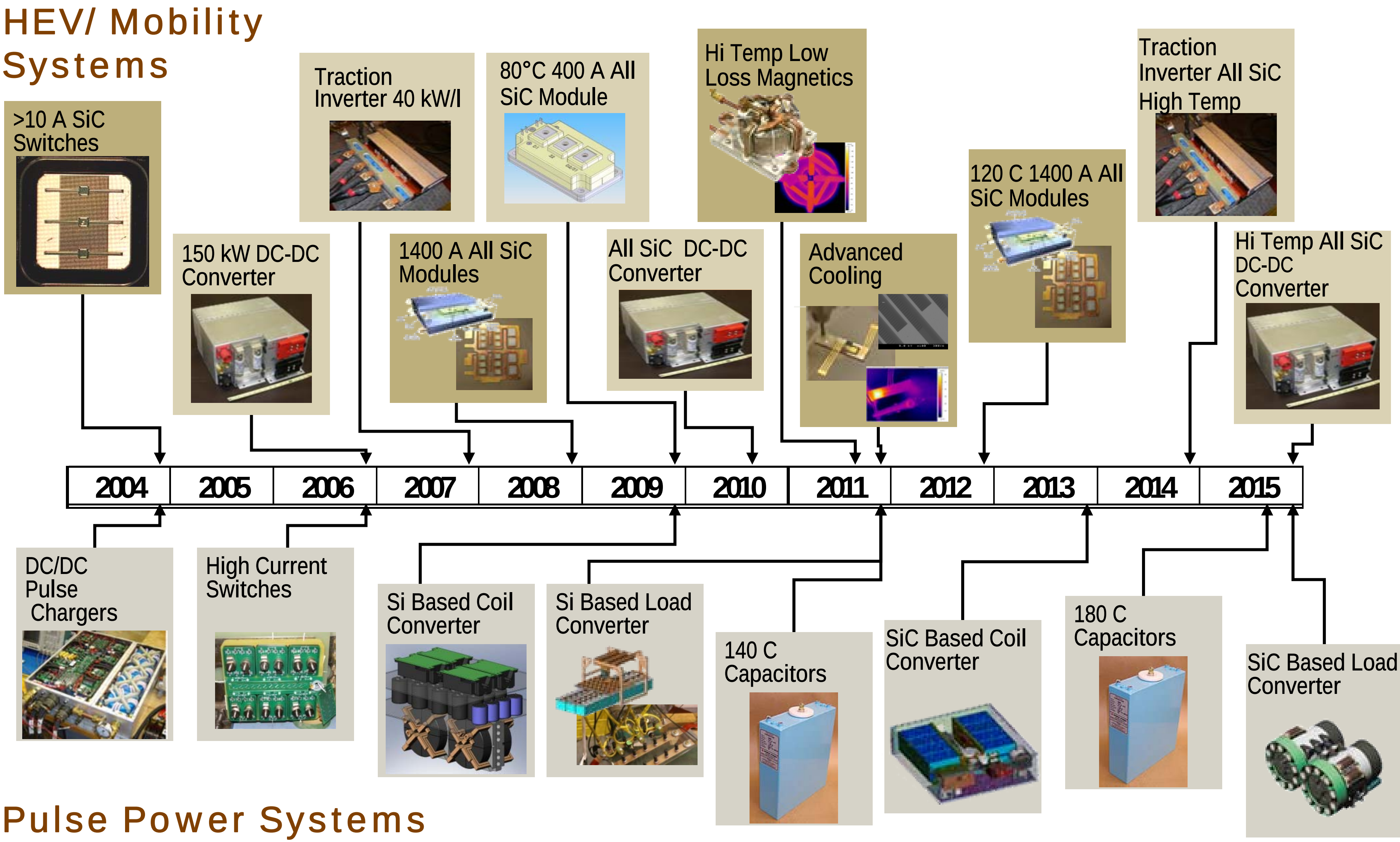
Accomplishments:

- 2X Battery-To-Bus efficiency increase
- 7X MEMS thermal management improvement

Technical Approach:

- Develop high heat rejection and low flow resistance designs.
- Materials with high electrical resistance and low thermal resistance that can replace current package materials.
- Improved die attach materials for increased reliability and reduced thermal impedance.
- Advanced computer models for phase change cooling methods.
- Improved di-electric isolation compounds for high temperature operation.

Platform Power: Power Electronic Components HEV and Pulse Power



Summary

Power and Energy Portfolio

- Enterprise approach to technology planning
- Analysis of in-place investments
- Accentuate commonality for underpinning science and technology (eg. materials and devices)
- Accommodate differences for application
- Tackling difficult challenges for both low power & high power technologies
- Seeking best technological solutions for the Army in part with the greater community

Backup