Power and energy research at the Army Research Laboratory

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ABSTRACT

The requirement for power and energy in a modernized, highly digital and network-centric Army is growing exponentially. In addition to the ongoing demand for improved soldier portable power sources, the need for more electric capabilities for combat and unmanned platforms and the requirements of emerging Operational Energy doctrine are driving development of high density, energy efficient power technologies. The Army Research Laboratory (ARL) is addressing these needs through developing a number of underpinning power and energy component technologies at the fundamental research level. ARL is leveraging core expertise in microelectronics and micro-electro-mechanical systems (MEMS), energy conversion, energy storage, and wideband gap materials and devices to advance selected niche areas that address military demands beyond commercial needs in partnership with the Army Research, Development and Engineering centers (RDECs), other services, other agencies, industry, and academia. The technologies under development can be broadly characterized under power generation and energy conversion, energy storage, power distribution, and thermal management. This discussion outlines progress, approach and the way ahead for ARL efforts.

Keywords: operational energy, micropower, power generation, energy storage, power distribution, power components, energy conversion, wide band gap materials, fuel cell, fuel reformation

1. INTRODUCTION

The US military is placing a renewed focus on energy as the critical resource that enables wide spectrum response in conducting operations. Current operations in the Middle East have highlighted the challenges associated with ensuring energy availability to forward deployed forces. As these operations wind down, the geostrategic environment will demand flexibility and agility to respond with a reduced deployed stationary sustainment footprint. Energy access will become more and more critical and competitive particularly in regions dependent upon it for economic growth, political stability, and military operations. Fossil based fuels are expected to dominate military energy needs, with attendant costs and risks due to significant oil production in politically unstable areas.

Recognizing this dynamic, the military is initiating plans and policies to "operationalize" energy. Energy and its application via power technologies is critical to every system supporting warfighter, platform, and unit performance, from sensors; mobility and propulsion; Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) systems; lethality and protection; and sustainment. The Army performs a wide range of tasks across diverse environments including within enduring infrastructure to expeditionary and sustained operations in unsecured and hostile areas. The Army has defined the energy needed to sustain these operations as "Operational Energy". Emerging doctrine defines Operational Energy as the energy and associated systems, information, and processes required to train, move, and sustain forces and systems for military operations, Operational Energy extends the tenets of military energy policy which have been traditionally focused on energy security for large installations and sustaining bases, into the operational and tactical arena. [1] Although current operations rely heavily on petroleum based fuels, a desired outcome of "operationalizing energy" is to ensure future forces can exploit alternatives and more readily reduce energy demand to optimize energy use. The US Army Research, Development and Engineering Command (RDECOM), which includes ARL and the Research, Development and Engineering centers (RDECs), along with other service laboratories, are developing technologies to address the challenges associated with Operational Energy.

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ARL's power and energy (P&E) portfolio is aligned with the Army RDECOM's P&E science and technology taxonomy. The taxonomy is structured to highlight key areas that enable more electric military capabilities. The main thrust areas discussed herein within this taxonomy are Power Generation and Energy Conversion, Energy Storage, and Power Distribution and Management:

- Power Generation and Energy Conversion: Fuel cells and reforming, Micropower; Photovoltaics; Thermo Electric and ThermoPhotovoltaic Conversion; Isotopic/isomeric sources; and Microcombustion
- Energy Storage: Primary, Rechargeable and Reserve batteries; Capacitors
- Power Distribution and Management: Wideband gap materials and devices; Power Electronics; and Thermal Management

2. RESEARCH FOCUS

2.1 Power generation and conversion

The development of new and improved compact power sources will give Soldiers and platforms increased mission duration, enhanced mobility and reduced logistics. In addition to traditional auxiliary power solutions, novel and alternative energy sources are included within the category of power generation. Goals include lightweight, power-dense, cost-effective power sources.

2.1.1 Fuel cells

The overall goal is to improve state-of-the-art fuel cell technology by providing better materials/components/designs at a low cost for present and future Army and DoD applications. ARL R&D fuel cell efforts are focused on materials, components and systems development. A current effort not being pursued elsewhere is development of alkaline membrane electrolyte fuel cells (AMFC). AMFC presents a number of possible technical advantages relative to other technologies, including facile electrochemical kinetics with non-noble metal catalysts, standard packaging materials, and simplified water/fuel management schemes. Current efforts are on the development of novel anion exchange membranes and ionomers with improved conductivity and stability, as well as the development of selective non-noble metal catalysts with large interfacial areas for the oxygen reduction, and hydrogen/alcohol oxidation reactions. Experimental and theoretical approaches are being taken to address these efforts. Long term focus is on Acid-alkaline hybrid fuel cell development and optimization; reduction in fuel cell system size and mass; exploring use of alternative liquid and solid fuels for portable applications; and continuing improvement of AEM and ionomer materials through multiscale modeling of materials and processing, thereby improving energy density and system performance. [2][3][4]

2.1.2 Fuel reforming

The goals of ARL fuel reforming efforts include improving state-of-the-art fuel processing technology by providing better materials/components/designs at a low cost, with focus on demonstrating lightweight, power-dense and cost-effective fuel processing technologies in the 10 kilowatt range and below. Several ongoing thrusts include desulfurization of liquid logistical fuel (i.e. JP-8); desulfurization of gas phase reformate; and hydrogen purification. Liquid phase removal of sulfur enables fuel processing and fuel cell technology to avoid any contact with poisonous sulfur compounds and allows for long system life and maximum system performance. ARL is developing room temperature, liquid phase sorbents based on dispersed metal ions bonded to porous silica. Current gas phase sorbents require that the reformate gas be cooled before sulfur absorption takes place, greatly increasing system complexity and mass, and reducing efficiency. ARL is developing high temperature sulfur absorbents that allow for easy thermal integration with reformer and high temperature fuel cell technology. Advanced PEM fuel cells require high purity hydrogen to operate. When processed into hydrogen, logistical fuel generates many byproducts deleterious to fuel cell performance. ARL is using microfabrication techniques to engineer thin film palladium membranes to separate hydrogen gas from the other reaction byproducts, enabling PEM fuel cells to run off of logistical fuel. Further efforts are envisioned to optimize organic sulfur sorbents performance and regeneration capability; develop a packed bed reactor with organic sulfur sorbents for a practical device; optimize Pd based composite membrane performance, thermal cycling and durability; and to scale up Pd based membranes for integration into JP-8 fuel cell systems.[5][6]

2.1.3 Micropower

ARL has established a unique niche in developing components for power conversion at small scales by leveraging its extensive micro-electro-mechanical systems (MEMS) and microelectronics expertise and capabilities. The Army is developing autonomous sensors and microsystems to enhance tactical awareness in urban and complex terrains. These systems are projected to be palm sized and smaller to provide a combination of stealth and accessibility to restricted areas. Although available batteries often provide sufficient power density (10-100+ W/kg) to serve as a primary power source, efficiently delivering this power to various loads is challenging given the small scales involved. As a result, ARL is developing high efficiency power conversion systems at the cubic-millimeter, milligram scale to enable a variety of loads, such as high efficiency, high power density piezoelectric drive systems for small robots. Our technical approach is three-fold: first, we have modeled various CMOS converter topologies for optimal high frequency operation (100+MHz vs 1-10MHz) while using enhanced design techniques like guard-rings and floating wells to handle >20V on chip in a 130nm 1.2V CMOS process. Secondly, we have developed new MEMS techniques to microfabricate ultra-miniature air-core inductors with high quality factors (Q>20) and inductance densities (>100nH/mm^2) – out-performing most inductors fabricated with thin magnetic films). Thirdly, we are developing a new technique for depositing nanoparticles in microstructures like capacitors or inductors. The technique uses nanoparticles suspended in a liquid solution where the structure geometry causes capillary wicking of the solution to the end of a channel. We have demonstrated that upon solvent evaporation, the nanoparticles are left behind to form the constituents of capacitor & inductor structures with high-k dielectric and magnetic nanoparticles, respectively. Current efforts for realizing a <5mm^3 power converter include using hybrid circuit design (high frequency switched-capacitor / switched-inductor topologies to enable high voltage gain), microfabricating 3-D high efficiency inductors, and novel integration of 3-D MEMS passive devices into PZT MEMS processes. [7][8]

2.1.4 Photovoltaics

Again, ARL is exploiting unique capabilities and expertise to pursue several novel approaches for improved photovoltaic materials and devices. Our approach is to utilize low-dimensional nanostructures to improve light trapping, photon absorption, and enhance maximum power output of the PV devices. A particular challenge has been how to address the Shockley Queisser (SQ) limit.[9] The SQ limit refers to the maximum theoretical efficiency of a perfect solar cell using a one p/n junction to extract electrical power. This limits the maximum solar conversion efficiency to less than 30% for a model silicon system. There are several approaches for exceeding the SQ limit but the two principle approaches are:

1. Multijunction solar cells which require individual solar cells of different bandgaps stacked so that light falls first on the cell with the largest bandgap, photons not absorbed are transmitted to the next cell and so forth. While the theoretically predicted efficiency is ~52% for a 3 junction multijunction cell, the maximum demonstrated efficiency is ~42% primarily due to lattice and current matching requirements and surface reflection.
2. Multi-level cells consisting of additional electron levels within the bandgap of the host semiconductor can be realized with one material system. This eliminates the current matching requirements, is less expensive and complex and have theoretically predicted efficiencies of ~ 63% for a single junction cell containing quantum dots (QDs) in the intrinsic region, which surpasses that of a three junction solar cell.

However, having additional impurity electron levels strongly enhances the recombination (Shockley-Read-Hall recombination) of electrons and holes and for that reason, has limited progress for that approach. In addressing how to effectively suppress recombination losses in multi-level cells and exceed the SQ limit, ARL is investigating a particularly promising approach using barrier enhanced quantum dots. These have the ability to enhance light absorption via multiple energy levels and extend the absorption edge into the infrared(IR) range. ARL's approach is based on the nano-engineering of electron-hole kinetics by use of dopant-induced potential barriers around the dots. N-doping of the inter-dot space of QD solar cells enhances harvesting of IR radiation and suppresses fast electron capture, resulting in a 50% increase in the power conversion efficiency vs similar non doped cells. The achievable efficiencies using our novel barrier-enhanced technology enables manufacturability of double junction solar cells with efficiencies that can surpass state of the art triple-junction cells. This approach reduces current matching requirements, complexity, and most importantly, cost. Current investigation includes structuring QD arrays, to include randomly distributed and spatially distributed QDs, and exploring approaches to further increase the absorption strength in QD layers while optimizing the number of QD layers, further improving inter-dot transport, and harvesting more IR spectrum radiation.[10]

2.1.5 Thermoelectric/thermophotovoltaic conversion

Improving the compact direct conversion of fuel energy into electrical energy would reduce the Army's fuel footprint and enable the use of higher power soldier systems. ARL is pursuing both Thermoelectric (TE) and Thermophotovoltaic (TPV) conversion technology. Both TE and TPV can perform direct fuel conversion for soldier and soldier system power sources. TE also has the potential to be used for waste heat recovery to boost efficiency of mechanical conversion. ARL's thermoelectric development program is focusing on improving the conversion efficiency of thermoelectric materials while addressing the parasitic aspects of the TE device packaging.[11] ARL's thermophotovoltaic development program is focusing on a cohesive effort to develop low bandgap, high efficiency photovoltaic conversion cells with high temperature, thermally stable, selective emitters and catalytic combustion-driven thermal sources. Challenges with existing thermoelectric technology include: low material conversion efficiencies; device design and packaging; and system level integration of heat recovery to realize net benefits in practical systems. Thermophotovoltaic converters need: reliable and high lifetime designs for temperatures in the range of 1000 °C (much of the radiated spectrum is below the bandgap of the available photovoltaic materials); spectral control solutions integrated onto high temperature surfaces; and proper integration of the converter components with high efficiency thermal sources.[12] Long term goals for thermoelectric device research include significantly improving TE material efficiency to >10%; transitioning to realize module conversion efficiencies up to 15%; and new electrical contact approaches to supplant brazing for longer lifetime operation at high temperature. TPV efforts will focus on reducing operating temperatures below 1000 °C to increase lifetime and reduce system costs, while at the same focusing on component development to improve conversion efficiencies beyond 10%.

2.1.6 Isotopic/isomeric sources

ARL is evaluating isotopic and isomeric materials for long lived energy sources. The intrinsic energy storage of isotopic sources (Wh/kg) can be over 100,000 larger than what chemical fuels, fuel cells or conventional batteries are able to provide. A nuclear battery consists of the isotope or isomer energy source and energy converter. The energy sources that are commonly examined are americium, lutecium, silver, and holmium. The isotopic energy source for mW output typically requires only pico-grams of material, which produces radiation far below background levels. Conceptual design includes identifying the optimum energy conversion technique, which may encompass beta, gamma, or heat emissions. ARL is investigating harvesting the energy from beta conversion (semiconductor junctions) and gamma converters (PIN structures) rather than the lower efficiency thermoelectric conversion. The conversion efficiency is optimized to provide to provide a maximum power density(using direct-energy-conversion in semiconductors or two-step optical-conversion techniques) while providing a robust and safe packaging for these energy-dense materials.

Investigating novel isomeric isotopes offers the possibility of enhancing the number of decays in the field to provide a higher power device with the same mass of material and form factor. Fundamental research is underway to identify, understand and characterize the most efficient mechanisms by which nuclei can be switched from isomers into high-power states upon demand. A direct-energy-converter takes the beta(or gamma) radiation from the isotope and efficiently (>10%) converts these emissions into electricity directly (no thermal conversion). Diode structures from SiC have been shown to be robust in a radiation environment and efficient at converting the radiation to electrical power directly.[13] The materials are compared for energy stored, ease of triggering, deliverable energy, availability of isotope, and form of energy output.

2.1.7 Microcombustion

. Due to the significant logistics required for placing fuel on the battlefield, energy efficiency and fuel flexibility are two critical aspects of projecting consistent electrical and mechanical power to the Soldier. The lack of scalable generators, flexible fuel reactors, and compact fuel processing units remain critical roadblocks to fulfill the Army's energy needs – Development and optimization of these generators, reactors and processing units are directly reliant upon solid understanding of the underlying chemical and thermo-mechanical issues. Use of alternate fuels such as butanol, a bio-renewable fuel with energy content close to JP-8 diesel, are a means to address these demands. A key achievement included the development of a scalable multi-purpose reactor capable of hydrogen reforming at greater than 80% of theoretical maximum yield, an efficiency previously unattained.[14]

ARL's research is addressing these challenges by (1) investigating the fundamental mechanism by which butanol is combusted or reformed in a catalytic reactor, (2) developing a scalable reactor operating in combustion, H_2 production, or olefin generating regimes, and (3) demonstrating electrical power generation via an integrated high temperature thermoelectric generator device.

Using ARL's unique catalytic reactor and chemical analysis tools, catalytic combustion pathways and butanol reforming mechanisms have been illucidated. Previous studies have either focused on gas phase reactions or catalytic conversion of bio fuels with lower energy density. Multiple chemical reactors were designed to investigate both gas-phase and surface reactions involved in butanol combustion by separating and quantifying the effects of residence time, surface area, and material composition on the combustion products and their selectivity to one another. ARL's multi-purpose compact reactors and related processes are particularly important for Army applications because understanding the fundamental chemical sequences and time scales involved in the process allows designers to scale the reactor geometry, catalyst surface area, and balance of plant components across a wide range of power levels, while ensuring high performance. A specific example is an ARL demonstration of an integrated high temperature (>600 C) PbTe thermoelectric module directly into the prototype reactor with initial electric power generation from butanol combustion.[15][16]

2.2 Energy storage

Advancements in energy storage can greatly improve military energy use by allowing higher efficiency, independence and security. ARL has a long term commitment to basic research dedicated to understanding the underlying chemical and kinetic interactions within primary, rechargeable, and reserve batteries. The research drivers unique to ARL's focus include enabling batteries to perform safely in regimes and at levels beyond that being considered for commercial battery development. Military batteries are required to function in environments as varied as the tropics, the poles and the desert. High temperatures in a battery cell will generally lead to accelerating the rate of irreversible chemical reactions that cause capacity fade and degradation. At reduced temperatures the solubility of salts and additives can become an issue,and the kinetics that determine the transport processes are reduced, yielding lower cell voltage, and possible over potentials which can drive unwanted reactions. Temperature stress will affect mechanical stability of the cell. ARL is doing extensive modeling and simulation, synthesis, analysis and characterization that has yielded transitions to industry both for soldier portable and military platform batteries. ARL has extended in-house energy storage expertise to other areas including high density and high temperature capacitor research and alternative paths to fuels.

ARL's advances will impact battery design in several ways. Improvements can expand the applications from small form factors in portable digital devices (such as cell phone batteries) to much larger energy storage configurations for electrified power systems, such as battery packs for heavily electrified vehicles or load levelling devices for electric grid optimization. High voltage cells developed at ARL enable very high density compact power, having energy density improvements by as much as 30%.

2.2.1 Primary batteries

The Army will continue to need very high energy, non rechargeable primary batteries at lower weight and cost for selected systems and niche applications. ARL has helped pioneer military and commercial efforts in metal air batteries, which have very high theoretical energy densities. ARL is researching multiple energy storage chemistries to improve future primary battery power sources. Current Li-air research focuses on new membrane materials that have enhanced ionic conductivity and chemical stability over the current state-of-art membranes. Membranes that are nearly 100% dense are being prepared from Li-perovskite and garnet powders using sintering and hot-pressing. These membranes are then undergoing conductivity, chemical stability, and mechanical property evaluation. Li-O_2 battery research focuses on new electrolyte solvents and salts that improve both discharge rate capability and discharge voltage. Discharge catalysts prepared on carbon are also being evaluated as possible agents to direct the O_2 chemistry. The development of Li-CF_x (lithium poly-carbon monoflouride) energy storage focuses on better understanding of the discharge mechanism by exploring new avenues to solve long standing performance issues such as heat generation and cathode swelling.[17] Current Li-S battery research has as a focus the development of electrolytes and new cell designs that will allow for the use of a Li-Sulfur primary battery that is both low cost and high energy with low self discharge. Some specific goals include: fundamental studies to understand the stabilization of the cubic (high ionic conductivity) phase of Garnet LLZO for Li-air; chemical composition modification of the Garnet to stabilize the cubic phase and develop a consistent model for cubic Garnet synthesis and processing; investigating additives and cathode structure of Li-S batteries to improve storage performance; mitigating cathode swelling behavior in Li-CFx batteries through control of particle morphology; developing prototype solid electrolyte cells based on the Garnet lithium lanthanum zirconium oxide (LLZO) LiSICON (LIthium Super Ionic CONductor) ; improving storage capability of Li-S batteries through anode protection and anode passivation additives; and investigating better membrane materials for Li-Air and Li-S batteries.[18]

2.2.2 Rechargeable batteries

The focus of ARL rechargeable battery efforts is to increase the energy density of Li ion batteries in a safe manner. Fundamental studies of electrode materials, electrolytes and their interfaces have allowed us to extend performance of Li ion batteries and to realize battery components that can operate at 5V -- a long sought goal of the Li ion industry. We have studied the Solid/Electrolyte Interface (SEI) and its formation to better understand its properties, SEI formation, and its role in charge transfer. Deciphering information collected from spectroscopic/electrochemical analyses of interphases and synthesized model compounds, a "Solvation Sheath Model" for the formation mechanism of these elusive interphases was proposed, and for the first time, the chemical identities of the interphases was linked with the solvation sheath structure of Li ion. Application of this model allowed deconvolution of the energy barriers that Li ion must overcome when migrating across such interphases, which pointed to desolvation of the Li ion as the rate limiting step. This was in contrast to ongoing approaches adopted by manufacturers in synthesizing commercial Li ion cells (ie, a thinner interphase is better). ARL's result challenges the current Li ion industry approach, because, as long as desolvation must occur before a Li ion intercalates into either anode or cathode, the activation energy barrier cannot be significantly reduced, despite having a thinner interphase._ In depth understanding of the interphase allowed us to tailor additives toward more stable surface formation that could operate at higher voltages. These additives (which are inherently inexpensive and used at <1% concentration) have led to a unique strategy for tailoring interphasial chemistry in Li ion devices, and enabled the design of new SEIs to target certain desired properties. New interphases have thereby been realized that can capture/release energy at faster rate, and support new Li ion chemistries operating at the 5 V plateau, to date unrealizable within industry.[19]

Concurrently, ARL has developed safer cathodes of olivine structure for higher voltages. $LiCoPO_4$ is of olivine structure with high discharge voltage (~4.8 V) and high theoretical capacity and energy density (~ 170 mAh/g[1] and ~820 Wh/kg), which potentially offers a much greater energy density in realizable cells vs. state of the art cathodes. However, previous use for cathodes has shown severe loss of discharge capacity upon multiple charge-discharge cycles. This has been attributed to irreversible structural changes or amorphization of the charged, low–lithium content material. To resolve the structure stability issue with $LiCoPO_4$, ARL explored, synthesized and characterized modified LiCoPO4 with various metals, including Mg, Ca, V, Mn, Fe, and Zr, substitutions on either Co sites or Li sites or both Co and Li sites. We have also found that a double substitution of Li and Co by Fe stabilizes the cathode so that capacity retention is substantially improved over that of the LiCoPO4 in either baseline electrolyte or our high voltage electrolyte containing ARL 3 additive. This clearly demonstrated that the structural stability plays a controlling role in improving the cycling capability of the high voltage LiCoPO4. [20][21]

2.2.3 Reserve batteries

Reserve batteries are a critical component of modern munitions to provide the electrical energy and power needed for ranging, targeting, guidance, positioning, and detonation. As such, the reserve battery needs to meet the following stringent demands: 1) long shelf life (>20 years), 2) high reliability and readiness, 3) wide temperature range, and 4) high acceleration and spin. In addition, it is highly desired that the reserve battery have high power and energy density, short rise time, low cost, good manufacturability, and a stable industrial base. At ARL, we are currently working on 1) developing a novel thin-film thermal battery and its heat source to shorten rise time, increase power density, improve mechanical robustness and flexibility, and improve the manufacturability; 2) improving traditional thermal batteries by developing and implementing integrated gas getters to reduce the heat loss and prolong run time; and 3) liquid reserve battery designs to improve performance and functionality of certain munitions. Recently, ARL has successfully used nanofoils in a traditional thermal battery as the sole source of heat,[22] and has built, initiated, and tested a nanofoil-heated pressed pellet thermal battery prototype and is partnering with Sandia National Laboratories and ARDEC in this effort. Improved liquid reserve battery designs and an improved version of pressed pellet thermal batteries have also been prototyped and successfully flight-tested.

2.2.4 Capacitors

Capacitors are a key component in power electronic circuits for achieving bypass, filtering, snubbing and coupling functions for power transfer and conditioning in devices such as inverters and converters. Capacitors can also function as energy storage devices for pulsed power systems that require energy delivery in time periods shorter than milliseconds. The Army needs compact high temperature capacitors for inverters and converters that operate in an elevated temperature (above 125 ^{o}C) environment in propulsion systems in order to achieve reliable operation and reduced thermal burden. The Army also needs fast high voltage and high energy density capacitors for electromagnetic (EM) based weapons, vehicle protection systems and directed energy systems such as high power microwaves for non-lethal applications. Polymeric dielectric films that have higher energy density ($\geq$ 10 J/cc) are needed for energy storage applications; for power conditioning, dielectric films that can be operated in temperatures $\geq$ 125 ^{o}C with low dissipation factor and high breakdown strength are needed. Graceful degradation is essential for reliability, safety and cycle life; self clearing capability of the dielectric film under high field breakdown is key to graceful fading. Understanding and development of techniques for film conversion processes are also needed, in addition to understanding the physicochemical nature of the films, including coating and metallization.

Metallized film capacitors (MFC) are preferable relative to ceramic, electrolytic, and super-capacitors because of the self-clearing capability, which avoids catastrophic failure as can occur in ceramic counterparts. MFC has an additional advantage of the ease of scaling to mega-joules at tens to hundreds of kV with reasonable footprints and low dielectric loss. Polypropylene (PP) and poly(ethylene terephthalate) (PET) are the two most common dielectrics, but each has its limitations. The need for ever greater energy density and higher operating temperature has motivated Army to establish R&D effort both in-house as well as with a capacitor manufacturer, General Atomics Electronic Systems Inc. A current approach includes using nano engineered dielectrics and insulators to increase energy density by improving breakdown strength (E_{bd}) of the polymer dielectric (initial results: 14% increase in E_{bd}.). Long term, we seek microsecond discharge capacitors with an energy density of 2.2 J/cc; design of novel high energy density nanocomposite films; and computational model characterization for improved understanding of breakdown strength in relation to polymer structure. [23][24]

2.3 Power control and distribution

Improved power control and distribution is an imperative to realizing rapidly reconfigurable, intelligent energy networks for future military operations. The vision is seamless energy availability to forces, as is being realized for communications and sensors networks enabled by enhanced technologies providing cloud type services. Key to realizing this vision are compact, high density, high efficiency materials, devices and subsystems with embedded intelligence allowing advanced energy situational awareness and power control.

2.3.1 Wide bandgap material and devices

ARL has made substantial long term investments in wide bandgap materials and devices. ARL helped pioneer a new generation of high power, high temperature power electronics to enable power conversion at levels and efficiencies 4-5x greater than possible with commercial Si based power devices and electronics. Army needs will continue to require more electric capabilities for combat vehicles and platforms. Widebandgap power electronics provide not only reduced SWAP (size, weight and power) for smaller power footprint conversion, reduced cooling requirements, increased efficiency at high voltage, and higher operating temperatures, but also can yield significant improvements in fuel economy and mobility performance. For example, on a Stryker vehicle, use of SiC vs Si power electronics may save roughly 2-2.5 gallons per hour of operation. Current focus includes developing more reliable, high-performance SiC power MOSFET switches for advanced power-conversion systems (high blocking voltage in OFF-state with low drain leakage, low ON-state resistance, low switching losses) and developing and demonstrating GaN based Schottky and Junction Barrier Schottky (JBS) diodes for power conversion systems.

In 2010, ARL discovered a critical failure mode and associated cause in the SiC power MOSFETs being readied for production by a major company under the Army's SiC power electronics program.[25] The identification avoided a premature release of these devices, saving not only the company, but the Army from the potentially catastrophic negative effects of SiC MOSFET failure. This company subsequently redesigned their devices to reduce this effect and recently released a commercial, 20-A MOSFET with limited negative bias and temperature range based upon the ARL team's findings. More significantly ARL determined the primary failure mechanism: a significant increase in leakage current under HTRB (high-temperature reverse bias) test conditions, due to a negative shift in the I-V (current-voltage) operating characteristics. This is in turn due to near-interfacial oxide traps related to an oxygen vacancy which is made worse at high temperature under bias. The identification of the failure mechanism provides critical insight in the reliability testing of similar power devices from the SiC industry in general which will lead to new standards of device testing. Silicon carbide (SiC) is the primary wide bandgap (WBG) semiconductor material to replace silicon for the development of efficient high-power, high-temperature electronic devices to meet significantly increased requirements for electrical power generation, distribution, and control.[26][27]

2.3.2 Power electronics

The objective of this effort is to develop advanced power switches and passives through the development of reliable wideband gap high-temperature power devices/modules and passives materials and components for compact efficient power electronics necessary to meet mobility, survivability and lethality systems for platforms and for tactical grid power conversion applications. Through the development of these devices, overall size and weight of electrical power systems will be reduced by 50 to 60 % and conversion efficiency will be increased by 7-10% enabling advanced mobility, survivability, and lethality systems.

Low voltage (1200V) devices must meet cost and reliability goals for high voltage and pulse devices. Near term success is measured by voltage level and reliability and long term success is measured by cost and scalability. ARL efforts include high-efficiency 600-1200 V / 70-1200 A all-SiC switch modules, reducing the cost of SiC based MOS-FET power switches, providing low loss high frequency passive components (inductors, capacitors) that will operate in ambient temperatures of 80° to >100°C and operate at high voltages (10kV-20kV) for advanced survivability and lethality systems. For soldier portable power, APUs and continuous conversion applications, improved power electronics enables reduced fuel usage, improved reliability of power conversion systems, advanced protection capabilities, and electrically powered lethality systems. Current ARL improvement metrics include reducing device costs down to no more than 3X the current cost per ampere; 1200 V components with demonstrated 1000 hour reliability at > 150ºC; new evaluation standards to provide proper qualification methods for SiC devices; demonstrating reliable 15 kV devices; handling longer pulse widths at high current densities; and integrated intelligence to allow improved device and module control and embedded prognostics and diagnostics. Future efforts include developing next generation GaN material with reduced defects [28][29] and improved device designs, and investigating indirect wideband gap materials with eV's of 4-5 for power devices.[30]

2.4 Thermal management

Compact thermal solutions can reduce the size & weight of power systems while improving their reliability and effectiveness. Developing an understanding of transient effects and methods to control them can reduce system overdesign. ARL is leveraging package-integrated cooling approaches and phase change thermal phenomena to increase power density and reduce thermal overdesign of power electronic components, by pursuing three primary thrusts:

- Continuous Cooling: Single-phase manifold microchannel coolers to reduce cold plate thermal resistance and pressure drop; two-phase boiling in mini-channel cold plates to improve power density, uniformity, and pumping power.
- Transient Mitigation: Integrate solid-to-liquid phase change material (PCM) into substrate for device peak temperature reduction; electrically stimulate nucleation to ensure thermal reset.
- GaN RF Device Modeling: Assess thermal performance impact of design changes in GaN HEMT devices related to layer thinning; quantify role of thermal boundary resistances.

ARL is addressing the scaling challenge: thermal systems are sized to handle rare, high thermal transient loads (>2X the average load); reducing system over-design to handle the low, average load can reduce SWaP but must still mitigate temporary surges. ARL is leveraging multidisciplinary competencies in thermodynamics, microfluidics, material development & analysis, device fabrication, packaging & manufacturing; these, coupled with thermal, mechanical, and electrical modeling, testing & characterization, and failure analysis, have led to electrical-thermal models of peak temperature suppression via integration of phase change materials (PCM); experiments indicate that over 30% improvements are possible. To date, we have demonstrated 4.6ºC peak temperature reduction via integrated islands of PCM (erithrytol) during transient events. Future efforts include analyzing the trade space between steady-state and transient cooling, and investigating alternative phase change material systems for stability and integration potential.[31]

3. EMERGING TECHNOLOGIES

The drive to provide soldier and soldier systems with compact efficient power will be facilitated through the investigation of novel materials and material systems. Just as GaAs has revolutionized the communications industry, other novel materials have the potential to provide enhanced power efficiencies for lower cost. Much emphasis has been placed on harnessing the electronic properties of novel materials, expanding the ways the army provides power. ARL is investigating new generation high- performance and printable electronic and sensor devices for Army-specific applications. Although exploration of novel materials and devices represents a continuation of similar "technology push" efforts within ARL, the demands arising from current operational needs in theater, ongoing force modernization requirements, and evolving military doctrine which places energy as a keystone for future operations all represent a "technology pull" dynamic, providing additional unique opportunities and challenges for the way ahead.

3.1 Graphene and carbon nanotubes

ARL has initiated modest research efforts into programs focused exploiting material characteristics of graphene and carbon nanotubes. Carbon nanotubes (CNTs) are stucturally similar to fullerenes, but have a cylindrical structure. This class of materials holds great promise due to their high thermal conductivity and electrical and mechanical properties. The electrical properties of the materials can be determined by the size, shape and aggregation of the nanotubes. Graphene represents a conceptually new class of materials that are only one atom thick and possess high electron and hole mobility, high thermal conductivity, extremely high tensile strength, high flexibility, high breakdown current density, very unique ambipolar properties (capable of conducting electrons when biased one direction and holes when biased in the other direction), and lacks a bandgap in the energy band diagram.

Due to their high surface area, electrical conductivity and mechanical robustness, CNTs and graphene are good candidate materials for use as supercapacitors. Commercially available supercapacitors use activated carbon (with a binder) as the electrode material and they have relatively low energy storage capacity (1-2 orders of magnitude lower than lithium ion batteries). Although, activated carbon has a large surface area, much of the surface is inaccessible to the electrolyte ions, and so does not contribute to the capacitance. CNTs and graphene have shown electrodes with improved accessible surface area due to atomically thick structures. Research performed in conjunction with university partners has indicates that 550 F/g should be achievable with single-wall CNT electrodes and possibly higher with graphene electrodes. ARL is developing methods to increase the available electrode surface area, and thus capacitance, through CNT/graphene deposition technique development, and by using electrode material consisting of mixtures of CNTs, graphene, and nanoparticles. As part of this work, flexible capacitors made by printing graphene onto flexible substrates or by coating Kevlar with graphene are being developed. The development of flexible printed capacitors will help usher in an era of low cost flexible electronics. Furthermore the technology lends itself to the development of carbon based energy harvesting rectenna devices. Based on nanoscale elements, the rectenna devices are projected to convert boardband, arbitrarily polarized IR/Visible radiation into direct current for energy storage.

3.2 Microgrids and intelligent power management

The last ten years of war in Iraq and Afghanistan has clearly illustrated that supplying energy forward poses an Achilles Heel for ground forces. Along with water, fuel and energy are vital life blood to Army forces. Providing for science and technology solutions to improve power generation, energy storage, and distribution has been a critical research and development (R&D) focus area throughout the OIF and OEF conflicts. To further compound the challenge, although these conflicts have yielded numerous technology derived capability improvements in other non-energy areas of Soldier and unit operations and capabilities, nearly all of these have placed increased burden on energy logistics. To address this dynamic, the DoD Operational Energy Strategy has clear mandates to provide more capability but at less energy cost.

One solution to this challenge that has emerged from Army R&D is the use of intelligent power management in networked energy (ie microgrid) environments. Studies have shown that the military's traditional paradigm of providing isolated generators (or other power sources) for a specific set of loads results in greatly under-loaded generators and vastly wasteful fuel use. Intelligent power management has been shown, in testing and demonstrations, to be a means of better aligning energy source availability to energy demand to use available energy sources more efficiently. Also, while there has been tremendous interest in using alternative and renewable energy sources as a means to reduce fuel logistics, the variability in output of these systems when used as stand-alone power sources makes them unsuited for operational forces use. However, integrating them into an intelligent power management structure that also includes traditional petroleum-fueled generators and large format energy storage would make the optimum use of them without limiting operational capability. Intelligent power management development within the Army is envisioned to encompass enhanced energy situational awareness; embedded controls within advanced power electronics based power conditioning and power distribution; source dispatching and energy balancing to include renewables and storage; load/ demand management to ensure reliability to critical loads and enhanced efficiencies; adaptive power interfaces; and embedded power system prognostic and diagnostics.

Research and development in microgrids and intelligent power management has shown that these systems can eliminate the current wasteful operating paradigms of generator-to-load concepts. Initial demonstrations (e.g., Net Zero JCTD) have shown that there is a potential for 20-40% fuel savings by integrating together power sources in an intelligent distribution grid (microgrid). Additionally, an intelligent power management and distribution grid is expected to be the best means of making the most optimal use of alternative and renewable energy sources (e.g., solar) without sacrificing operational capability.

3.3 Wireless power transmission

There is currently considerable interest in exploring more robust means for wireless power transfer toward realizing a vision of seamless energy operations for Soldiers and small units. Beaming power over long distances is possible through the use of Laser power beaming, where directed light is sent through the air (or fiber optic) to a remote receiver such as power station or an unmanned aerial vehicle (UAV) [32]. Although power beaming has many advantages, the approach is limited due to the necessity of directing power to a target. There are some promising solutions being developed for commercial applications based on inductive charging and magnetic resonance being investigated for adaptation to military requirements; however, these solutions are currently limited to short distances (meters) and have non optimal configurations and energy transfer efficiencies. In addition to further improving these technologies for military use, there is potential to further explore and multisource energy scavenging. A near term objective is to develop a capability to wirelessly transmit power (200 to 500W) over short distances to supply the electric power to a Soldier Power Manager (SPM) that intelligently manages Soldier power needs for all devices/gear carried by a Soldier using a centralized power source in the form of a Soldier carried conformal battery. Various RF, inductive, and magnetic resonant solutions are being explored which include smart RFID to activate energy transfer and optimized charging. Such autonomous charging, using a vehicle platform or command post power source, can significantly free up the Soldier from mental and physical burdens of managing the energy balance and ensure "energy top off" and availability for all carried kit - ensuring needed electric power anytime anywhere.

In the future, low and self powered electronics, sensors, and devices will exploit available ambient energy and reduce the need for battery resupply and external recharging. ARL has a variety of novel technologies including nano structured materials, bio inspired structures, and MEMs based devices that can provide the capability of capturing energy from vibrations, RF, and other modalities within highly integrated low power electronics. For example, ARL has developed MEMS based logic which provides some power and noise immunity advantages vs conventional digital circuits. There is the potential to explore low power integrated circuits allowing unused charge to be recycled back into the power source instead of being dumped within the circuit as heat - this class of special integrated circuits is known as adiabatic logic and has been a topic of research interest for some time. Novel antenna structures at various scales are being investigated to explore energy capture, such as nano rectennas embedded on the surface of materials, and quadrifilar helix antennas painted onto sensor and electronic surfaces which can be used for signal or energy transmission and reception.

4. SUMMARY

ARL has developed a variety of materials and devices to enable enhanced energy and power capabilities for military applications. It is anticipated that it will continue to play a critical role in as energy's role becomes further refined for future operations within the Operational Energy paradigm. The value of alternative sources and energy storage has already been established for selected situations, such as for remote patrol bases that can be securely resupplied only by air. The use of photovoltaic arrays, battery storage banks, and associated power electronics can replace portable and mobile generators and reduce and in some cases eliminate associated fuel resupply. In the future, low or no power electronics may be available that scavenge and store energy from ambient sources, thus minimizing the need for changing or externally recharging batteries now found in many portable devices. Development of high density power interface modules, for intelligent power control and distribution, can allow universal access to a variety of military, commercial, and locally available power generation and energy storage sources, including local grid and infrastructure assets, alternative energy sources, and vehicle based power. An open energy architecture for mobile, reconfigurable microgrids can allow seamless energy availability to Soldiers and units, and the ability to realize more adaptable, self sufficient energy networks across a variety of operational regimes and environments. ARL will continue to lead efforts among service labs and government agencies, industry, and academe toward achieving this energy vision for our forces.

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