The Center for Research on Extreme Batteries

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How much would you spend on a battery if your life depended on it? Rarely is that question asked as the vast majority of battery development is focused on bringing down battery cost for widespread consumer acceptance. However, for many industries, extremes in performance, environment, safety, and reliability are the primary criteria, and cost, while important, is not the deciding factor. Moreover, these extreme environmental and performance requirements are not met by conventional consumer batteries, or are even being considered as primary drivers for research and development by funding agencies like the Department of Energy (DOE) which is focused on transportation and stationary storage. Therefore, it was out of this vacuum that the Center for Research on Extreme Batteries (CREB) was formed to develop batteries to meet the extreme needs of the defense, aerospace, and biomedical industries.

Department of Defense Energy Storage Needs

As C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance) reshapes the future battlefield, military infrastructure becomes more energy intensive. The Department of Defense (DoD) is seeking diversified solutions to the power needs of the battlefield, considering new approaches for power generation, energy storage, power distribution, alternative energy/energy efficiency, and thermal management. Although technologies such as fuel cells, capacitors of both electrochemical and dielectric natures, photovoltaics, as well as alternate fuels are being actively developed, batteries will continue to play a central role.

The categories of batteries used in DoD span multiple platforms, similar to commercial sector's portable electronics, transportation and grid-storage, can be described as three main categories: (1) *Soldier Power*: These are either stand-alone battery packs or hybrid systems which can support electronic, sensing, and computing devices of dismounted soldiers for certain length of missions (Fig. 1); (2) *Mobile Power*: This is on-board power for combat and tactical vehicles as well as manned and unmanned autonomous vehicles (air, ground underwater (UAV, UGV, UUV). Batteries for these platforms include two types: those serving as automotive power source as in unmanned vehicles, and those as part of Ancillary Power Units (APU), where they only support communication/surveillance functions of the platforms, especially when the main engine is switched off during the "silent watch"; (3) *Local Grids*: These are power distribution systems used for expeditionary camps and bases. Currently, larger energy storage battery packs are used here for UPS type capabilities/spot power and for integration with renewable (PV/wind). Beside those main categories, there are two unique battery types for military applications: reserve batteries, which serve to activate the munitions (munitions, missiles, smart-bombs, etc.) upon launching, and batteries for unattended ground sensors.

Between the two key parameters, energy and power density, Soldier Power especially favors the former (>200 Wh/kg at cell level), because resupply and/or recharging (from mobile power or power grids) are usually inaccessible for the dismounted soldiers during extended duration missions; ideally soldiers would operate independently from energy resupply for up to 72 hours. For this same reason, and also due to limited charging infrastructures on battlefield, primary rather than rechargeable batteries have been traditionally preferred by the soldier, with mature Li/thionyl chloride and Li/SO_2 chemistries being the main batteries in use. However for future extended missions (72 hrs), rechargeable high energy batteries are preferred to reduce the weight carried by the soldier. On strategic level, employment of more rechargeable batteries is favored in order to reduce the logistic burden. As such, rechargeable batteries are gaining more and more penetration in the Soldier Power applications.

Some Mobile and Grid Power applications emphasize power rather than energy densities (>10 kW/kg on cell level), because, like battery packs in hybrid electric vehicles, the energy output of the whole system is provided by the power conversions units, e.g., combustion engines, fuel cells, solar panels, etc. The exception is for the unmanned systems or fully electric platforms, where energy density determines the duration of that platform's missions.

Fig. 1. *Power-hungry gadgets on a dismounted soldier for a 72-hour mission (left). Soldier in the photo is U.S. Army Staff Sgt. Carlos Garcia, of Bravo Company, 2nd Battalion, 508th Parachute Infantry Regiment, taken in the Andar province of Afghanistan June 6, 2007 by U.S. Army Staff Sgt. Marcus J. Quarterman; Unmanned air (Stalker, upper right) and ground (Squad Mission Support System, lower right) vehicles (manufactured by Lockheed-Martin).*

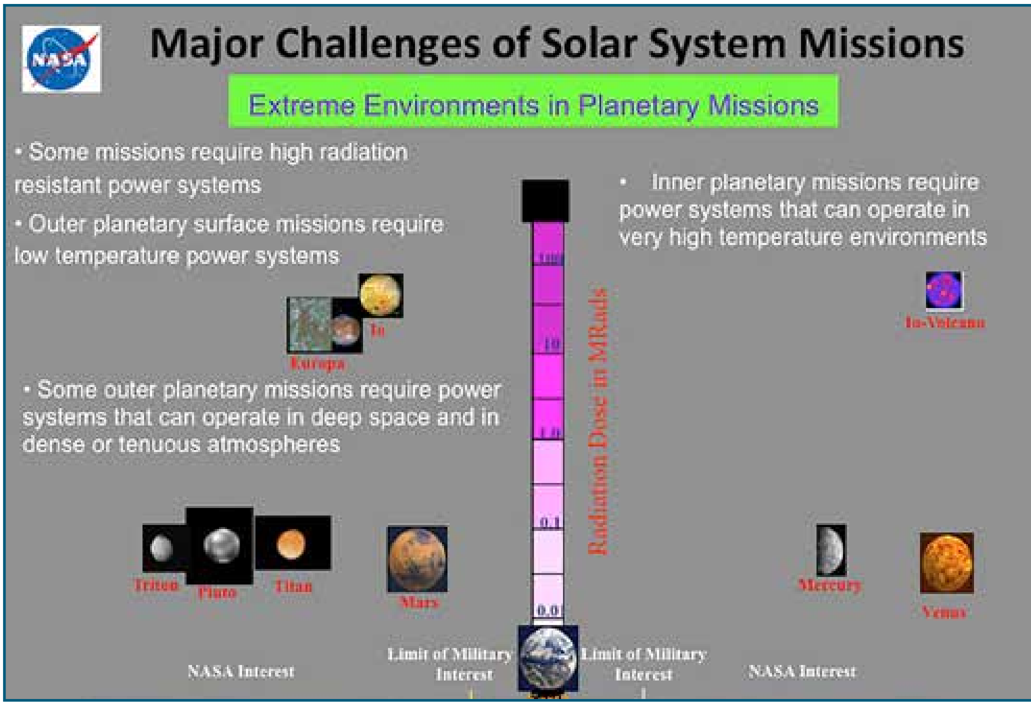

FIG. 2. *Temperature and radiation exposure for planetary space missions (from Ref. 2).*

Besides energy and power, safety might be the single most important requirement for batteries that will be used in a battlefield environment. It is important that the battery pack carried by a soldier never experience thermal runaway; the batteries should also survive rough use such as crashing, impacting, and even ballistic penetration without generating fire or explosion. Battery packs in vehicles, APUs and local grids for camps or bases are better protected from such abuses than soldier-carried batteries; however, a unique exception is battery packs used in underwater vessels (submarines), where any thermal runaway process poses fatal danger to crew members because the oxygen in the confined space could be rapidly consumed. High tolerance against those military-specific abuses are usually achieved through robust packaging and engineering on the system or pack level, but solutions on a chemistry and materials level would be ideal considering both energy density and cost. Such a solution is best exemplified by the advanced aqueous electrolytes that are being jointly developed by the University of Maryland (UMD) and Army Research Lab (ARL), whose wide electrochemical stability window (>3.0 V) has enabled energy densities (>150 Wh/kg) competitive to that of commercial Li-ion batteries, with intrinsic safety on chemistry level ensured by their aqueous nature.[1] This class of advanced aqueous battery chemistries could represent a main direction for future military battery development.

Compared with their civilian counterparts, the batteries for military applications often have much more stringent requirements for temperature range (−40 °C to +75 °C). On a battery pack level, such extreme temperatures could be handled with thermal management such as air- or water-cooling systems or phase change materials as part of the packaging. However as space is usually at a premium in any military vehicle, the decrease in volumetric density for these solutions is a disadvantage. For Soldier Power, such systems add dead weight to the batteries and drive down the energy densities. Therefore the most ideal solution for both platforms would still be on a chemistry level, i.e., finding electrode and electrolyte materials that can operate within wide temperature ranges.

Batteries for munitions and missiles have unique requirements. The most challenging is a 20 year shelf life, as these power sources are built into the platform and may be stored for up to 20 years before use. They usually have high power requirements so energy density is not as much a concern as the duration of use is limited. The temperature requirements are even more extreme than for other batteries. Reliability is however the utmost requirement: munitions have to be activated upon launching.

For unattended ground sensors, energy density is the prime consideration, as soldier lives and the mission are at put at risk replacing the batteries. But they need to be sufficiently power-intense for communications, which usually have a high power pulse at initiation.

Unlike their civilian counterparts, especially those in the vehicle or grid-storage markets where large-scale application constantly induces cost and environmental concerns, batteries for military applications are less constrained by these standards, although they are still important.

Energy Storage for Future Space Missions

For space exploration, high energy density is critical given extreme limitations on both mass and volume for rocket-launched payloads. But the battery requirements for NASA extend beyond extreme energy density to extremes in temperature and radiation exposure (Fig. 2). For example, the surface of Mars ranges from a high of 20 °C to a low of −125 °C, and for future missions to our other neighboring planet, Venus, the average temperature is 462 °C. As for deeper space such as the moons of Jupiter, radiation dose rates are several thousand times higher than on Earth; moreover, lifetime and reliability are mission critical as there is no one to change your batteries in space. To date, reliability concerns have dominated NASA's battery selection so they have tended to stick with older lower energy density batteries that had a track record of high reliability in launched systems, slowly progressing from Ni-Cad, to Ni-H_2, and only recently adopting Li-ion.[2] However, future planetary missions cannot be achieved with those battery technologies, so a renewed focus on extreme batteries for space flight is critical to future mission success.

One example of an extreme battery being developed for space applications is an all solid-state Li-S battery being developed at UMD under the NASA Game Changing, Advanced Energy Storage Program.[3] Due to its Li metal anode, sulfur cathode, and novel ceramic electrolyte structure it has projected energy densities of ~540 Wh/kg, more than double that of conventional batteries. Moreover, its

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solid electrolyte has stable conductivity across the entire temperature range envisioned for NASA's future planetary missions potentially allowing it to go where no battery has gone before.

Battery Power for Implantable Biomedical Devices

Batteries utilized to power implantable biomedical devices have contributed to the widespread use of medical devices for the treatment of human disease.[4,5] The devices monitor the condition of a patient and provide therapy on a predetermined schedule or as required. The implanted batteries are the sole source of energy and provide the power for monitoring, therapy as well as communication with the device. While the functional requirements for the batteries may vary with the type of device and therapy, some characteristics are demanded by all the medical applications. The batteries must provide many years of service, safety during installation and use, display predictable performance and be highly reliable. Additionally, high volumetric energy density is important to enable the design of small devices that minimize discomfort for the patient.

Both primary and secondary batteries are used to power medical implants (Fig. 3). The power demands differ by orders of magnitude depending on the device. The varying demands are met by battery systems based on lithium metal anodes for primary batteries and by lithium ion systems for secondary batteries due to their high energy density and stability. Specifically, cardiac pacemakers typically require microampere levels of current and are most commonly powered by lithium/iodine type batteries which were the earliest lithium battery used for human implant.[6] In contrast, implantable cardiac defibrillators (ICD) demand microampere level current for patient monitoring and ampere level pulses are needed to charge capacitors when needed to defibrillate the patient. ICDs are most often powered by lithium/silver vanadium oxide or lithium/manganese oxide batteries. The internal electrodes are configured in multiplate or wound internal geometries to provide higher electrode surface area.[7-9] Devices such as neurostimulators, and drug delivery systems are in the middle of the power requirement range needing milliampere level pulses. Some of these systems are powered by primary battery systems including lithium/manganese oxide,[10,11] lithium/carbon monofluoride,[12-15] or hybrid cathode systems based on silver vanadium oxide in conjunction with carbon monofluoride.[16-20] Notably, some of the devices are designed with charging systems for the implementation of secondary batteries with lithium-ion being the battery system of choice.[13,21,22] The voltage, capacity and energy density characteristics of medically relevant battery systems are summarized in Table I. While the functional performance of the batteries varies, high reliability, high volumetric energy density, long service life, state of discharge indication, and safety during implant and use are characteristics common to each successful medical battery.

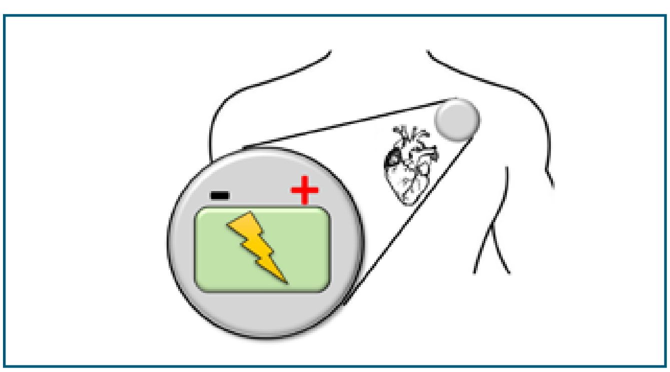

Fig 3. *Implantable cardiac defibrillator battery schematic (R. DeMayo graphics).*

Table I. Batteries uses for implantable medical devices.

Battery System	Open Circuit Voltage	Nominal Voltage	mAh/g Theoretical, Cathode Material	mAh/cm³ Theoretical, Cathode Material	mWh/g Energy Density of Battery
Li/I_2	2.8*	2.8†	211	1041	210-270*
Li/MnO_2	3.3†	3.0†	308	1540	270 (low rate)† 230 (high rate)†
Li/CFx	3.1†	3.0†	865	2335	440†
Li/SVO	3.24†	3.2†	315	1510	270†
$C/LiCoO_2$	4.2‡	3.88‡	155‡	783	155‡

**Ref. 23; †Ref. 24; ‡Ref. 25.*

About CREB

The goal of the Center for Research on Extreme Batteries (CREB) is to foster and accelerate collaborative research in advanced battery materials, technologies and characterization techniques with a focus on batteries for extreme performance, environments and applications, such as those needed for the defense, space, and biomedical industries. The concept grew out of a partnership between ARL and UMD, with the addition of National Institute of Standards and Technology (NIST) and NY BEST (Fig. 4). The CREB Steering Committee consists of the authors of this article.

ARL and UMD have established a separate non-profit organization, the CREB Consortium,[a] administered by UMD, to participate in activities associated with CREB. Membership in the CREB Consortium is open to individuals, national and defense labs, universities, and industry through membership fees. Benefits of CREB Consortium membership include:

- Access to unique research laboratories and prototyping/manufacturing facilities applicable to battery research
- Introduction to unique and state of the art characterization capabilities and guidance with their selection, application, and optimization for battery research
- New ideas and collaborators with expertise in multiple disciplines
- Ability to formulate joint proposals with partners to pursue external funding
- Joint publications with nationally and internationally renowned experts in the field
- Access to IP generated by CREB funding to members on a non-commercial basis
- Unique technology transition pathways

More information and how to join the CREB Consortium can be found at: http://creb.umd.edu/.

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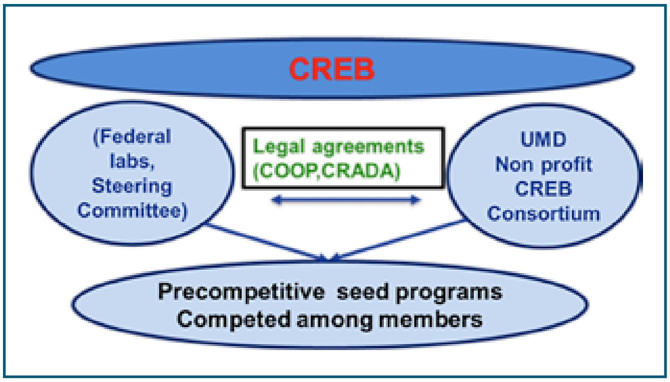

FIG 4. *Diagram of the CREB structure.*

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