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Leveraging COTS technologies to accelerate DOD's Capabilities with Large Capacity Battery Standardization

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ABSTRACT

In support of the Army's Modernization Strategy focus on Next Generation Combat Vehicle (NGCV), GVSC with OSD partners (OECIF, NAVY) is developing a Joint Service High-Voltage (HV) Specification for Energy Storage Modules (ESMs), i.e. Li-ion batteries. Greater penetration of safe, low cost ESM in support of electrification will result in improved platform survivability, maneuverability and capability. It is anticipated that an HV ESM specification for an adaptable, scalable energy storage based on commercial practices, will benefit multiple DOD platforms resulting in an acquisition life cycle cost reduction and a reduced logistical burden. To support multiple platform requirements, the specification is being developed to allow for a modular electrical architecture from 50V to 1000V. Analysis is also presented on the ability to obtain an optimum solution using a combination of standard power and energy battery modules vs. a platform unique battery, demonstrating the viability of a modular battery specification effort. This work also reviews the development of the specification including module format, power and energy requirements, environmental, safety, control, shock and vibration requirements. Additionally a case study of Hybrid Electric Vehicle is also presented that illustrates the value of a specification.

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1. INTRODUCTION

In support of the Army's Maneuver Force Modernization Strategy focus on Next Generation Combat Vehicle [1] (NGCV) and Navy's Electric Weapons and Electric Ship Efforts [2,3], GVSC has been evaluating current technologies to develop and demonstrate the feasibility of a Joint Service High-Voltage (HV) Specification for Energy Storage Modules (ESMs) *i.e.* batteries.

Batteries are a foundational and enabling technology for increasing a vehicle's electric capabilities also known as electrification. Greater penetration of safe, low cost batteries in support of electrification will result in increased platform survivability, maneuverability and capability.

Electrification increases platform capabilities by enabling greater silent watch / mobility, and increased electrical platform systems. Furthermore additional on-board and export electrical power results in the ability to support modular mission equipment packages, e.g. Autonomous systems, Electro-Magnetic (EM) active protection.

Electrification also enables power train hybridization that results in greater fuel efficiency / range leading to increased maneuverability. Additionally, future naval and army weapons systems require high power electric pulses, to enable High Energy Lasers (HEL) and High Power Microwave (HPM). Batteries are well suited to meet this pulse power requirement.

To accelerate platform electrification, the development of a HV ESM specification and associated battery prototypes is desirable. The use of performance specification is highly effective to maximize use of state of the art technology in military applications [4] .

Similarly to GVSC's effort on 6T specification, it is anticipated that the development of a HV ESM specification with a modular, open interface will also enable acquisition life cycle cost reduction, through greater competition and a larger acquisition base.

Specification also supports increased standardization for energy storage solutions across DOD platforms, resulting in a reduced logistical burden.

It can be seen that the development of an ESM would accelerate new capabilities across the DOD. The following paragraphs describe the specification development.

2. Modular Energy Storage

The concept of utilizing modular, scalable and adaptable high voltage energy storage is shown in Figure 1. A module will include multiple cells in a combination of parallel and series configurations. The module can then be placed in a series or parallel string with other modules, and with the appropriate features including thermal management, master controller and module enclosure forms a battery pack.

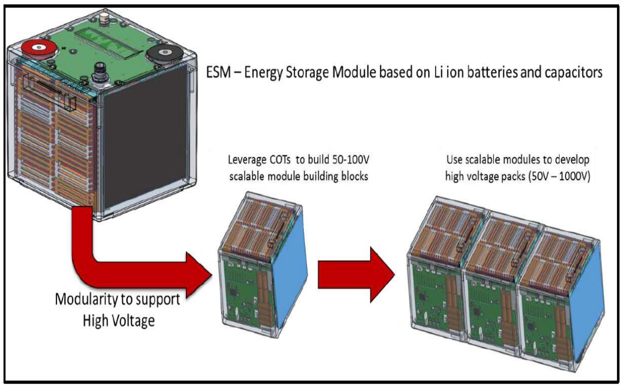

Figure 1 As shown in Figure 1, a modular battery approach allows adaption to different platform needs, with interface control specifications that allow the ESM to be integrated to support a variety of battery packs for multiple military systems.

As appropriate, this common module can be scaled and integrated in various DOD manned and unmanned systems.

2.1. Existing Specification

Unlike the broad scope of Li-ion cell format specification [5] there exists limited commercial specification for modules. An automotive industry attempt was made to standardize EV modules [6] for aqueous electrochemical (non-Li-ion) systems, with four module types proposed. However there exists no automotive consensus on a Li-ion battery based ESM specification, as there are multiple and competing vehicle architectures. Bespoke modules provide maximum packaging efficiency. Additionally planned obsolescence of the platform with battery life, provides the highest commercial market value.

The US ARMY expects key platforms to have long service lives. For example both the light tactical HMMWV and the armored personal carrier M113 are expected to be service for multiple decades [7]. Thus the development of a specification is critical to ensure a strong industrial base of supply.

2.2. Module Format Specifications

The specification of physical dimensions is a key component of Battery Standardization. Although there exists Electric Bus Module physical size specifications [8], the specification provides limited information on capabilities housed in the module.

There is also an automotive starting, lighting, & ignition, 24 VDC Li-ion battery based on a MIL-PRF-32565 specification, which is being fielded in the US ARMY. There is also a large amount of experimental data on MIL-PRF-32565 Li-ion batteries relevant to the DOD. To leverage this data and to support legacy system compatibility, the 6T size specification is the basis of module size format, as shown in Table 1.

Table 1: Energy Storage Module Physical Dimensions

H (mm)	W (mm)	L (mm)	W (kg)
230	290	290	< 30

Following is a discussion on the end use platform requirements to develop appropriate ESM Power and Energy performance specifications.

2.3. Module Power & Energy Specification

Based on the operational requirements for ARMY platforms to operate in austere environments with no fixed charging infrastructure, it is anticipated that Hybrid Electric Vehicles would be the initial users of an ESM. Advancements in battery energy density are required to enable Battery only Combat Vehicles.

Table 2 shows the estimated, desired key ESM Power and Energy attributes of a set of ground vehicles. The Heavy ground vehicle is based on a 50 t tank vehicle. This vehicle has the greatest amount of armor, and thus to maintain mobility, requires a high power density ESM. Energy Storage is required for silent watch and tactical idle conditions. The Medium ground vehicle is based on 25 t infantry transport vehicle. This vehicle transport soldiers and equipment and requires mobility for a fast changing battlefield and energy storage for silent mobility / watch operations. The Light 2.5 t platform accompanies dismounted infantry, to provide supply transport and battery charging on the move. The light platform requires the largest energy density ESM as silent mobility is a highly desirable attribute. An example of the light platform is shown Figure 2.

Table 2 Power & Energy Objective Targets

Description	Ground Vehicle Weight		
	Heavy	Medium	Light
Power Density (kW/l)	3.7	1.8	0.61
Energy Density (kWh/l)	0.12	0.11	0.47

Figure 2 Example of the light platform vehicle [9]

Mission Equipment Package (MEP) There are a large number of MEPs including Directed Energy Weapons, Active Protection Systems, Tactical Electrical Grids and Unmanned Systems. Although the power and energy requirements for the various MEPs is beyond this document's scope, discussions were held with the technology developers. The findings indicates that the power and energy objective targets identified in Table 1, would adequately provide host capabilities for the aforementioned MEPs.

It can also been seen that the Light platform is significantly different from the Heavy platform, suggesting the use of a battery pack optimized for each platform's Power and Energy targets.

For conventional Li-ion systems the relationship between power and energy density is a Pareto front., *i.e* the increased cell energy density occurs with decreased power density. This occurs because at higher current (I), cells are thermally limited by heat generation (Q), A method to increase power density, is to use low resistance (R) cells (Eq. 1.), usually assembled by replacing energy dense active material with conductive materials.

$$Q = I^2 R \qquad \text{Eq. 1}$$

For the same heat generation, the power cell's current is higher than the energy cell, based on the cell's resistance as shown in Eq. 2.

$$I_{POWER} = I_{ENERGY}\sqrt{\frac{R_{ENERGY}}{R_{POWER}}} \qquad \text{Eq. 2}$$

To meet platform power and energy requirements in the smallest volume, cells with the appropriate resistance can be selected. Although this cell selection provides the optimum platform packaging, it results in a custom module for each platform.

An alternative approach is a combination of standard power and energy modules. Despite the increased control complexity of dissimilar modules, this approach supports the preferable standardization goal. The potential benefits of a combination of power and energy modules are further discussed below.

Power and Energy Modules

Consider Eq.3. and Eq. 4., where V_{POWER}, V_{ENERGY} are the volumes of Power and Energy module respectively, while P_i and E_i are the Power and Energy density for the modules respectively. The objective goals are Total Power (P_{TOT}) and Total Energy (E_{TOT}).

$$V_{POWER}P_{POWER} + V_{ENERGY}P_{ENERGY} \geq P_{TOT} \qquad \text{Eq. 3}$$

$$V_{POWER}E_{POWER} + V_{ENERGY}E_{ENERGY} \geq E_{TOT} \qquad \text{Eq. 4}$$

The minimum volume is then a linear optimization of the combination of the module volumes:

$$V_{POWER} + V_{ENERGY} = V_{Minimum} \qquad \text{Eq. 5}$$

This is shown graphically in Figure 3 using available cell data [10].

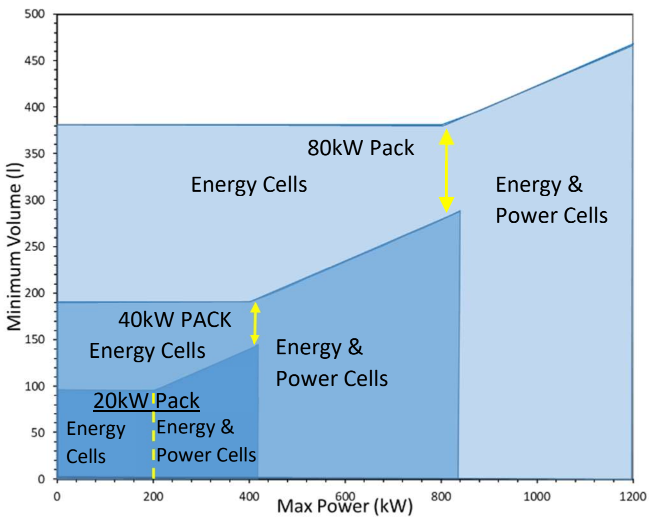

Figure 3 Minimum Battery Pack volume as a function Maximum Power and Capacity. The volume savings using a combination of Power and Energy Modules vs Energy Module only, is also indicated.

It can been seen that for increased power, the minimum pack volume is obtained by the combination of power and energy modules. For example, using a combination of power and energy modules in a 20 kWh pack allows a volume savings of up to 25%, at 400kW vs. using a similar power capable 40 kW battery pack, consisting of Energy modules only. Thus, the availability of power and energy modules provides packaging efficiency using standardized modules similarly to a platform custom module.

2.4. Environmental Operating Conditions

The DOD's must have the ability to operate in extreme temperatures [11], and coupled with under armor conditions results in limited thermal management options. To minimize the thermal load, it is beneficial to operate the battery at the maximum safe operating temperature, at the cost of battery life. A battery temperature increase from 35 to 55°C, at a 20°C ambient condition, with a subsequent 2x decrease in R, results in a six fold reduction in the battery thermal system. The lifetime requirements are discussed below.

2.5. Lifetime Requirements

Commercial automotive battery packs are targeted for a 15 year / 150 000 mile life requirement [12], with cycle life targets ranging from 1000 battery cycles for EVs [13] - 75 000 battery cycles for mild hybrids [14] to ensure economic operation

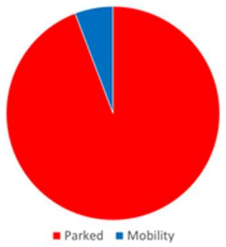

Figure 4. Commercial vehicles operational use

In identifying lifetime requirements, operation at higher temperature can increase degradation in an exponential manner, without appropriate thermal management. Additionally, unlike commercial vehicles that spend the vast majority of their lifetime in the parked state [12] (Figure 4), military vehicles spend a substantial amount of time at silent watch or tactical idle.

Thus the objective battery lifetime was selected as 1000 cycles for a 20% loss in capacity. To minimize testing costs, life cycle testing is based on a commerical standard drive cycle profile IEC 62660-1:2018 IEC BEV Hill test profile B.

2.6. Safety Requirements

Due to their higher energy content, large capacity Li-ion battery packs are inherently hazardous. Following commercial practice to mitigate the risk, safety requirements are imposed at the cell, module, section and enclosure levels. Relevant commercial standards include SAE J2289 [15], J2344 [16] and J2910 [17] that provide electric vehicle safety guidelines and best practices.

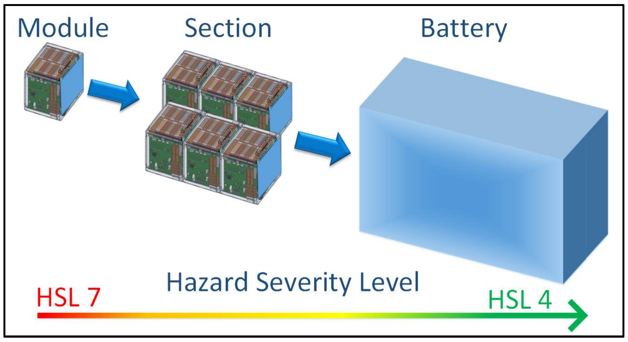

Figure 5 Integration of Module in Section and Battery Enclosure, with decreasing Hazard Severity Level

The unique nature of military operation requires abuse testing, similar to SAE J2464 abuse procedures and response characterization [18]. The following tests are done at the cell level or module: Overcharge, Forced Discharge, Short-circuit, Penetration and Crush abuse tests.

Figure 6 Battery Enclosure with top removed

The abuse response is characterized in terms of Hazard Severity Levels (HSL) [18] from 1 (No effect) to 7 (Explosion). As shown in Figure 5, it is acceptable to use high energetic Cells, Modules / Section with the HSL 7, as long as the enclosure is able to contain and produce an < HSL 4 (Venting) for > 30 minutes (Objective). Figure 6 shows an example of a Battery enclosure with a vent connection point for routing gases.

To minimize high voltage electrical hazards during depot assembly and maintenance, the module's nominal voltage is 50 VDC. Similarly the ESM will have electrical protection (finger-proof) terminals and connections that protect personnel based on ISO 60529 with a minimum rating of IP2XB.

The modules and communication interfaces should have sufficient isolation to operate safely and communicate with other modules connected in series configurations up to 1000 VDC.

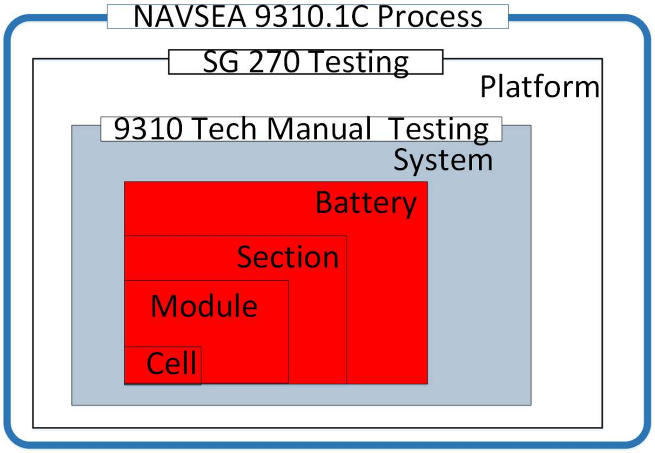

Figure 7 The NAVY's Lithium Battery Safety Process to minimize hazards associated with their use for use or transportation on Navy facilities

Navy Specific Safety Testing The US NAVY implements a Li-ion battery safety program for ship use or transportation [19]. As shown in Figure 7, the process includes Battery system level tests (9310 Tech Manual

Testing) and platform level tests (SG270) [20]. Battery system level tests can be considered as a subset of the platform level tests, and it is possible to identify tests that satisfy the needs of both requirements. The 9310 Tech testing is similar to commercial test standards and includes short circuit, ESD testing, overcharge, over-discharge, and thermal abuse. Furthermore, NAVSEA has a database that consists of already characterized batteries.

2.7. Battery Control Requirements

The Battery Management System (BMS) of multiple ESMs is shown in Figure 8. Each ESM has a module management system that provides at a minimum the following functions: Monitoring, Communications and Balancing. For effective battery pack management, the module management system must report cell level information including the temperature (to avoid thermal runway), cell voltages (to avoid over charging and forced discharge), and cell balancing status (to avoid capacity loss). Similar to commercial practice, the ESM transmits and receive messages on an isolated high speed Controller Area Network (CAN) bus in accordance with SAE J1939. This bus provides the interface between the ESM and the Master BMS (neXt Battery Management Unit (BMU)) for multiple module management.

The neXt BMU is government furnished equipment intended to provide functionality to meet exposure to the radiation levels, blast levels and thermal levels specified in APTD-2404 nuclear hardness criteria. Additionally, the battery must be able to maintain performance under exposure to high power microwave sources, electromagnetic pulse, electromagnetic interference, and electrostatic discharge environments (ATPD-2407). The battery must also meet the electro-magnetic emissions and susceptibility requirements when tested to MIL-STD-461.

Standard BMS functions including algorithms for cell balancing, capacity estimation, state of charge and power capability can be housed in the neXt BMU. The neXt BMU aggregates reported ESM data, including cell voltages, module voltage, temperatures, current and other information required to support battery pack management. The neXt BMU also provides the interface to the Engine Control Unit (neXt ECU).

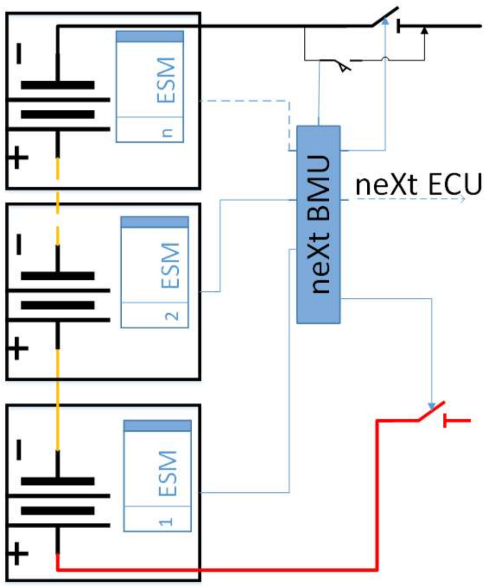

Figure 8 Integration of modular ESM into BMS (neXt BMU) and vehicle controller (ECU)

2.8. Vibration and Shock Requirements

The battery pack and subcomponents must be capable of withstanding vibration without sustaining physical or electrical damage. Specific areas of concern include damage to connections, wiring and circuit boards. Additionally, cell movement and subsequent electrolyte leakage must be avoided.

The relevant vibration standard is MIL-STD-810 [21], Method 514.8 Procedure I - General vibration, and Procedure III-large assembly transportation, for vehicle and trailer respectively. Vibrational profiles for different vehicle types and locations are also found in AECTP-400 [22].

Similarly the battery pack must meet the basic and functional shock requirements of ATPD-2404 [23].

3. Case Study

A case study on the battery solution for a serial hybrid logistic resupply vehicle is presented. Mission objectives for this light platform are silent, long range operation and export electric power for dismounted soldier equipment. Thus, to provide maximum performance, battery selection is critical.

Table 3 Battery Solutions Comparison

Solution	Type	Thermal Management	Mass (kg)	Heat of Reaction (kJ/Ah)
EV Battery	NMC	Liquid	70	11.3
Legacy Battery	LFP	Convective Air	125	6.6

A battery module from a commercial EV battery pack was acquired. The pack was based on Lithium Nickel Manganese Cobalt (NMC) Oxide with liquid cooling. The legacy battery solution is based on the use of a Lithium Iron Phosphate (LFP) batteries with convective air cooling. As shown in Table 1, there is a significant weight savings utilizing the EV battery module. It should be noted that the additional mass of the liquid based thermal management system was not included in the total mass.

Based on further optimization, it is expected that this can potential result in a 2x improvement in range.

The use of this higher energy chemistry has an increased hazard due to the onset of thermal runway at a lower temperature, and higher Heat of Reaction [24], vs. the legacy battery solution.

To mitigate this increased hazard, commercial vendors have developed and implemented improved pack and cell designs, production and validation requirements to ensure acceptable risk in EV products.

In a similar fashion, it is expected that further development of DOD large capacity battery standard will allow developers to leverage commercial battery technologies to conform to the DOD performance requirements. This will allow DOD to utilize the best available technology without unacceptable safety risks.

4. Conclusion

As discussed, developing a modular, standard battery solution that meets military requirements is possible. As shown in Figure 9, developing this performance specification by including military requirements and current technology capabilities will accelerate the fielding of improved energy storage solutions to multiple military platforms.

Future work includes developing battery relevant ballistic and survivability requirements and evaluating the relevant mitigation strategies.

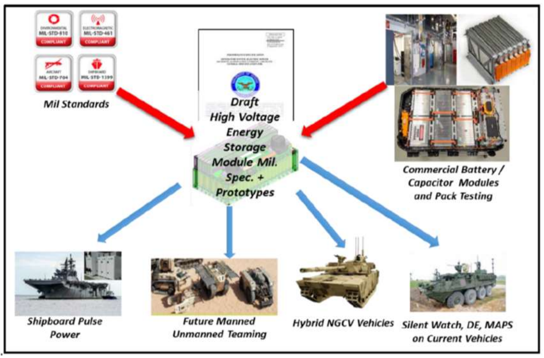

Figure 9 Developing Large Capacity Battery standardization based on commercial technology and military performance requirements. This supports a scalable, modular and adaptable battery solution for mutiple military platforms.

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