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Review of Battery Technologies for Military Land Vehicles

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ABSTRACT

This report provides an overview of battery technologies and related issues relevant to their use in military land vehicles. It explains the advantages and disadvantages of specific battery technologies along with integration considerations for military land vehicles and the future direction of each technology. It concludes that lead-acid batteries will remain relevant for military land vehicles in the immediate future, but variants of lithium ion batteries have the potential to improve operational performance and should be investigated further for implementation in current and future military land vehicles.

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Executive Summary

The functions of military land vehicles are becoming increasingly dependent on electrical energy. As these vehicles are fitted with more electronic equipment, their electrical energy demands will continue to increase and it is anticipated that their limited electrical energy storage capabilities (i.e. their batteries) will present issues during the vehicles' life of type. Insufficient electrical energy storage can inhibit operational performance, particularly when conducting silent watch (i.e. engine-off operation of electrical equipment) where batteries with low energy capabilities will last short periods of time when providing power and will have to be regularly recharged.

Military operations present unique requirements, which differ from those of most cars and commercial vehicles. Batteries on military land vehicles require high energy (for silent watch) and must also be capable of delivering high power (for engine starting and load levelling). Furthermore, they must withstand harsh military environmental conditions and should provide sufficient overhead to accommodate future growth in vehicle electrical power requirements.

Lead-acid batteries are currently used on the majority of military land vehicles and they are expected to remain in use in the immediate future since they are reliable and low cost. However, the low energy capabilities of lead-acid batteries combined with their long charging times have significantly restricted silent watch performance of military land vehicles.

The purpose of this report is to explore current and emerging secondary (i.e. rechargeable) battery technologies and to assess their suitability for improving the operational capability of military land vehicles. Key aspects considered are the ability to improve silent watch endurance, the ability to be fast charged (to minimise engine-on time during silent watch operations), cycle life, cost, safety, and the effect of temperature. In addition, this report aims to introduce batteries and how they function, and highlight key considerations pertaining to the integration of batteries on future military land vehicles. It is intended that the findings of this report will inform Defence stakeholders involved in the acquisition and sustainment of military land vehicle capabilities as to the benefits, potential drawbacks and integration requirements for various battery technologies.

Information presented in this report has been sourced through discussions with experts in this field, attendance at relevant conferences and through being conversant with open source literature. Furthermore, an understanding of the electrical energy storage needs of Australian military land vehicles has been established through ongoing research and analysis in this space by the authors of this report. The combination of information from these activities has allowed identification of the battery technologies that are relevant for military land vehicles and those that warrant attention into the future.

In conducting this review, it was identified that the most suitable battery technologies for military land vehicles are those that can be used as drop-in replacements for lead-acid batteries (e.g. compatible voltage window and similar form factor). In this case, the vehicle's electrical system requires no or minimal modification to accommodate the alternative battery. This reduces the integration overhead and cost required for new battery technologies. Two of the most promising battery technologies that meet this requirement are variants of lithium ion batteries, namely lithium iron phosphate batteries and lithium titanate batteries.

Lithium ion batteries in general offer improved power and energy performance and improved cycle life compared to lead-acid batteries. It is expected that silent watch endurance on military land vehicles could improve if utilising lithium iron phosphate batteries or lithium titanate batteries owing to their greater energy capabilities. However, the distinguishing aspects of these batteries (compared to other lithium ion batteries) is their compatible voltage window, which permits them being used as drop-in replacements for lead-acid batteries, and their improved safety properties, which reduces their risk of catching fire when damaged. These batteries have the added benefit of being able to be fast charged. The high cost of lithium ion batteries may be an inhibiting factor in replacing lead-acid batteries, but this will be partially offset by their higher cycle lives, which will reduce frequency of replacement and lifetime costs. Further investigation of lithium iron phosphate batteries and lithium titanate batteries for military land vehicles is warranted, but is outside the scope of this report.

A number of other battery technologies are considered in this report that may offer performance improvements over lead-acid batteries in military land vehicles, including the UltraBattery, lithium ion batteries using ionic liquid electrolytes, and lithium-sulphur batteries. The UltraBattery, an advanced lead-acid battery, has improved performance at high discharge rates and very high cycle life, but it is unlikely to significantly improve silent watch performance. Furthermore, it is primarily being developed for hybrid electric vehicle applications therefore its characteristics are not being developed to suit conventionally-powered vehicles (i.e. powered by an internal combustion engine only). Lithium ion batteries using ionic liquid electrolytes are of interest due to their potential for improved safety and lithium-sulphur batteries (a subset of lithium-metal batteries) are of interest due to their low cost and high energy capabilities. However, both of these batteries are immature technologies and are not expected to be immediately relevant for military land vehicles, but their development should be monitored.

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Brendan Sims graduated from the University of Adelaide with a Bachelor of Mechatronic Engineering (Hons) in 2008. He has been employed at DST Group Edinburgh (Land Operations Division and Land Division) since October 2009. In that time, he has worked in the Vehicle Electronics and Architectures (VE&A) team and the Advanced Vehicle Systems (AVS) group. Brendan's work within the VE&A team focussed on electrical power and energy usage and integration considerations for military land vehicles. He had also developed expertise in open architectures to support systems integration and interoperation on military Land vehicles. Brendan's latest role within the AVS group involves research and development of distributed decision making and control techniques to support the realisation of adaptable and autonomic digital military vehicle systems.

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He joined DST Group in 2002 where he has conducted technical and analytical work for military field trials and experimentation, provided support to the Australian Defence Force's Operations in Iraq, Afghanistan, Timor Leste and the Solomon Islands, led the Operational Data Exploitation team, deployed on a 'fly away team' to Timor Leste, and led a multidisciplinary Reachback team providing support to deployed scientists and analysts. In 2011, Simon returned to his engineering roots to lead the Vehicle Electrical Power and Energy team within Land Division's Advanced Vehicle Systems group and is now working on adaptability and autonomic control of military vehicle systems.

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Acronyms and Abbreviations

AC	Alternating Current
AGM	Absorbed Glass Mat (Battery)
Ah	Ampere hours
BMS	Battery Management System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DC	Direct Current
DoD	Depth of Discharge
DST Group	Defence Science and Technology Group
ELF	Extended Life Flooded (Lead-acid Battery)
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LCO	Lithium Cobalt Oxide (Battery)
LCP	Lithium Cobalt Phosphate (Battery)
LFP	Lithium Iron Phosphate (Battery)
Li-ion	Lithium ion (Battery)
Li-metal	Lithium-metal (Battery)
Li-S	Lithium Sulphur (Battery)
LMO	Lithium Manganese Oxide (Battery)
LTO	Lithium Titanate (Battery)
NCA	Lithium Nickel Cobalt Aluminium Oxide (Battery)
Ni-Cd	Nickel Cadmium (Battery)
Ni-MH	Nickel Metal Hydride (Battery)
NMC	Lithium Nickel Manganese Cobalt Oxide (Battery)
RWS	Remote Weapon Station
SLI	Starting, Lighting and Ignition (Battery)
SoC	State of Charge
SoH	State of Health
UAV	Unmanned Aerial Vehicle
V	Volts
VDC	Volts DC
VRLA	Valve Regulated Lead-Acid (Battery)
W	Watts
W/kg	Watts per kilogram
W/L	Watts per litre
Wh	Watt-hours
Wh/kg	Watt-hours per kilogram
Wh/L	Watt-hours per litre
ZEBRA	Zeolite Battery Research Africa

Definition of Terms

The following list provides a definition of terms as they are intended to be used within this report.

Calendar Life: The duration a battery can operate (in years) before it fails to meet specified performance criteria (e.g. its capacity has fallen to 60% or 80% of its initial rated capacity). May also be referred to as service life.

Capacity: The quantity of current, expressed in Ampere hours (Ah), that a fully charged battery can deliver to an electrical load under specified conditions (e.g. discharge rate, cut-off voltage, temperature) until the battery is fully discharged.

Capacity Fade: The gradual permanent loss in capacity of a battery over time.

Cell: The basic electrochemical unit providing a source of electrical energy by direct conversion of chemical energy. The cell consists of an assembly of electrodes, separators, electrolyte, container and terminals [1].

Charge Acceptance: The ability of a battery to accept charge. May be affected by temperature, charge rate and state of charge [1].

Charge Rate: The current applied to a secondary cell or battery to restore its capacity [1].

Controlled (Battery) Charging: The process of battery charging with controls in place to ensure that certain battery characteristics remain within safe operating limits.

Cut-off Voltage: The battery voltage at which discharge is terminated [1]. May also be referred to as end voltage.

Cycle: A cycle (discharge-charge cycle) is the discharge and subsequent or preceding charge of a battery such that it is restored to its original conditions [1]. The range through which a battery cycles may be of any size depending on application requirements (e.g. 5% or 100% of capacity).

Cycle Life: The number of discharge-charge cycles a battery can complete under specified conditions before it fails to meet specified performance criteria (e.g. its capacity has fallen to 60% or 80% of its initial rated capacity).

Deep-cycling: Deep-cycling is an operation where a battery is regularly deep-discharged using most of its capacity.

Deep-discharged: A battery state where at least 80% of the battery capacity has been used.

Depth of Discharge: The ratio of the quantity of electricity (usually in Ampere-hours) removed from a cell or battery on discharge compared to its rated capacity [1]. This is the complement of state of charge.

Discharge Rate: The rate, usually expressed in Amperes, at which electrical current is taken from a cell or battery [1].

Energy: The ability of an electrical current to do work, measured in Watt-hours (Wh). A battery's Wh capacity is the quantity of electrical energy, measured in Wh, that may be delivered by a cell or battery under specified conditions [1].

Engine-On: The mode of operation when the engine of a vehicle is turned on. This includes both driving and engine idling. In this mode, the vehicle's alternator will deliver a nominal voltage (e.g. 14 Volts (V) or 28 V) to the vehicle's electrical system.

Fully charged: A battery state where 100% of the battery capacity is remaining.

Fully discharged: A battery state where 0% of the battery capacity is remaining.

Gassing: The evolution of gas from one or more of the electrodes within a battery [1].

Gravimetric Energy Density: Also referred to as specific energy, gravimetric energy density is energy per unit mass, expressed in Watt-hours per kilogram (Wh/kg).

Gravimetric Power Density: Also referred to as specific power, gravimetric power density is power per unit mass, expressed in Watts per kilogram (W/kg).

Integrated Starter Generator: A device that replaces the starter motor and the alternator in a land vehicle to perform both engine cranking and power generation functions.

Internal Resistance: The opposition or resistance to the flow of an electric current within a cell or battery; the sum of the ionic and electronic resistances of the cell components [1].

Nominal Voltage: The typical voltage or range of voltages of a battery during discharge [1]. May also be referred to as working voltage or operating voltage.

Overcharge: A condition where a battery has been fully charged and continues to be charged after its full capacity has been returned.

Overdischarge: A condition where a battery is discharged beyond its recommended discharge level (e.g. past the point where full capacity has been obtained).

Partial State of Charge Operation: The operation of a battery where it is frequently cycled (charged and discharged) but rarely full charged or fully discharged.

Power: The rate at which electrical energy is transferred or converted by a circuit or machine, measured in Watts (W).

Rated Capacity: The capacity of a battery corresponding to manufacturer-specified discharge conditions. Battery capacity is commonly specified by manufacturers at a discharge rate corresponding to a 5 hour, 10 hour or 20 hour discharge.

Self-discharge Rate: The rate of reduction in state of charge of a battery due to internal chemical reactions. Self-discharge rate is typically expressed as a percentage of capacity lost per month or per year.

Silent Watch: The act of running electrical equipment on a vehicle with the vehicle's engine switched off. This may be performed through the use of energy stored in a vehicle's batteries, delivering a nominal voltage (e.g. 12 V or 24 V) to the vehicle's electrical system.

Silent Watch Batteries: Vehicle batteries used to power a vehicle's electrical equipment during silent watch. These may also referred to as Communications batteries, as this is the equipment they typically power during silent watch, or Auxiliary batteries.

SLI Batteries: Batteries specifically used to provide power for the Starting, Lighting and Ignition (SLI) electrical loads on a vehicle. They may also be referred to as cranking batteries as they are used to 'crank' or start a vehicle's engine.

Start-stop: A process used in hybrid electric vehicles where the vehicle's internal combustion engine is turned off when at idle.

State of Charge: The available battery capacity expressed as a percentage of its capacity when fully charged.

State of Health: A measure of the condition of a battery relative to a new battery. State of Health may be derived based upon any number of characteristics, such as internal resistance, capacity, voltage, self-discharge, charge acceptance and cycle number.

Thermal Runaway: Thermal runaway refers to a process where an increase in temperature in a battery on charge or discharge causes a further increase in temperature, causing the battery to overheat, catch fire and destroy itself through internal heat generation. Thermal runaway is typically triggered by high overcharge or overdischarge current or other abusive conditions.

Volumetric energy density: Also referred to as energy density, volumetric energy density is energy per unit volume, expressed in Watt-hours per litre (Wh/L).

Volumetric power density: Also referred to as power density, volumetric power density is power per unit volume, expressed in Watts per litre (W/L).

1. Introduction

The functions of military land vehicles are becoming increasingly dependent on electrical energy. Batteries are currently the only form of electrical energy storage on these vehicles in the Australian Army; therefore they form a vital component of these vehicles' electrical systems[1]. The electrical energy demands of military land vehicles will continue to increase as they are fitted with more electronic equipment such as radios, surveillance equipment, battle management systems, remote weapons stations and electronic warfare counter measures. Considering the long life of type of military land vehicles, which is typically in excess of 20 years, it is anticipated that their electrical energy storage capabilities will present issues during their lifespan. Insufficient electrical energy storage can inhibit operational performance, particularly when conducting silent watch. Silent watch refers to an operational scenario where a vehicle's on-board electrical equipment is operated while its engine is off and electrical power is provided to this equipment by the vehicle's energy storage capability (i.e. its batteries).

In addition to the provision of electrical power for silent watch, batteries on military land vehicles must provide power for standard starting, lighting and ignition (SLI) functions. They may also be required to provide power to support large engine-on electrical loads (e.g. turrets and remote weapon stations (RWS)) where they make up for the difference between the power drawn by the load and the power generated by the alternator (i.e. load levelling). This has placed unique requirements on the batteries used in military land vehicles compared to cars and commercial vehicles. Furthermore, the development of hybrid electric vehicles (HEV) and electric vehicles (EV) has introduced new performance requirements on the batteries used in land vehicles. Although not presently used in the Australian Army, it is possible that these vehicles will be used in the future. Therefore, consideration and understanding of advanced battery technologies and battery technology research is important.

This report explores current and emerging secondary (i.e. rechargeable) battery technologies and assesses whether they are suitable for military land vehicles. The report will focus on battery applications in conventionally powered vehicles (i.e. powered by an internal combustion engine only), which are likely to remain commonplace in the Australian Army for the near future. HEV and EV applications will be a secondary consideration. Any reference made in this report to "battery" or "batteries" refers to secondary batteries as opposed to primary (non-rechargeable) batteries. Primary batteries are not addressed as they are not suitable for land vehicles since they cannot be charged.

The batteries presented in this report have been chosen because they are used or have been proposed for land vehicle applications, or because they possess desirable characteristics (e.g. high energy, high cycle life, good safety) that may create performance advantages or improve the operational effectiveness of Australian military land vehicles. Relevant

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[1] The electrical system on military land vehicles in the Australian Army is either 12 VDC or 24 VDC and typically consists of an internal combustion engine (ICE) and an alternator for electrical power generation and a battery or set of batteries for electrical energy storage. In some cases an auxiliary power unit may also be used for power generation when the ICE is off.

battery technologies for military land vehicles have been identified through a number of means. This has included discussions with relevant expertise from within Australia (e.g. the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Defence Science and Technology Group (DST Group)) and internationally (e.g. the Army Research Laboratory in the United States of America), attendance at relevant conferences (e.g. International Battery Association 2014), and being conversant with literature (e.g. books, reports, and journal articles) to understand mature battery technologies and the cutting edge research in this field. Furthermore, an understanding of the electrical energy storage needs of Australian military land vehicles has been established through ongoing research and analysis in this space by the authors of this report. The combination of information from these activities has allowed identification of the battery technologies that are relevant for military land vehicles and those that warrant attention into the future.

This report begins by describing the fundamental aspects of batteries, which is followed by a summary of relevant battery performance characteristics and factors that affect battery performance. Operational and integration considerations for batteries in military land vehicles are then discussed. The remainder of the report focuses on individual battery chemistries, including their advantages, disadvantages, integration considerations, applications and expected future development.

2. Battery Fundamentals

A battery is a device that converts chemical energy directly into electrical energy through a redox reaction (electrochemical reduction-oxidation). The fundamental element of a battery is a cell. A battery may consist of one or more cells connected in series, parallel, or both, depending on the desired output voltage and capacity [1]. A cell consists of three main components, an anode, a cathode and the electrolyte, whilst a separator is also used to separate the anode and cathode mechanically [1]. A basic battery cell is shown in Figure 1. The anode, or negative electrode, is typically a metal, such as zinc or lithium and the cathode, or positive electrode, is typically a metallic oxide [1]. When a battery is discharging, the anode is oxidised and releases electrons to an external circuit (to provide power to a connected load) whilst the cathode accepts electrons from this external circuit and is reduced [1]. The anode and cathode vary in electrical potential and are electrically separated, but remain connected ionically through the electrolyte [2]. The electrolyte may be a liquid, a gel-type polymer or a solid, and provides a medium for the transfer of charge, as ions, between the anode and cathode [1]. Ions may be distinguished as anions (those that travel towards the anode during charge and discharge) and cations (those that travel towards the cathode). In a rechargeable battery, the reactions at the anode and cathode, and the flow of ions and electrons, reverse when the battery is being charged[2].

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[2] Batteries must be charged by a Direct Current (DC) power supply.

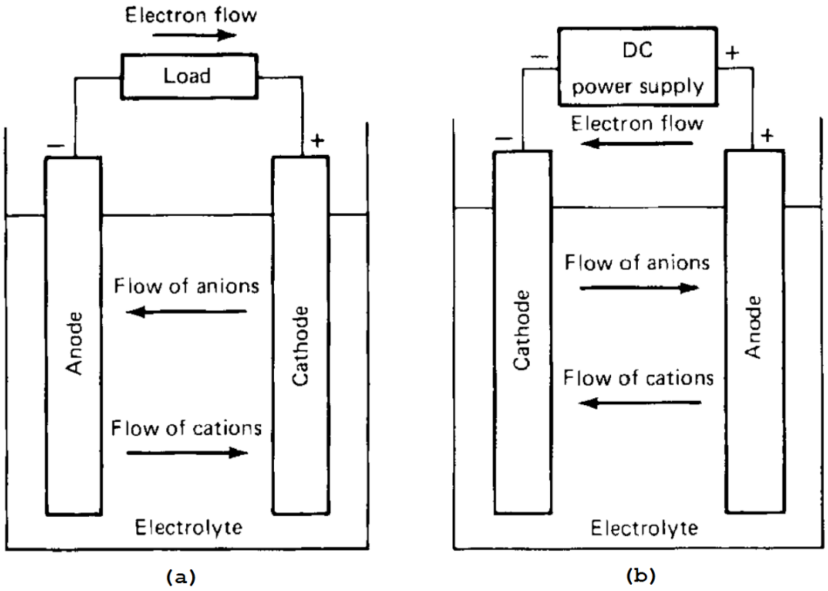

Figure 1 The basic battery cell; discharging shown in (a) and charging shown in (b) [1].

3. Battery Performance

This section considers the characteristics[3] that can be used to compare battery performance as well as common factors that influence battery performance and their effects. The characteristics that are most important for military land vehicles are highlighted and they form the basis for comparison of individual battery technologies within this report.

A number of characteristics can be used to compare battery performance. They include operating voltage, capacity, gravimetric and volumetric energy density (also termed "specific energy" and "energy density" respectively), gravimetric and volumetric power density (also termed "specific power" and "power density" respectively), cycle life, calendar life, self-discharge rate, and operating temperature range. When comparing batteries, other characteristics that must be taken into account include safety and reliability, regulatory requirements and cost. Cost should be assessed in many aspects including initial cost, the number of cycles delivered during a battery's lifetime, and any maintenance costs [1]. The combination of these aspects constitutes the lifetime cost of a battery.

Several battery characteristics are particularly important for military land vehicles. Gravimetric and volumetric energy density correlate to battery discharge duration, hence larger values for specific energy and energy density are likely to translate into improved silent watch performance for vehicles. Cycle life indicates the amount a battery can be used before it has to be replaced. Higher cycle life means less frequent replacement and

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[3] Definitions for relevant battery characteristics are included in the Definition of Terms.

lower maintenance costs. Calendar life corresponds to the length of time (usually in years) a battery will last before it should be replaced. This is important for military land vehicles that are not operated for long periods of time whilst in storage. Operating temperature range specifies the safe operating temperature limits for batteries and provides an indication as to whether a particular battery is capable of withstanding temperature extremes presented by harsh military environments. Gravimetric and volumetric power density may also be important as high power loads (e.g. RWSs) and high-rate charging (e.g. HEVs) become more common on land vehicles. Larger values for power density are likely to translate into improved performance at high rates (e.g. greater capacity retention at high rates of discharge).

Battery characteristics can vary for specific battery chemistries depending on the battery design [1], which is usually dictated by application requirements. There may be many possible battery designs and many possible characteristics for a specific chemistry. For example, a lead-acid battery optimised for high power will maximise the surface area of its electrodes, whereas a lead-acid battery optimised for high energy will maximise the volume of active material in the battery. For a given battery design, there may also be slight performance differences that arise due to the materials used and the manufacturing processes. Manufacturer specifications tend to present battery performance under favourable conditions [1]. Furthermore, many of the characteristics listed above will vary to a certain extent depending on the manner in which a battery is used [1].

In addition to battery characteristics and design, there are many other factors that affect the performance of a battery. Since there are many possible interactions, these effects cannot be isolated and they are usually greater under extreme operating conditions [1]. It should also be noted that the magnitude of these effects will vary for different battery chemistries and the information presented here represents a general case. These factors, as described in [1], include the rate of discharge, the temperature during discharge, the depth of discharge (DoD) and the type of discharge. Other factors that affect battery performance are the state of health (SoH) of the battery and charging characteristics. The effect of these factors on various battery performance measures, such as voltage, discharge time, capacity, energy, cycle life and calendar life, are now discussed.

3.1 Effect of Rate of Discharge

The rate of discharge (i.e. magnitude of discharge current) of a battery affects the operating voltage of a battery, its delivered capacity and energy, and its cycle life and calendar life. At higher discharge rates, a battery's operating voltage will drop (rate of decrease is usually more rapid at lower temperatures) and its delivered capacity and energy will typically be reduced [1]. Furthermore, consistently discharging a battery at high rates will reduce the cycle life and calendar life of a battery [3], although the effect of the rate of discharge is less significant than DoD or temperature [4]. These effects are reversed for lower discharge rates.

3.2 Effect of Temperature

The operating temperature of a battery will affect its operating voltage, capacity, energy, self-discharge rate and charging performance. It may also impact a battery's calendar life, cycle life and safety. During operation at lower temperatures, battery voltage, capacity and energy are reduced [1]. At higher temperatures, battery voltage, capacity and energy may increase or decrease depending on the chemistry of the battery, and a battery's rate of self-discharge will increase [1]. Nickel Metal-Hydride (Ni-MH) batteries exhibit capacity and energy drops at higher operating temperatures whereas lead-acid batteries and lithium ion (Li-ion) batteries do not (capacity and energy actually increase slightly) [1].

Operating a battery (generally any chemistry) at a temperature above its recommended temperature range may irreversibly damage the battery, reducing its calendar life and cycle life, and it may pose safety issues [1]. Therefore, high temperature operation should be avoided. Furthermore, battery self-discharge rate increases at higher temperatures [1], which means it is advisable to store batteries in low temperature environments to maximise their storage time. Temperature affects charging performance by causing an increase in charging time at lower temperatures and by lowering the overcharging current threshold at high temperatures (leading to more overcharging, harmful effects on the battery and reduced battery life if it continues to be charged) [5]. In general, the best overall performance for batteries is obtained when operated (and stored) between 20 °C and 40 °C [1].

3.3 Effect of Depth of Discharge

The DoD of a battery will affect its delivered capacity, its energy available, and its cycle life. Increasing the DoD of a battery[4] will increase its delivered capacity and energy, which means the amount of time it is discharging will increase. However, batteries that are consistently deep-discharged exhibit shorter cycle lives than those that are shallowly discharged [1, 6] and they must be replaced more regularly. Therefore, there is typically a trade-off between cycle life and DoD for a battery in an application where it is regularly deep-discharged.

3.4 Effect of Type of Discharge

The type of discharge affects the total discharge time and subsequent capacity and energy delivered by a battery. Intermittently discharging a battery, as opposed to continuously discharging, may increase the total discharge time as battery voltage after a heavy discharge will rise after a rest period, which permits further discharge [1]. As a result, the total capacity and energy delivered by the battery will be greater.

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[4] Batteries are not typically discharged to 100% DoD.

3.5 Effect of State of Health

The SoH of a battery will diminish as a battery ages and as it is used. The rate at which SoH declines depends on the battery chemistry, battery design and the manner and conditions in which it is used (e.g. temperature, charge and discharge rate, average state of charge (SoC), and DoD [7]). At lower states of health, battery capacity is reduced, which means its discharge duration is shorter for a given discharge rate [8], and battery charge acceptance is lower (due to higher internal resistance), which means it takes longer to charge [9]. Manufacturer specifications for battery capacity and charge performance are representative of new batteries and it should be recognised that battery performance will deteriorate over its lifetime.

3.6 Effect of Charging Characteristics

The manner in which a battery is charged will affect its capacity and energy on subsequent discharges and its overall cycle life and calendar life. Battery charging is a key factor in the proper operation of a battery and inadequate or improper charging is a common cause of premature battery failure [6]. Battery charging is an inefficient process as more charge will be required to go into a battery during charge than will be delivered during discharge [1]. Therefore, a fully discharged battery will need to be charged with an amount of charge equivalent to at least 100% of its rated capacity to become fully charged. The optimal amount varies for different battery chemistries. If a battery is not fully charged, it will not deliver all of its available capacity on the subsequent discharge. However, overcharging a battery (or charging it at too high a rate or voltage) will cause its internal temperature and pressure to rise and may damage its internal components or cause a serious safety hazard [1]. As a result the battery's cycle life and calendar life may be reduced (corresponding to a reduced SoH) and its subsequent discharge performance may be diminished [1]. Therefore it is important to take care when charging batteries to maximise battery life.

4. Operational and Integration Considerations for Military Land Vehicles

There are a number of important considerations for battery technologies (and energy storage capabilities more generally) on military land vehicles. This includes the effect of military operational requirements on battery performance, the integration requirements for individual battery technologies, and the increasing use of HEVs and EVs and the associated impact on vehicle battery requirements. Each aspect is discussed in the following sections and at various stages in Section 5 of this report for individual battery technologies.

4.1 Military Operational Requirements

Military operations present unique requirements for vehicle battery technologies. In many automotive applications, batteries are only used for SLI functions[5] such as engine starting. However, military operations such as silent watch require vehicle batteries to provide engine-off power to a vehicle's electrical equipment for long periods where they are regularly deep-discharged. The batteries on a military land vehicle may also be required to perform load levelling when the engine is on where they make up for the difference between power drawn by a large electrical load and the power being generated. This means that a battery in a military land vehicle must be capable of delivering high power to meet engine starting requirements, it must be able to perform load levelling, and it must also be capable of deep cycling to maximise the amount of energy it can deliver, hence maximising silent watch endurance. Many military land vehicles implement separate batteries for SLI functions (e.g. SLI batteries), and engine-off power (e.g. silent watch batteries), but often the same battery chemistry is used.

As power and energy requirements on modern military land vehicles continue to grow due to the greater amount of electronic equipment, the demand on vehicle battery technologies is increasing. Traditional lead-acid batteries used in vehicles have reached the limit of their performance capabilities in these applications, which means that alternative battery technologies must be considered.

Operational issues have arisen relating to limited endurance from military vehicle batteries during silent watch. Short silent watch endurance may impact operational effectiveness as the resultant frequent engine operation increases the acoustic and thermal signature of a vehicle and increased fuel usage can reduce mission endurance. Excessive idling also increases the associated logistics burden through extra fuel usage and servicing liability on the vehicle's main engine. Batteries with insufficient energy are a primary cause of these issues, which can be addressed by replacing them with batteries of higher energy. However, certain aspects of military land vehicle operation may also impact battery performance during silent watch, which are described as follows. Military vehicles with a vast amount of electronics draw a large electrical load, which is likely to significantly limit battery capacity since capacity tends to reduce at higher rates of discharge [1], as described in Section 3. Improper charging, discussed in Section 3, may prevent batteries from being fully charged, which will also limit their available capacity during subsequent discharges and their silent watch performance. These factors should be considered when analysing vehicles exhibiting poor silent watch performance.

Another aspect of military operational requirements is the harsh environmental conditions to which vehicles are often subjected. These conditions are characterised by temperature

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[5] The operating mode for batteries used to perform SLI functions is characterised by "floating" in a high SoC with shallow cycling where full discharge is never achieved [10]. The two main functions performed are engine cranking (high electrical power required for a very short period) and a service function to ensure an electrical buffer between a vehicle's power generation and its consumption of electrical power (low to medium power required for long periods) [10].

extremes[6], high vibration, high impact, dust, dirt and moisture. It is important that any battery technology integrated onto a military land vehicle is able to withstand these conditions or they are to be enclosed in a container[7] that is able to withstand these conditions. For example, vehicle battery technologies must be able to meet the cold cranking requirements of vehicles whereby they must provide high current for a few seconds in very cold ambient temperatures (such temperatures typically reduce battery voltage and performance).

The need to investigate alternative battery technologies is especially important when considering future upgrades of electrical and electronic systems on military land vehicles and the introduction of high power devices (e.g. RWS, electric armour) on these vehicles. These upgrades will increase the vehicle's total electrical load. As traditional lead-acid batteries already have limited performance in current operational scenarios, their ability to accommodate upgrades and maintain satisfactory performance is likely to be severely restricted. It is expected that alternative battery technologies will be required on military land vehicles to ensure a sustainable vehicle upgrade cycle during the life of modern vehicles.

4.2 Integration of New Battery Technologies

The integration of new battery technologies into military land vehicles introduces a number of considerations beyond the performance characteristics and capabilities of the battery. These considerations are discussed below and, where relevant, they are highlighted in Section 5 of this report.

The physical dimensions of a battery (or a set of batteries) and the space available on a vehicle is a primary consideration and constraint when integrating new batteries. For ease of integration, the battery (or batteries) must be able to fit into an existing vehicle without significant structural modification. It is recommended that drop-in replacement batteries have very similar form factors to existing batteries to minimise the likelihood of vehicle modifications. Furthermore, although batteries form a very small percentage of the total weight of a vehicle, drop-in replacement batteries ideally will not increase the overall vehicle weight.

If mounting new batteries in new locations on a vehicle, it is important to consider the temperature that a battery will be exposed to and the type of mounting for the battery. Temperature extremes should be avoided to ensure reliable performance and maximum battery life and proper mounting should be used to minimise vibration. Batteries may be mounted outside of a vehicle's engine bay to aid in battery temperature management. In this case or in any other case where the battery distance from the alternator and starter motor is increased, longer electrical cables must be used which will increase electrical

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[6] The environmental temperature experienced by a land vehicle typically ranges from anywhere between -30 °C and +60 °C [10]. Australian military land vehicles operating in outback or desert conditions may experience even higher maximum temperatures.

[7] Some batteries vent gas during operation, which means they are not able to be operated in sealed containers.

losses and reduce the overall system efficiency. Such losses must be accounted for when considering the integration of batteries in new locations. Furthermore, consideration must be given to the potential venting of harmful gases from batteries if they are mounted in the operator or passenger compartment of a vehicle.

The voltage of a vehicle's electrical system will also place requirements on the batteries employed. Conventional military land vehicles with lead-acid batteries employ a 12 Volts DC (VDC) or 24 VDC electrical system. The voltage window of batteries employed in these vehicles typically ranges from 10 VDC to 14 VDC for 12 VDC systems (or 20 VDC to 28 VDC for 24 VDC systems) [10]. Batteries used on these vehicles must be compatible[8] with these voltages (when the engine is on and when it is off). If a battery's operating voltage is too high (i.e. it is not compatible with the required voltage window), it may damage electrical equipment on a vehicle (most electrical systems have an upper limit to their acceptable voltage range) or it may never be fully charged [11]. Therefore, a separate conversion device would need to be implemented or significant changes would need to be made to a vehicle's electrical system (e.g. upgraded alternator). Changes to a vehicle's electrical system would be very expensive and additional conversion devices will introduce cost, complexity and inefficiency to this system.

Battery charging is another relevant factor that must be considered. Traditional lead-acid batteries are relatively robust when being charged in that they will accept a wide range of current without damage to the battery. They are able to absorb the excess current when float charging to intrinsically balance themselves. Therefore, vehicles in the past have not required charging control systems. However, alternative battery technologies such as Li-ion batteries have much stricter limits on charging current to ensure battery safety since they cannot intrinsically absorb excessive charging current. It is likely that additional charging controls will be required to be added to military land vehicles using these batteries. This may be extended more generally to a wider control suite (e.g. sophisticated battery management systems (BMS)) to control a number of aspects, including battery voltage, temperature and pressure, to ensure battery safety during charge and discharge and to optimise battery cycle life. Modification of a vehicle's charging system or addition of a BMS could lead to significant changes to a vehicle's electrical system at a large cost in resources.

Adjustments to maintenance and standard operating procedures may also be required if military land vehicles are fitted with new types of batteries. For example, batteries with higher cycle lives will require less frequent replacement and data from batteries using BMSs could be used to optimise battery maintenance and condition.

Although most conventional military land vehicles are fitted with alternators for power generation, consideration should be given to upgrades of this capability and the ability of vehicle batteries to accommodate high power generation systems (e.g. integrated starter generators). These upgraded systems offer the potential for fast charging of vehicle

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[8] To ensure compatibility, the battery must deliver a voltage not lower than 9.9 VDC (or 19.8 VDC) when the vehicle's engine is off and must be charged safely between 13 VDC and 15 VDC (or 26 VDC and 30 VDC) when the vehicle's engine is on [10]. Slight deviations in these values may be acceptable, which may only require fine tuning of an alternator's regulation parameters [10].

batteries (within one hour), which could provide significant operational advantages. For example, the amount of engine-on time during silent watch operations would be reduced. If fast charging is to be realised, it is important to ensure that the battery technologies integrated into military land vehicles are able to safely handle the associated high currents being generated and that there are no adverse effects on performance or battery life.

4.3 Electric and Hybrid Electric Vehicles

A consideration into the future for battery technologies on military land vehicles is the introduction of HEVs and EVs. These vehicles will introduce new electrical load and cycling requirements, such as start-stop requirements [1], which will cause a greater demand and reliance on vehicle batteries. This will require batteries with good cycle life especially under high-rate partial SoC operation[9] [1]. High specific power and high power density is important here. HEVs and EVs will also benefit from batteries with high specific energy and high energy density to maximise driving endurance. Traditional flooded lead-acid vehicle batteries used in SLI applications cannot meet these requirements [1], hence other batteries including advanced lead-acid batteries (e.g. UltraBattery – see Section 5.1.3), Ni-MH batteries, Li-ion batteries and other advanced chemistries are in scope for HEV and EV applications.

5. Battery Technologies

There are many battery technologies in scope for military land vehicles into the future. They range from extant solutions on conventional vehicles, such as flooded and sealed lead-acid batteries, through to newer technologies, which includes various nickel-based and lithium-based battery chemistries. Although advances are being made in battery technology, there are theoretical limits to the amount of energy available from a battery [1]. This should be kept in mind when specifying requirements or goals for battery performance on vehicles. Modern improvements to batteries are focussing on improving gravimetric and volumetric energy density, increasing conversion efficiency and rechargeability, maximising performance under extreme operating conditions, and enhancing safety [1].

A map of battery types is presented in Appendix A and a table of battery characteristics is presented in Appendix B. This table should be referred to for quantified data relating to the performance of different battery types. It is important to note that much of the data within this table is generalised to provide an indication of the relative performance of various battery technologies. As discussed in Section 3, battery performance may vary depending on many factors and as such, the values presented in Appendix B should not be

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[9] High-rate partial SoC operation corresponds to charging and discharging a battery at high power where the battery is rarely fully charged or fully discharged. Such operation is associated with regenerative braking and acceleration assistance in HEVs and EVs.

considered indicative for all battery use cases and all conditions. The battery types relevant for military land vehicles are now discussed.

5.1 Lead-Acid Batteries

Lead-acid batteries are widely used in automotive applications [1, 10], including most military vehicles [12]. There are multiple designs of lead-acid battery available, but the two most relevant designs for vehicles are SLI batteries (also referred to as starting or cranking batteries) and deep-cycle batteries (also referred to as traction batteries) [1]. SLI batteries are designed to provide high power over a short period of time while deep-cycle batteries are designed to provide continuous power over longer periods of time, be deep-discharged and be repeatedly cycled [1, 13]. SLI and deep-cycle batteries achieve different performance because they have different cell designs. The SLI design is what is typically used in land vehicles for SLI applications while deep-cycle batteries are used in forklifts, golf carts and EVs.

Lead-acid batteries are constructed with a lead anode, a lead oxide cathode and a sulphuric acid electrolyte [1]. The first lead-acid batteries were manufactured with a liquid electrolyte and were not sealed. These batteries are known as flooded (or wet) lead-acid batteries. Sealed lead-acid batteries have since been developed. Both flooded and sealed lead-acid batteries have similar chemistry and have common advantages and disadvantages, which are described below.

There are a number of common advantages for all lead acid battery types and designs. A significant advantage and one of the main reasons they remain in widespread use is their low cost and their robustness [1, 14]. Their ease of manufacture contributes to their low cost [1, 14]. This means lead-acid batteries are much cheaper than other rechargeable batteries for automotive applications and they are reliable and more tolerant to abuse and the environmental conditions inside vehicle engine bays. For SLI lead-acid batteries, another advantage is their high specific power (approximately 215 W/kg for flooded lead-acid batteries and up to 235 W/kg for sealed lead-acid batteries [15]), which results in good performance at high discharge rates (e.g. engine cranking) [1, 14]. SLI lead-acid batteries also tend to be cheaper upfront than deep-cycle lead-acid batteries [1].

A disadvantage of lead-acid batteries is that their specific energy and energy density is lower (25-40 Wh/kg) than many other secondary battery chemistries, such as Ni-MH and Li-ion batteries [1], which restricts silent watch endurance. Another disadvantage is that they cannot be stored in a discharged state since this irreversibly damages the battery's electrodes [1, 14], which will cause decreased capacity and calendar and cycle life. Therefore, they must be regularly charged if they are in long-term storage. When disposing of lead-acid batteries, care must be taken since they contain harmful substances including lead, antimony, arsenic and sulphuric acid [1, 14]. However, a significant amount of lead-acid batteries are recycled [1], which offsets this disadvantage. SLI lead-acid batteries also have relatively short cycle lives (200-700 cycles) [1, 14] compared to Ni-MH batteries and Li-ion batteries (and deep-cycle lead-acid batteries (1500 cycles)). This means they require more regular replacement, which increases their lifetime costs.

Lead-acid batteries are a mature technology in automotive applications and military land vehicles. However, their low specific energy and energy density presents issues. SLI lead-acid batteries are not designed to be regularly deep discharged [1], which is typically required in silent watch applications. This significantly reduces their calendar life and cycle life [1]. Conversely, deep-cycle lead-acid batteries are not designed for maximum current output, which restricts their use in automotive SLI applications (they can be used for engine cranking if required). Without dedicated deep-cycle batteries for the provision of electrical power during silent watch, silent watch endurance is likely to be severely reduced if SLI lead-acid batteries are used. However, the ability to increase the amount of energy on a land vehicle fitted with lead-acid batteries is restricted by the large weight and volume of these batteries. Therefore, alternative battery technologies should be considered that offer higher specific energy and energy density to improve silent watch performance.

The poor silent watch performance of lead-acid batteries may also be attributed to batteries that are not being fully charged, as described in Section 3. An approach to overcome this is to upgrade a vehicle’s alternator to provide a greater amount of current when charging. For SLI lead-acid batteries (flooded and sealed), this may be a viable solution because they can be fast charged within one hour [1]. The inherent physical and chemical characteristics of lead-acid batteries make charge control relatively simple in this case as they will draw only the amount of current that they can accept efficiently, which reduces as the battery approaches full charge [1]. Charge control is still important during fast charging to ensure the electrodes are not damaged, to prevent temperature rises and to limit overcharge and gassing [1]. This charge control is performed in vehicles by their alternators, which typically have voltage and current limiters (unless there is a fault with the alternator) [1]. It should be noted that there is a physical limit to the maximum rate at which lead-acid batteries can be charged, so such a solution would be constrained by the properties of the battery.

Lead-acid battery technologies are expected to remain in consideration for future military vehicle applications since they are a cost effective solution and the development of advanced lead-acid battery technology and design fabrication processes is ongoing [1, 14]. An example of lead-acid battery technology development is the UltraBattery, which is discussed in Section 5.1.3. Unique considerations for flooded lead-acid batteries and sealed lead-acid batteries are now presented in Section 5.1.1 and Section 5.1.2 respectively.

5.1.1 Flooded Lead-Acid Batteries

Flooded lead-acid batteries, sometimes referred to as vented lead-acid batteries, are the more traditional lead-acid battery type. They are used extensively in many applications, which include long-term use in automotive SLI applications [1, 16].

The general chemistry described for lead-acid batteries in Section 5.1 applies to flooded lead-acid batteries. Compared to sealed lead-acid batteries, their unique aspect is that the cells are flooded with liquid sulphuric acid electrolyte [16]. In addition, in flooded lead-acid batteries, gasses produced from overcharging are vented externally [16] and the battery has removable caps for the addition of water to compensate for lost hydrogen and oxygen.

A distinct advantage of flooded lead-acid batteries compared to sealed lead-acid batteries is that they have lower upfront costs [17, 18]. For SLI flooded lead-acid batteries, another advantage and an example of their robustness is that they can generally be discharged (and charged) at high rates of current without harm [1], which makes them excellent candidates for engine starting applications in military land vehicles. However, this is not the case for deep-cycle flooded lead-acid batteries.

Flooded lead-acid batteries have several unique disadvantages. Regular maintenance (addition of water) is required to replenish the electrolyte lost as gas through the battery's vents during charging [1]. The generation of gasses during charging requires that flooded lead-acid batteries are well ventilated when in use, with hydrogen evolution presenting a potential explosion hazard [1]. In addition, they must be mounted upright to prevent sulphuric acid electrolyte leakage or spillage [14, 19]. These issues present restrictions when integrating flooded lead-acid batteries into vehicles. Electrolyte stratification is another issue, where higher concentration acid collects at the bottom of battery cell resulting in an uneven concentration of electrolyte [1]. Stratification causes shortened calendar and cycle life and reduced charge and discharge performance, but can be overcome by gassing or stirring the electrolyte [1]. For SLI flooded lead-acid batteries, another disadvantage is that their self-discharge rate is quite high (up to 30% per month) [1], which means they must be regularly recharged when in storage.

"Maintenance-free" flooded lead-acid batteries are also available. These batteries eliminate the requirement to top up the battery with water [1] since they contain excess electrolyte and gases produced from charging are not vented from the cell. Their performance is similar to flooded cells, but their self-discharge rate is much lower (2-3% per month), which equates to better capacity retention during storage [1]. Downsides of "maintenance-free" flooded lead-acid batteries are that they fail more rapidly (i.e. lower cycle life) than regular flooded lead-acid batteries in high temperature environments (e.g. under a vehicle's bonnet) and they are difficult if recharge if left drained for an extended period of time (e.g. several days) [20]. While these "maintenance-free" batteries are considered sealed, they differ from sealed lead-acid batteries (see Section 5.1.2), which use a limited amount of electrolyte.

Flooded lead-acid batteries continue to be developed with a major focus now on the application of this technology in HEVs [1]. This includes the development of active material additives to improve lead-acid battery cycling performance and charge acceptance [1], which is important in HEV applications (e.g. to accommodate high currents from regenerative braking). Extended life flooded (ELF) lead-acid batteries, which incorporate electrode additives, alternative separator designs and may use different lead alloys, are being developed for hybrid vehicle applications [1]. The flooded version of the UltraBattery (see Section 5.1.3) is a type of ELF battery and the Enhanced Flooded Batteries offered by Bosch [21] and Energizer [22] are examples of ELF lead-acid technology already on the market.

5.1.2 Sealed Lead-Acid Batteries

Sealed lead-acid batteries, also known as Valve Regulated Lead-Acid (VRLA) batteries, are the other main type of lead-acid battery. The term "valve regulated" is used because these batteries have a resealable low pressure safety valve to maintain internal pressure and chemical balance when gases are generated during charging or overcharging [1, 14]. Sealed lead acid batteries have become popular in telecommunications and backup power applications [1, 14], but new developments are making them more attractive for automotive applications, in particular HEVs [1].

Sealed lead-acid batteries have essentially the same chemistry as flooded lead-acid batteries, but they are differentiated because they are sealed and they use a limited amount of immobilised electrolyte [1]. The electrolyte is immobilised by either soaking it in an absorptive glass mat separator, as in absorbed glass mat (AGM) lead-acid batteries, or by forming a gel through the addition of silica, as in gel lead-acid batteries [1, 23, 24, 25]. The unique aspects of gel lead-acid batteries and AGM lead-acid batteries are discussed in Section 5.1.2.1 and Section 5.1.2.2 respectively.

Sealed lead-acid batteries are improved compared to flooded lead-acid batteries in several aspects. Their immobilised electrolyte enables them to retain their electrolyte internally regardless of orientation, which means they can be mounted and can operate in any orientation without leakage [1, 23]. They also have less stringent ventilation requirements since any gasses produced during charging are recombined inside the battery under normal conditions [1, 14, 24]. By using a sealed design and an immobilised electrolyte, the need for regular battery maintenance is reduced since cells do not need to be topped up with water [1, 14, 24]. Sealed lead-acid batteries also reduce electrolyte stratification [23, 24, 26]. As with lead-acid batteries in general, certain VRLA designs have good high-rate capabilities, which enable them to be fast charged (thin-plate sealed lead-acid batteries can be charged to 100% of their rated capacity in less than one hour) [1].

A drawback of sealed lead-acid batteries is that they are more sensitive to high temperature environments than flooded types due to their limited electrolyte (the major internal heat sink) [1], with reduced performance and life (calendar and cycle life) at high temperatures [23]. Sealed lead-acid batteries also do not handle certain types of abuse as well as flooded lead-acid batteries. If they are incorrectly charged or not properly thermally managed they are more prone to thermal runaway, where the battery produces more internal heat than it can dissipate [1, 27]. However, this does not occur often in sealed lead-acid batteries [28].

The ability of sealed lead-acid batteries to operate in any orientation is advantageous for their integration into military land vehicles, but there are also some other important aspects to consider to ensure their safe and proper usage in these vehicles. Although they are sealed, these batteries do release hydrogen gas at times through their safety value and therefore they should have some form of ventilation to prevent hydrogen build up. Furthermore, they should be integrated with consideration given to the temperature of their operating environment. High temperature should be avoided where possible since it increases the risk of thermal runaway, which could lead to vehicle damage or operator injury. For example, integrating these batteries on a vehicle outside of the engine bay is one potential solution to minimising exposure to high temperatures.

The market share of sealed lead-acid batteries, specifically AGM lead-acid batteries (see Section 5.1.2.2), is predicted to grow relative to other lead-acid batteries [1]. This will be assisted by ongoing innovation and improvement to the technology to improve rate capability and cycle life, such as improved separators, high capacitance cells (e.g. UltraBattery), improved alloys and structures, and by providing higher charge-rate capabilities [1].

5.1.2.1 Gel Lead-Acid Batteries

Gel lead-acid batteries are a type of sealed lead-acid battery with an immobilised gel electrolyte, formed through the addition of silica [1, 23, 24]. They are typically used in deep-cycle applications and they are not as common as flooded and AGM lead-acid batteries in automotive applications.

Gel lead-acid batteries share the advantages described in Section 5.1 and Section 5.1.2 and perform better than AGM lead-acid batteries when deep discharged [14, 24]. This suggests they could offer better performance than AGM lead-acid batteries in silent watch applications. In addition, they perform better than AGM lead-acid batteries at higher operating temperatures and are less sensitive to thermal runaway [29], which is important in harsh military environments.

A disadvantage of gel lead-acid batteries is that they have poor specific power and power density compared to other lead-acid batteries (approximately 155 W/kg and 325 W/L in SLI designs [15]) [16, 25]. They must be charged slowly and carefully as fast charging can damage the battery [17] and they are not suited to applications requiring high current discharge (e.g. engine cranking). Furthermore, they require a lower charging voltage than other lead-acid batteries[10] [14, 17, 30], which is typically lower than the voltage produced by vehicle alternators (14.2 V). This means the alternators in military land vehicles would need to be modified or additional electronics may be required otherwise the battery may be overcharged, which would cause irreversible damage to the battery. Another disadvantage of gel lead-acid batteries is that they have poor performance at low temperatures [31]. In terms of cost, gel lead-acid batteries are more expensive than AGM (and flooded) lead-acid batteries [24, 25].

Although gel lead-acid batteries offer potentially improved silent watch performance compared to other lead-acid battery chemistries, their additional charging requirements and restrictions along with their poor high current discharge performance suggest that it is unlikely this technology will be suitable for military land vehicles in the future.

5.1.2.2 Absorbed Glass Mat (AGM) Batteries

The other type of sealed lead-acid battery is the AGM lead-acid battery, which uses a sulphuric acid electrolyte soaked in a porous AGM separator to immobilise the electrolyte [1, 23, 24]. These batteries offer good all-round performance in terms of deep discharging and high power provision, and are more suited to automotive SLI applications than gel lead-acid batteries.

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[10] Charging voltages higher than 14.2 V on vehicles may destroy gel lead-acid batteries, hence charging voltages should be kept to 14.1 V or less [30].

A key advantage of AGM batteries is that they perform well at high discharge rates and they are able to be fast charged [1, 14]. They have higher specific power and power density (235 W/kg and 570 W/L in SLI designs [15]) than flooded lead-acid batteries and gel lead-acid batteries since they have low internal resistance[11] [14, 24, 33]. Improved performance at high discharge rates is important for engine cranking and supporting large electrical loads, while the ability of AGM lead-acid batteries to be fast charged is useful in minimising battery charging time, and hence engine-on time, during silent watch operations. Another benefit of AGM lead-acid batteries is their resistance to vibration [14], which suggests they are well-equipped to handle harsh military environments.

A disadvantage of AGM lead-acid batteries is that they are more expensive upfront than flooded lead-acid batteries (approximately three-times higher [32]), although they tend to be cheaper than gel lead-acid batteries [24] and are significantly lower cost than Li-ion or Ni-MH batteries [10, 18]. Although AGM lead-acid batteries are able to be fast charged, regular fast charging reduces cycle life in most cases [26]. Furthermore, AGM lead-acid batteries do not tolerate overcharging as well as gel and flooded lead-acid batteries, which may lead to premature failure [14]. They also have a greater risk of thermal runaway [28, 29], which may impose restrictions on mounting locations in vehicles to ensure high temperature environments are avoided.

Into the future, AGM lead-acid batteries may find greater use in vehicle applications as they are the most suited lead-acid battery technology (along with the UltraBattery) to meet load and cycling requirements introduced by EVs and HEVs [1]. Their good all-round performance means that they remain attractive for military vehicle applications.

5.1.3 UltraBattery

The UltraBattery is a relatively new technology development combining lead-acid battery technology and supercapacitor[12] technology in a single package. These technologies are integrated in a passive manner without the need for additional electronic controls [34]. The UltraBattery was invented by CSIRO and is now being manufactured by Furukawa Battery Company and East Penn Manufacturing Company [1, 34].

The UltraBattery (see Figure 2) has similar chemistry to lead-acid batteries, but the major difference is that a lead/carbon electrode material is used instead of lead as the anode [1, 34]. The anode is vertically divided in half, consisting of half lead and half carbon double layer capacitor, while the cathode remains as lead oxide [1, 34]. Both flooded and sealed versions of the UltraBattery are available, with the flooded version categorised as a type of ELF battery [1].

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[11] AGM batteries have low internal resistance due to their electrode design and since they use pure lead electrodes (unlike flooded lead-acid batteries) [32].

[12] A supercapacitor is a high-capacity electrochemical capacitor.

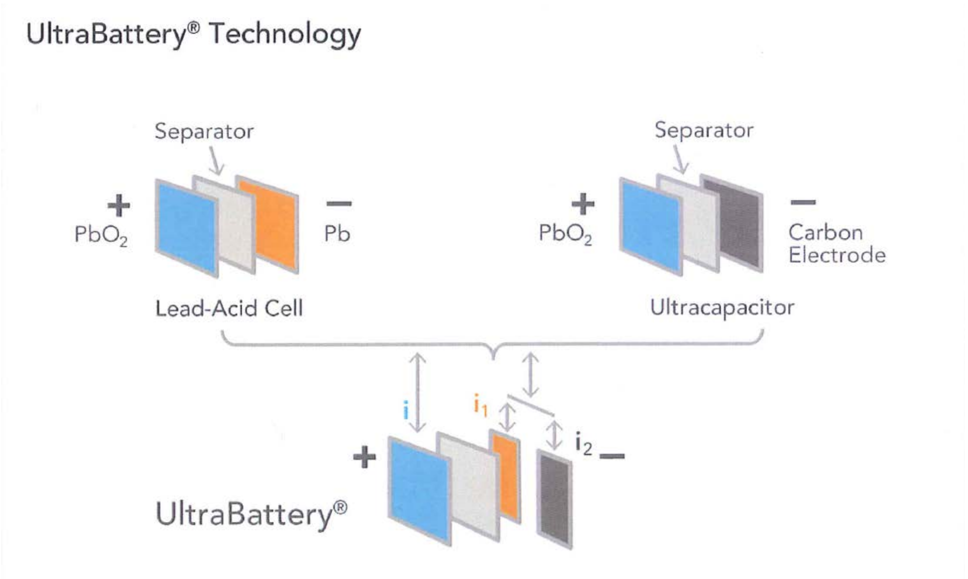

Figure 2 Schematic design of the UltraBattery [34].

A key benefit of the UltraBattery is that it has significantly increased cycle life compared to lead-acid batteries [34, 35]. This advantage is highlighted in high-rate partial SoC applications, where the UltraBattery has demonstrated cycle life an order of magnitude greater than lead-acid batteries [34, 35]. These partial SoC applications (i.e. the battery is never fully charged or fully discharged) are characteristic of HEV operation. The UltraBattery operates well in these applications due to its construction (i.e. supercapacitor and lead-acid battery combination) whereas lead-acid batteries do not as they fail due to sulphation[13] of their electrodes [36]. Another advantage of the UltraBattery is that it has higher specific power and power density than lead-acid batteries[14] (specific power may exceed 1000 W/kg depending on layout [31]) [35]. This means that it can be charged more quickly. In silent watch scenarios, this ability to charge quickly is important to minimise the amount of time the vehicle's engine or a generator is required to operate (assuming sufficient power is available). Many of the advantages of the UltraBattery can be attributed to the use of the lead/carbon electrode, with the capacitor component of the UltraBattery accommodating high electrical currents and the lead-acid battery component not being strained by these currents.

A disadvantage of the UltraBattery is that it is more expensive upfront than standard maintenance-free lead-acid batteries (1.5 times the cost), but it is estimated to be cheaper than Ni-MH batteries in HEV applications and it has a lower-cost design than AGM VRLA batteries [1]. Any higher upfront costs are likely to be offset by the longer lifetime offered by UltraBattery technology. Although not specifically a disadvantage, the UltraBattery also does not have greater energy density than lead-acid batteries [37]. This means that use

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[13] Sulphation refers to a process where sulphate crystals form inside a lead-acid battery during operation. A small amount is formed under normal circumstances, but large deposits form on the electrodes if the battery is not fully charged for a long period of time. This reduces the amount of active material in the battery and reduces its charging and discharging performance.

[14] The UltraBattery's handling of charging power is significantly improved compared to VRLA AGM batteries, but it is slightly poorer in power handling on discharge [25].

of the UltraBattery in military vehicles would not create significant improvement in silent watch endurance.

It is proposed that the UltraBattery may be used in many applications, including for use in HEVs [1, 34]. For example, the UltraBattery has undergone extensive testing in a Honda Insight HEV [1]. There does not appear to be significant interest in the development of UltraBattery technology for SLI applications, but as the UltraBattery is being considered for micro HEV applications [38], which use a single 12 V battery, it could be used in regular vehicles as an SLI battery.

It is unlikely that the UltraBattery would present any significant issues if it were to be integrated into extant military land vehicles. The UltraBattery is based on lead-acid battery technology and it is expected to be able to handle the extreme conditions experienced by military land vehicles. As stated above, no additional control circuitry is required and it is able to be produced with a similar operating voltage to lead-acid batteries (2.0 V), which suggests that the UltraBattery may be able to be used as a drop-in replacement. The increased cycle life of the UltraBattery suggests that it will reduce maintenance requirements as it will not have to be replaced as regularly as lead-acid batteries.

In the future, further technology development and automotive market penetration of the UltraBattery is expected [1, 34]. Technology development may include alternative components, such as thin-plate technology [37]. UltraBattery performance results from commercial operations are also expected to assist in improving this technology [34].

5.2 Nickel Metal-Hydride (Ni-MH) Batteries

Ni-MH batteries were originally developed as a replacement for Nickel Cadmium (Ni-Cd) batteries due to environmental concerns with Cadmium [1], and large-format Ni-MH batteries have now become common in many HEV applications [1]. The development of Ni-MH batteries has enabled widespread commercialisation of HEVs, which has in turn resulted in further growth of Ni-MH battery technology (e.g. improved charge retention) [1].

The Ni-MH battery uses a nickel-based cathode, a hydrogen-storing metal alloy anode and an alkaline electrolyte [1]. Ni-MH batteries can be designed to optimise energy or power by trading off electrode thickness and the number of electrodes depending on application requirements [1].
Compared to lead-acid batteries, Ni-MH batteries have greater specific energy (90-110 Wh/kg), volumetric energy density (430 Wh/L) and cycle life (500-1000 cycles) [1, 39]. Therefore, there is the potential for improved silent watch endurance on military vehicles by using Ni-MH batteries. Ni-MH batteries also have high specific power (865 W/kg), which enables them to be rapidly charged [1, 2]. Assuming sufficient charging current is available, they can be charged within one hour [1]. This makes them attractive for EVs and HEVs as they can utilise energy from regenerative braking, but may also be beneficial in silent watch applications to minimise battery charging times and the amount of time a vehicle’s engine is on. Furthermore, the Ni-MH battery has good safety properties [1, 40], as evidenced by its widespread adoption in HEVs. Another advantage of Ni-MH batteries

is that they are sealed, which means they do not require any maintenance [1], unlike flooded lead-acid batteries.

A common disadvantage of Ni-MH batteries is that they suffer from a “memory effect”. This results in a drop in battery voltage and a loss of battery capacity when a battery is only partially discharged and recharged on repetitive cycles [1]. However, this effect is reversible and the battery can be restored to full capacity with several full discharge-charge cycles [1]. Other disadvantages of Ni-MH batteries are that they are more expensive than lead-acid batteries (but cheaper than Li-ion batteries), they have lower specific energy than Li-ion batteries (see Appendix B for a comparison), and they have decreased performance at low temperatures (inferior cold-cranking performance compared to lead-acid batteries) [1]. Poor low temperature performance and high cost have restricted the use of Ni-MH batteries in SLI applications in vehicles [40].

There are a number of requirements relating to thermal management and charge control that must be considered when integrating Ni-MH batteries into vehicles. These measures are important to ensure maximum battery capacity and to avoid high temperatures and other conditions that may reduce battery life [1]. Ni-MH batteries need to be charged at relatively low temperatures because at elevated temperatures, they have reduced charge acceptance (reduced efficiency) due to oxygen evolution inside the cell, which may cause further heating and further reductions in charge efficiency [1]. Controlled charging (including effective charge termination) is also required to prevent excessive overcharging of the battery and sharp rises in battery temperature and pressure, which may cause cell damage, venting or overheating [1, 2]. Therefore, these requirements dictate that additional control systems beyond the capabilities of conventional alternators are incorporated on vehicles powered by Ni-MH batteries.

It is expected that development of Ni-MH battery technology will continue since it remains a competitive technology for EV and HEV applications [1]. A major focus is reducing the cost of the technology further to improve its attractiveness for these applications [1]. Other development includes improving specific power and specific energy capabilities, increasing cycle life for higher depths of discharge, and improving safety [1]. Although Ni-MH batteries are a safer and more reliable technology than Li-ion batteries, Ni-MH batteries are seen by some as an intermediary step in EV applications due to the superior energy capabilities of maturing Li-ion battery technologies. Despite having increased energy compared to lead-acid batteries, there are a number of other factors presented here which suggest that the use of Ni-MH batteries in military land vehicles in the future is unlikely.

5.3 Lithium Ion (Li-ion) Batteries

Over the past 10 to 15 years, Li-ion battery technology has grown to become one of the major secondary battery technologies across a wide range of applications. This is due to improvements in many aspects including electrode materials and cell design. Li-ion batteries are now very common in portable electronics and power tools due to a number of desirable properties (e.g. high energy and high cycle life) and they are gaining increased use in vehicles with the advent of EVs (e.g. Chevrolet Volt, Nissan Leaf, Tesla Roadster).

They are now an important technology in the scope of electrical energy storage systems on military land vehicles.

The family of Li-ion batteries typically use a carbon anode and a lithiated metal oxide or lithium metal phosphate cathode, along with an organic liquid electrolyte or gel electrolyte [1, 2]. There are many different cathode materials that may be used in Li-ion batteries. Those of interest are summarised in Section 5.3.1. Alternative anode materials and alternative electrolytes are summarised in Section 5.3.2 and Section 5.3.3 respectively. The vast range of material options and cell construction formats for Li-ion batteries means that Li-ion batteries have a wide range of performance and safety characteristics, which make them attractive for many applications. These characteristics will be generalised here and explained further for each of the different cathode and anode materials and electrolytes in their respective sections.

The use of Li-ion batteries on military vehicles is appealing because they have the potential to improve silent watch endurance. This is due to the higher specific energy (typically 100-240 Wh/kg) and higher energy density (typically 250-640 Wh/L) of Li-ion batteries than those of lead-acid batteries [1, 39]. Li-ion batteries also have higher cycle lives (typically 500-1000 cycles) [1]. One aspect that contributes to the high energy of Li-ion batteries is their higher operating voltage (e.g. for a single battery, a higher average voltage during discharge typically translates to a greater amount of energy obtained). Single Li-ion cells (typically 3.6-3.7 V) operate at a voltage three times greater than Ni-MH cells (1.2 V) and almost double that of lead-acid cells (2.0 V) [1]. This means that fewer cells are required for a battery of a given voltage and Li-ion batteries can be made smaller and/or lighter. Their higher specific energy means that Li-ion batteries are able to power electronic equipment for longer than lead-acid or nickel-based batteries of equivalent weight and volume while higher cycle life means that they would be replaced less often. The need for battery replacement over the life of a vehicle could potentially be eliminated [10]. Li-ion batteries can be designed with high power capabilities (at a cost to energy and vice versa) to meet application requirements [1]. Another advantage of Li-ion batteries is their lower self-discharge rate (2-10% per month) [1], which means they will not lose charge as quickly as lead-acid or Ni-MH batteries while in storage. Li-ion batteries do not suffer from a memory effect either, as seen in Ni-MH batteries, and they are sealed cells so they have low maintenance requirements [1].

Li-ion batteries have a number of disadvantages that have impeded their implementation, especially in automotive applications. One of the main concerns is their safety and thermal stability when misused [1, 39, 41]. Improper use, such as overcharging, overdischarging or operating above the maximum operating temperature, can result in thermal runaway at high temperatures (less harmful effects are permanent capacity loss or rapid performance drops) [1, 39]. Venting and thermal runaway may also be caused by severe impact, such as bullet penetration or crushing the battery [1]. More exaggerated effects from damaging Li-ion batteries include intense burning or explosion. This requires Li-ion batteries to use additional protective circuitry to monitor and control battery operation, particularly if they are to be charged directly from a vehicle's alternator. Despite the added complexity of the protective battery management circuitry, a potential benefit is that it may provide an accurate measure of a battery's SoC and SoH.

Another inhibiting factor in the adoption of Li-ion batteries is their large upfront cost when compared to lead-acid batteries[15] [1, 10, 39, 40]. The increased costs can be attributed to the materials used in Li-ion batteries and the additional electronics required [1]. However, the overall cost may be offset somewhat since Li-ion batteries have higher cycle lives and do not need to be replaced as often as lead-acid batteries. Li-ion batteries also have power and energy performance issues at low temperatures [42, 43, 44]. This results in poor engine cranking performance at low temperatures, which has restricted their use in SLI applications [40].

One of the most important aspects in considering the integration of Li-ion batteries into land vehicles is the need for a BMS to monitor and control battery charging and discharging. This is necessary since Li-ion batteries cannot intrinsically absorb excessive charging current and they need to be protected from high temperatures [10]. In addition, their charge and discharge rate must be managed to ensure it does not exceed safe limits. A BMS would manage battery voltage, current, temperature and pressure, and may include a mechanism for balancing the charge of individual Li-ion cells[16] [10]. It may be inbuilt in a battery, but if not, additional electronics will need to be integrated on a vehicle along with the battery, which may require modifications to the vehicle. Battery thermal management can be achieved through appropriate battery design (e.g. cell layout, inbuilt BMSs) but may also require additional vehicle modifications to ensure adequate airflow or to accommodate the installation of cooling systems. Cooling systems are particularly important for large battery banks in EVs.

Drop-in replacement Li-ion batteries have been developed to replace 12 V lead-acid SLI batteries in land vehicles. These batteries make use of the lithium iron phosphate (LFP) cathode material (see Section 5.3.1.5) [10] or the lithium titanate (LTO) anode material (see Section 5.3.2.1) and typically include inbuilt electronics to manage charging/discharging, temperature and safety. A number of companies offer drop-in replacement Li-ion batteries, including Braille Battery [45], A123 Systems [46] and Saft [47]. Of the Li-ion cathodes discussed in Section 5.3.1, Li-ion batteries based on the LFP material most closely match the voltage window of lead-acid batteries in SLI applications [10]. Li-ion batteries using other cathode materials would require modifications to a vehicle's electrical system or some form of voltage conversion if used on land vehicles, which restricts them from being used as drop-in replacement batteries. However, these cathode materials may still be suitable for batteries used in EV applications. It is important to note that there appears to be no consensus on which Li-ion cathode material should be used in EV applications [1]. Further information on voltage windows for individual cathode chemistries is provided in their respective sections.

The Li-ion battery market continues to rapidly grow as Li-ion battery performance and safety improves. These improvements are being supported by a large amount of interest worldwide in Li-ion battery technology research and development. This includes the development of new electrode materials, electrolytes, and other battery components [1].

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[15] Figures provided in [10] suggest that Li-ion batteries are expected to cost approximately two to three times that of lead-acid batteries in passenger car applications.

[16] Cell balancing (all cells at a common voltage) may be achieved passively by discharging higher voltage cells in resistors or actively by transferring their charge to lower voltage cells [10].

Examples of Li-ion battery research and development include electrolyte additives to improve battery lifetimes [48], alternative anode materials (based on silicon, tin and germanium) to improve battery capacity and energy [49], alternative cathode materials to achieve higher voltage Li-ion batteries (leading to higher energy) [1], and cathode coatings to improve high voltage charging performance [1].

Although Li-ion batteries have not been widely used in automotive applications in the past, gradual technology development and the advent of EVs has seen Li-ion batteries become more relevant in this space. It is expected that the percentage of Li-ion batteries implemented in all automotive applications will continue to increase as the technology matures.

5.3.1 Lithium Ion Cathodes

There are many cathode materials available or in development for Li-ion batteries. The most common include lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA), lithium manganese oxide (LMO) and LFP [1, 10, 39, 41]. Each Li-ion cathode material will now be discussed.

5.3.1.1 Lithium Cobalt Oxide (LCO) Batteries

The LCO cathode (chemical formula $LiCoO_2$) was used in the first Li-ion batteries and remains the most common Li-ion cathode material in many applications [1]. It is popular because it has good electrical performance (relatively high capacity and voltage compared to other Li-ion cathode materials) and it is easy to manufacture [1]. The main disadvantages of the LCO cathode is that it uses Cobalt, which is expensive, it has poor low temperature performance (substantial capacity drops) and it has safety issues at high temperatures (thermal management can be achieved through appropriate battery design) [1]. It is important to note that Li-ion batteries using LCO cathodes are less suitable as drop-in replacements in SLI applications as they do not have a compatible voltage window[17] [10]. Furthermore, there appears to be less focus on research and development of LCO cathodes compared to other cathode materials, which offer improvements in performance, cost and safety.

5.3.1.2 Lithium Nickel Manganese Cobalt Oxide (NMC) Batteries

The NMC cathode (basic chemical formula $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$) was developed as a safer and less expensive alternative to Li-ion batteries using LCO cathodes. It has improved thermal stability during abuse and the use of magnesium reduces the cost of Li-ion batteries [1]. Furthermore, Li-ion batteries using NMC cathodes can be designed for high energy or high power applications [1]. These batteries are available commercially [1], but there remains a large amount of ongoing research to further develop Li-ion batteries using NMC cathodes. This includes efforts to achieve batteries with very high cycle lives (over

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[17] A Li-ion battery with an LCO cathode with four cells in series most closely replicates the voltage window of a 12 V lead-acid SLI battery. Its voltage window (Maximum-Nominal-Minimum) is 16.8 V-14.8 V-10.8 V [10]. The maximum voltage of 16.8 V exceeds the upper limit of the 12 V lead-acid battery voltage window (see Section 4.2).

6000 cycles) [50] and investigating additives to improve battery lifetime [48]. There is expected to be huge growth in Li-ion batteries using NMC cathodes [51]. However, as with LCO cathodes, Li-ion batteries using NMC cathodes are less suitable as drop-in replacement batteries in SLI applications due to their incompatible voltage window[18] [10].

5.3.1.3 *Lithium Nickel Cobalt Aluminium Oxide (NCA) Batteries*

The NCA cathode (basic chemical formula $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) is a cathode material that offers higher specific capacity than the LCO cathode (200 mAh/g compared to 155 mAh/g) albeit at a lower operating voltage (3.6 V compared to 3.7 V) (higher voltage typically indicates higher capacity) [1]. This means they have similar specific energy (175-240 Wh/kg). However, Li-ion batteries using NCA cathodes have poor safety properties, similar to Li-ion batteries using LCO cathodes [1]. Li-ion batteries using NCA cathodes are available commercially and manufacturers of NCA batteries include Toda Kogyo and BTR New Materials [1]. They too are less suitable as drop-in replacement batteries in SLI applications due to their incompatible voltage window[19] [10].

5.3.1.4 *Lithium Manganese Oxide (LMO) Batteries*

The LMO cathode (basic chemical formula $Li_{1+x}Mn_{2-x}O_4$) is another commercially available Li-ion cathode material [1]. Advantages of this material are that it is cheaper and safer than LCO, while it also has a good combination of power and energy capabilities compared to the other Li-ion cathode varieties (see Appendix B for a comparison) [1, 52]. Drawbacks of the LMO cathode is that the specific energy achievable using LMO is slightly lower than LCO (100-150 Wh/kg compared to 175-240 Wh/kg) and it has higher capacity loss during storage or cycling, especially at high temperatures, compared to batteries using LCO or NCA cathodes (this is improving with research and development) [1]. Research and development into Li-ion batteries using LMO cathodes is ongoing, such as at CSIRO, who see LMO as a very promising material but have acknowledged further electrolyte development and improvement of cycle life is required [53]. As with many other Li-ion cathode materials, Li-ion batteries using LMO cathodes are less suitable as drop-in replacement batteries in SLI applications due to their incompatible voltage window[20] [10].

Blended cathode materials may also be used in Li-ion batteries, such as the LMO:NMC blended cathode, which is used in the Chevrolet Volt EV [1, 54, 55]. These materials offer

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[18] A Li-ion battery with an NMC cathode with four cells in series most closely replicates the voltage window of a 12 V lead-acid SLI battery. Its voltage window (Maximum-Nominal-Minimum) is 16.8 V-14.4 V-10.8 V [10]. The maximum voltage of 16.8 V exceeds the upper limit of the 12 V lead-acid battery voltage window (see Section 4.2).

[19] A Li-ion battery with an NCA cathode with four cells in series most closely replicates the voltage window of a 12 V lead-acid SLI battery. Its voltage window (Maximum-Nominal-Minimum) is 16.8 V-14.4 V-10.8 V [10]. The maximum voltage of 16.8 V exceeds the upper limit of the 12 V lead-acid battery voltage window (see Section 4.2).

[20] A Li-ion battery with an LMO cathode with four cells in series most closely replicates the voltage window of a 12 V lead-acid SLI battery. Its voltage window (Maximum-Nominal-Minimum) is 16.8 V-14.8 V-11 V [10]. The maximum voltage of 16.8 V exceeds the upper limit of the 12 V lead-acid battery voltage window (see Section 4.2).

improvements in cycle life and energy density [1], which are important for EV applications. However, this material is more expensive than LMO alone [1].

5.3.1.5 Lithium Iron Phosphate (LFP) Batteries

Li-ion batteries using LFP cathodes (chemical formula $LiFePO_4$) have been developed to address the safety issues associated with other Li-ion chemistries. An example of their application is as part of the Kinetic Energy Recovery System on the McLaren Formula 1 car during the 2009 season [1]. They are also available from a number of manufacturers as drop-in replacement batteries for 12 V lead-acid batteries in land vehicles [10]. For example, M2 Power produce a series of 12 V LFP batteries (voltage 12.8 V) [56] and A123 Systems produce a 12 V LFP battery (nominal voltage 13.2 V) [46], both for SLI applications.

This commercially available material is significantly more stable than other Li-ion cathode materials, which means the battery is inherently safer and has a greater resistance to thermal runaway [1, 10, 57, 58]. LFP batteries also do not use metals such as cobalt, nickel and manganese, as in other Li-ion batteries, which means their cost is lower and they are more environmentally friendly [58, 59, 60]. They have high cycle lives (greater than 1000 cycles) and good power capabilities compared to most other Li-ion batteries (and lead-acid batteries) (see Appendix B for a comparison) [1, 10], with the latter characteristic enabling them to be fast charged [39, 61]. Assuming sufficient power is available for charging, this may reduce the engine-on time required for battery charging during silent watch operations.

A disadvantage of LFP batteries is that their cells have a lower nominal voltage (3.3 V), which results in slightly lower specific energy than other Li-ion batteries (60-120 Wh/kg) [1, 10, 41], although it is still higher than lead-acid batteries. Along with their better safety and thermal stability, the lower nominal voltage of LFP batteries actually means that they are more suitable (compared to other Li-ion batteries) as drop-in replacements for 12 V lead-acid batteries used in automotive SLI applications [10]. Of Li-ion battery alternatives, four LFP cells in series most closely replicate the voltage window of a 12 V lead-acid battery[21] [10]. If used to replace lead-acid batteries in military land vehicles, LFP batteries would provide greater silent watch endurance and weight savings, which is likely to reduce fuel consumption since the engine would need to be used less often to charge the batteries. A comparison of specific energy and energy density between both technologies suggests that energy is increased in LFP batteries by three to five times for a battery of equivalent weight and two to three times for a battery of equivalent volume. This is expected to result in improvements in silent watch endurance on military land vehicles. The higher upfront costs of LFP batteries compared to lead-acid batteries has restricted their adoption in automotive SLI applications, although lifetime costs are expected to be similar since they are replaced less often [10].

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[21] A Li-ion battery with an LFP cathode with four cells in series most closely replicates the voltage window of a 12 V lead-acid SLI battery. Its voltage window (Maximum-Nominal-Minimum) is 14.6 V-12.8 V-10 V [10].

Li-ion batteries using LFP cathodes are relatively mature, but they are still a focus of research and development efforts. For example, researchers in Germany are developing LFP batteries with extremely high cycle life, up to 12000 cycles[22] with 80% capacity retention [50]. Their research is focussing on improving electrode manufacturing processes and reducing electrode thickness changes during cycling to increase the battery's cycle life [62]. These cycle life figures are significantly higher than all other Li-ion batteries available today, but they have only been demonstrated at a small-scale in a laboratory. The next phase of research involves scaling the chemistry up to large prismatic cells [50, 63]. Further development of this technology could provide benefits (e.g. cost savings) to many applications, including EVs.

5.3.1.6 Lithium Cobalt Phosphate (LCP) Batteries

The lithium cobalt phosphate (LCP) cathode (chemical formula $LiCoPO_4$) is an emerging cathode material for Li-ion batteries that may offer several desirable advantages compared to other Li-ion cathodes. Researchers at the Army Research Laboratory in the United States of America are developing Li-ion batteries based on this material and they anticipate that it will lead to Li-ion batteries with higher energy density than LFP batteries and comparable safety [64, 65]. However, there are a number of issues with this chemistry, which includes its cycling stability (insufficient compared to LCO and LMO batteries), operation at high temperature, and the toxicity of the LCP material [66]. Cobalt is also quite expensive [1]. These issues have kept LCP batteries at a relatively low Technical Readiness Level and there are currently no commercial products, but it is worth tracking research progress given the potential benefits of this technology.

5.3.2 Lithium Ion Anodes

Li-ion batteries were first produced with coke anodes (a compound made from coal), but graphite anodes are now used in almost all Li-ion batteries since it results in batteries with better capacity, cycle life and power characteristics [1]. Despite the versatility of graphite, there are promising alternative Li-ion anode materials available and in development.
LTO is one such promising anode material and it is discussed in the following section. Other anode materials containing tin are being manufactured by Sony while silicon anodes are also in development [1]. Both may improve the specific energy and energy density of Li-ion batteries (compared to batteries using graphite), but metal alloy anodes are expensive and they typically undergo significant volumetric changes during cycling, which has so far restricted their commercialisation [1]. Metal alloy anodes in Li-ion batteries are expected to become more common by 2020 [1].

5.3.2.1 Lithium Titanate (LTO) Batteries

The LTO battery is a relatively new variant of Li-ion battery and it is a promising technology for SLI applications in military land vehicles. This battery uses a lithium titanate anode (chemical formula $Li_4Ti_5O_{12}$) instead of graphite, and a manganese-based

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[22] The cycle life of LFP batteries is typically in the order of 1000 to 2000 cycles while lead-acid battery cycle life may range between 200 and 1500 cycles [1, 10].

cathode (LMO) [1, 41]. It is commercially available [1] and has been proposed as a drop-in replacement for lead-acid batteries in land vehicles [11].

There are a number of desirable characteristics of LTO batteries that make them attractive for use in land vehicles. Two main advantages are their improved safety (compared to traditional Li-ion batteries) and their high cycle life. The lithium titanate material is exceptionally stable, which reduces the risk of thermal runaway and ensures that Li-ion batteries using LTO anodes are very safe [1, 11]. In terms of cycle life, LTO batteries are capable of deep-discharge cycles of over 4000 cycles [1, 11, 41], which would result in reductions in battery replacement if they were used on military land vehicles. This cycle life is higher than all lead-acid batteries and most Li-ion batteries. Another key benefit of LTO batteries is their ability to be rapidly charged [11, 41], which has been shown to be superior to LFP batteries [41]. As with LFP batteries, this may reduce the engine-on time for battery charging during silent watch operations.

A disadvantage of LTO batteries relative to other Li-ion battery types is that their specific energy (70 Wh/kg) and energy density (120 Wh/L) are lower due to their lower nominal voltage (2.4 V) [1, 41]. However, their specific energy and energy density is slightly higher than lead-acid batteries [1] and it has been demonstrated that they have the potential to improve silent watch endurance (or reduce vehicle weight) compared to lead-acid batteries[23] [11] although this is unlikely to be as significant an improvement as other Li-ion battery types.

LTO batteries are now produced by multiple companies including Altairnano (Altairnano offer a 24 V battery module) and Toshiba [1, 41, 67, 68] and they have been adopted in a number of EV applications. This includes Mitsubishi's i-MiEV EV [69] and Honda's Fit EV [70]. It suggests that the technology is quite mature and can be considered for military land vehicle application.

5.3.3 Lithium Ion Electrolytes

There are two main types of electrolyte used in Li-ion batteries, liquid electrolytes and gel electrolytes. Liquid electrolytes are typically solutions of lithium salts in one or more organic solvents while gel electrolytes are ionically conductive materials combining salts, solvents and polymers [1]. Li-ion batteries using gel electrolytes may often be termed lithium gel-polymer batteries or lithium polymer batteries [1]. An advantage of gel electrolytes is that they are less likely to leak [1]. There are many other possible electrolytes for Li-ion batteries and most of these make use of additives to modify certain properties of the battery to improve performance or safety [1]. A particularly promising alternative electrolyte for Li-ion batteries is an ionic liquid electrolyte. Ionic liquid electrolytes are discussed in the following section.

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[23] It was predicted that drop-in replacement LTO batteries may offer an increase in battery operational endurance on military land vehicles of up to 290% (not verified) when compared to equivalent lead-acid batteries [11].

5.3.3.1 Ionic Liquid Electrolytes

A recent development that may improve the safety and stability of Li-ion batteries is the use of ionic liquid electrolytes, as opposed to organic solvents which are typically used in Li-ion battery electrolytes. These organic solvent electrolytes have low thermal stabilities and high vapour pressures, which poses an explosive risk if the battery is misused or mistreated [71].

Unlike organic solvent electrolytes, ionic liquid electrolytes have negligible vapour pressures and a corresponding reduced explosive risk [71, 72, 73]. Additionally, they have good electrochemical and thermal stability, low volatility and flammability, and they are more stable towards lithium metal [1, 71, 72, 73, 74]. Therefore, the use of ionic liquid electrolytes in Li-ion batteries is likely to improve battery safety and stability. This makes Li-ion batteries using ionic liquids attractive for vehicle applications.

Although there has been significant development of ionic liquid electrolytes since 1995 [74], they require further development. Limitations of ionic liquid electrolytes include their high viscosity, which results in low rate capabilities for ionic liquid-based batteries (i.e. poor performance at high current), and poor ionic conductivity at low temperatures [1, 72, 73]. Furthermore, ionic liquids are very expensive [1, 73, 74, 75]. As such, there are currently no commercial applications of batteries incorporating ionic liquid electrolytes [73].

Despite their lack of commercial application, there is a lot of ongoing research and development of ionic liquids for batteries. This includes investigation of alternative anions and cations to lower costs [74, 75], novel production methods [75], and the application of ionic liquids in Lithium metal (Li-metal) batteries (see Section 5.4) [73, 76] and fast charge-discharge systems [74]. Batteries incorporating ionic liquids may soon become available. Patents for ionic liquid technology have been granted (to CSIRO and Hydro-Quebec) and Boulder Ionics are in the process of producing ionic liquid electrolytes for Li-ion batteries and other advanced battery chemistries with a current focus on optimising production and the effect of certain impurities [77, 78]. This suggests that batteries using ionic liquids will become relevant for vehicle batteries in the near future and their development is worth monitoring.

5.4 Lithium Metal (Li-metal) Batteries

Li-metal batteries are a relatively immature technology compared to Li-ion batteries, but they are of interest to military land vehicle applications as they may lead to high energy batteries in the future. Large Li-metal batteries have been previously produced by Avestor for EV battery applications, but they are no longer produced as the company has shut down [1].

Li-metal batteries use lithium metal anodes and their cathodes are those typically used in Li-ion batteries (see Section 5.3.1) or they may use sulphur-based cathodes or air-based cathodes [1]. Lithium sulphur (Li-S) batteries and Lithium air (Li-air) batteries are discussed in Section 5.4.1 and Section 5.4.2 respectively. Li-metal batteries may use liquid electrolytes, polymer electrolytes or solid inorganic electrolytes [1]. Liquid electrolytes are most common since Li-metal batteries using these electrolytes have the highest specific energy and energy density [1]. However, polymer electrolytes are promising (and are being developed) for Li-metal batteries because they are less reactive with lithium, which may enhance battery safety, they have good high-rate capabilities, they offer design flexibility in terms of battery shape and size, and they do not leak [1].

Advantages of Li-metal batteries is that they have good charge retention, which means they would not have to be charged regularly when in storage, and they have much higher specific energy than Li-ion batteries (up to 350 Wh/kg cells are currently available and 30-50% higher energy is predicted in the next few years) [1]. The latter could result in significant improvements to silent watch or EV endurance if the technology matures and reaches commercialisation in sizes appropriate for vehicles.

Very small capacity (mAh) Li-metal batteries have been commercialised [1], but some technical aspects have restricted commercialisation of larger of Li-metal batteries. This mainly relates to the reactivity of the lithium anode with the battery's electrolyte (resulting in irreversible capacity loss) and rapid degradation of the lithium anode during cycling due to formation of lithium dendrites (leading to internal short circuiting) and highly porous lithium [1, 79]. These aspects significantly affect the cycle life, thermal stability and safety of Li-metal batteries.

In the past, Li-metal battery development has been restricted by a focus on Li-ion batteries (Li-ion batteries are safer and have longer cycle lives), but there is a renewed focus on Li-metal batteries as there is a growing demand for higher energy in various applications [1]. Research and development is ongoing into protective layers and caps for the lithium anodes and alternative (polymer and inorganic) electrolytes to manage lithium anode degradation [1, 79]. Other efforts are focussing on improving cycle life, thermal stability (greater operating temperature range) and safety [1]. Although they are unlikely to be commercialised (in appropriate form factors) within five years, the potential for high energy Li-metal batteries means that their development should continue to be monitored.

5.4.1 Lithium Sulphur (Li-S) Batteries

The Li-S battery is a particularly promising variant of Li-metal battery due to its potential as a high-energy, low-cost solution. Although, it is not a mature technology and not yet commercialised [80], further development may see it become of interest for many applications including automotive applications. In terms of their chemistry, Li-S batteries use a lithium anode, sulphur cathode and a liquid organic electrolyte [1].

High specific energy is a major advantage of Li-S batteries. Li-S batteries with specific energy significantly higher than Li-ion batteries have been developed (approximately 350 Wh/kg) [1], which could further increase silent watch endurance in military land vehicles and enhance EV performance with batteries that last longer (i.e. longer discharge duration) than those that are currently available. Another advantage of Li-S batteries is that they are very cheap as they use sulphur, which is abundant and inexpensive [1, 81, 82]. The combination of these two characteristics makes Li-S batteries attractive for many applications.

A major issue with Li-S batteries that has restricted their application is their poor cycle life. This is due to corrosion and rapid degradation of the sulphur electrode as it is cycled (polysulphides form when lithium bonds to sulphur, which dissolves in the battery's electrolyte) [80, 82, 83]. Cycle life of Li-S batteries is typically no more than 100 cycles [1], which is an order of magnitude less than most Li-ion batteries. Further improvements in the cycle life of Li-S batteries along with improving their safety are required before they can compete with other rechargeable battery technologies [1].

There has been limited application of Li-S batteries, although their energy benefits have been demonstrated in a solar-electric high altitude Unmanned Aerial Vehicle (UAV) developed by QinetiQ known as Zephyr. The UAV, which was powered by solar panels during the day and Li-S batteries (developed by Sion Power) at night, broke the world record for the longest duration unmanned flight [1, 84]. Along with Sion Power, other companies who are developing Li-S batteries include PolyPlus and Oxis Energy [80]. The suitability of Li-S batteries for SLI applications does not appear to have been studied, but it has been suggested that Li-S batteries can be designed to provide high discharge rates competitive with high-rate Li-ion batteries [1]. It is expected that Li-S batteries would face integration issues similar to Li-ion batteries if retrofitted into vehicles for SLI application [53].

Research into Li-S batteries has grown significantly in recent years since researchers have improved methods for designing the sulphur electrode structure and managing polysulphide products [80, 85]. Specific Li-S battery research pursuits include further development of the sulphur cathode and Li-S electrolytes [82, 85], investigating the use of ionic liquid electrolytes in Li-S batteries (to improve high temperature stability and safety) [1, 86], and coatings for the lithium anode [1]. CSIRO are also developing electrodes and electrolytes for Li-S batteries (at the coin cell scale) [53]. It is predicted that there will be resurgence in commercial sources of Li-S batteries in the future due to recent improvements in performance and safety [1], but this is not expected to occur within the next five years [80].

5.4.2 Lithium Air (Li-air) Batteries

Li-air batteries, which may also be classified as metal-air batteries, are another promising battery technology due to their potential for very high energy provision (approaching fossil fuels). However, they have not yet progressed beyond experimental systems since they were first demonstrated in 1996 [1, 87]. Li-air batteries use a lithium anode and an air-based cathode (oxygen is used from air) [1] while the most suitable electrolyte material is the subject of ongoing research [87, 88].

The theoretical specific energy of Li-air batteries is far higher than conventional batteries (2800 Wh/kg) [87, 89] and this is attracting interest in this technology. Their energy capabilities may see Li-air batteries adopted in EV applications in the future [87], although this may not be for many years.

Despite their high specific energy, there are many technical challenges with Li-air batteries that must be addressed. Some of the main challenges are difficulty in reliably recharging (carbon in the cathode is unstable and decomposes during charging) and charging Li-air batteries at reasonable rates [88]. The instability of the cathode results in capacity fading and reduces the cycle life of Li-air batteries [88, 90], which suggests they may only be suitable as a non-rechargeable battery. Improving the rate at which they can be charged (and discharged) will be important for potential EV applications [87]. Li-air batteries are also sensitive to moisture and impurities in atmospheric air [1, 80, 91], which degrades their performance.

Li-air batteries remain an active area of research and development [1, 88] with some cells (10 Ah, 800 Wh/kg) already being tested by the US Army [82], but opinions are divided as to their future [87]. Considering their potential high specific energy capabilities, it is worth monitoring the development of Li-air batteries, however they are not expected to be available commercially for at least ten years [53].

5.5 Sodium-Nickel Chloride (ZEBRA) Batteries

Sodium-nickel chloride batteries, also known as ZEBRA[24] batteries, are molten salt batteries that are widely used in large-size HEV and EV applications (e.g. buses and trucks) [40]. These batteries are not suitable for use in SLI applications or small HEVs (e.g. passenger cars) [40]. They are likely to become more relevant to military land vehicles once HEVs and EVs begin to be adopted in this space.

ZEBRA batteries use a molten sodium anode, a cathode based on nickel, nickel chloride and sodium chloride, and a dual electrolyte, one a solid ceramic and one a solution of sodium-aluminium chloride [40, 93, 94, 95]. These batteries operate at temperatures between 250 °C and 350 °C [40]. This requires that they use thermal insulation to maintain their internal temperature and external heating when they are not being used to ensure the battery is ready to operate. They also use a BMS for thermal management and to reduce the risk of abuse [40]. If allowed to cool, ZEBRA batteries must be reheated slowly and steadily, which can take up to 24 hours [95].

Two key advantages of ZEBRA batteries are high energy density (120-125 Wh/kg, comparable to Li-ion), and long cycle life (greater than 1000 cycles) for discharge cycles to 100% DoD [40, 96]. Furthermore, they are intrinsically safe [94, 95, 96] and are tolerant to overcharge and overdischarge [93]. ZEBRA batteries are also cheaper than Li-ion batteries [96]. This makes them a good candidate for large-scale HEV and EV applications.

A key disadvantage of ZEBRA batteries is low specific power (180 W/kg [40]) [96, 97], which means they do not perform well when required to provide high power. As such, ZEBRA batteries may have to be combined with another source of power, such as a supercapacitor [96]. The long reheating time of ZEBRA batteries is a disadvantage in a military context because it prevents vehicles with these batteries from being used in quick response missions if the vehicles' batteries are cold. Another disadvantage is the self-discharge rate of ZEBRA batteries, which is very high to maintain internal battery

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[24] The ZEBRA battery is so-called because it was developed by the Zeolite Battery Research Africa (ZEBRA) project group at the Council for Scientific and Industrial Research in South Africa in the 1980s [92].

temperature when not being used [95]. It is also acknowledged that their resistance to strong vibration must be improved [40].

ZEBRA batteries are expected to be increasingly used in large-scale automotive HEV and EV applications [40]. Therefore, they should remain in consideration for military land vehicles in the future, but only for EVs or large HEVs.

5.6 Other Batteries

It should be noted that numerous other battery technologies were considered for this report, including Ni-Cd batteries, various Metal-air battery chemistries (other than Li-air), Silver-zinc batteries, Nickel-iron batteries, Nickel-zinc batteries, Sodium-ion batteries, and Sodium-sulphur batteries. However, they do not feature in the review for the following reasons.

Ni-Cd batteries have largely been replaced by Ni-MH batteries in many applications due to the safety and environmental concerns with Cadmium [1, 2]. Metal-air batteries are cheap, have high energy density [98] and are being considered for automotive applications [99, 100], but developing electrically rechargeable cells remains a challenge [98]. Li-air was an exception in this report due to its potential for very high energy density. Silver-zinc batteries offer good specific power and energy (105 Wh/kg, 180 Wh/L [1]), but they are very expensive and they have limited cycle life (10-50 cycles for high-rate designs), and have limited commercial and industrial applications for these reasons [1].

Nickel-iron batteries were used in automotive applications up until the 1970s, but they were replaced with lead-acid batteries and are now not widely used [1, 40]. Nickel-iron batteries have lower specific energy (30 Wh/kg [1]), poor charge retention, poor low temperature performance and they are more expensive to manufacture [1]. Similarly, Nickel-zinc batteries are not widely used in any automotive application despite intensive research efforts over several decades [40]. Nickel-zinc batteries have good power and energy capabilities (60-110 Wh/kg, 110-360 Wh/L [1]) and are lower cost than Ni-MH batteries, but a disadvantage of this technology is that it has a high risk of zinc dendrite growth leading to internal short circuiting during cycling [1, 40, 89].

Sodium-ion batteries are promising as a potential low-cost battery technology, but they require further development before reaching commercialisation and they appear to be more suited to stationary applications [101, 102, 103]. Similarly, Sodium-sulphur batteries have safety issues and are only used in applications other than automotive applications, hence they are not relevant in this report [40, 95].

6. Conclusion

This report has presented a number of considerations for battery technologies used on current generation military land vehicles and for those in the future, and has summarised the relevant battery technologies in this space.

Current military operations present unique requirements for vehicle batteries, which differ from those of most cars and commercial vehicles, because batteries on military land vehicles require high energy and must also be capable of delivering high power. High energy is required for silent watch applications, while high power is required for engine starting and load levelling applications. When determining appropriate battery technologies for military land vehicles, this must be considered and planned for along with the harsh military environmental conditions and the ability to accommodate increased electrical load in future military land vehicle electrical systems. It is also important to keep in mind that battery performance may be affected by a number of factors, such as rate of discharge, temperature and charging characteristics, and figures specified by manufacturers may not be achieved under all conditions.

Lead-acid batteries (flooded and absorbed glass mat) are currently used in the majority of military land vehicles, and will remain relevant for these vehicles in the immediate future. They are reliable and low-cost, and for these reasons they remain common in automotive SLI applications. However, they have reached the limit of their performance capabilities on military land vehicles, particularly during silent watch due to their low specific energy and energy density. This has led to other battery technologies being considered for these vehicles.

There are many alternative battery technologies that may offer improved performance in military operations, which includes extension of silent watch endurance and the ability to be fast charged. For existing military land vehicles, a key requirement for these technologies is their ability to be used as a drop-in replacement for lead-acid batteries such that the vehicle's electrical system requires no or minimal modification to accommodate the alternative battery. For example, they must have a compatible voltage window and they must have a similar form factor. Future generations of military land vehicles would also benefit from using similar batteries to ensure commonality across mixed vehicle fleets, and ease of upgrade.

In terms of ability to improve silent watch endurance, Li-ion batteries are the most promising battery technology in the near future. They have higher specific energy, energy density and cycle life compared to lead-acid batteries. Specifically, lithium iron phosphate batteries and lithium titanate batteries are suitable as drop-in replacements for lead-acid batteries due to their compatible voltage window, good safety properties relative to other Li-ion batteries and ability to be fast charged. Although other Li-ion batteries would also improve silent watch endurance, their integration would require modification to a vehicle's electrical system and may require an external battery management system if not inbuilt to the battery. The high cost of Li-ion batteries may be an inhibiting factor in replacing lead-acid batteries, but this will be partially offset by their higher cycle lives, which will reduce frequency of replacement, reduce logistics burden, and hence reduce lifetime costs. Research and development of Li-ion battery technology continues to grow and it is expected that the performance, safety and reliability of Li-ion batteries will improve further into the future and their share of automotive battery applications will increase.

The UltraBattery is another technology of interest as it offers improved performance over lead-acid batteries at high discharge rates, very high cycle life and can be used as a drop-in replacement for lead-acid batteries. However, it is unlikely to significantly improve silent watch endurance and it is primarily being developed for hybrid electric vehicle applications. This means that its characteristics are not being developed to suit conventionally-powered military land vehicles. Ni-MH batteries have also been considered in this report since they have higher specific energy and energy density than lead-acid batteries and can be fast charged, but they too are only likely to be relevant for electric vehicle and hybrid electric vehicle applications, albeit to a lesser extent with the growth in Li-ion battery technology. As with the UltraBattery, the characteristics of Ni-MH batteries are not suited for present day conventionally-powered military land vehicles.

Beyond lead-acid, Ni-MH and Li-ion batteries, other battery technologies are being developed that may offer performance or safety improvements in automotive applications in the future. This includes Li-ion batteries using ionic liquid electrolytes due to their potential for improved safety. Li-metal batteries are also promising, particularly lithium sulphur batteries, due to their low cost and potential for improved specific energy. Although they will not be immediately relevant for military land vehicles, the development of these batteries should be monitored.

The information presented in this review suggests that lead-acid batteries and Li-ion batteries, specifically lithium iron phosphate batteries and lithium titanate batteries, will be the main technologies in scope as energy storage solutions for military land vehicles in the foreseeable future. The high energy capabilities of Li-ion batteries (leading to improved silent watch performance), their high cycle lives and the ability to be fast charged are significant advantages over lead-acid batteries when considering batteries for new or upgraded military land vehicles. As such, further investigation of lithium iron phosphate batteries and lithium titanate batteries for application on land vehicles in battlefield scenarios is warranted. However, such analysis is beyond the scope of this report.

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Appendix A Map of Battery Technologies

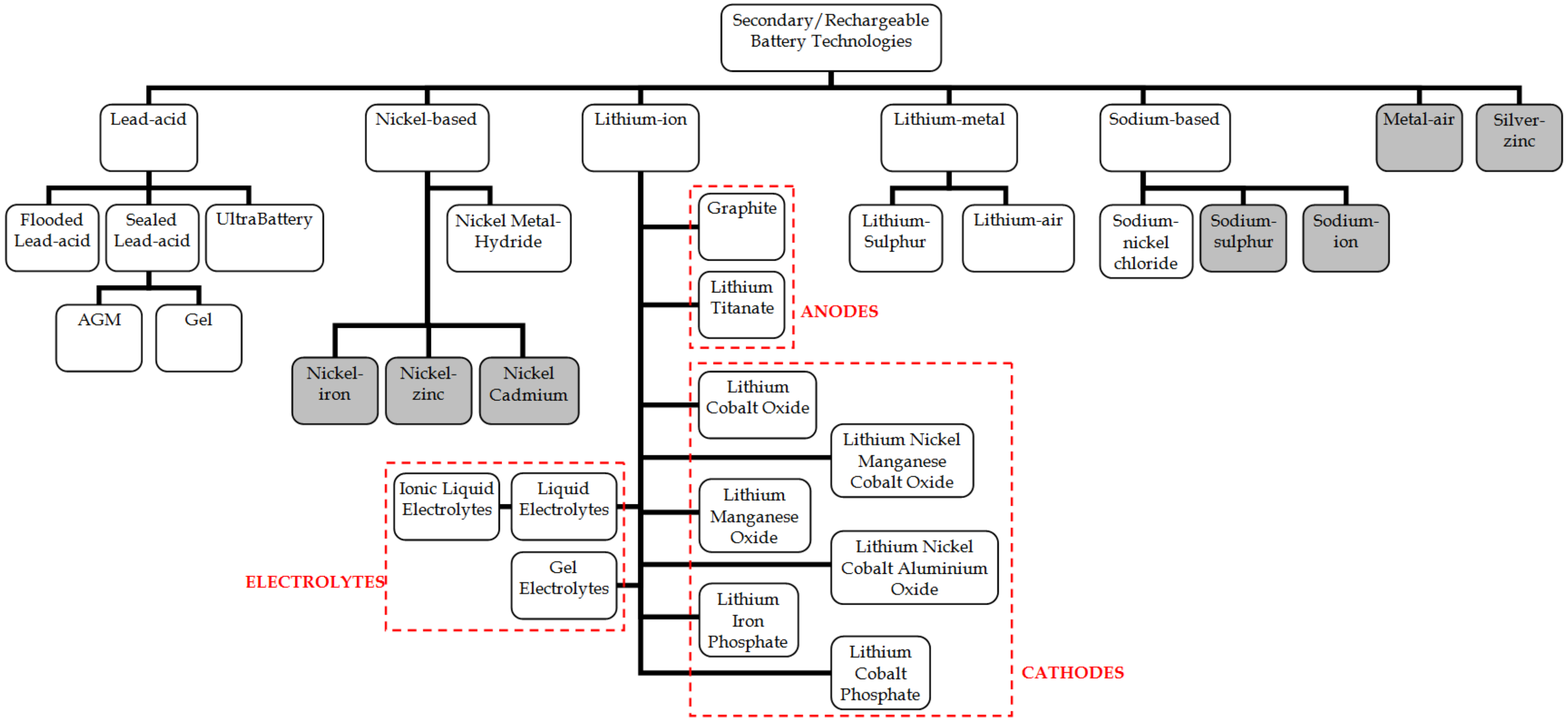

Figure 3 Map of battery technologies covered in this report. Batteries are grouped by "type" and those in grey are not covered in this report.

Appendix B Table of Battery Characteristics

Table 1 Battery characteristics for battery types considered in this report. Empty cells correspond to data that was unable to be sourced. Data in this table has been collated from the following references: [1, 6, 10, 15, 31, 34, 35, 39, 40, 64, 88, 93, 95, 96, 104, 105, 106].

Battery Type		Nominal Voltage (V)	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Specific Power (W/kg)	Power Density (W/L)	Cycle Life (cycles)	Calendar Life (years)	Self-Discharge Rate (% per month)	Operating Temperature Range (°C)
Lead-acid	Flooded (SLI)	2.0	40	80	215	445	200-700	3-6	20-30	-40 to +55
	Flooded (Deep-cycle)	2.0	25	80			1500	6	4-6	-20 to +40
	Sealed (AGM)	2.0	39	95	235	570	300-450	3-4	4	-15 to +50
	Sealed (Gel)	2.0	34	71	155	325	200-450	3-4	4	-15 to +50
	UltraBattery	2.0	30-39	71-86	1000					
Nickel-based	Ni-MH	1.2	90-110	430	865	2882	500-1000	5-10	15-30	-20 to +65
Lithium ion	LCO	3.7	175-240	400-640	~1000	~2000	> 500	> 5	2-10	-20 to +60
	NMC (Energy cells)	3.6	175-240	400-640	~1000	~2000	> 500	> 5	2-10	-20 to +60
	NMC (Power cells)	3.6	100-150	250-350	~4000	~10000	> 500	> 5	2-10	-30 to +60
	NCA	3.6	175-240	400-640	~1000	~2000	> 500	> 5	2-10	-20 to +60
	LMO	3.7	100-150	250-350	~4000	~10000	> 500	> 5	2-10	-30 to +60
	LFP	3.3	60-120	125-250	~4000	~10000	> 1000	> 5	2-10	-30 to +60
	LCP	5								
	LTO	2.3	70	120	~1100	~2000	> 4000	> 5	2-10	-30 to +60
Lithium-metal	Li-S	2.3	~350	~350	~3000		100			
	Li-air	2.8	700-1000							
Sodium-based	Na-NiCl	2.5	120-125	185-190	180	270	> 1000	5	N/A	-40 to +60

Please note that much of the data within Table 1 is generalised to provide an indication of the relative performance of various battery technologies. As discussed in Section 3, battery performance may vary depending on many factors and as such, the values presented here should not be considered indicative for all battery use cases and all conditions. Please also note the following points when considering the battery characteristics shown in the table above:

- Values shown for specific energy, energy density, specific power and power density correspond to room temperature where possible.
- Values shown for specific power and power density correspond to pulse discharges for most batteries.
- Cycle life is dependent on DoD, but it is shown for 100% DoD where possible.
- The self-discharge rate for SLI maintenance-free lead-acid batteries is 2-3% per month [1].
- Cycle life of the UltraBattery in HEV applications undertaking partial SoC operation is up to 300,000 cycles [35].
- The figures presented for Ni-MH batteries are based on commercial Ni-MH batteries. Values for Ni-MH batteries used in HEV applications are as follows: specific energy 45-60 Wh/kg, energy density 177 Wh/L, specific power 1000-1300 W/kg and cycle life 300,000 cycles [1].
- The operating temperature range shown for Li-ion batteries corresponds to discharging. The operating temperature range for charging for all Li-ion variants is 0 °C to +45 °C apart from LTO which is -20 °C to +45 °C [1].
- The specific energy figure shown for Li-air batteries is a projected figure [88].
- Values shown for Na-NiCl batteries correspond to performance in HEV applications.
- Energy must be used to continually keep Na-NiCl batteries up to temperature when not in use [95], therefore a comparable self-discharge rate is not applicable for these batteries.
- The operating temperature range shown for Na-NiCl batteries represents ambient temperature. The internal operating temperature of these batteries is 270-350 °C [40].

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19. ABSTRACT

This review provides an overview of battery technologies and related issues relevant to their use in military land vehicles. It explains the advantages and disadvantages of specific battery technologies along with integration considerations for military land vehicles and the future direction of each technology. It concludes that lead-acid batteries will remain relevant for military land vehicles in the immediate future, but variants of lithium ion batteries have the potential to improve operational performance and should be investigated further for implementation in current and future military land vehicles.