Australian Government
Department of Defence
Defence Science and
Technology Organisation

# Land 125 – Power Technologies Review

*Brendan Sims*

**Land Operations Division**
Defence Science and Technology Organisation

DSTO-GD-0710

## ABSTRACT

This review provides an overview of the technologies and issues relevant to future dismounted soldier power systems. The issues with current systems are identified, namely weight, volume, cost and logistics, and power source technologies to address these issues are discussed.

**RELEASE LIMITATION**

*Approved for public release*

*Published by*

*Land Operations Division*
*DSTO Defence Science and Technology Organisation*
*PO Box 1500*
*Edinburgh South Australia 5111 Australia*

*Telephone: (08) 7389 5555*
*Fax: (08) 7389 6567*

*AR-015-439*
*November 2012*

# Land 125 - Power Technologies Review

## Executive Summary

The evolution of capability requirements for dismounted soldiers prescribes greater use of electronic equipment by soldiers in the battlefield. This is increasing the amount of power and energy required by soldiers. Primary batteries, and to a lesser extent secondary batteries, are the predominant technologies used by soldiers to power their electronic devices. However, primary batteries cannot be recharged. This results in a large weight burden for soldiers, who must carry many battery spares, and demanding logistics requirements to regularly replace batteries. Without reducing the power and energy required by soldiers, these issues are likely to be exacerbated in the future. Therefore, alternative technologies are being developed and effort is being applied to reduce soldier power consumption.

The information presented in this document was gathered from a range of resources discussing issues and technologies relevant to dismounted soldier power provision. These resources included conference presentations, journal articles, reports and relevant expertise within the Defence Science and Technology Organisation (DSTO). This information was used to identify the key extant issues with soldier power provision and technologies that may address these issues.

The main purpose of this document is to discuss alternative solutions for providing electrical power to dismounted soldiers. The discussion aims to highlight the benefits of each solution and known issues that may arise as a result of their use, as well as identifying aspects known to require further development. A number of power source technologies are discussed, including advanced primary and secondary batteries, supercapacitors, fuel cells, energy harvesting devices and microengines. Technological maturity, system weight and associated logistical requirements are key factors that affect the suitability of these technologies for soldier power provision, although other aspects, such as safety and cost are considered.

The development of improved primary batteries may reduce associated weight and logistics issues by increasing the energy available from individual cells. Secondary batteries are attractive replacement for primary batteries because they may reduce resource and logistics costs. Further implementation of secondary batteries is likely to depend on the development of battery charging capabilities. Without lightweight battery chargers, soldier load on extended missions may increase if heavy battery chargers need to be carried. Fuel cells could offer large energy improvements for longer missions, but significant additional logistics infrastructure may be required if non-standard military fuels are used. Similar energy improvements may be achieved

with microengines, but they require a number of technical issues to be addressed. Energy harvesting devices provide an opportunity to reduce the amount of energy carried by soldiers and the associated logistics burden. However, their implementation is likely to depend on improvements in conversion efficiencies and effective integration with the soldier power system to prevent soldiers from being overburdened.

The integration of soldier power systems is an important consideration to optimise soldier energy usage. These systems connect all electrical loads to one or more central power sources. Although integrated systems have added overhead for the distribution and conversion of power, they facilitate system-level power management. This allows smarter use of energy through the utilisation of energy conservation strategies with the potential for weight savings if energy saved through power management can offset the overhead of the integrated system. Where high power requirements exist for soldiers and single source solutions are insufficient, hybrid power systems should be considered to provide both high power and energy. Ideal soldier power solutions will reduce the weight and logistics burdens of soldier power provision, but they must be adaptable to the battlefield environment.

# Author

**Brendan Sims**
Land Operations Division

*Brendan Sims graduated from the University of Adelaide with a BEng (Mechx) (Hons) in 2008. He has been employed at DSTO Edinburgh (Land Operations Division) since October 2009. In that time, he has worked in the Vehicle Electronics and Architectures team.*

*This page is intentionally blank*

# Contents

# List of Acronyms and Abbreviations

| | |
|---|---|
| ADF | Australian Defence Force |
| AFC | Alkaline Fuel Cell |
| ANU | Australian National University |
| ASAP | Advanced Soldier Adaptive Power (Project) |
| C4I | Command, Control, Communication, Computers and Intelligence |
| CERDEC | Communications Electronics Research, Development and Engineering Centre |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| CTD | Capability Technology Demonstrator |
| DARPA | Defence Advanced Research Projects Agency |
| DMFC | Direct Methanol Fuel Cell |
| DRDC | Defence Research and Development Canada |
| DSTO | Defence Science and Technology Organisation |
| FIED | Flexible Integrated Energy Device |
| HHV | Higher Heating Value |
| ICE | Internal Combustion Engine |
| ISSP | Integrated Soldier System Project |
| JP-8 | Jet Propellant 8 (NATO Code F-34) |
| LHV | Lower Heating Value |
| $Li/(CF)_x$ | Lithium Carbon Monofluoride (Battery) |
| $Li/MnO_2$ | Lithium Manganese Dioxide (Battery) |
| $Li/SO_2$ | Lithium Sulphur Dioxide (Battery) |
| $Li/SOCl_2$ | Lithium Thionyl Chloride (Battery) |
| $LiFePO_4$ | Lithium Iron Phosphate (Battery) |
| $LiFeS_2$ | Lithium Iron Disulphide (Battery) |
| Li-ion | Lithium Ion (Battery) |
| Li-poly | Lithium Polymer (Battery) |
| Li-S | Lithium Sulphur (Battery) |
| LTO | Lithium Titanate (Battery) |
| MEMS | Micro Electro Mechanical System |
| MICE | Miniature Internal Combustion Engine |
| MIT | Massachusetts Institute of Technology |
| NATO | North Atlantic Treaty Organisation |
| Ni-Cd | Nickel Cadmium (Battery) |
| Ni-MH | Nickel Metal Hydride (Battery) |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| PNNL | Pacific Northwest National Laboratory |
| RF | Radio Frequency |
| SLA | Sealed Lead Acid (Battery) |
| SOFC | Solid Oxide Fuel Cell |
| SPE | Solid Polymer Electrolyte |
| STANAG | (NATO) Standardisation Agreement |
| TRL | Technology Readiness Level |
| UAV | Unmanned Aerial Vehicle |

| | |
|---|---|
| UAS | Unmanned Aircraft System |
| UGV | Unmanned Ground Vehicle |
| VRLA | Valve-Regulated Lead Acid (Battery) |
| $Zn/MnO_2$ | Zinc Manganese Dioxide (Battery) |

# 1. Introduction

In the modern military environment, improvement of dismounted soldier capability and situational awareness prescribes greater use of electronic equipment by soldiers. This is increasing the amount of energy dismounted soldiers are required to carry into the battlefield. The aim of this document is to identify current issues with dismounted soldier power provision and to present a general overview of the technologies and approaches being developed for future dismounted soldier power systems.

The advantages, disadvantages and aspects for further development of potential solutions for dismounted soldier power provision are discussed in this document, but a comprehensive comparison of solutions is not provided. The ability to compare the validity of different technologies for dismounted soldier provision is restricted as the Australian LAND program is currently in development and dismounted soldier power objectives are yet to be defined.

This document focuses on power source technologies that are able to be worn by soldiers or carried in their packs. Although, some discussion of portable and stationary power source technologies is included, they are not the focus of this document. Technologies relevant for the near term, mid term and far term are discussed in this document[1].

A brief background to dismounted soldier power is given, followed by a discussion of key concepts in power and energy. The main body of the document provides an overview of power source technologies considered relevant for dismounted soldier power systems. A discussion of topics relevant to the integration of the soldier power system is also presented, including hybrid power systems, in addition to a discussion of the logistics considerations associated with dismounted soldier power provision.

## 1.1 Background

A universal issue for dismounted soldiers and defence organisations around the world is the excessive amount of weight that soldiers are carrying [1, 2], which has the potential to decrease soldier effectiveness. A major contributing factor to a soldier's load is the large number of batteries and battery spares required to power their mission-essential electronic devices [3]. Any increase in soldier capability requirements may necessitate soldiers to carry even more electronic devices into the battlefield, such as personal computers, radios and sensors. This is likely to increase the power and energy required by dismounted soldiers and cause a subsequent increase in the number of power sources and hence weight being carried. To maintain a high level of soldier performance, it is critical to develop and implement power sources that are compact, lightweight, safe, reliable, and meet the power and energy demands of future dismounted soldiers.

---

[1] The US National Research Council uses three timeframes to analyse the development of dismounted soldier power systems, namely near term (within five years), mid term (between five and ten years) and far term (greater than ten years) [1]. Any reference to these timeframes within this document should be interpreted similarly.

Currently, dismounted soldiers rely predominantly on primary (non-rechargeable) batteries to power their electronic devices [1]. Many of these devices require different types of batteries and as a precaution, double the number of batteries required for a mission are usually carried [4]. This leads to dismounted soldiers carrying many batteries of many different types, which is a significant weight and volume burden. Soldiers may be carrying between 10kg and 20kg of batteries depending on their role and mission duration [5, 6]. Any depleted batteries must not be discarded on the battlefield [6], therefore they must be carried by soldiers until their mission is resupplied or completed, compounding the weight problem for soldiers. Additionally, soldiers will often take a fresh set of batteries on a mission even if their existing cells are not completely depleted [7]. This results in significant logistics overhead and resource costs.

The restrictions associated with primary batteries have led to other power sources being researched and developed that have the potential to eliminate many of these restrictions and improve dismounted soldier operational effectiveness. The technologies identified as potentially replacing or complimenting primary batteries include secondary (rechargeable) batteries, supercapacitors, fuel cells, microengines and energy harvesting devices [1]. Some of these technologies are already used in the battlefield, while others may become relevant for soldier power provision in the future.

# 2. Soldier Power System Concepts – Power and Energy[2]

Electrical power and energy are two key concepts within the scope of this document. Energy, measured in Watt-hours, is the ability of an electrical current to do work, while power, measured in Watts, is the rate at which energy is transferred or converted by a circuit. This means that a source of electricity is capable of providing a certain amount of power at an instant in time and will provide a certain amount of energy over a period of time. The power and energy consumed by an electrical device can be defined similarly.

Specific energy (expressed in Wh/kg) and energy density (expressed in Wh/L) refer to gravimetric energy density (energy per unit mass) and volumetric energy density (energy per unit volume) respectively. Likewise, specific power (expressed in W/kg) and power density (expressed in W/L) refers to gravimetric power density (power per unit mass) and volumetric power density (power per unit volume) respectively. The amount of energy that is generated or stored by a system is affected by operating conditions so there is often a range of specific energy and energy density values quoted for various sources.

Often, a trade-off between specific power and specific energy exists for various sources. The power and energy performance of various storage systems, such as batteries, and conversion systems, such as fuel cells, can be compared in a Ragone chart (see Figure 1 and Figure 2). These plots can also be used to demonstrate the relationship between specific power and energy for a given energy storage or generation system as it is discharged at different rates.

---

[2] Key power and energy concepts have been taken from [1].

Note that for most batteries, energy is inversely proportional to power. Discharging a battery quickly (high current therefore high power) will reduce the amount of energy it can provide since electrical losses are proportional to current, while discharging it slowly (low current therefore low power) will maximise the amount of energy available since these losses are reduced.

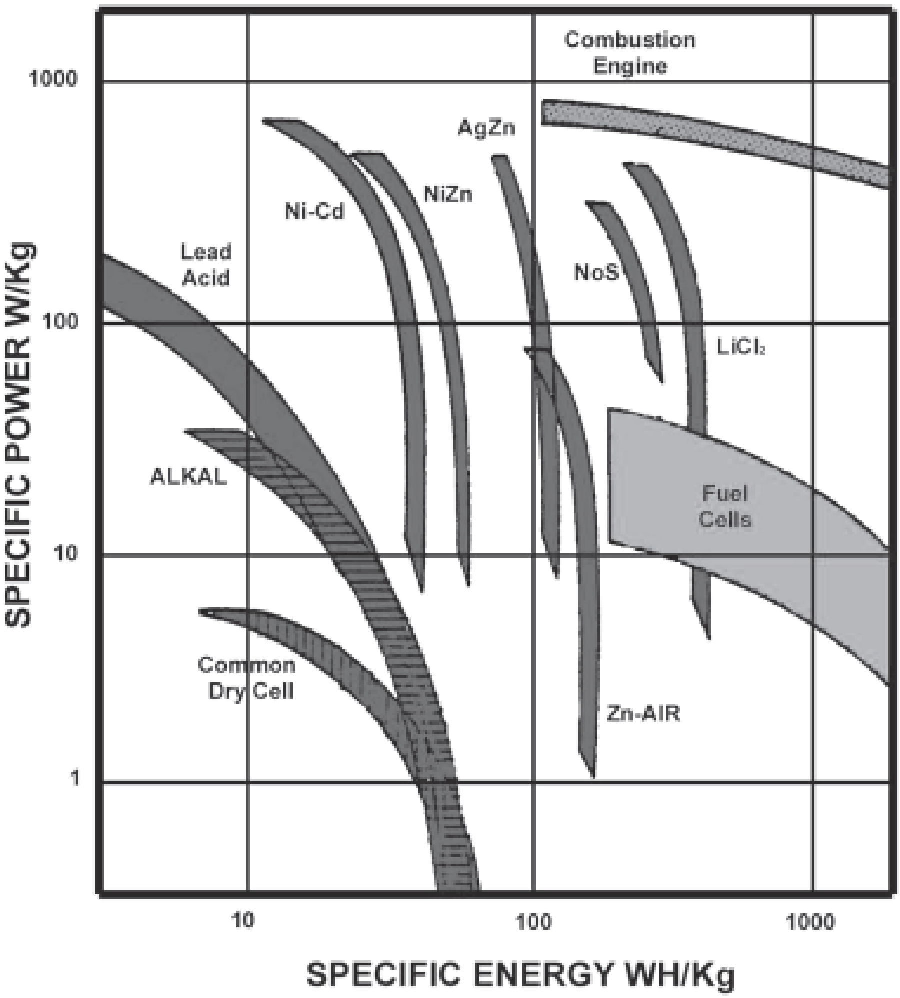

*Figure 1 Ragone chart comparing battery chemistries, fuel cells and combustion engines [1]*

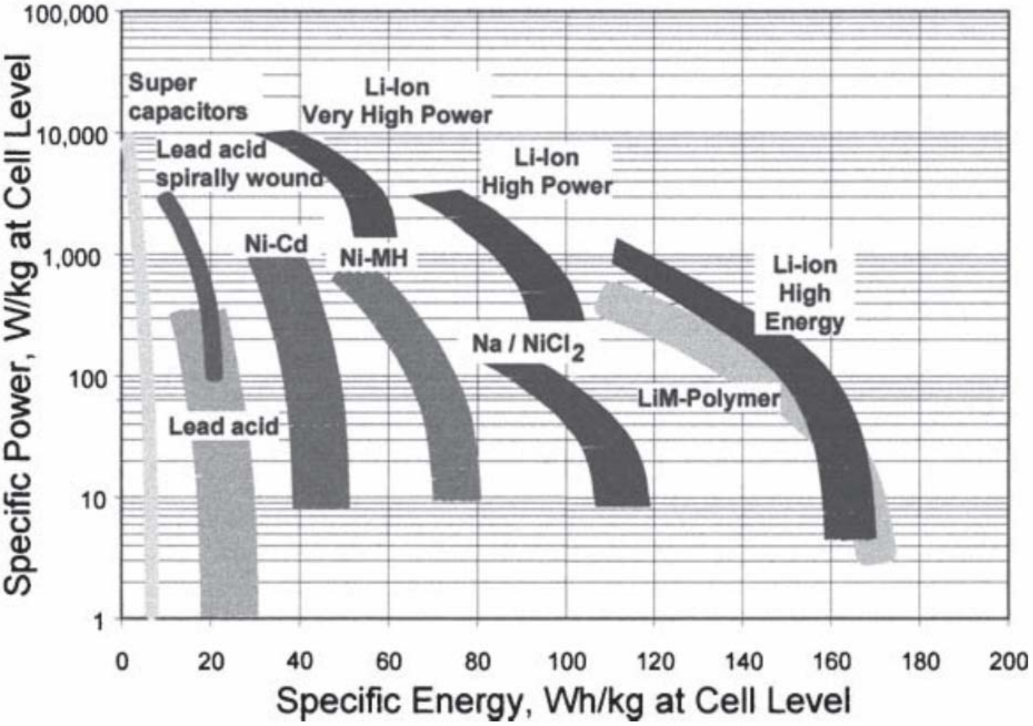

*Figure 2 Ragone chart comparing various battery chemistries and supercapacitors [8]*

One of the main capability limitations for dismounted soldiers is the operational endurance of their electrical devices. The power and energy capabilities of a soldier's power source (or sources) have a significant effect on operational endurance. These sources are chosen, or designed, so that they are capable of providing sufficient power to enable a soldier's electrical devices to operate, while the key to achieving long mission endurance is to maximise the energy capacity of these sources. Although soldiers may carry spare power sources for redundancy, using a source with high energy density reduces the requirement for soldiers to carry many spares, therefore reducing the weight they are carrying. If high power devices, such as laser target designators [1] are required by future soldiers, the soldier power system's energy will be diminished even when operating at low rates [6]. This is demonstrated for many battery chemistries in Figure 2 and may necessitate the use of hybrid power systems (see Section 4.5), such as battery-supercapacitor hybrids. In this system, the supercapacitor is used to provide high power and the battery's energy is not diminished.

A challenge in developing integrated soldier systems is estimating future power and energy requirements for soldiers. This problem is exacerbated by the wide range of electronic equipment carried by soldiers to fulfil various roles and missions. Hence, significant variability in the power and energy requirements of soldiers exists [6]. Although Australian Defence is aware that soldiers will require more power to sustain their electronic devices in the future [9], the Australian LAND program is currently in development and target gravimetric and volumetric energy and power densities have not yet been defined. It is expected that future dismounted soldier power requirements will be informed by the North Atlantic Treaty Organisation (NATO) [9].

An indication of expected power requirements for future dismounted soldiers can be sourced from programs undertaken in the US, such as the Land Warrior program. Over three generations of this program, the average and peak power estimates for the soldier power system were in the order of 20W and 50-60W respectively [1]. Therefore, energy required would range from 240Wh for a 12 hour mission, up to 1440Wh[3] for a three day mission. This figure grows proportionally for longer missions. The National Research Council presents findings from a workshop on Energy and Power for the Soldier conducted by the US Army Research Laboratory in 2002, which recommend a target weight of 1kg for power source technologies independent of mission length [1]. This translates to a target specific energy of 240Wh/kg for 12 hour missions up to 1440Wh/kg for three day missions and a target specific power of 50-60W/kg. Although these figures provide a reasonable indication of potential power and energy requirements for dismounted soldiers, they are based on equipment proposed for the Land Warrior ensemble rather than a fielded system. They are used as an approximate objective for dismounted soldier power systems.

# 3. Power Source Technologies

As the need for soldiers to carry more electronic devices into the battlefield grows, increased importance is placed on the source technologies used to power these devices. Present fielded technologies have a number of shortfalls, such as large weight and space requirements [1], which has led to other power sources being researched and developed.

An important consideration for the technologies presented here is their Technology Readiness Level (TRL). The TRL of a particular technology provides an indication of its technical maturity and can be used as a guide as to when technologies will be mature for military application. The TRL of specific technologies will be given at various points throughout Section 3. TRL values provided are based on referenced values or an estimate is made where sufficient information has been discovered about a technology. TRL values are not specified for technologies where insufficient information is available to make an estimate. Further information on TRLs along with a TRL summary is provided in Appendix A.

## 3.1 Batteries

A battery is an electrochemical device used to convert stored chemical energy into electrical energy. A battery cell comprises three main components, a positive and negative electrode (cathode and anode) and an electrolyte [1]. The electrodes vary in electrical potential and are connected ionically through the electrolyte, whilst remaining electrically separated [1]. Batteries fall into two categories:

- Primary batteries – a non-rechargeable battery; and
- Secondary batteries – a battery that can be recharged.

---

[3] Based on an average power consumption of 20W.

Each category of battery is available in various sizes and chemistries, which produce a variety of individual characteristics including capacity, discharge rate, voltage, operating temperature, shelf life and safety. Hence, they are able to meet a range of power and energy requirements. Batteries are the main source used to power dismounted soldiers' electronic equipment [1], but the development of improved battery technology can address current issues, such as excessive soldier loads and logistics issues (see Section 5).

## 3.2 Primary Batteries

Primary batteries are a non-rechargeable battery; once their initial chemical energy potential has been consumed, it cannot be restored by electrical means and the battery must be replaced. Primary batteries are the predominant energy source used by dismounted soldiers in the battlefield [1]. There are several reasons for their preferred use, which are discussed below.

- Technological maturity – Many primary battery technologies are mature [1] and some have been used for many years to power soldiers' electronic devices in the battlefield [10]. These primary batteries are a proven technology capable of withstanding battlefield conditions, such as high and low temperatures, high impacts and excessive vibrations.
- Energy readiness – Primary batteries provide an immediate source of energy and unlike secondary batteries, they require no charging prior to use, making them convenient for soldiers. Compared with fuel cells, most of which require time to heat to their operating temperature [6], the energy readiness of primary batteries is particularly advantageous.
- High specific energy – In general, primary batteries have higher specific energy than most types of secondary battery [11]. This means they are replaced less often than secondary batteries need to be recharged. However, the energy capabilities of fuelled sources are far superior, as shown in Figure 1 in Section 2 [1].

Although primary batteries have some advantages, they also have associated disadvantages that limit their potential for use in future dismounted soldier power systems:

- Significant weight burden – Weight is a large concern since primary batteries are only able to be used once and then must be replaced, which requires many spares to be carried. Expended batteries should also be carried for the duration of a mission to ensure they are properly disposed [6].
- Demanding resupply/disposal logistics – The use of primary batteries provides a significant logistical burden in the military environment [12]. The regular replacement of primary batteries requires a reliable resupply infrastructure to deliver batteries to the battlefield and distribute them to dismounted soldiers. A disposal infrastructure is also required to safely dispose batteries once they have been used.
- High lifetime cost – Primary batteries provide a non-reusable form of energy with a relatively short operational life. They need regular replacement and thus the lifetime

cost to power a device using primary batteries is higher than a power source that can be recharged or refuelled [5, 14, 15]. However, costs associated with recharging and refuelling, including the cost of recharging equipment and fuel transport, should be considered when considering alternative power sources.

- Energy wastage – A lot of energy is wasted when using primary batteries to power a soldier's portable electronic devices. As fresh batteries are always taken on missions [10], any remaining capacity in the batteries from a previous mission remains unused.
- Safety concerns – Primary batteries, in particular lithium-based primary batteries, have several safety concerns [11] since they utilise flammable materials. They have the potential to vent, ignite or explode if they are abused [11]. Situations such as severe impact, discharging a primary battery at too high a rate, operation in very high temperatures or short-circuiting the battery may cause damage [11], posing a safety risk to soldiers.
- Temperature effects – Operation in very cold temperatures can reduce the capacity of alkaline primary batteries, although these effects are less significant for lithium-based primary batteries [3]. Operation at very high temperatures can damage primary batteries, while storage in high temperatures reduces shelf life [11].

### 3.2.1 Primary Battery Technologies

Although some primary battery technologies are quite mature, significant effort is being applied to further develop this technology. An overview of some of the main primary battery technologies of interest for dismounted soldiers is now presented, while a summary of their characteristics is given in Section 3.2.2.

#### *3.2.1.1 Alkaline ($Zn/MnO_2$) Batteries*

Alkaline batteries (also known as Zinc Manganese Dioxide batteries) are a well established technology (TRL 9 [4]) after being introduced in the 1960s and gradually became the preferred battery in portable electronics [11]. They use a zinc anode, a manganese dioxide cathode and a potassium hydroxide electrolyte [13].

Alkaline batteries have moderate specific energy (approximately 145Wh/kg for cylindrical cells [13]) and possess a number of other advantages. They perform well at low temperatures (operating temperature range is from -18°C to +55°C [13]), at low and high rates and in continuous and intermittent duty cycles [11]. Alkaline batteries also tend to be cheaper than primary lithium batteries [3, 11].

As of 2008, Canadian soldiers used 13 AA alkaline batteries for 24 hour missions to power some of their devices, with double this number carried as a precaution [4]. These AA batteries are typically used to power devices such as flashlights, night vision equipment and laser sights [14].

### *3.2.1.2 Lithium Sulphur Dioxide (Li/$SO_2$) Batteries*

The first commercialised primary lithium batteries were Li/$SO_2$ batteries [8]. This battery uses a lithium anode, a porous carbon cathode and a non-aqueous electrolyte consisting of sulphur dioxide and lithium bromide dissolved in an organic solvent [8].

There are several benefits of this technology. Li/$SO_2$ batteries have a wide operating temperature range (-55°C to +70°C), long shelf lives (up to ten years when stored at room temperature) and quite high specific energy (260 – 280Wh/kg) [13]. These batteries are also noted for their ability to handle high current and high power requirements and good performance at low temperatures [11].

A major issue with Li/$SO_2$ batteries is safety since they are pressurised and contain toxic and flammable materials, which can result in venting, rupture, explosion or fire if the battery experiences physical or electrical abuse [11]. Despite their safety issues, Li/$SO_2$ batteries have been used in military communications applications for many years (TRL 9 [1, 4]).

### *3.2.1.3 Lithium Thionyl Chloride (Li/$SOCl_2$) Batteries*

The Li/$SOCl_2$ battery is a high voltage, high energy primary lithium battery. This battery has a lithium anode, a porous carbon cathode and an electrolyte consisting of thionyl chloride ($SOCl_2$) (also the active cathode material) and lithium tetrachloroaluminate ($LiAlCl_4$) [11].

The main benefits of Li/$SOCl_2$ batteries are their high specific energy (450 – 600Wh/kg [13]), long shelf life (10 – 15 years [13]), high nominal voltage, flat discharge curve and wide operating temperature range (-55°C to +85°C [13]). Some versions of these batteries are capable of operating at even higher temperatures, up to 150°C [13]. However, these batteries are quite expensive and have performance issues after storage for long periods of time. They exhibit a voltage delay, where the battery takes some time to reach its operating voltage, due to the formation of a lithium chloride film on the lithium anode surface during storage [11]. Li/$SOCl_2$ batteries also have several safety concerns. Over-discharging the battery can cause a significant increase in pressure and temperature in the cell [13].

Li/$SOCl_2$ batteries are typically used in applications such as memory back-up and security systems due to their high energy densities and long shelf lives, while higher-rate cylindrical Li/$SOCl_2$ batteries have been used in military applications to provide standby power (TRL 9) [11]. Wide consumer application is limited due to the high cost of these batteries and safety concerns [11].

### *3.2.1.4 Lithium Manganese Dioxide (Li/$MnO_2$) Batteries*

The Li/$MnO_2$ battery is the most widely used primary lithium battery for commercial applications [11]. It uses a lithium foil anode, a heat treated magnesium dioxide cathode and an electrolyte consisting of lithium salts and organic solvents [11].

Li/$MnO_2$ batteries are replacing Li/$SO_2$ batteries in military applications because they have fewer safety concerns [1, 13], in particular the use of non-pressurised cells improves battery safety [11]. Li/$MnO_2$ batteries also have a number of other advantages. They have a higher nominal voltage than most other primary lithium batteries, apart from Li/$SOCl_2$ batteries, long shelf life (up to ten years at room temperature [13]) and are relatively low cost [11]. The operating temperature range of Li/$MnO_2$ batteries is -30°C to +70°C [12] and their specific energy (230 to 300Wh/kg [11, 13]) is similar to Li/$SO_2$ batteries.

Li/$MnO_2$ batteries tend to have moderate specific power, although high rate Li/$MnO_2$ batteries are available [11]. Li/$MnO_2$ batteries designed for high rate operation are used in military applications (TRL 9 [1]), including powering radios [1, 11].

#### *3.2.1.5 Lithium Iron Disulphide ($LiFeS_2$) Batteries*

$LiFeS_2$ batteries are a recently commercialised technology that have the same nominal voltage as alkaline batteries [11]. This means that they could directly replace alkaline batteries in military applications in the future. Their construction incorporates a lithium anode, an iron disulphide cathode and lithium salt in an organic solvent as the electrolyte [11].

$LiFeS_2$ batteries have a much flatter discharge curve than alkaline batteries and improved specific energy (approximately 300Wh/kg) [11, 15]. The flatter discharge curve allows for more consistent output (than alkalines) throughout the life of the battery. $LiFeS_2$ batteries also provide higher specific power than alkalines, which means they perform better in high rate applications. Other advantages over alkalines include lower self-discharge rates (10 to 15 year shelf life [15]) and improved performance at low temperatures (operating temperature range is -40°C to +60°C [11]) [11, 15].

Due to their higher specific energy, $LiFeS_2$ batteries provide approximately 50% weight savings for single missions compared with alkalines, however, they are very expensive and the weight benefit is insufficient to offset this cost in most cases [3]. $LiFeS_2$ batteries (TRL 8[4]) may find military application in specialised high priority devices that require power for high current electrical loads or where weight saving is the primary objective and for which cost is less important.

#### *3.2.1.6 Lithium Carbon Monofluoride (Li/$(CF)_x$) Batteries*

Lithium carbon monofluoride batteries are a very promising technology in the scope of dismounted soldier power systems (TRL 8 [1]). As with other lithium primary batteries, they use a lithium-based anode and an organic electrolyte, but the cathode is a polycarbon monofluoride material [11].

Li/$(CF)_x$ batteries have many distinct advantages over other primary lithium batteries. These include superior specific energy (up to 600Wh/kg, therefore less weight), the lowest self-discharge rates of any primary lithium cell (shelf life of 15 years at room temperature) and a wide useful operating temperature range (-40°C to +85°C) [13]. As Li/$(CF)_x$ batteries have

---

[4] TRL estimate based on information provided by the following sources: [3, 11]

such high energy densities, the run-times for some military devices could be doubled compared with batteries (such as $Li/SO_2$) of equivalent weight and volume [16].

A restriction of $Li/(CF)_x$ batteries is their low power capabilities [8]. High discharge rates may cause $Li/(CF)_x$ batteries to vent and should be avoided [11]. Therefore, they are suited to low rate applications and should not be used with devices requiring high power, which may limit their potential military application. Work is being conducted to improve this aspect by reducing the resistance of the cathode [17]. The other main disadvantage of this battery is that they are very expensive. Coin-sized $Li/(CF)_x$ batteries are typically used to power devices such as watches or calculators while larger cylindrical cells can be used in memory applications [11].

### *3.2.1.7 Metal-Air Batteries*

Metal-air batteries are a unique form of battery. They use a solid metal anode (various metals can be used, some of which are described in the following sections), which is consumed during the operation of the cell, and oxygen in air as the cathode reactant. Neutral or alkaline electrolytes are used [11]. Although metal-air batteries are predominantly primary batteries, some forms have the potential to be used as secondary batteries.

The striking characteristic of metal-air batteries is their potential for very high specific energy since air is used as the cathode reactant and does not have to be stored in the cell [1], ensuring a lightweight design. This makes metal-air batteries relevant for dismounted soldier power systems. However, since the cell is open to air, it is sensitive to its environment when operating and water vapour can be transferred to or from the cell or contaminants may be absorbed. Water loss increases the electrolyte concentration, which leads to drying out and limits the shelf life of the battery once activated, while water gain leads to dilution of the electrolyte and flooding of the air electrode, limiting the power output of the battery [11]. The absorption of contaminants, such as carbon dioxide (known as carbonation), may also damage the air electrode and decrease its performance [11]. Another disadvantage of metal-air batteries is their limited operating temperature range, with battery capacity degrading significantly at lower temperatures [11].

In general, metal-air batteries have limited power output, which makes them suited to low and moderate rate applications [11]. A potential application of this technology for dismounted soldier power provision is as a field recharging unit [11], where the metal-air battery would be used to recharge secondary batteries. Several of the main types of metal-air batteries are discussed in the following sections.

#### 3.2.1.7.1 Zinc-Air (Zn-air) Batteries

Zn-air batteries are a well-established technology that have been used for decades to power devices such as hearing aids and pagers [11]. A number of advantages make Zn-air batteries attractive for portable electronics applications, which include quite high specific energy (300Wh/kg [13]), low cost and good safety characteristics [11]. The disadvantages of Zn-air batteries are similar to those discussed in Section 3.2.1.7. Larger sized Zn-air batteries have been developed for mobile phones and laptop computers [11]. These prismatic Zn-air batteries are also used in a number of military applications for powering devices such as soldier radios (indicating TRL 9[5]), for example the BA-8180/U battery [1].

#### 3.2.1.7.2 Magnesium-Air (Mg-air) Batteries

Mg-air batteries are not in common commercial use although they have been used in some undersea, low-rate applications in the past (where they use dissolved oxygen in seawater as the cathode reactant) [11]. They have higher specific energy than Zn-air batteries (up to 700Wh/kg [1]), but they suffer from several issues such as hydrogen generation and a voltage delay, similar to $Li/SOCl_2$ batteries (see Section 3.2.1.3), due to the formation of a magnesium hydroxide film on the anode [11]. These issues, along with the high self-discharge rate of Mg-air cells, have restricted their commercialisation. Improved Mg-air batteries are in development [17], but without commercialisation these batteries are unlikely to be relevant to soldier power applications.

#### 3.2.1.7.3 Aluminium-Air (Al-air) Batteries

Al-air batteries are a non-commercialised metal-air battery. Although they have very high specific energy (up to 800Wh/kg for saline electrolytes and up to 400Wh/kg for alkaline electrolytes [11]), further development of the aluminium alloys used for the Al-air anode is needed to address issues with hydrogen gas generation[6] [1]. Al-air batteries can be either low-rate or high-rate depending on the electrolyte used. Saline electrolytes are used in low-rate cells while alkaline electrolytes are used in high-rate cells, but they suffer from high corrosion rates [1]. Al-air batteries are designated as reserve systems due to their inherent hydrogen generation, but Al-air batteries using saline electrolytes may find use in portable battery applications [11].

#### 3.2.1.7.4 Lithium-Air (Li-air) Batteries

Li-air batteries are a promising metal-air battery technology since they are predicted to be able to achieve the highest specific energy (up to 1000Wh/kg [18]) of this group. However, safety problems exist since lithium reacts with moisture in air (producing hydrogen) [1] and Li-air batteries have issues with high rates of self discharge [11].

A significant amount of effort is going towards developing Li-air battery technology (TRL 3-4[7]) [18]. Polyplus Battery Company has made good progress towards commercialising Li-air batteries by developing lithium anodes with a protective coating to improve performance, with specific energy in excess of 700Wh/kg achieved [1, 19]. IBM is also working on developing Li-air technology, albeit for vehicle applications [20]. Li-air battery developments are also focussing on making these batteries rechargeable [19].

---

[5] TRL estimate based on information provided by the following sources: [1]

[6] Aluminium reacts with water in the electrolyte to form hydrogen and aluminium hydroxide.

[7] TRL estimate based on information provided by the following sources: [1]

#### 3.2.1.7.5 Carbon-Air (C-air) Batteries

C-air batteries are different from metal-air batteries since they do not use a metal anode and they operate at very high temperatures (greater than 650°C [1]). They use a finely divided source of carbon at the anode and oxygen as the cathode reactant [6]. The final reaction product in the cell is carbon dioxide and, unlike metal-air batteries discussed previously, C-air batteries do not suffer from the build up of solid reaction products [1].

These batteries possess several desirable features, namely very high specific energy and they are non-toxic [1]. Claims of specific energy up to ten times greater than the highest energy batteries available (potentially 2000Wh/kg [18]) have been made [6]. Despite having great potential, C-air batteries are relatively immature and require further development to overcome issues including long start up times and heat management [1]. The high operating temperatures of these batteries suggest that they are unlikely to be suitable for dismounted soldier power provision. A number of other technical issues identified by Lewis et al. [6], also suggest that C-air batteries require further development before they can be realistically considered for soldier power applications. In the future, they may find use as a forward field battery charger [18].

### 3.2.2 Primary Battery Summary

A number of different primary battery chemistries have been discussed in Section 3.2.1, which are summarised in Table 1. The values shown for specific energy and energy density correspond to favourable discharge conditions and the performance of these batteries is highly dependant on the specific conditions of use[8] [11]. Specific power data shown is a relative figure for the different primary battery chemistries and shelf life data is for storage at room temperature. It should be noted that reliable information for some primary cells (in particular many of the metal-air batteries) could not be found; hence it is not included in the following table. Data in Table 1 has been adapted from the following sources: [11, 12, 13, 15].

*Table 1 Summary of primary battery characteristics*

| Chemistry | Nominal Voltage (V) | Specific Energy (Wh/kg) | Energy Density (Wh/L) | Specific Power | Operating Temperature Range (°C) | Shelf Life (Years) |
|---|---|---|---|---|---|---|
| $Zn-MnO_2$ | 1.5 | 145 | 400 | Medium | -18 to +55 | 6 – 7 |
| $Li-SO_2$ | 3.0 | 260 – 280 | 400 - 450 | High | -55 to +70 | 10 |
| $Li-SOCl_2$ | 3.6 | 450 – 600 | 700 – 1100 | Medium | -55 to +85 | 10 – 15 |
| $Li-MnO_2$ | 3.0 | 230 – 300 | 580 – 650 | Medium | -30 to +70 | 10 |
| $Li-FeS_2$ | 1.5 | 300 | 500 | Medium/High | -40 to +60 | 10 – 15 |
| $Li-(CF)_x$ | 2.8 | 530 – 600 | 900 – 1050 | Low | -40 to +85 | 15 |
| Zn-Air | 1.4 | 300 | 800 | Low | 0 to +50 | 6 – 7 |

---

[8] The standard rate at which battery capacity is quoted is the capacity of the battery corresponding to a five hour discharge. It is assumed that the specific energy and energy density figures correspond to discharging the battery at this rate (or a similar rate where a range is shown).

Approximate specific power and specific energy objectives for dismounted soldier power systems are presented in Section 2. From Table 1 it can be seen that only alkaline batteries are unable to meet the specific energy target of 240Wh/kg for 12 hour missions. The specific energy figures also suggest that only Li-$SOCl_2$ and Li-$(CF)_x$ batteries have sufficient energy for 24 hour missions, whilst no primary battery technology is capable of meeting three day mission energy objectives without battery spares.

### 3.2.3 Future Direction

It is likely that primary batteries will continue to be used for soldier power provision in the near future due to the technological maturity of in-service primary batteries, ease of use and generally higher specific energy than secondary batteries. They are able to support current soldier capabilities, albeit at a large cost in weight and resources. This is driving interest in other power source technologies for dismounted soldier power provision, such as secondary batteries. Replacing primary batteries with secondary batteries is likely to result in resource savings and therefore lifetime cost savings. However, primary batteries may still be preferred on extended missions where recharging opportunities are limited.

Efforts to improve primary battery technologies are ongoing. In terms of specific primary battery technologies, alkaline batteries and $Li/SO_2$ batteries are commonly used by soldiers [1, 4]. However, $Li/SO_2$ batteries are gradually being replaced with $Li/MnO_2$ batteries due to their safety improvements [1, 13] and it is anticipated that they will be completely replaced within two years [21]. $LiFeS_2$ batteries may be a direct replacement for alkalines since they operate at the same nominal voltage and have significant specific energy improvements. However, they are much more expensive and their application is likely to be limited by their high cost. Further energy improvements may be provided by $Li/(CF)_x$ batteries, but their power densities must be improved. They are predicted to replace $Li/MnO_2$ batteries within 12 years [21]. Li-air batteries may also provide significant energy improvements, but the technology is not mature and requires further development.

## 3.3 Secondary Batteries

Secondary batteries are a rechargeable form of battery; they are capable of having their chemical potential energy restored by electrical means after they have been discharged. Secondary batteries are mainly used by soldiers for training purposes and are not as common as primary batteries in the battlefield [21, 22]. As the infrastructure to support secondary batteries improves, and charging systems are developed, it is likely that they will become more common for powering soldiers' electronic devices since they have some advantages over primary batteries, which are outlined below.

- Low lifetime cost – Secondary batteries are cheaper than primary batteries over the lifetime of a battery [23], despite their greater initial cost and the costs associated with battery recharging on the battlefield. The use of secondary batteries results in significant resource and cost savings since they are replaced less often than primary batteries.

- Simplified resupply/disposal logistics – Compared to primary batteries, the weight and volume of batteries that the logistics system must bring to forward positions is reduced since secondary batteries can be recharged on the battlefield and they are not replaced as regularly [1]. As mentioned above, this results in significant resource and cost savings.

Several disadvantages exist with secondary batteries that limit their potential as the power source of choice for dismounted soldiers in the future. The following points discuss these disadvantages.

- Low specific energy – Secondary battery technologies provide lower energy output per unit of weight compared to most of their primary counterparts. This means they require recharging more often than primary batteries are replaced and may create a significant load on soldiers if they are required to carry battery spares or battery chargers on extended missions. However, secondary batteries may offer weight and volume savings on these missions if compact and lightweight recharging devices are developed and implemented since many battery spares would not be required. Improvements in the specific energy of secondary batteries are also being achieved with newer technologies, such as lithium-ion (Li-ion) batteries.
- Demanding recharging logistics/requirements – Secondary batteries must be regularly recharged. This may be in the form of a portable charger carried by the soldier or from a larger dedicated charging unit in the field. The recharging process creates an additional burden for soldiers and introduces additional items of equipment that must be proliferated and supported in forward areas, which may necessitate additional vehicles or personnel [1].
- Safety – There are safety concerns relating to the use of flammable materials such as lithium and organic solvents in batteries. Leakage, venting, intense burning or even explosions may be caused from severe impact, operation at high temperatures, over-charging or over-discharging [11]. These effects pose a particular safety risk to dismounted soldiers, who may be carrying a number of these batteries in an operational environment.
- Poor energy readiness – Secondary batteries have higher self-discharge rates than primary batteries [13]. Therefore, it is likely that an unused secondary battery will need to be recharged before being used if it has not been recently charged.
- Temperature effects – As with some primary batteries, certain secondary batteries have significantly reduced capacity when operating at low temperature extremes, while storage in raised temperatures increases self-discharge rates and reduces the life of secondary batteries [13].
- Limited cycle life – Although secondary batteries are rechargeable, there is a limit to the number of times they can be recharged and they must eventually be replaced. This number varies for different chemistries, and is influenced by operating conditions and the charge and discharge profiles for the battery.
- Storage state of charge – The state of charge of a secondary battery during storage influences the lifetime of the battery. For most secondary batteries, permanent capacity

loss is reduced for storage at a reduced state of charge, while lead acid batteries (see Section 3.3.1.1) should be stored at full state of charge [13, 24].

### 3.3.1 Secondary Battery Technologies

A significant amount of effort has gone into the development of secondary batteries to address some of their disadvantages (see Section 3.3). Lithium-based secondary batteries have improved many of these aspects, including higher specific energy and higher nominal voltage [8]. An overview of the main secondary battery technologies of interest for dismounted soldiers is now presented, while a summary of their characteristics is given in Section 3.3.2.

#### *3.3.1.1 Lead Acid Batteries*

Lead acid batteries are one of the most widely used battery technologies throughout the world [11], with the main areas of use being automotive and stationary applications. Within the portable power domain, small, sealed lead acid batteries (SLAs) are less common [13].

SLA batteries, also known as Valve-Regulated Lead Acid (VRLA) batteries, differ from other types of lead acid batteries, namely vented (or flooded) lead acid batteries because they are able to retain their electrolyte inside the cell regardless of orientation [11]. Lead acid batteries are constructed with a lead anode, lead oxide cathode and a sulphuric acid electrolyte [11].

The main advantages of SLAs are their technological maturity, long-term reliability and low maintenance requirements [11, 13]. They are also simple and inexpensive to manufacture. However, compared with other rechargeable batteries, SLAs have quite low specific energy (approximately 30Wh/kg [13]). Other issues that restrict their potential use in dismounted soldier power systems include their relatively low cycle lives and the safety of their constituents (in particular lead and sulphuric acid), with hydrogen evolution a potential explosion hazard in some designs if the battery is abused [11].

Small SLAs have been used in the past for portable televisions, measuring instruments and lighting equipment [13]. However, they are more commonly used in large format applications, such as in vehicles and as backup power supplies. The low energy density of lead acid batteries suggests that they are unlikely to be widely used for dismounted soldier power applications in the future.

#### *3.3.1.2 Nickel Cadmium (Ni-Cd) Batteries*

Sealed nickel-cadmium batteries are a rechargeable battery technology that have been used in the past to power portable devices (TRL 9[9]), although within the last 20 years they have become less common with the advent of nickel-metal hydride (Ni-MH) and lithium-ion battery technologies. Vented Ni-Cd batteries are also available, which tend to be large format and used in industrial applications [8]. Ni-Cd batteries use a cadmium anode, a nickel-based cathode and a potassium hydroxide electrolyte [11]. They operate best between -20°C and +30°C [11].

---

[9] TRL estimate based on information provided by the following sources: [1, 17]

Several advantages of Ni-Cd batteries facilitated their widespread commercialisation in the past. They can be stored for long periods of time across a wide temperature range (in any state of charge [11]) and they have high-rate capabilities [13]. However, they have lower specific energies (approximately 35Wh/kg [13]) compared to many other rechargeable technologies, they experience high self-discharge rates and there are safety and environmental concerns with using cadmium [11]. Ni-Cd batteries are also more expensive than lead-acid batteries [11]. A further issue is the "memory effect", which results in a loss of battery capacity when Ni-Cd batteries are only partially discharged on repetitive cycles [11]. However, this effect is reversible and the battery can be restored to full capacity with several full discharge-charge cycles [11].

The concerns associated with Ni-Cd batteries have led to safer, higher energy secondary batteries being developed for portable power applications to replace Ni-Cd batteries.

### *3.3.1.3 Nickel Metal-Hydride (Ni-MH) Batteries*

Another secondary battery that makes use of a nickel electrode and an aqueous electrolyte is the nickel metal-hydride battery. Several characteristics of these batteries are improved when compared with Ni-Cd batteries, in particular they have less environmental concerns as they do not use cadmium. Hence, Ni-MH batteries have largely replaced Ni-Cd batteries in portable power applications (TRL 9[10]) (along with Li-ion batteries) [1].

Ni-MH batteries use a nickel-based cathode and an alkaline (most often potassium hydroxide) electrolyte [11]. However, the use of Ni-MH batteries eliminates the safety and environmental problems of Ni-Cd batteries by using a hydrogen-storing, metal alloy anode instead of a cadmium anode [11].

Ni-MH batteries have an operating range between -30°C and +65°C [13] and achieve high specific power by using a highly conductive electrolyte and electrodes that react at a rapid rate [1]. This enables rapid recharging. They have improved specific energy (60 – 80Wh/kg [13]) compared to SLAs and Ni-Cd batteries, but they are outperformed by Li-ion batteries. Ni-MH batteries need to be charged at relatively low temperatures, require controlled charging to prevent cell damage or overheating [13] and they have higher self-discharge rates than Ni-Cd batteries, but this characteristic is being improved.

As with Ni-Cd batteries, Ni-MH batteries also suffer from a "memory effect", where they experience a reversible capacity loss when repetitively partially discharged [11]. This can be corrected with several full discharge-charge cycles [11]. Ni-MH batteries remain relevant for dismounted soldier power in the future, mainly due to their high specific power.

### *3.3.1.4 Lithium Ion (Li-ion) Batteries*

Li-ion batteries were introduced in the early 1990s and now have a significant commercial market share for powering portable electronics [1, 11]. Li-ion batteries typically use a carbon anode and a lithiated metal oxide cathode, along with an organic liquid electrolyte [13]. There

---

[10] TRL estimate based on information provided by the following sources: [5, 17]

are a number of different cathode materials used in commercial products, with the most common including lithium cobalt oxide, lithium manganese oxide and lithium nickel cobalt oxide [11].

Li-ion batteries have a significant number of advantages over older rechargeable batteries. They have much higher specific energy (100 – 240Wh/kg [13]) and energy density, which means they can provide power to a soldier's electronic devices for much longer periods of time compared with batteries of equivalent weight and volume. It also means that they do not have to be recharged as regularly as other secondary batteries. Other benefits of Li-ion batteries include good cycle life, low self-discharge rates, long shelf life, a wide operating temperature range (-20°C to +60°C [13]), no memory effects and they have higher nominal voltages [11]. Li-ion batteries are able to be produced with very thin form factors [13], meaning they could be miniaturised and tailored to an optimal design for soldiers.

Although Li-ion batteries are improved in several areas, they exhibit some weaknesses that have restricted their application in dismounted soldier power systems, with safety being the main issue. Severe impact, such as bullet penetration or crushing the battery, may lead to venting and thermal runaway[11] [11]. Improper use of Li-ion batteries, such as over-charging, over-discharging and operating above the maximum operating temperature, can also cause thermal runaway [11]. More exaggerated effects from damaging Li-ion batteries may include intense burning or explosion. This is a significant safety risk to soldiers who may be carrying many of these batteries. Li-ion batteries also require additional protective circuitry to prevent improper use since the batteries themselves do not incorporate any chemical mechanisms to manage over-charge or over-discharge, unlike Ni-Cd and Ni-MH batteries [11]. Otherwise permanent capacity loss or rapid performance drops may result [11]. In terms of cost, Li-ion batteries are more expensive to produce than other secondary batteries [13].

Li-ion batteries are highly relevant to soldier power in the near future since they are the most developed high energy secondary batteries (TRL 9 [1]) [25]. Many different Li-ion varieties are in development, which aim to improve the performance of the battery. Similarly, there is a large focus on addressing the problems of Li-ion batteries, in particular their safety, through developing new electrode materials and non-flammable electrolytes, such as ionic liquid electrolytes (see Section 3.3.1.4.1) [17]. Examples of Li-ion battery technology development are the lithium iron phosphate ($LiFePO_4$) battery (see Section 3.3.1.4.2) and the lithium titanate (LTO) battery (see Section 3.3.1.4.3). These technologies aim to specifically improve the battery's safety with alternative electrode materials.

###### 3.3.1.4.1 Ionic Liquid Electrolytes

A recent development to improve the safety and stability of Li-ion batteries (along with other primary and secondary lithium-based batteries) is the use of ionic liquid electrolytes as opposed to organic solvents, which are usually used in lithium-based batteries. These organic solvent electrolytes have low thermal stabilities and high vapour pressures, which pose an explosive risk [26]. This is a significant safety issue for soldiers.

---

[11] Thermal runaway refers to a process where an increase in temperature causes further increase in temperature until fire occurs.

Ionic liquid electrolytes have negligible vapour pressures and a corresponding reduced explosive risk [26, 27]. They also have good electro-chemical stability, high thermal decomposition temperatures and are more stable towards lithium metal [26, 27]. The result is improved battery safety, which makes lithium-based batteries with ionic liquid electrolytes highly relevant for soldier power applications. However, ionic liquid electrolytes require further development, such as improving ionic conductivity at low temperatures [27]. Ionic liquid electrolytes are used in the battery for the Flexible Integrated Energy Device (see Section 3.6.2), being developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [26].

#### 3.3.1.4.2 Lithium Iron Phosphate ($LiFePO_4$) Batteries

Lithium iron phosphate batteries have been developed to address the safety issues associated with other Li-ion chemistries. They use an alternative cathode material, namely lithium iron phosphate [12].

$LiFePO_4$ batteries have a number of advantages compared to other Li-ion batteries. The main advantage is that they are inherently safer since the lithium iron phosphate cathode is significantly more stable than other cathode materials used in Li-ion batteries (see Section 3.3.1.4) [28]. Since $LiFePO_4$ batteries don't use rare metals, such as cobalt, their cost is reduced compared to other Li-ion batteries and they are more environmentally friendly [12, 29]. $LiFePO_4$ batteries also have the potential for fast charge capabilities [30], but they have a lower nominal voltage than other Li-ion batteries, which results in slightly lower specific energy (85 – 120Wh/kg [31]), although it is higher than lead acid, Ni-Cd and Ni-MH batteries [32].

Small form factor $LiFePO_4$ batteries have significant potential for dismounted soldier power provision (TRL 6-8[12]). They are already being used in power tools [34], due to their improved safety and robustness, which also makes them attractive for military applications.

#### 3.3.1.4.3 Lithium Titanate (LTO) Batteries

Lithium titanate batteries are a type of Li-ion battery being developed with improved safety and the ability to be rapidly recharged (TRL 6-7[13]). These batteries use a lithium titanate anode instead of carbon, and a manganese-based cathode [35].

Lithium titanate batteries have several advantages compared to other Li-ion batteries. This includes significantly improved cycle life (in the order of 5000 cycles) and improved safety [33]. In addition, they can be rapidly recharged (in approximately ten minutes) [33] and they have high specific power [36]. However, LTO batteries have a lower nominal voltage, hence lower specific energy (60 – 70Wh/kg [33]), than other Li-ion batteries [36].

---

[12] TRL estimate based on information provided by the following sources: [17, 29, 33]

[13] TRL estimate based on information provided by the following sources: [21, 33, 35]

A number of companies are developing lithium titanate batteries, including Altairnano and Toshiba [37, 38]. The high power and low energy characteristics of these batteries suggest that they are suited to applications requiring high power.

### *3.3.1.5 Lithium Polymer (Li-poly) Batteries*

Lithium polymer batteries are a derivative technology of Li-ion batteries. They have similar electrochemistry, but they use a polymeric electrolyte instead of a liquid electrolyte [8]. The electrolyte may be a dry solid polymer electrolyte (SPE), a gelled or plasticised polymer electrolyte or a composite polymer electrolyte [39, 40]. Although the concept for these batteries was formulated in the 1970s, they have only recently reached commercial markets [1].

Li-poly batteries have several unique advantages that make them a worthwhile consideration for dismounted soldier power systems in the future. The main advantage is that Li-poly batteries can be produced in a thin, high-aspect ratio form factor, whilst maintaining comparable performance to Li-ion batteries, which makes them well suited to compact portable communications and computing devices [11]. Li-poly batteries also have a greater ability to sustain physical and electrical abuse than Li-ion batteries [11]. This includes shock, vibration, impact, over-discharge, over-charge, high altitude and high temperature operation [11]. Certain types of Li-poly batteries are able to sustain nail penetration without explosion or fire, whilst in a fully charged or over-charged state [11]. Other advantages of Li-poly batteries include low self-discharge rate and long shelf life [11].

A particular advantage of SPE-based Li-poly batteries is that they do not use volatile organic solvents in their electrolyte [41], which improves battery safety. However, these batteries suffer from low ionic conductivity of their electrolyte at ambient temperatures [41]. This prevents SPE-based Li-poly batteries from operating efficiently unless operated at elevated temperatures. In particular, they have poor high rate capabilities [11]. Work is being undertaken to improve the ionic conductivity of solid polymer electrolytes at room temperature towards that of liquid electrolytes used in Li-ion batteries [39, 41]. Other types of polymer electrolytes are gelled or plasticised by adding organic liquid solvents to improve the ionic conductivity of the electrolyte [11]. However, these electrolytes are more reactive with the lithium anode in Li-poly batteries [11, 39], which reduces battery safety. Composite polymer electrolytes incorporate a small amount of ceramic filler particles into an SPE electrolyte and are being developed to provide increased ionic conductivity of the electrolyte, whilst maintaining good battery safety [39, 40]. Other disadvantages of Li-poly batteries are their decreased cycle lives compared to Li-ion batteries and slightly lower energy density [11].

Li-poly batteries are common in several commercial electronic devices, such as mobile phones and personal digital assistants [11]. The ability to produce Li-poly batteries with thin form factors is particularly relevant for dismounted soldier application since they could potentially be tailored to an optimal wearable design for soldiers (TRL 8[14]). Their ability to sustain abuse also suggests they could be well suited to the battlefield environment.

---

[14] TRL estimate based on information provided by the following sources: [1, 11, 21]

#### *3.3.1.6 Lithium Sulphur (Li-S) Batteries*

The lithium sulphur battery is yet another lithium-based secondary battery technology currently being developed (TRL 6[15]). Li-S batteries are likely to present several benefits over Li-ion batteries, including less weight, improved specific energies (up to 600Wh/kg [18, 43]) and lower costs by using an inexpensive sulphur cathode.

A major problem with Li-S batteries is that they currently suffer from short cycle lives. In the past, the use of sulphur as a cathode material resulted in rapid capacity drops after several cycles [44]. Improving this characteristic, which includes investigating alternative electrolytes [1], is a large focus on ongoing research into this technology.

A number of companies are developing Li-S secondary battery technology, including Sion Power and Polyplus [18]. Recently, Sion Power's Li-S battery was used in the Zephyr, an Unmanned Aerial Vehicle (UAV) developed by QinetiQ, which broke the world record for the longest duration unmanned flight [42]. The 350Wh/kg Li-S batteries were combined with solar panels to achieve continuous day and night operation with weight minimisation of the system a critical factor [42]. The high energy capabilities of Li-S batteries suggests they are very promising for military applications in the future [45], including dismounted soldier power provision.

### 3.3.2 Secondary Battery Summary

A number of different battery chemistries have been discussed in Section 3.3.1, which are summarised in Table 2. The values shown for specific energy and energy density correspond to favourable discharge conditions and it should be noted that the performance of these batteries is highly dependant on the specific conditions of use[16] [11]. Specific power data shown is a relative figure for the different secondary battery chemistries and the cycle life of secondary batteries is dependant on their depth of discharge. Data in Table 2 has been adapted from the following sources: [1, 11, 13, 31, 33, 37, 38, 46, 47, 48].

*Table 2 Summary of secondary battery characteristics*

| Chemistry | Nominal Voltage (V) | Specific Energy (Wh/kg) | Energy Density (Wh/L) | Specific Power (W/kg) | Operating Temperature Range (°C) | Cycle Life |
|---|---|---|---|---|---|---|
| Pb-Acid | 2.0 | 30 | 90 | High | -40 to +60 | 250 – 500 |
| Ni-Cd | 1.2 | 35 | 100 | Medium/High | -40 to +45 | 300 – 700 |
| Ni-MH | 1.2 | 60 – 80 | 200 – 270 | Medium/High | -30 to +65 | 800 – 1200 |
| Li-ion | 3.6 | 100 – 240 | 230 - 630 | Medium | -30 to +60 | 800 – 1200 |
| Li-$FePO_4$ | 3.3 | 85 – 120 | 220 – 290 | Medium/High | -40 to +55 | 1000 – 3000 |
| LTO | 2.4 | 60 – 70 | 65 - 90 | Very High | -40 to +55 | > 5000 |
| Li-Poly | 3.6 | 100 - 150 | 130 - 300 | Medium | -20 to +60 | 600 - 800 |
| Li-S | 2.15 | 350 | 320 | High | -20 to +45 | 300 - 650 |

---

[15] TRL estimate based on information provided by the following sources: [42]

[16] The standard rate at which battery capacity is quoted is the capacity of the battery corresponding to a five hour discharge. It is assumed that the specific energy and energy density figures correspond to discharging the battery at this rate (or a similar rate where a range is shown).

Approximate specific power and specific energy objectives for dismounted soldier power systems are presented in Section 2. From Table 2 it can be seen that only high energy Li-ion batteries or Li-S batteries may be capable of meeting specific energy objectives for 12 hour missions. However, no secondary battery currently has sufficient energy for single day missions without being recharged or soldiers carrying battery spares. The specific energy figures indicate that most mature secondary battery technologies are likely to require recharging within eight hours or less.

### 3.3.3 Future Direction

Secondary batteries are an attractive technology for dismounted soldier power provision in the future. Unlike primary batteries, they can be recharged. This is likely to present reduced logistics and resource costs. Secondary batteries are already used in a number of military applications, and their advantages over primary batteries suggest that they will eventually become the prevalent battery type for dismounted soldier power provision.

Further implementation of secondary batteries for soldier power provision is likely to depend on improvements in battery specific energy, energy density and safety. Another important factor is the development of supporting infrastructure to enable regular charging in an efficient and simple manner on the battlefield. Otherwise, secondary batteries may present similar weight issues to primary batteries, especially on extended missions, if many battery spares and charging devices have to be carried.

There is a large focus on the development of lithium-based secondary batteries due to their superior performance compared to older types of secondary batteries, namely Ni-Cd and Ni-MH batteries. A key issue for lithium-based secondary batteries is their safety, which must be addressed before they are accepted for widespread use in dismounted power systems.

Li-ion batteries are already used by soldiers (mainly for training) [12], but they are being developed further to improve their safety and performance. Examples are $LiFePO_4$ batteries and LTO batteries, which are safer, but require further development to improve their specific energy [33]. Li-poly batteries are also relevant to future soldier power systems as they can be designed with very thin form factors [11], enabling easier integration onto soldiers. Another secondary battery of interest is the Li-S battery, which could provide improved specific energy and may eventually replace Li-ion batteries. However, Li-S batteries are not yet mature.

## 3.4 Supercapacitors

A capacitor is an electrical device used to store electric energy by the separation of charge, consisting of two electrodes (conductors) separated by a vacuum or an insulating dielectric material [49]. The major performance difference between a capacitor and most batteries is the amount of power and energy they can provide and they rate at which they can be charged. Capacitors are able to provide higher power than batteries at an instant in time, but they provide less energy over a period of time [49], whilst they are capable of being charged much quicker than batteries.

A recent development in capacitor technology is the supercapacitor (or ultracapacitor). It is similar to an electrolytic capacitor except its dielectric material contains activated carbon. This distinction enables supercapacitors to store one to two orders of magnitude more energy [1] due to the increased dielectric surface area of the porous activated carbon. With their ability to provide high power output and more energy than capacitors, they are a bridge between batteries and capacitors [49]. The main advantages of supercapacitors are summarised in the following points.

- High specific power – Supercapacitors can be charged and discharged at high rates since they experience no internal chemical change [49]. Compared to batteries, supercapacitors have much higher specific power [49] and they can more easily handle peak power requirements.
- Long cycle life – There are no chemical or structural changes to supercapacitor electrodes during cycling, hence there is minimal degradation of the electrodes over time or between cycles [1]. Therefore, supercapacitors have much longer cycle lives than secondary batteries. Burke suggests that some supercapacitors can be deep-cycled at high rates for 500,000 to 1,000,000 cycles with relatively small degradation in capacitance and resistance [50].
- High cycle efficiency – Supercapacitors operate with very high cycle efficiencies, up to 95% [50]. This reduces the amount of energy that is wasted during power provision.
- Safe and environmentally friendly – Unlike a number of battery technologies, supercapacitors do not use corrosive electrolytes, toxic chemicals or heavy metals that could potentially make operation, charging or disposal hazardous [51]. This makes supercapacitors safer to use than many batteries for soldier power provision.

Supercapacitors also have several disadvantages, which are outlined below.

- Low specific energy – Supercapacitors have lower specific energy than batteries [1]. This means that they are not suited to providing power for long periods of time and suggests they are unable to be used as the sole power source in a soldier power system.
- High self-discharge rates – The self-discharge rate of supercapacitors is much higher than batteries [1], which means they cannot store energy for long periods of time. Although they may self-discharge more quickly than batteries, supercapacitors retain their capacitance after self-discharging and can be recharged to their original condition [50].
- Voltage variation – Supercapacitor voltage varies with the amount of energy stored, with energy a function of capacitance and voltage squared [49]. Therefore, voltage decreases more quickly as the supercapacitor is discharged. This may dictate the use of some form of electronic control and switching equipment to effectively store and recover energy. Such equipment will introduce losses and is a significant detraction to using this technology. However, it does provide good intrinsic state of charge indication [1]. Voltage variation is also an issue with primary and secondary batteries, albeit to a much lesser extent [52].

- Low voltage – Supercapacitors have lower voltages than batteries and hence they need to be connected in series to achieve higher voltages needed to power military equipment, which may require voltage balancing [51].

### 3.4.1 Future Direction

The low energy capabilities of supercapacitors are likely to restrict their use as a sole power source for soldier power provision in the future. Instead, supercapacitors may be used in soldier power systems as a supplementary power source to provide high power to meet peak power requirements. In this case, the supercapacitor would ensure the power requirements of the system are achieved, allowing higher specific energy sources to be used, increasing the overall energy available. Refer to Section 4.5 for further discussion on hybrid power systems. An example of ongoing supercapacitor development is a program being conducted by Defence Research and Development Canada (DRDC) Atlantic to develop new high performance electrode materials, which aims to improve supercapacitor specific power and specific energy [49]. However, such improvements will not bring supercapacitor energy performance to the level of batteries.

## 3.5 Fuel Cells

A fuel cell is an electrochemical device used to convert chemical potential energy into electrical energy. It consists of an electrolyte sandwiched by two electrodes, an anode and cathode [11], with reactants flowing into each electrode. The electrolyte, which often defines the specific type of fuel cell, provides a passage for ions between the electrodes [11]. The reactants are a fuel on the anode side and an oxidant on the cathode side [11]. Hydrogen and oxygen are a common fuel and oxidant, although others may be used. In some cases, a fuel processor is required to convert the fuel into a suitable form (e.g. hydrogen) prior to it entering the fuel cell [6].

In simple fuel cells, the following reaction process[17] occurs [11]: the fuel is oxidised at the anode, producing protons and electrons; the electrons cannot pass through the electrolyte and instead pass through an external circuit to produce electricity. The protons pass through the electrolyte and recombine with the electrons and the oxidant at the cathode. The only by-products from a fuel cell are heat, water and in some designs, carbon dioxide [1]. In practice, individual fuel cells are combined in series and/or parallel circuits to form a fuel cell stack [6] to produce a desired amount of power, based on voltage or current requirements.

Most batteries form a closed thermodynamic system since they store electrical energy chemically, but fuel cells consume their reactants from an external source so these reactants must be replenished. The reactants flow into a cell and the reaction products flow out, whilst

---

[17] Proton exchange membrane fuel cells (PEMFC) and direct methanol fuel cells (DMFC) follow this reaction process, while solid oxide fuel cells (SOFC) have a slightly different reaction process [1]. In SOFCs, the fuel is oxidised at the anode to produce water, carbon dioxide and electrons. The electrons pass through an external circuit and are used in the reduction of oxygen at the cathode to produce oxygen ions. These ions pass through the electrolyte and are used in the oxidation of fuel at the anode.

the electrolyte remains in the cells. Continuous operation of a fuel cell is possible if these flows are maintained. The efficiency of a fuel cell is defined as the electrical energy produced compared with the heat that would be produced if the fuel used by the fuel cell was burned (sometimes known as the calorific value) [53]. Fuel cell efficiency can be defined in terms of a lower heating value (LHV) or a higher heating value (HHV)[18]. Efficiencies described in terms of LHV are more commonly used.

As previously mentioned, many fuel cell types employ hydrogen as a fuel. There are a number of alternative fuels, but hydrogen gas has the highest specific energy [1]. Conversely, it has the lowest energy density[19], but this can be improved depending on storage method [1]. Alternative hydrogen sources are attractive for fuel cells due to concerns associated with the safety of hydrogen gas storage and transportation [54]. These sources include various hydrocarbons, alcohols or other hydrogen-based chemicals [53]. Diesel and JP-8[20] are particularly attractive fuels as they are mandated in the current Australian Defence Force (ADF) Battlefield Fuel Policy for Land Based Equipment [56]. However, for most fuel cells, fuel from an alternative hydrogen source will require reformation to produce hydrogen. This is likely to decrease the effective energy content of the fuel and add significant size and weight to the fuel cell system. Whether hydrogen or an alternative fuel is used, care must be taken to ensure the fuel is free from impurities, such as carbon monoxide or sulphur-containing compounds, to prevent fuel cell "poisoning". Fuel cell poisoning is caused by impurities in the fuel reacting with anode catalysts, significantly reducing the performance of the fuel cell [57]. Further discussion on fuel issues is included in Section 3.5.2.

In terms of fuel cell oxidants, pure oxygen can be stored and used, but air breathing systems are simpler and they remove the need to carry an oxidant [18]. This reduces the fuel cell system weight, but air breathing systems are susceptible to contaminants and altitude. Hence, some problems may be faced if air breathing systems are used in a battlefield situation.

The underlying principles of fuel cells have been known for over one hundred years [58], but fuel cells have only recently become relevant for providing power in military applications as the technology has become more mature [1]. There are a several specific fuel cell technologies relevant to dismounted soldier power systems, with a large variation in characteristics and performance between each of these technologies. The most relevant of these are discussed in later sections. Fuel cells remain an emerging technology for dismounted soldier power provision, but they are becoming more attractive as a power source as soldier energy demands increase and weight issues become more severe. There are several key advantages of fuel cells that make them a realistic contender to provide power to future dismounted soldiers. These are discussed below.

---

[18] The HHV refers to the energy required to burn the fuel and subsequently bring all products of the burning process back to their original temperature. The LHV refers only to the energy required to burn the fuel.

[19] Refer to Section 2 for definitions of specific energy and energy density.

[20] JP-8, or Jet Propellant 8, is a kerosene-based aviation turbine fuel. It is used by the US Army as a replacement for diesel fuel in the engines of military vehicles [55].

- High specific energy and energy density – Fuel cells are capable of using fuels directly, resulting in much higher specific energy and energy density than batteries. Hence, they can store much more energy per unit mass and volume and are capable of much longer run-times (if the necessary inflows are maintained). This makes fuel cells more suitable than batteries for longer missions [45]. The only significant limitation to the specific energy of fuel cells is the mass of fuel storage and conversion devices.
- Lightweight – Fuel cell systems are particularly advantageous compared to batteries in terms of weight. Research has shown [59] that for longer missions, where the required energy is above a certain threshold, fuel cells are significantly lighter than using batteries. Primary battery weight scales linearly for a required increase in energy, whereas only additional fuel (and a corresponding storage container) is required to increase the energy capacity of a fuel cell system.
- High efficiencies – Fuel cells are generally more efficient than conventional energy conversion systems [53], with conversion efficiencies up to 70% (relative to LHV) for some fuel cell technologies [6]. This results in greater utilisation of the fuel and reduces the amount of energy wasted. The operation of fuel cells at their rated power output is important to maximise operating efficiency since their efficiency approaches zero as their power output is decreased [1].
- Low emissions – The most common by-product from a fuel cell is water. While some fuel cells produce carbon dioxide, they produce fewer harmful emissions than other energy converting technologies, such as small combustion engines.
- Quick refuelling – Fuel cell systems can be designed with fuel cartridges that facilitate quick and easy replacement. Their potential as an instantly "rechargeable" energy source has caused strong military interest [1].
- Water by-product – One of the main by-products of fuel cells is water, which is often a scarce commodity in the battlefield [1], and hence the production of water from fuel cells may be valuable to dismounted soldiers. However, proper treatment methods would be needed to ensure it is safe to use and consume.

As previously mentioned, fuel cells are an emerging technology, and several disadvantages with this technology still exist. These issues are being addressed, but they currently limit the potential of fuel cells for providing power to dismounted soldiers. They are discussed below in the following points.

- High cost – The high cost of fuel cells is a significant disadvantage. Costs will remain high unless widespread commercialisation or implementation of fuel cells is achieved. The use of expensive components, such as platinum catalysts contributes to the high cost of fuel cells [11].
- Fuel storage and supply issues – The use of technologies requiring new fuels to be introduced to the battlefield, such as hydrogen or methanol, presents a number of storage and supply issues. In particular, hydrogen storage is inefficient and would be difficult to support in a battlefield environment if high pressures or low temperatures are needed. The use of these fuels poses safety risks to soldiers in combat and during fuel transportation. The introduction of new fuels also requires additional

infrastructure to support their distribution, which is likely to be costly and complex. These issues are further discussed in Section 3.5.2 and Section 5.

- Thermal signature – Some fuel cell technologies operate at very high temperatures, which could make soldiers easily identifiable on the battlefield (through IR sensors) and is undesirable if undertaking stealth operations.
- Environmental sensitivity – Fuel cells are susceptible to contaminants in their inflows, such as sulphur-containing compounds in the fuel, which may affect performance since many electrode catalysts are very sensitive to contamination [53]. This particularly affects those cells that require continuous airflow. Altitude and liquid immersion issues with fuel cells remain pertinent since they require certain temperatures and pressures to remain efficient. Immersion in liquids could cause blockages and contamination that significantly impacts performance.
- Poor energy readiness – Some specific fuel cell technologies have long start-up and shut-down times due to operation at very high temperatures [6]. To reach these high operating temperatures requires a slow and uniform heating process [1] to minimise the risk of thermal expansion[21]. Lower temperature fuel cells also require time to heat to their operating temperature.
- Slow dynamic response – Fuel cells have a slow response to changing energy needs; hence they are not suited to providing high power in short bursts. Rapid increases in the required output power from a fuel cell are likely to cause a significant drop in output voltage, deteriorating power quality or causing the system to shut down [61]. This limits the application of fuel cells as the sole power source for dismounted soldiers.
- Complexity – Compared to batteries, where power is supply is relatively simple, fuel cells do have some complexities, which for some technologies includes fuel reformation, water management, contaminant control and temperature management.
- Safety concerns – The use of alternative fuels on the battlefield, such as hydrogen or methanol, presents several safety concerns. Methanol is highly flammable and toxic, while hydrogen is highly volatile and flammable [53]. Methods to minimise these safety risks are necessary before these alternative fuels are ready to be used on the battlefield.

### 3.5.1 Fuel Cell Technologies

An overview of the fuel cell technologies of interest for dismounted soldiers in portable applications is presented in the following sections. Note that there are a number of other fuel cell types that are not discussed here since they were not considered relevant for soldier power applications.

---

[21] Ceramic components used in SOFCs are particularly susceptible to stress induced by thermal expansion [60].

#### *3.5.1.1 Proton Exchange Membrane Fuel Cells (PEMFC)*

The proton exchange membrane fuel cell is one of the simplest forms of fuel cell. It has a solid polymer membrane as the electrolyte, uses hydrogen (directly or reformed) as the fuel and oxygen, typically sourced from air, as the oxidant [1]. For reliable operation, it is necessary to saturate the electrolyte with water, which requires careful control, and allows the flow of protons through the electrolyte [6].

PEMFC operating efficiencies are in the order of 50 to 60% (relative to LHV) [6] with typical system outputs ranging from less than a kilowatt up to 250 kilowatts [62]. Since cells are stacked in a module, this output could be scaled to a desired size for dismounted soldiers. PEMFCs operate between 60 and 80°C [1], and this relatively low operating temperature allows shorter start-up times compared to other fuel cells [62]. PEMFCs also have a high power density [1], making the fuel cell stack compact and lightweight. Note that the added requirements for fuel storage may diminish this advantage.

The use of a solid electrolyte in the PEMFC is advantageous since it simplifies sealing of the anode and cathode gases, reducing manufacturing costs, it is immune to orientation problems faced with liquid electrolytes and corrosion problems are reduced, resulting in longer cell lifetimes [63]. However, the need for water management in the PEMFC is a disadvantage, and as they require pure hydrogen to operate optimally, they are sensitive to any impurities in the reactant inflows. These impurities, such as carbon monoxide, are undesirable since they may poison the anode catalysts (often platinum), thus preventing hydrogen fuel from reaching the catalysts and significantly reducing the performance of the cell [53]. Carbon monoxide results from the fuel reformation process, but it can be converted to carbon dioxide using steam to reduce its concentration [53]. The use of hydrogen also presents several other issues, as discussed in Section 3.5 and Section 3.5.2.

PEMFCs are widely regarded as the most likely candidate for standard consumer fuel cell applications, in particular for vehicle applications as a replacement for internal combustion engines (ICE) [63]. They also have potential to be used for low power applications [6], which may include soldier power provision if their associated issues are addressed or appropriately managed. They are currently TRL 6-7 [1, 12].

#### *3.5.1.2 Direct Methanol Fuel Cells (DMFC)*

Direct methanol fuel cells are a subset of PEMFCs, with similar construction and characteristics. They use a polymer membrane as the electrolyte, oxygen as the oxidant and liquid methanol as the fuel [6]. The DMFC is designed so that the catalysts at the anode can directly draw hydrogen from the liquid methanol fuel, which does not require any reformation or complex storage systems [1]. Instead, the storage systems are simple and compact. However, the use of methanol as a fuel results in undesirable carbon dioxide emissions, since it is generated as a waste product in the methanol oxidation process at the anode. The use of methanol as a fuel is discussed further in Section 3.5.2.2.

DMFCs operate between 50 and 90°C with system outputs typically ranging from less than one watt up to one kilowatt [62]. Their lower operating temperatures and power outputs makes them well suited to small portable power applications, however, they have relatively low conversion efficiencies, in the order of 30 to 40% (relative to LHV) [1]. DMFCs also use expensive catalysts and they need to manage water in their electrolyte [1, 12], similar to PEMFCs.

Another disadvantage of DMFCs is methanol crossover. Methanol crossover is the leakage of fuel from anode to cathode, causing methanol to react with oxygen at the cathode and preventing electricity from being produced [1]. It occurs due to the high solubility of methanol in water, which is readily absorbed by the membrane electrolyte, but is overcome by modifying the electrolyte or limiting the concentration of methanol at the anode through dilution with water [53]. This ensures higher cell efficiency but reduces the specific energy of the fuel. It is likely that significant additional infrastructure will also be required to deliver methanol to the battlefield, since it is not part of the ADF's endorsed hierarchy of fuels for land materiel [56]. This may be a major limiting factor in implementing DMFCs for soldier power in the near future and is discussed further in Section 3.5.2.3.

Significant commercial development of DMFCs is being undertaken [64]. Several companies are also currently working on developing DMFC prototypes (TRL 6-7 [1, 12]) to be used by the military for powering electronic equipment in the field [54]. An example is the Jenny 600S DMFC [65, 66] from Smart Fuel Cell. It is used in conjunction with a power management device in a man-portable system that can be worn by a soldier to charge their batteries on-the-move without any interaction from the soldier. The system can charge up to seven battery cells (recommended type is lithium-ion) at once and weighs less than 3kg, which is a significant reduction opposed to numerous battery spares. The Jenny fuel cell can produce up to 600Wh/day (or 1.1 – 1.4kWh/kg of methanol). Another DMFC, the UltraCell XX55 fuel cell system is being developed as a battery charger for US soldiers in Afghanistan [67]. This system produces 50W continuously with specific energy of 108Wh/kg for a 250mL cartridge and 227Wh/kg for a 550mL cartridge [68].

#### *3.5.1.3 Solid Oxide Fuel Cells (SOFC)*

Solid oxide fuel cells are distinguished from other fuel cells through the use of a hard, non-porous ceramic compound of solid metal oxide as the electrolyte and operation at very high temperatures, in the order of 600 to 1000°C [62]. Another distinguishing factor is that oxygen ions are conducted by the electrolyte instead of protons (as in PEMFCs and DMFCs) [1]. Typical outputs from these fuel cells range from a few watts up to several megawatts for large-scale cells [69]. In the past, SOFCs have been designed for larger applications such as auxiliary power units or in large distributed generation systems, but recently they have become of interest to man-portable military and commercial applications with systems producing less than one kilowatt being developed [1].

A particular advantage of SOFCs is that they can use a wide variety of hydrocarbon fuels without requiring reformation due to their high operating temperature. This causes internal reforming of the fuel to hydrogen at the anode. The ability of SOFCs to operate on a variety of fuels is a major advantage over other types of fuel cells since SOFCs can use diesel or JP-8 for fuel. These fuels are already standard battlefield fuels used by the ADF [56] and their use avoids the logistical issues encountered when introducing a new fuel (such as hydrogen or methanol) to the battlefield. However, the use of JP-8 directly may reduce fuel cell performance as it can result in coke formation at the SOFC anode [1]. As with other fuel cells, oxygen, sourced from air, is used as the oxidant.

Since they operate at high temperatures, SOFCs are quite efficient, with energy conversion efficiencies of approximately 50 to 55% (relative to LHV) [6] and unlike other lower temperature fuel cells, they are insensitive to carbon monoxide poisoning, which can instead be used as a fuel [6, 53]. Other advantages include reduced electrolyte management problems (compared with PEMFCs and DMFCs) and a lack of corrosion problems due to the use of a solid electrolyte.

There are several drawbacks of SOFCs for use in portable power applications, which include long start up times to reach operating temperatures [1]. The ceramic components used in SOFCs are particularly susceptible to stress induced by thermal expansion [60]. A uniform and slow heating process minimises the risk of thermal expansion and thus SOFCs are ideally operated continuously. SOFCs also require robust materials to handle the high operating temperatures and to ensure correct sealing [69]. These high operating temperatures are also likely to pose both signature management and safety problems for soldiers carrying or wearing such devices.

Smaller SOFC systems are not as efficient as larger systems as they do not produce enough heat from their electrode reactions to maintain the heating temperature of the fuel cells [1], which necessitates the burning of fuel to keep the fuel cell stack hot. The potential application of SOFCs, in terms of dismounted soldier power, is likely to be as a dedicated charging unit rather than being incorporated in a wearable system. The TRL of SOFCs is currently 2-5[22].

Progress in SOFC development for military applications has been made by the Defence Advanced Research Projects Agency (DARPA), who have recently developed a SOFC-powered unmanned aircraft system (UAS). Their SOFC operates on propane and is combined with a lithium polymer battery in a hybrid system to increase mission endurance by more than four times compared to existing UASs powered only by batteries [70]. DARPA claim a notable achievement of this demonstration was the ruggedisation of the SOFC power source with the UAS subject to high wind gusts and high altitudes [70].

#### *3.5.1.4 Alkaline Fuel Cells (AFC)*

Alkaline fuel cells use an aqueous potassium hydroxide electrolyte soaked into a porous matrix and they require pure hydrogen as the fuel and pure oxygen as the oxidant [71]. Apart from electricity, the only outputs from these cells are potable water and heat. AFCs are a very well developed technology, having been used since the 1960s when they were used on the Apollo spacecraft [6]. They generally operate between 80 to 100°C and are one of the most efficient fuel cells with efficiencies between 50 and 70% (relative to LHV), depending on the operating temperature [6]. Operation at higher temperatures can be achieved for higher concentrations of potassium hydroxide.

---

[22] TRL estimate based on information provided by the following sources: [1, 12, 70]

Water management is simplified in this type of fuel cell since it is produced at the anode and consumed at the cathode and any remaining water will evaporate under operating conditions [6]. Another major benefit of AFCs is that they are very cheap to manufacture since they can use a number of inexpensive materials as catalysts due to the speed of the reactions at the electrodes [6, 53]. Pure fuel and oxidant are required to avoid carbon contamination in an AFC, which is a major disadvantage of this fuel cell since it is very sensitive to carbon dioxide in the fuel or air [71]. Carbon dioxide reacts with the electrolyte and significantly reduces the performance of the fuel cell. Consequently, the AFC needs to operate in closed conditions with no direct interaction with the external environment. This dictates that additional equipment is required to store the fuel and oxidant in a dismounted power system, or fuel reformation and air purification systems are required.

### 3.5.2 Fuels, Fuel Storage and Fuel Policy

The introduction of most fuel cell technologies is likely to require a concurrent introduction of a new fuel to the battlefield and supply chain. There are number of fuels that are of concern when considering the potential implementation of fuel cells, including hydrogen, methanol, diesel and JP-8. Many other fuels have been considered for fuel cells [53], but they are not discussed here. These fuels may be used directly or they may require reforming. Several issues must be addressed prior to the introduction of any new fuel onto the battlefield, in particular their storage and logistical requirements. Other issues that may arise include hazardous material requirements and legislative issues.

Decisions regarding the implementation of fuel cells for dismounted soldier power systems is likely to be determined to a large degree by logistics [12] rather than their performance and reliability alone, as many current fuel cell prototypes are fueled by non-standard fuels [1]. The implementation of these fuel cells will require expansion of the current logistics infrastructure to accommodate the storage and transportation requirements of the new fuel, as well as any additional processing and reformation requirements. This is likely to be very costly and complex, and would require changes to the ADF’s single fuel policy (see Section 3.5.2.3). The Army would need to determine whether these alternative, non-standard fuel sources are logistically acceptable by conducting a proper analysis of the trade-offs between any operational advantage gained by using fuel cells and the added logistics complexity and costs [1].

Pre-packaging fuels into cartridges may be an option to enhance the attractiveness of fuel cells by minimising the added logistical requirements. The pre-packaged fuel could be treated as a battery pack as long as appropriate safety and handling procedures are developed [1]. This would present similar logistics issues to primary batteries, albeit much less severe due to the significantly higher energy content of the pre-packaged fuel compared to a primary battery [1]. The following sections discuss the storage requirements and other issues with some of the alternative fuels used by fuel cells, while logistics is discussed further in Section 5.

#### *3.5.2.1 Hydrogen*

Hydrogen is attractive as a fuel for fuel cells due to its high specific energy, but it has very low energy density[23] and it is very difficult to liquefy, hence it has strict storage requirements [53]. The use of hydrogen as a fuel has a number of safety concerns. Hydrogen has a leak rate through orifices faster than all other gases, it is highly volatile and flammable and can detonate when mixed with air in certain circumstances [53]. Hence, safety considerations must feature prominently in hydrogen-based fuel cell systems.

There are a number of methods for storing hydrogen. They include storing hydrogen as a compressed gas, storing hydrogen as a liquid at cryogenic temperatures, storing hydrogen in metal hydrides, or absorbents, and generating hydrogen as the result of a chemical reaction from a reagent (or set of reagents). Storing hydrogen as a compressed gas in storage cylinders requires large and heavy tanks to ensure safe storage of high pressure hydrogen (tank and fuel makes up 70 – 80% of the system weight), but such systems still provide much better specific energy for longer missions than batteries [6].

Cryogenic hydrogen storage provides the most storage by mass of hydrogen and is being developed by some automobile manufacturers for fuel cell demonstrator vehicles [6]. However, no such system has been developed on a scale that is suitable for soldier power systems and, in any case, implementing and maintaining such a system on the battlefield would be very logistically complicated [6]. Larminie and Dicks [53] suggest this method is not suitable for small-scale applications.

Metal hydride storage of hydrogen uses certain metal alloys, inside a container, that react with hydrogen to form a metal hydride in an easily reversible reaction. This method is advantageous in terms of safety since hydrogen is not stored at high pressure [53], but the mass fraction of hydrogen stored is very low (less than 2% by weight), which has a significant impact of the specific energy of a fuel cell system using metal hydride storage of hydrogen [6]. It should also be noted that this method requires containers to be refilled from a local source of hydrogen [53], which could present logistical issues if hydrogen is transported to the battlefield as a compressed gas.

As mentioned above, gaseous hydrogen can be generated as the result of a chemical reaction. Theoretically, hydrogen generation systems have the potential to produce relatively high mass fractions of storable hydrogen, but a number of engineering issues for soldier-scale systems restrict the actual mass fraction of hydrogen that can be stored [6]. Therefore, they are unlikely to be used in future soldier power systems.

---

[23] Refer to Section 2 for definitions of specific energy and energy density.

An alternative method for hydrogen production is by reformation[24] of a liquid hydrocarbon fuel, such as methanol or diesel. Fuel reformation avoids the logistical issues and costs of transporting and carrying hydrogen in the battlefield. However, in addition to the fuel reformer, several other units are required to produce pure hydrogen suitable for feeding into the fuel cell anode as the initial reformate may contain a number of impurities that can damage the fuel cell catalysts [6]. Reformer efficiencies are as high as 80%, but small-scale versions are likely to be less efficient due to heat losses to the environment, with a micro-reformer developed by the Pacific Northwest National Laboratory (PNNL) approximately 50% efficient [6]. Although carrying a liquid hydrocarbon fuel is likely to be safer for soldiers than carrying hydrogen, the added weight and complexity of fuel reformation systems suggests that fuel cells with reformers may only be suitable to stationary applications on the battlefield.

#### *3.5.2.2 Methanol*

In fuel cell applications, methanol may be used directly by DMFCs or it may be reformed to hydrogen for use in PEMFCs. It is stored as a liquid in tanks, canisters or cartridges. Methanol avoids several of the storage problems faced when using hydrogen (since it does not require high pressures or very low temperatures), whilst still having quite high specific energy [53]. However, as discussed in Section 3.5.1.2, methanol concentration tends to be limited to avoid methanol crossover, so the effective specific energy may be slightly reduced. The use of methanol in portable electronics equipment raises some safety concerns since it is highly flammable and poisonous [53].

Methanol fuel cartridge design is important to ensure safety. Systems using methanol vapour should be avoided since the vapour can easily enter the body [53]. In addition, methanol mixes very easily with water and the resulting mixture is corrosive, which suggests ordinary materials, such as steel, should not be used for storage containers [53]. Methanol is also a good solvent, which means that not all plastics are suitable if storing methanol in a plastic container [53].

#### *3.5.2.3 ADF Fuel Policy*

Currently, JP-8, along with diesel form part of the hierarchy of fuels used by land-based equipment [56]. Developing a fuel cell that is capable of using these fuels is advantageous as it would require minimal additional infrastructure. The latest ADF Fuel Policy for Land Based Equipment mandates that all future ADF land materiel should be capable of running on a single battlefield fuel, JP-8, in accordance with NATO Standardisation Agreement (STANAG) 4362 [56]. This policy recognises that JP-8 may not be universally adopted, but land-based equipment should be capable of running on this single battlefield fuel. Hence, it may be

---

[24] The main methods of reformation for hydrogen production are steam reforming or partial oxidation [6]. Steam reforming uses a hydrocarbon fuel, steam and heat to produce hydrogen with carbon monoxide and carbon dioxide also produced as reaction products. Partial oxidation uses a hydrocarbon fuel, oxygen from air and heat to produce hydrogen along with carbon monoxide, carbon dioxide and water as reaction products. Another method of reformation is thermal cracking, where the hydrocarbon fuel is heated in the absence of air to decompose the hydrocarbon into hydrogen and solid carbon [53].

difficult to introduce fuel cells that operate on hydrogen or methanol as they are likely to violate this policy.

### 3.5.3 Future Direction

Fuel cells are an attractive technology for dismounted soldier power systems. They are capable of providing much more energy than batteries and offer significant weight savings on extended missions. However, fuel cells are an emerging technology and require further development before they are sufficiently mature for direct dismounted soldier power provision. This includes developing lighter, smaller and more efficient cells, improving fuel cell ruggedness, improving their dynamic response, improving methods for fuel storage and the development of systems to manage their interaction with the environment.

A number of fuel cell technologies require non-military standard fuels, such as hydrogen and methanol and use of these fuel cells will necessitate the introduction of new fuels to the battlefield. This is likely to require significant additional logistics support and expansion of the existing logistics infrastructure. Such requirements may restrict the implementation of certain fuel cell technologies. For those fuel cell technologies fueled by non-military standard fuels, the development of methods for safe and efficient storage of fuel, in particular for hydrogen, will also be important in realising fieldable fuel cells.

The ability of SOFCs to operate from standard military fuels is a key advantage of this technology because the logistics and storage issues associated with non-military standard fuels are avoided. However, small-scale PEMFCs and DMFCs appear to be more promising for future soldier power systems due to their lower operating temperatures enabling them to be worn or carried by soldiers. The high operating temperatures of SOFCs is likely to restrict them to stationary applications. For DMFCs, the issue of using and supporting methanol on the battlefield may be avoided by pre-packaging it into cartridges.

The slow dynamic response and long start-up times of some fuel cells may be addressed by coupling them with a battery or supercapacitor (see Section 4.5 for further information on hybrid power systems). This would ensure peak power requirements can be met and power is available during fuel cell start-up. Such a system could substantially reduce the weight of power sources carried by dismounted soldiers on extended missions. However, for missions with minimal energy requirements, batteries are likely to remain the preferred power source. It is predicted that small-scale fuel cells will be ready for use in soldier power systems within ten years [12].

## 3.6 Energy Harvesting Technologies

Energy harvesting is likely to play a significant role in the future of dismounted soldier power since it makes use of renewable energy to produce electricity. There is a range of energy harvesting technologies of interest for dismounted soldier power provision:

- photovoltaic cells that capture solar energy from the sun;

- kinetic energy harvesting devices that use motion to produce electricity; and
- thermal energy harvesting devices that convert heat to usable energy.

The use of such technologies could greatly reduce the amount of energy needed to be carried by soldiers into the battlefield if lightweight harvesting devices are developed since energy could be generated in the field. This would reduce costs, reduce the weight of a soldier's load and improve operational endurance.

The main restriction of energy harvesting is the amount of usable energy that can be produced. Therefore, it is unlikely that energy harvesting technologies will be used as the main source of power for dismounted soldiers, but instead may be used to supplement or charge other power sources, such as secondary batteries. The use of energy harvesting devices as a main power source would most likely require backup batteries in any case, to account for periods of low or intermittent harvesting opportunities. Some form of power management (see Section 4.4) may also be required to control charging of the other power sources and to ensure a consistent power supply.

Assuming sufficient energy is produced, energy harvesting devices offer significant weight savings on longer duration missions since they reduce the requirement to carry as many battery spares. However, carrying harvesting equipment will be an additional burden and in some cases soldiers will be required to perform additional work to produce energy, particularly for kinetic and thermal energy harvesting. Efficient system designs will be necessary to realise weight savings and reduce the burden on soldiers to acceptable levels.

The emergence of harvesting technologies is one of the key drivers for the reduction in power demand of electronic devices used by soldiers, since the energy provided by harvesting is renewable, but the maximum power output is likely to be limited. As mentioned, energy harvesting technologies have several distinct advantages over other forms of power sources in the scope of dismounted soldier power provision. They are outlined in the following points.

- Renewable energy – The major benefit of energy harvesting is that the energy used to power a soldier's electrical equipment is renewable[25] and can be replenished on the battlefield. This has considerable benefits for soldiers on longer missions, where their capability can be increased by boosting their energy production capacity with harvesting technologies.
- Improved supply logistics – The logistical requirements associated with supplying energy harvesting devices to soldiers are reduced compared to technologies such as primary batteries, which have much shorter lifetimes for single units and require regular replacement.
- Improved safety – The materials used in energy harvesting devices do not present the safety issues encountered with other technologies such as lithium-based batteries or

---

[25] Note that kinetic energy harvesting depends on soldier movement and thermal energy harvesting depends on temperature gradients. Therefore, energy from these technologies is only available in certain situations or under certain conditions and may impose a burden on soldiers if they are required to do additional work to produce energy.

fuel cells, which contain highly reactive substances that pose severe safety risks to soldiers.

With the advantages of energy harvesting in mind, there remain a number of disadvantages with these technologies that must be addressed. These are discussed below.

- Low conversion efficiencies – This restricts the amount of usable energy able to be produced by energy harvesting technologies.
- Low power output – Compared with other technologies, energy harvesting provides relatively low power output [1]. This may restrict the amount of devices that can be supplied with power at one time or it may necessitate the use of a complimentary power source to meet this shortfall.
- Variable and intermittent power output – Since energy harvesting technologies rely on resources such as the sun or human movement, to produce electricity, they cannot provide power consistently, which may lead to situations where power is unavailable. For example, soldiers are unlikely to be as active when fatigued, which reduces their capacity to produce electricity through kinetic energy harvesting. This may present significant issues for soldiers, when they require consistent power for their electronic devices over long durations. Hence, energy harvesting devices are likely to be combined with other power sources to ensure power is always available.
- Increased maintenance – Ongoing maintenance is necessary for in-service energy harvesting devices to ensure they maintain high levels of performance. This is likely to be costly and will create additional logistics requirements.

### 3.6.1 Photovoltaics

Photovoltaic technologies harness solar energy from the sun and convert it into electricity. Photovoltaic, or solar, cells use light absorbing materials[26] to produce this electricity. Solar cells are particularly relevant to dismounted soldiers because they offer a lightweight solution for providing power from a renewable energy source [72]. Further benefits to soldiers include reduced supply logistics since solar cells do not require refuelling or regular replacement and solar cells have no acoustic signature or moving parts [72].

In the past, solar cells have been used by military in stand-alone applications to power devices such as remote sensors. However, several shortfalls have restricted their implementation in other areas. The main issue with photovoltaic technologies is their limited conversion efficiencies [18]. This results in relatively low power output and requires solar cells to have a large surface area to produce a sufficient amount of power. Additionally, they need direct sunlight to operate at maximum efficiency [59] and they are expensive and energy-intensive to manufacture [73]. Another major issue with solar cells is that they cannot be used at night and hence can only provide power for a limited number of hours per day [59]. This issue suggests that solar cells are only applicable for day-time applications where they would most likely be

---

[26] The light absorbing material in photovoltaic cells is traditionally silicon, although newer technologies may make use of certain types of dyes or polymers.

used as a battery charger or as a supplementary power source. Thermal detection is also an issue since all types of solar cells have high infra-red signatures.

New developments in photovoltaic technology have evolved the traditional rigid solar panel into thin, lightweight, flexible forms. Thin-film solar cells have less light absorbing material than traditional crystalline silicon cells, which makes them cheaper and easier to manufacture and, as previously mentioned, lightweight and flexible. However, they tend to have lower conversion efficiencies, in the order of 10 to 20% [74]. The main thin-film photovoltaic technologies of interest are discussed in the following sections.

#### *3.6.1.1 Elongate Solar Cells*

Elongate solar cells, or Sliver cells, are an Australian technology developed by the Australian National University (ANU) and commercialised by Origin Energy [75]. They have efficiency improvements over other thin film technologies, in the order of 18 to 20% [75] compared to approximately 10%, and are less expensive to produce [76]. As with other thin film technologies, they are lightweight and flexible.

Elongate solar cells are constructed with single crystal silicon wafers approximately 1mm thick. Slivers are cut from these wafers and processed using standard techniques to produce a solar cell. The key difference between elongate solar cells and other thin film solar cells, in terms of cell processing, is that elongate cells are formed in the wafer volume (with the slivers mounted on their sides) whereas conventionally, only the wafer surface is used [76]. This produces a substantial increase in the active surface area of the solar cell.

Unique advantages of elongate solar cells are that they are perfectly bifacial[27], they perform well in low-light conditions and in shade and they are semi-transparent. This could enable visual camouflaging of the cells. Since they are small and easily integratable, elongate solar cells have potential for power provision to dismounted soldiers in the future. Work is currently ongoing to further develop this technology for military applications through a Capability Technology Demonstrator (CTD) agreement between ANU and the Defence Science and Technology Organisation (DSTO) [77].

#### *3.6.1.2 Dye-sensitised Solar Cells*

The dye-sensitised solar cell, also known as a Graetzel cell, is a photo-electrochemical cell that is differentiated from other solar cells because it separates the two functions provided by silicon in traditional solar cells[28] [78]. The dye-sensitised solar cell typically consists of a transparent conductive glass anode, a layer of porous titanium dioxide nanoparticles coated with a photosensitive dye, an iodide electrolyte and a platinum-based or graphite-based cathode [78, 79]. The photosensitive dye absorbs light and produces electrons, while the titanium dioxide semiconductor is used to transport electrons.

---

[27] Bifacial solar cells are double-sided and use light reflected onto the rear surface of the solar cell to generate additional power per cell.

[28] In traditional solar cells, silicon is used as the source of electrons and for transporting electrons.

Dye-sensitised solar cells perform well in low-light conditions, they can be multicoloured, enabling visual camouflaging, and they are cheap to process [72]. However, issues relating to low overall conversion efficiencies (10% compared to 20 – 30% for silicon solar cells [80]) may affect the viability of these cells to provide a useful amount of energy for soldier power provision. Another disadvantage of dye-sensitised solar cells is their chemical stability of their electrolyte [80], with sealing problems experienced at high temperatures. Dye-sensitised solar cells are produced commercially by a number of companies including Konarka [80].

#### *3.6.1.3 Polymer Solar Cells*

Polymer solar cells use semiconducting polymers instead of silicon as the active component in the process of converting solar energy to electricity [81]. Advantages of this technology are that they are lightweight, flexible and simple and cheap to manufacture. As with several other thin-film technologies, polymer solar cells suffer from relatively low efficiencies, in the order of 4 to 5% [81], which may restrict their application in dismounted soldier power systems, while they also have shortened lifetimes due to environmental degradation. However, this could allow these cells to potentially be used in disposable systems.

#### *3.6.1.4 Nanocrystal Solar Cells*

Nanocrystal solar cells, also known as quantum dot solar cells, use silicon nanocrystals[29] to form solar cells with the potential for very high efficiencies [83]. Unlike other photovoltaic technologies, these cells are able to free more than one electron when a single photon of light is absorbed [83]. Due to their small size, the nanoscale crystals used in this technology are able to capture certain wavelengths of light that are wasted as heat in other cells. In turn, more electrons are produced and hence more electricity is generated.

The potential for much higher efficiencies, upwards of 40% [83], is the major benefit of quantum dot solar cells. In addition, this technology is cheap to manufacture, which is important in eventually achieving commercialisation. Although quantum dot cells have shown to increase photovoltaic efficiencies, they remain immature, and are unlikely to be in scope for dismounted soldier power systems in the near future.

#### *3.6.1.5 Multi-Junction Solar Cells*

Multi-junction solar cells are a unique class of photovoltaic cell that combine multiple layers of semiconductor materials with differing bandgap energies[30] [84]. This allows these cells to collect light from across the solar spectrum and to produce cells with high conversion efficiencies. Conversion efficiencies over 40% have been achieved in a laboratory environment with concentrated light [85]. Silicon may be used as one of the layers in these cells, but alloys combining Group III and Group V elements from the Periodic Table are commonly used [84]. By applying this technology to flexible thin-film photovoltaic cells, the conversion efficiencies

---

[29] A nanocrystal is a crystalline nanoparticle with a diameter anywhere between one and a few hundred nanometres [82].

[30] The bandgap energy of a semiconductor material refers to the energy required to make the material conduct electricity.

of flexible thin film cells could be improved [85]. The main disadvantage of multi-junction solar cells is their high cost [85], which is likely to restrict widespread application in dismounted soldier power systems, although DARPA are further developing this technology through their Very High Efficiency Solar Cell program [86].

### 3.6.2 Kinetic Energy Harvesting

Kinetic energy harvesting uses soldier motion and movement to produce a usable form of energy for powering electronic devices. The main benefit of kinetic energy harvesting technologies is that they use renewable energy from a natural source (human movement) to produce electricity. The only restriction for producing energy in this manner is the amount of movement a soldier is willing or able to do due to fatigue.

Kinetic energy can be harvested passively, where minimal additional effort is required by the soldier (e.g. a knee harvesting device could be used to harvest energy from natural soldier movement), or actively, which requires exerting a specific force in a specific manner to produce energy, such as hand cranking. Successful system design must be careful not to overburden a soldier or require too much additional effort [18], which could increase fatigue and reduce operational performance. Since these technologies are based on soldier movement, passive systems in particular would not be suited to missions where a soldier remains stationary for long periods of time. Hence, if kinetic harvesting technologies are implemented in the future, consideration must be made to ensure they are only used in situations where they would be beneficial.

A large number of developments worldwide are currently taking place to produce devices capable of using kinetics to produce electricity. One such technology is the Flexible Integrated Energy Device (FIED), being developed by CSIRO through a CTD agreement with DSTO [26]. The FIED harvests energy using transducers attached to the shoulder straps of a soldier's pack. This energy is conditioned with a harvesting rectifier and stored in a flexible battery (see Section 3.3.1.4). The harvesting rectifier connects the system to a soldier's electronic devices and is used to control charging of the battery. The transducer used in the FIED harvests parasitic energy from soldier motion. Several materials are being evaluated, including piezoelectric fibre composites and macro fibre composites. A specific trade-off for the FIED is the amount of weight carried by the soldier and the amount of power that can be produced since more power is harvested for a heavier soldier load. Harvesting efficiencies of 20 to 35% are predicted for the FIED [26].

There are many other kinetic harvesting technology developments taking place. These include devices to harvest energy from a soldier's knee joint, the heel of their shoe and their backpack [87]. Such devices are capable of producing between several hundred milliwatts to tens of watts of power [18]. Many of these devices make use of piezoelectric materials that are able to produce electricity when deformed. A particularly promising technology is a Canadian product, the "Bionic Energy Harvester", which is a knee brace that harvests energy from the motion of the knee joint. It is based on regenerative braking technologies that take advantage of the energy-absorbing work produced by walking. Currently, the total weight of the system (for both knees) is 1.2kg and it is capable of producing 5 to 7W without effort or upwards of

10W with additional effort [87]. Ongoing research and development is focussing on ergonomic issues and system integration [4].

### 3.6.3 Thermal Energy Harvesting

A third area of energy harvesting relevant to dismounted soldiers is thermal energy harvesting. Thermal energy harvesting makes use of thermoelectric materials that convert thermal gradients into electricity. Miniaturised thermoelectric devices for thermal energy harvesting capable of converting small thermal gradients in the order of tens of degrees or less into electricity [88] are in scope for future soldier power systems.

The ability of a thermoelectric material to generate an electrical potential when exposed to a thermal gradient is quantified by calculating a figure of merit, which depends on the thermoelectric properties of the material [89]. Higher figures of merit indicate greater thermodynamic efficiency. The actual power output from a thermoelectric device also depends on the temperature differential between the hot and cold sides of the device [88, 89], with greater power output for increased thermal gradients.

Thermoelectric devices have a number of advantages for soldier power provision. They are reliable, they have low noise signatures with no moving parts and they can be operated continuously for long periods of time [12, 88]. In addition, thermoelectric power generation has the potential to reduce the logistical burden of soldier power provision [88] since the materials used do not need to be replenished, unlike primary batteries or fuel in engines. However, the amount of power miniature thermoelectric devices can produce for a small temperature differential is quite limited[31]. This suggests that heat from the human body alone may be insufficient for useful thermal energy harvesting. Other drawbacks include low conversion efficiencies (i.e. less than 10%), low specific power [1] and high cost [90]. Although bulk thermoelectric modules are available commercially, their low conversion efficiencies have limited their commercial adoption [88].

The power limitations of miniature thermoelectric devices suggest they are not suitable as the sole source in a dismounted soldier power system. However, they could be used in low-power, niche applications, such as providing power to wearable sensors or other low-power electronics [91]. This application could see these devices being entirely self-sufficient with no power requirement from the main power sources in a dismounted soldier power system. To achieve higher power output, thermoelectric devices may be combined with other heat or power sources to capture waste heat, but this may not be feasible for a dismounted soldier power system due to the high temperatures involved.

Since the efficiencies of thermoelectric materials are directly related to their properties, a significant amount of research and development is ongoing to improve these properties [1], such as the work being undertaken by the Research Triangle Institute (RTI). In collaboration with several US government organisations, they are developing thin-film thermoelectric

---

[31] Amow discusses a high power density miniature thermoelectric generator that is capable of producing upwards of 90mW for temperature differentials of 70°C and upwards of 260mW for temperature differentials of 120°C [88].

materials with high figures of merit at room temperature [92]. This technology makes use of nanoscale materials called superlattices, which have the potential to enable efficient micro-scale thermoelectric devices for energy harvesting [91]. RTI have developed millimetre-sized arrays capable of generating 100mW from temperature differentials less than 10°C, which is useful for a variety of sensors or wireless electronic devices [91]. Further material development could see thermal harvesting become more relevant to dismounted soldiers in the mid to long-term future [21].

### 3.6.4 Future Direction

The future direction of photovoltaic technologies for dismounted soldier power provision is likely to largely focus on the development of flexible thin-film photovoltaics [21, 93]. Flexible thin-film solar cells are particularly relevant for soldiers since this technology could eventually be adapted into a wearable form that could be incorporated into a soldier's equipment, uniform or webbing [12, 72]. Flexible solar arrays that can be folded and carried by soldiers have already been developed and are being tested by the US Army (TRL 8-9) [12, 16, 72]. These devices are used for trickle charging of batteries. Although photovoltaic cells are suited to static daytime applications, the application of wearable photovoltaic cells (TRL 5-6[32]) may be beneficial since it could provide a supplementary battery charging source for a soldier on-the-move without significant additional burden. This could greatly simplify battery recharging logistics for soldiers and could reduce the size and weight of the main power source in soldier power systems. Other focus areas for photovoltaic cell development are likely to include developing cells with reduced infra-red signatures and improving performance in low-light conditions.

There are some key challenges facing kinetic energy harvesting technologies for soldier power provision. This includes the development of miniaturised, lightweight kinetic energy harvesting devices that have a minimal impact on soldier mobility and require minimal maintenance. Passive kinetic energy harvesting devices appear to be TRL 6-7[33] although some hand-cranked devices are commercially available. A number of developments are currently undergoing to further develop kinetic energy harvesting technologies for dismounted soldiers, which suggests they will be in scope for future soldier power systems.

Miniaturised thermoelectric devices are not yet mature for soldier power provision (TRL 5-6 [88]). However, advancements are being made in this technology, particularly those based on thin-films, which offer small footprints and high power densities [88]. The utilisation of such devices requires very highly customised solutions with specific materials chosen for certain operating temperature ranges to achieve adequate heat transfer to/from a device [88]. Nevertheless, thermoelectric power generation should remain a consideration for future dismounted soldier power systems.

The viability of energy harvesting technologies in dismounted soldier power systems is likely to depend on several factors. This includes their ability to be efficiently integrated onto the soldier as a wearable solution without impeding soldier performance and mobility. Improving

---

[32] TRL estimate based on information provided by the following sources: [12, 94, 95]

[33] TRL estimate based on information provided by the following sources: [4, 12]

the cost and overall conversion efficiencies of these technologies will also increase their attractiveness for soldier power provision. Most energy harvesting technologies discussed require further development before they are ready for use in dismounted soldier power systems, although, for some, this may be within five years [12].

## 3.7 Microengines

A microengine is a small engine that produces mechanical energy from combustion and requires coupling to an electrical generator to produce electricity. The main benefit of microengines is their high energy capabilities achieved through the use of high specific energy fuels. Compared to batteries, microengines may offer large weight savings for soldiers on extended missions once soldier energy requirements exceed a certain threshold (to offset the overhead of the microengine). Many designs are also attractive because they are capable of operating on standard military fuels [12].

Disadvantages of microengines for dismounted soldier power provision are likely to include engine starting difficulties, thermal/acoustic signatures, vibration and hazardous exhaust gases [12]. High operating temperatures may also pose safety issues for soldiers carrying these devices. Lewis et al. [6] identify a number of technical issues with scaling engines down to a size suitable for dismounted soldier power provision (a power output of 20W is designated as a goal). At this size, engine efficiency is very low due to heat loss, the combustion kinetics and the required mechanical tolerances [6]. This suggests that it will be challenging to develop microengines at a suitable scale for individual dismounted soldier power provision.

There are several separate classifications of microengine technologies, which include micro internal combustion engines, microturbines and Stirling engines. These are discussed in more detail in the following sections. Micro diesel engines, a specific type of micro internal combustion engine, such as the commercial Cox engine series used in model airplanes, are of particular interest since they demonstrate a mature microengine technology [6].

### 3.7.1 Micro Internal Combustion Engines (ICE)

Micro internal combustion engines are miniaturised versions of standard ICEs. There is potential for micro ICE applications in the commercial sector to be adapted for military purposes. To provide power to a soldier's electronic devices, a suitable electrical generator is also required, with predicted maximum system efficiencies in the order of 20% [1]. Micro ICEs have the potential to be used as portable battery chargers in the battlefield and with further development a wearable solution for dismounted soldiers could be realised. Such a device may provide battery charging on-the-move, or it may be used to power a soldier's electronics directly, although this may require coupling with a battery for engine start-up.

Micro ICEs are advantageous since they are based on an inexpensive technology and can be made to function with a variety of fuels [1]. This means they can operate from standard military fuels and may avoid the logistical complexity of introducing a new fuel to the battlefield. By using the combustion of fuel to produce energy, micro ICEs can achieve much higher energy densities than conventional forms of soldier power provision, such as batteries

[96]. However, weight savings will only be realised once the soldier energy requirements for a mission exceed a certain threshold due to the overhead of the engine and generator. Compared with other power sources, combustion engines are particularly beneficial since they combine high energy density and high power density characteristics [1]. This suggests that micro ICEs have good potential to provide a high performance single source solution for soldier power provision. If they are maintained properly, micro ICEs can have long life cycles [1]. Their use could see mission times greatly extended and soldier loads greatly reduced.

The adaptation of commercial micro ICEs for military applications, including soldier power provision, may present a number of issues. Small-scale ICEs typically have problems with durability and reliability [1] while thermal and frictional losses are likely to be more significant, and engine sealing and combustion kinetics more difficult, at this scale [96]. Combustion-based air-breathing engines also have safety and environmental concerns since they produce harmful emissions such as nitrous oxides, carbon monoxide and sulphur dioxide from the combustion of hydrocarbon fuels [97]. For soldiers, the thermal and acoustic signatures of micro ICEs are major issues [6]. The high operating temperatures of micro ICEs could easily be detected via infrared sensors and these temperatures may pose safety risks for soldiers carrying such devices. Noise produced from micro ICEs is likely to increase the risk of detection for soldiers and may inhibit tasks such as radio communication [6]. ICEs also require continuous airflow [97], which could limit the applicability of micro ICEs.

There are a number of miniature reciprocating engines being developed that are of interest for dismounted soldier power systems. They include the Miniature Internal Combustion Engine (MICE) by Aerodyne Research [98] and the Tectonica Generette [99]. Commercially available micro diesel engines are also of interest [6].

The MICE is a free piston system consisting of a two-stroke engine, a spring and a linear alternator in a linearly oscillating configuration that resembles an automotive spark plug in terms of shape [6]. Aerodyne Research have developed MICE generators in a number of sizes, namely the 5-10W range, the 300-500W range and a 100W version [100]. The MICE provides a high energy density solution[34] and can be used with light or heavy fuels [18]. The MICE does not have to address many of the problems associated with fuel cells, such as the requirement for hydrogen as a fuel or very long startup times. However, this technology is in a preliminary stage of development (TRL 4[35]) since it has only been demonstrated (and had its performance quantified) in a laboratory environment [100]. The MICE is being developed for UAVs and Unmanned Ground Vehicles (UGV) [98], but it could be adapted for dismounted soldiers since it is designed to be lightweight and compact.

---

[34] For mission durations of 24 hours, the 100W MICE system (75W when operating on JP-8) has a calculated energy density of 1000Wh/kg and the 300W MICE system has a calculated energy density of 900Wh/kg, while calculated energy densities for both systems exceed 1500Wh/kg for mission durations of 72 hours or more [100]. Calculated energy density is similar to batteries for mission durations of several hours, while no energy density data was provided for a 5-10W MICE system. These figures suggest that the MICE system would be sufficient to meet the approximate energy objectives for one or three day missions, as outlined in Section 2.

[35] TRL estimate based on information provided by the following sources: [100]

The Generette, developed by Tectonica through a CTD agreement with DSTO, consists of a micro-generator powered by a micro ICE capable of running on standard Army logistics fuel [101]. The Generette was designed specifically for soldier power provision as a replacement for batteries, but there appears to be no recent investment in further developing this technology after a final prototype was delivered through the CTD agreement.

Micro diesel engines are another micro ICE technology that could be adapted for use in dismounted soldier power systems. They are advantageous because they can be designed to run on JP-8 fuel [6]. However, micro diesel engines such as the commercial Cox engine series used in model airplanes, are not ruggedised and have high acoustic signatures [6]. Similarly to other microengines, micro diesel engines are capable of high energy densities. However, a number of technical issues must be overcome to develop a device suitable for soldier power provision. In particular, diesel engines require a robust structure to handle their high compression ratios, which means they can be quite heavy [6]. This may impact the specific energy available from these systems, although they should still offer improvements over batteries for extended operations [6].

### 3.7.2 Microturbines

Miniaturised gas turbines, known as microturbines, have gained interest within the last 20 years for distributed power production and in small-sized machines, with power outputs in the order of kilowatts to hundreds of kilowatts [102]. Further development of microturbines is focussing on millimetre-scale microturbines that make use of micrometre to millimetre-sized parts and assemblies and are produced using semiconductor manufacturing techniques [102]. These assemblies are known as Micro Electro Mechanical Systems (MEMS).

MEMS-based microturbine technology was conceived by the Massachusetts Institute of Technology (MIT) [103], but is now being developed by many other companies and institutions worldwide [1]. Such devices are potentially capable of producing between 10W and 20W of power from 5cm$^3$ engines weighing approximately 10g (excluding fuel and fuel tank) [104]. The initial design goal for the MIT program is 5% chemical to electrical conversion efficiency, although Jacobson et al. suggests this may increase to 10% with design improvements [104]. These specifications suggest MEMS-based microturbines could be used in mobile power source applications in the future, such as soldier power provision.

There are a number of potential advantages of MEMS-based microturbines. They are expected to have a high energy density of approximately 700Wh/kg [1] and high power density [103]. MEMS-based microturbines are also attractive because they are designed to be very compact and lightweight [6]. The potential for high energy densities and the small, lightweight nature of MEMS-based microturbines is particularly beneficial for supporting long duration missions and reducing soldier load. Additionally, these devices are quiet because they operate at very high frequencies beyond the audible range and Epstein suggests that any sound produced is relatively easy to muffle [102].

Although MEMS-based microturbines offer great potential as a compact, lightweight and high energy power source, a working device with net power production has not yet been demonstrated [12]. MEMS-based microturbines are limited by a number of technical issues caused by their small size, high operating temperatures (in the order of 800°C [12]) and high operating speeds (up to millions of revolutions per minute [102, 103]). The high operating temperatures present problems in developing robust silicon materials for these devices and further bearing development is needed to handle the high engine speeds [1]. Such high operating temperatures are also problematic for soldiers since they produce a significant infrared signature and are likely to present safety issues for soldiers carrying microturbines.

Many early MEMS-based microturbine developments have focussed on using hydrogen as a fuel, but the usefulness of these microturbines will depend on whether they can efficiently and reliably operate from hydrocarbon fuels, such as JP-8 [6]. However, Lewis et al. highlights a number of associated difficulties, such as the slower burn speed of hydrocarbon fuels, which is likely to present challenges in developing a microturbine capable of operating efficiently from diesel or JP-8 [6]. Another issue with MEMS-based microengines is they cannot be changed once built due to the use of microscale components and should a component malfunction, the whole device may have to be replaced [12, 104].

MEMS-based microturbines are a relatively immature technology in the context of this document (TRL 2-3[36]). Gardner suggests that further work is needed to improve aerodynamic performance, hydrocarbon combustors, thermal isolation, high temperature materials, bearings and electric generators [12]. Until these areas are addressed, it is unlikely that MEMS-based microturbines will be a viable alternative for soldier power provision.

### 3.7.3 Stirling Engines

Unlike the other microengines discussed above, a Stirling engine is an external combustion engine. A number of sources provide information on the operation of Stirling engines [1, 105, 106], which is summarised as follows. The Stirling engine produces mechanical energy from heat energy by alternately compressing and expanding a working fluid at different temperature levels. This working fluid is a fixed quantity of gas, such as air or helium. The expansion and compression of the gas, which drives a piston connected to an electrical generator, is achieved with temperature differentials at opposite ends of the engine. All of the engine’s heat flows in and out via the engine wall.

Stirling engines have several advantages. Since the Stirling engine is a closed system, with no valves and is heated from an external source, it is a reliable and low maintenance system [105]. The design of Stirling engines also results in low acoustic signatures [105], which makes them well suited to military applications, in particular stealth missions. Dual free-piston versions of the Stirling engine can be operated so that all vibration is cancelled, resulting in a very quiet system [1]. Another important advantage of Stirling engines is their ability to operate from any source of heat [106]. Therefore, they are capable of operating from standard battlefield fuels, environmentally friendly fuels or they could be used in conjunction with energy harvesting technologies.

There are several disadvantages of Stirling engines for soldier power provision. Compared with other engines, Stirling engines produce relatively low power for their size and weight [1,

---

[36] TRL estimate based on information provided by the following sources: [12, 102]

105]. This suggests that it may be difficult to create a compact and convenient design for dismounted soldier power provision. Stirling engines also take a long time to heat to their operating temperature and their power output is relatively constant [107]. As a result, they are suited to continuous operation and they are unable to provide fast power output changes [105].

An example of Stirling engine development is the 160W Stirling engine developed by the Communications Electronics Research, Development and Engineering Centre (CERDEC) in collaboration with DARPA [16]. It uses dual opposed 80W engines connected to JP-8 fuel burners and weighs less than 10kg. This device is portable and can be used as a platoon level power source for battery charging. A further example is the system developed by Sunpower, Yale University and Precision Combustion as part of the DARPA Palm Power program [108]. They developed a wearable, JP-8 fueled, 35W free-piston Stirling engine. Huth and Collins claim that this system will weigh 1.7kg and have an energy density of 870Wh/kg with design optimisation [108]. These examples suggest a TRL of 5-6.

Although Stirling engines have the potential to increase the energy available to dismounted soldiers and can operate from standard battlefield fuels, their inability to quickly change output power levels and long start-up times may restrict their application for soldier power provision. Combination with secondary batteries may alleviate some of these issues or Stirling engines may be used as portable battery chargers in the future.

### 3.7.4 Summary

The development of microengine technologies appears to be relatively limited compared to other portable power technologies. Although microengines have the potential to provide higher energy densities than batteries, a number of technical issues exist with each specific technology. These technical issues are mainly associated with the scaling of engines to small sizes suitable for dismounted soldier provision. For micro ICEs, issues associated with noise are likely to be problematic, while the thermal signature of most microengine technologies may pose detection and safety issues for soldiers. This suggests microengine technologies will require further development before they are ready for application in soldier power systems.

The viability of microengines in dismounted soldier power systems is likely to depend on their technical issues being addressed and the development of devices capable of operating from standard battlefield fuels. The technical issues associated with scaling microengines to small sizes may lead to larger format microengines being used in portable battery charging applications, such as a battery charging device for a platoon. Should microengine technologies be developed and used for direct soldier power provision, it is likely that they will require coupling with batteries to handle tasks such as engine start-up.

# 4. Power Integration

Section 3 reviewed a number of power source technologies that could be used in future soldier power systems. In addition to the development of individual power source technologies, the development of integrated soldier power systems is gaining increased attention around the world [109]. Integrated soldier power systems provide the potential to optimise energy usage on the soldier, with subsequent weight and logistics savings.

Aspects for consideration in developing integrated soldier power systems include the architecture of the system, power distribution technologies, automated power management, the interoperability capabilities of the system and the use of hybrid power sources. Another important consideration is the development of low power components to minimise the amount of power required by soldiers' electronic devices, which may reduce the amount of energy that soldiers need to carry. Each of these topics is now discussed.

## 4.1 Power Architecture

The power architecture determines how each component of the soldier power system is connected. There are three types of power architecture, distributed, centralised and mixed. A distributed architecture uses an individual power source for each electronic device carried by a soldier [10, 110]. Conversely, a centralised architecture uses a central power source to provide power through a network distributed on the soldier to all electronic devices a soldier is carrying [10, 110]. The central power source may be a single source or a central combination of multiple power sources [10]. The devices do not have their own power sources [110] and must remain connected to the system to receive power. A centralised architecture has several potential configurations, including a star configuration, a bus or a daisy chain[37] [23] (see Figure 3). Mixed architectures combine aspects of distributed and centralised architectures since they have a central power source connected to individual electronic devices, which may also have their own power sources for short periods of independent operation [110]. These individual power sources are typically recharged by the central power source. Table 3 summarises the power architecture definitions.

---

[37] A star configuration connects each node to a central hub with a point-to-point connection. A bus configuration connects each node to a single cable. A daisy chain configuration connects each node in series or in a ring.

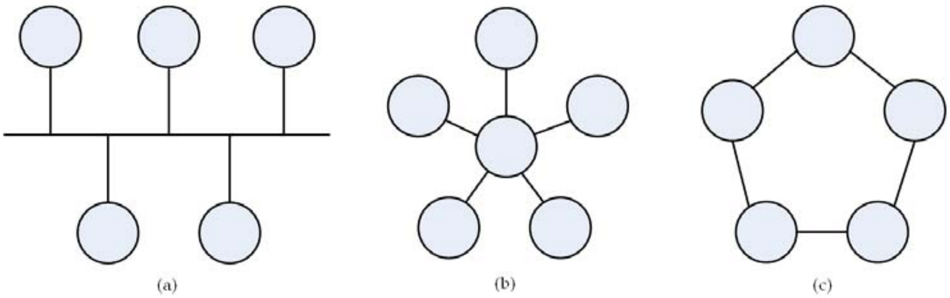

*Figure 3 Network configurations: (a) bus, (b) star, and (c) daisy chain*

*Table 3 Summary of Soldier Power Architecture definitions*

| | |
|---|---|
| Distributed | Individual power source used for each electronic device. Devices are not networked. |
| Centralised | Central power source (or sources) powers all electronic devices. Electronic devices do not have their own power sources. Source and devices are networked. |
| Mixed | Central power source (or sources) powers all electronic devices. Electronic devices also have their own power sources for independent operation. Source and devices are networked. |

A distributed architecture is simplistic and modular, affording ease of upgrade, with failure of a power source only likely to affect a single device. Equipment required for distribution of power between devices, such as cabling, is avoided, improving the freedom of movement for soldiers. However, this will be offset by the need to carry spare power sources for each device, such as spare batteries, which increases soldier load and logistics issues [10, 110]. In addition, management of power at the system level, such as redirecting power to critical devices (e.g. radios) in emergency situations, is not possible with a distributed architecture since the devices are not networked [10, 110].

Centralised architectures provide potential for reducing the burden on soldiers. Although a centralised soldier power system has added overhead for the distribution and conversion of power[38], it facilitates system-level power management [10, 23, 110] (see Section 4.4). This allows smarter utilisation of energy through the adoption of energy conservation strategies utilising different power states for a soldier's electrical devices resulting in subsequent energy savings. This may reduce the burden on soldiers if these energy savings can offset the overhead of the centralised architecture. The use of a centralised architecture may also simplify logistics since only one or two power sources need to be supported rather than potentially several different varieties in a distributed architecture [10].

A centralised architecture does have a number of drawbacks. The dependence on a central power source could result in a complete loss in powered capability for the soldier should it fail [10, 23, 110]. In addition, any point of a system using a centralised architecture, whether it is a cable, harness or a connector, could become a single point of failure [10, 23, 110]. This highlights the importance of incorporating redundancies and fail-safes, and fully field ruggedising components in such a system to minimise the risk of failure. Finally, the harness design is likely to dictate the number of connections to the system, which places a limit on the

---

[38] Cabling is required to distribute power and power conversion may be required if devices connected to the system have different operating voltages [23, 110].

number of electronic devices that can be connected [110] and may result in capability trade-offs for some missions.

Mixed power architectures provide similar benefits and drawbacks to centralised architectures [111]. They too have added overhead for the distribution and conversion of power, but are also able to facilitate system-level power management. As with centralised architectures, this provides the potential for reduced weight burden on soldiers if the energy saved through power management can offset the overhead of the system. However, cabling harnesses and connectors remain potential points of failure and the harness design dictates the number of connections to the system, restricting the number of devices that can be connected to the central source [110]. In terms of logistics, although multiple distributed power sources may be used in a mixed architecture, such sources are charged by the central power source and it is unlikely that they will require regular replacement. For the central source, logistics requirements will be similar to those used in centralised architectures. A unique advantage of mixed architectures is that the use of a central power source (or sources) in combination with individual device sources reduces the impact of a single point of failure, including failure of the central power source [23, 110].

## 4.2 Power Distribution

Reliable and robust power distribution on the soldier is a key enabler for centralised and mixed systems [111]. This section provides an overview of various distribution technologies that could potentially be used to connect the devices and sources in a networked soldier power system.

Currently, ruggedised cables and connectors are a mature option to network the power system components of a soldier power system. However, they are heavy, stiff and bulky and are likely to impede soldier motion [4], which could reduce operational performance. They can also snag or tangle easily [4], which means they could be easily damaged. Their use in the future is predominantly an engineering issue since a well engineered design may eliminate some of their problems.

There are a number of alternative power distribution technologies in development that aim to eliminate the current problems of cabling. Electronic textiles (e-textiles) are one such technology. E-textiles are conductive fibres that have been integrated into fabric or clothing to provide a wearable electronic network for data and power transmission [112]. They are much lighter and more flexible than conventional ruggedised cables [113] and can be integrated into combat clothing, reducing impedance to soldier motion. It is estimated that using e-textiles could save up to one kilogram for centrally powered systems [4]. However, further development must be undertaken to ensure they are ruggedised and sufficiently redundant for the battlefield environment [113]. This includes developing robust connectors. Several other issues such as garment design and integration, detection signatures (including thermal and radio frequency (RF)) and electromagnetic interference also need to be addressed before e-textiles become a feasible option for dismounted soldier power systems [113].

Wireless power transfer, also known as inductive or contactless charging, is another technology in development that could be used in future dismounted soldier power systems. Contactless charging replaces standard connectors with inductive couplings to charge batteries without mechanical or electrical contact [10] and is commonly used to charge household appliances such as electric toothbrushes [114]. It has several advantages over direct contact charging through conventional connectors. There are no exposed connectors, power tethers (which have the potential to be snagged) are eliminated and power can be transmitted through fabrics [10]. However, it is much less efficient than direct connection[39] and produces a higher RF signature [10]. For this charging method, it is essential to minimise the air gap to maximise power transfer efficiency [10].

Power over Ethernet, a Power-over-Data technique, is also being contemplated as an alternative to conventional cabling [4]. It uses Ethernet data cabling for the transmission of power, combining data and power distribution together on the soldier, with the potential for less wiring and weight/cost savings [115]. However, Power over Ethernet remains a maturing technology. It is limited in the amount of power it can provide [116, 117], which means it may be unable to support some high power devices used by soldiers, it is quite expensive [116] and interference with any data signal transmission is likely to be experienced [117].

## 4.3 Power Interoperability and Standardisation

A desirable feature of dismounted soldier power systems is interoperability. For soldier power systems, interoperability covers the ability of these systems to use equipment from multiple sources, including allied nations in the field. This includes the ability to use different power sources. Designing a system to be interoperable should not only consider current technologies, it should also consider legacy and future technologies [118], although this may present significant challenges in accommodating such a range of technologies. There are three levels of technical interoperability defined by NATO in STANAG 4619 [119]:

- the capability of the dismounted soldier power system to operate from an external source (System level);
- the capability of the dismounted soldier power system to use another nation's power source or recharge sources (Module level); and
- the capability of the dismounted soldier power system to use and recharge another nation's power components (Component level).

Standardisation of power sources, form factors and connectors is important in realising a high level of interoperability [119]. To achieve standardisation, the soldier power system should be based on open standards, describing common interfaces, connectors and protocols. This is

---

[39] The efficiency of wireless power transfer is dependant on a number of factors, including the size of the inductive coupler and the length of the air gap between coupler halves [10]. Efficiency decreases significantly as the air gap is increased: the inductive coupling system described by Soar is 90% efficient for air gaps of 2mm, but this drops below 60% for air gaps of 10mm [10]. If soldier equipment was to be powered wirelessly from a central source on the soldier, these air gaps may be much greater and the power transfer much less efficient.

likely to allow the system to be interoperable with a number of different power sources. Ideally, standardisation would cover a range of allied nations to allow coalition forces to support each other in the field.

Standardisation could address the growing variety of power sources on the battlefield [1]. This is likely to save resources, reduce costs and reduce the associated logistical burden. For example, standardisation of batteries would minimise the variety of batteries and maximise the quantity of specific types of batteries on the battlefield. This would reduce the likelihood of soldiers running short of supply and the need to carry as many types of battery spares. Working groups have been implemented within NATO to address the issue of standardisation, but there remains further opportunities to develop open standards for the design and integration of many aspects of soldier power systems [120].

## 4.4 Power Management

For a dismounted soldier power system, power management refers to the management of energy consumed by a soldier's electronic devices based on run-time conditions [23]. Efficient and reliable power management is desirable for integrated soldier power systems that incorporate multiple power sources and electrical loads (devices that consume power) [18] and should allow both manual and autonomous control [111]. The introduction and integration of advanced batteries, fuel cells and energy harvesting technologies together into soldier power systems demonstrates the need for power management capabilities [4]. Power management capabilities provide an opportunity for simultaneous battery charging, energy harvesting and power provision. A number of power management systems for soldier power systems have already been developed, such as the Smart Fuel Cell Power Manager 3G [66] and the Protonex BPM-602 power manager [121].

There are several key areas that need to be considered for a dismounted soldier power management system. They include electrical load prioritisation, remaining energy indication, power source selection, high efficiency voltage conversion [18] and fault management [111].

Electrical load prioritisation is crucial to enable graceful degradation of a soldier power system. This requires awareness of the devices connected to the system so that power can be directed to the most important devices (e.g. radios) when there is limited energy available or if the system is damaged.

A major issue that currently exists in the battlefield is soldier confidence in the state of health of their batteries [25]. By providing soldiers with accurate system information, including remaining energy indicators, they can utilise the full capacity of their power sources by only replacing or recharging them when needed.

For systems with multiple power sources, correct power source selection is critical for certain conditions to ensure electrical load requirements are met and to prevent power source damage. The power management system must be able to determine which source to use based on run-time conditions. High energy sources, such as fuel cells or high-energy batteries, should be used to handle the majority of the electrical load over time while high power sources, such as supercapacitors or high-power batteries, should be used in peak electrical load periods.

Efficient voltage conversion is very important to reduce losses in the power system. Most devices carried by soldiers operate at different voltage levels and future centralised and mixed power systems may introduce power sources that operate at a different voltage. Efficiencies close to unity will ensure minimal power is lost during the conversion process and may assist in minimising the thermal signature of soldier power systems.

Fault management, encompassing fault detection, resolution (if possible) and feedback to the soldier [111] is important in minimising the impact of any failures in the system. These failures may be caused by manufacturing errors or due to damage to system components.

Power management presents several key benefits to soldiers. By using power sources efficiently and adopting an energy conservation strategy with different power states for devices in the system, significant energy savings can be realised. It is estimated that managing power dynamically based on real time electrical load conditions could result in energy savings of up to 30% [4]. This could allow extended mission times and lighter soldier loads since they would not be required to carry as much energy, in the form of batteries or fuel, into the battlefield. Soldiers may also be able to use more electronic devices or more advanced devices, with higher power requirements, to improve their capability. Energy savings from power management could also simplify the logistics of soldier power provision by reducing the dependency on the daily provision of power [10]. The main problems associated with power management are the complexity in developing an optimal solution for multiple, and potentially undefined mission profiles, and the high initial costs of implementing such systems [54].

## 4.5 Hybrid Power Systems

A hybrid power system combines different types of power sources in a centralised (or mixed) architecture to meet a range of soldier power requirements. Typically a high energy, low power source (or sources) is used with a low energy, high power source (or sources) [122] to provide power to a soldier's electronic devices. This system can achieve energy gains by operating the best source or combination of sources to meet a soldier's electrical load requirements at any given time. Examples of high energy sources include high energy batteries or fuel cells and examples of high power sources include high power batteries or supercapacitors [1].

As discussed in Section 1.1, any increase in soldier capability or operational effectiveness requirements may require soldiers to carry greater amounts of electronic equipment into the battlefield. To sustain this equipment, it is likely that more energy will be needed. Atwater et al. demonstrates that a number of the high energy sources being considered for future soldier power systems, including zinc-air batteries (see Section 3.2.1.7.1) and fuel cells (see Section 3.5), are unable to sustain intermittent high-power electrical loads [122]. These electrical loads are characteristic of some equipment being introduced to the battlefield, such as laser target designators [1] and demonstrates the potential need for hybrid power systems.

In a hybrid system, the high energy source is sized to meet mean power requirements and provides the majority of power over time, but electrical load levelling and peak power requirements are met by the high power source [122]. This reduces the instantaneous electrical loading on the high energy source, which increases the energy available since large peak power can significantly reduce the energy delivered by power sources such as batteries [1].

The configuration of power sources in a hybrid system should consider several factors to determine the most appropriate hybrid combination. These include power source characteristics, power load characteristics, mission requirements and duty cycles [1]. Modelling may be used to determine an optimal combination of sources for certain electrical load conditions and mission scenarios [1]. To ensure optimal performance and the appropriate power source is used under certain conditions, power management capabilities are also required in the soldier power system [122].

Hybrid systems have a number of benefits in situations where both high energy and high power load requirements exist. If there is no such requirement, a hybrid system is likely to be a burden for soldiers in terms of weight, volume and logistics. A well-designed hybrid power system can offer longer mission durations, reduced weight and volume, reduced costs and enhanced power capabilities [1, 54]. Lewis et al. claims that hybrid battery-battery systems could reduce soldier battery pack mass from 20kg to 6-7kg for certain missions [6]. For liquid fuelled hybrid power systems, the weight and volume benefit is greater for longer missions, but the overhead from the fuel conversion system creates a cut-off point, prior to which it is more mass-efficient to use batteries alone [1]. The weight benefit for hybrids is also dependent on peak power requirements. There is a greater benefit as the peak power to average power ratio increases (energy available from a single source decreases to meet peak power requirements) and as the peak power duration decreases as a percentage of total time[40] (the high energy hybrid source has greater utilisation) [1].

Although there are many benefits of hybrids, they should only be considered for applications where a single source solution (e.g. a battery) is unable to meet the power and energy requirements of the system. This avoids the additional weight and volume burden, logistics overhead and complexity of such an approach.

## 4.6 Low Power Components

There are two approaches to address growing power requirements for soldiers. The first is to increase the power output capabilities of soldier power sources, which is the main focus of this document. The second is to reduce the power required by soldier equipment by developing low power components [5].

An example of efforts to reduce soldier power system power consumption is the Advanced Soldier Adaptive Power (ASAP) technology demonstration project being undertaken by

---

[40] It may be more efficient to use a single power source if the peak power duration is sufficiently short to avoid the overhead of a hybrid system.

DRDC as part of the larger Integrated Soldier System Project (ISSP). One of the aims of the ASAP project is to optimise power provision and consumption through power management. Specifically, the ASAP project is attempting to reduce the average power requirements of Canadian soldiers below 10W [88]. To achieve a lightweight and efficient soldier power system, DRDC are focussing on developing 10W modular power sources, considering electro-textiles (see Section 4.2) and flexible cabling for power distribution, investigating new power connectivity concepts and using advanced power management [123].

A detailed discussion of low power components and strategies to reduce power consumption is beyond the scope of this document. Nevertheless, it is important to highlight this issue as a reduction in power required by soldiers is likely to contribute to a reduction in weight carried by soldiers.

## 4.7 Soldier Power System Developments

The development of advanced, lightweight, integrated soldier power systems is a goal for many countries around the world. These systems aim to address a number of essential requirements for soldiers, including mobility, survivability, sustainability and Command, Control, Communication, Computers and Intelligence (C4I) capabilities [109]. The integration of these systems may range from full integration of all newly developed subsystems to integration of existing or modified equipment.

The French FELIN system, developed by Sagem, is currently one of the most advanced in terms of technology [109]. It consists of a Portable Electronic Platform at the core of the system, which manages the main elements of the system (e.g. radios and vision systems) and is capable of prioritised power distribution [109]. The total system weighs approximately 26kg and can sustain soldier operations for 24 hours [124]. It is powered by two central 125Wh/kg Li-ion batteries, which are complimented by 100Wh/kg Li-ion batteries for stand-alone equipment [125]. Spare batteries can be charged with a collective battery charger unit run off mains electricity, a generator or vehicle power, while soldiers within certain vehicles can plug into individual power ports to charge batteries that are in use [125]. Sagem are contracted to deliver 22,600 FELIN systems, with the first versions expected to be deployed before the end of 2011 [124].

The US Land Warrior system consists of a number of subsystems (Computer, Radio, Navigation, Weapon and Power subsystems, and a Soldier Control Unit) integrated together through a cabling system inserted in the soldier's vest [109]. The system is powered by the Ultralife Li-145 Li-ion battery (140Wh/kg, 1.021kg [126]), mounted on the backplate of the soldier [125]. Two of these batteries are carried by soldiers, one connected to the system and the other used as a spare. The batteries have a reported operational life of eight hours and can be recharged in charging bays on the Stryker Infantry Carrier Vehicles [127]. Ongoing development is occurring to reduce the weight, volume and power consumption of the system [109].

As part of its CTD program, DSTO recently announced funding for Tectonica, in collaboration with the ANU and CSIRO, to develop the Soldier Integrated Power System [128]. Tectonica claims that this system "will provide integrated power generation, distribution and management for the Australian soldier" [128]. The project aims to reduce the battery weight carried by soldiers and integrate a number of novel technologies, such as flexible solar cells and conductive textiles, into the soldier power system.

There are many other soldier system developments ongoing around the world [109]. It can be seen from the above examples that all of these developments are moving the soldier system towards an integrated solution. These development efforts aim to achieve integrated soldier systems that are better equipped to accommodate soldiers' improved electronic capabilities, whilst reducing the weight and bulk of a soldier's load. Therefore, the implementation and ongoing development of these systems and their constituent technologies can assist in realising an advanced integrated soldier system, which should be a key focus for the Australian Army.

# 5. Logistics

The soldier power system itself is the central focus of this document, but the logistics associated with the delivery of power to soldiers must also be considered as it is a significant contribution to the cost of soldier power provision [1]. For the benefits of advanced technologies in future soldier power systems to be realised, it is important that these systems are supported by a reliable logistics infrastructure.

There are many logistical considerations for Army in delivering power to the battlefield. To get power to the soldier, it must be procured, shipped, stored, distributed, maintained and protected before it is used. During the lifetime of a power source, proper maintenance is necessary, and once the power source has been expended, it must be recovered and disposed, further increasing the logistical requirements. These logistical considerations are key factors when comparing power source solutions for dismounted soldiers. A poor choice can be expensive not only in terms of financial costs, but also in terms of excessive manpower and vehicle support to deliver, maintain and dispose the power source.

Primary batteries are the most commonly used power source by soldiers in the battlefield [1] and their associated logistical burden is a major issue for soldier power provision [10]. Since primary batteries are only able to be used once and then must be replaced, significant logistics infrastructure is required to both deliver them to the battlefield and then to dispose of them once used [10]. The proliferation of unique battery types, sizes and shapes has further exacerbated this logistical problem [21]. The logistical issues associated with primary batteries were highlighted during Operation Iraqi Freedom in 2003, when an inadequate supply of radio batteries almost caused operations to be ceased and tactics to be altered [129]. Battery manufacturers around the world were unable to keep up with the rate at which they were being used by soldiers [129]. Alternative power source technologies may reduce the logistical burden associated with primary batteries, although they may also introduce new logistics requirements, which are now discussed.

Methods to simplify the logistical requirements of soldier power provision are crucial as soldier power systems evolve [10]. Power sources that can be reused may assist in addressing logistics issues, therefore reducing the cost of soldier power provision. An increased use of secondary batteries, which can be recharged in the battlefield, could address the proliferation of primary battery types and reduce the number of batteries to be transported to the battlefield [21]. If using secondary batteries, consideration must also be given to the added logistical requirements to charge these batteries and to fuel and maintain the battery chargers. This issue is discussed further in the following paragraph. The use of fueled power sources as a direct power source for soldier power provision, as opposed to being used for battery charging, may also avoid the proliferation of primary batteries in the battlefield. However, there may be a proliferation of liquid fuels if alternative fuels, such as methanol, are needed [21]. In addition, the use of energy harvesting technologies, which provide renewable energy, could address logistics issues by reducing the number of other power sources transported to the battlefield [21], although maintenance or servicing of these devices creates added logistical complexity.

Any reusable soldier power sources are likely to introduce new logistics requirements and require additional logistics infrastructure. Such requirements include recharging, refilling or maintenance of the power source. Secondary batteries create added logistical complexity through the need to be regularly recharged [1]. To sustain capability, soldiers may have to regularly return to charging locations or a soldier may be responsible for gathering and charging discharged batteries within his unit. This will also require soldiers to be trained to recharge in combat [1]. Recharging can be achieved with portable battery chargers, on-board vehicle battery chargers or at a base, but these solutions create a risk of bottlenecks and diminished operational flexibility [1]. This may dictate the use of a recharging capability that forms part of the dismounted soldier power system (depending on technology development) and can be carried or worn by the soldier. Regardless of the form or configuration, rechargers will also introduce additional items of equipment that must be supported in forward areas [1], adding to the logistical complexity.

Similarly to the ADF's single fuel policy (see Section 3.5.2.3), which mandates that all future land-based equipment be capable of using JP-8, the US Army has a commitment to only having one fuel, JP-8, on the battlefield and in the supply chain [6]. There has been a push for soldier power systems to operate from this fuel, with JP-8 fuel cells currently being trialled in Afghanistan [130]. However, the use of battery rechargers or small-scale technologies for soldier power provision, such as fuel cells, may necessitate that an alternative fuel be introduced to the battlefield and supply chain. The introduction of new fuels, such as hydrogen or methanol, will require expansion of logistics infrastructure, to ensure safe and reliable storage and transportation of the fuel, and to accommodate any potential reforming requirements.

The added logistical issues with deploying alternative fuels are discussed further in Sections 3.5.2.1 and 3.5.2.2, and suggest that pre-packaging fuel cartridges may be necessary [6], which could then be treated as high energy battery packs [1]. This would prevent the logistics system from having to support an alternative fuel. However, similar logistics issues to primary batteries may be encountered if using a disposable fuel cartridge albeit to a lesser extent due to the higher energy content of the fuel cartridge. Consideration must also be given to the extra conversion losses in converting this fuel to a usable form, which may diminish the energy benefits of fuel cartridges over primary batteries.

# 6. Conclusion

Future soldier systems are fast becoming integrated solutions incorporating a range of advanced electronic equipment. The means of powering soldiers' electronic equipment is an important consideration. Currently, the predominant power source for dismounted soldiers in the battlefield is primary batteries, and to a lesser extent, secondary batteries. However, primary batteries have significant limitations including weight issues and demanding logistical requirements. These issues are likely to be exacerbated with the introduction of advanced electronic equipment, which is expected to have higher energy demands. Therefore, improved batteries, both primary and secondary, and alternative power source technologies are being investigated and developed. These alternative technologies include supercapacitors, fuel cells, energy harvesting devices and microengines.

Although the Australian LAND program is currently in development and dismounted soldier power objectives are yet to be defined, programs from the US were used to provide an indication of approximate power and energy requirements. These figures suggest that most primary batteries considered have sufficient energy for missions less than 12 hours in duration, but battery spares would be required for longer missions. In addition, most mature secondary batteries apart from high energy Li-ion batteries are unable to meet energy objectives for 12 hour missions, with recharging likely to be required within eight hours. Many of the fuelled sources considered are likely to meet energy objectives, but a number of other technical issues must be addressed before they are implemented in soldier power systems.

The development of improved primary batteries may reduce the severity of associated weight and logistics issues. However, secondary batteries are an attractive replacement due to their ability to be recharged and the subsequent resource and cost savings. Their implementation is likely to depend on specific energy and energy density improvements and further development of battery charging capabilities for the battlefield. Without lightweight battery charging capabilities, soldier load may increase if soldiers need to carry heavy chargers on extended missions. High energy primary batteries may remain the preferred battery type when recharging opportunities are limited. Supercapacitors may also be useful for future soldier systems, in particular as a high power source in hybrid systems, due to their high specific power and high cycle life.

Fuel cells are promising because they address the energy and weight deficiencies of batteries for long missions, but most types use non-standard military fuels. This is likely to dictate that significant additional logistics infrastructure and safe storage methods are developed to support these fuels. Therefore, fuel cells capable of operating from standard military fuels may be preferred for the battlefield. Microengines present similar energy benefits to fuel cells and the added ability to operate from standard military fuels, eliminating additional logistics issues, but they are at a low level of technical maturity and signature issues would need to be addressed for microengines to be feasible for soldier power provision.

The dependence on the logistics system to provide soldiers with power sources is a key issue for the future. Energy harvesting devices are being developed since they make use of renewable energy and can be replenished on the battlefield, which could reduce the supply logistics overhead associated with soldier power provision, in addition to reducing the amount of energy being carried by soldiers. However, energy harvesting devices require further development to improve conversion efficiencies and to effectively integrate them into soldiers' power systems. In the future, these devices may be used for battery charging or as a supplementary power source in integrated soldier power systems.

The key to realising the benefits of many of the technologies presented in this document is the supporting system infrastructure. Integrated soldier systems utilising centralised or mixed architectures may help to address the weight, cost and logistical issues currently encountered by primary batteries in distributed power systems. Power distribution in integrated soldier power systems can be achieved with ruggedised cabling and connectors, although this tends to be heavy and impede soldier motion, hence other technologies, such as e-textiles, are being developed. System-level power management is also a key aspect of integrated soldier systems to optimise power and energy usage, with the potential to reduce the amount of energy being carried by soldiers. Weight savings may be achieved if the energy savings can offset the overhead (added weight and bulk for the distribution and conversion of power) of an integrated system.

Hybrid power systems are another important consideration for future soldier power systems, particularly those incorporating high power devices. Although high energy sources are important in addressing soldier load and logistics issues, the use of high power devices will diminish the energy benefits offered by high energy sources. This is likely to dictate that hybrid power systems, combining high power and high energy sources, are implemented to meet the high power requirements whilst maintaining high energy. However, hybrid systems should only be considered when a single source solution is unable to meet the power and energy requirements of the system.

Soldier power is a vast technological domain and there are many areas that must be considered and developed to realise an optimal solution for future dismounted soldiers. There is a number of promising source technologies, ranging from advanced batteries to portable fuel cells to energy harvesting devices. The technological maturity, system weight and logistical requirements of power source technologies are key factors in determining a preferred soldier power solution, although other aspects, such as cost and safety, must be considered. Ideal solutions will reduce the weight and logistical burden of soldier power provision, but they must be adaptable to the battlefield environment.

# 7. Reference List

[1] National Research Council. Meeting the Energy Needs of Future Warriors. Washington D.C., USA: The National Academies Press, 2004.

[2] Task Force Devil Combined Arms Assessment Team. The Modern Warrior's Combat Load - Dismounted Operations in Afghanistan. U.S. Army Centre for Army Lessons Learned, 2003.

[3] Dobias, P, Po, K. Power Requirements for Dismounted Infantry – Phase II: Alternative Solutions for AA Batteries. Ottawa, Canada: Defence Research and Development Canada - Centre for Operational Research and Analysis, 2009.

[4] Andrukaitis, E, Soulliere, P. Power Systems Issues For Canada's Integrated Soldier Systems Project, in Soldier Technology Global Conference, London, UK, 2008.

[5] Stone, J. Directorate of Combat Developments U.S. Army Infantry Center, in Soldier Technology Global Conference, London, UK, 2008.

[6] Lewis, N, et al. Portable Energy for the Dismounted Soldier. McLean, USA: The MITRE Corporation, 2003.

[7] Erwin, S. Army, Marines Face Uphill Battle To Lighten Troops' Battery Load, 2011. Last viewed 18 October 2011, <http://www.nationaldefensemagazine.org/archive/2011/May/Pages/ArmyMarinesFaceUphillBattleToLightenTroops%E2%80%99BatteryLoad.aspx>.

[8] Broussely, M, Pistoia, G. Industrial Applications of Batteries - From Cars to Aerospace and Energy Storage. Amsterdam, The Netherlands: Elsevier, 2007.

[9] Sorial, N. Soldier Modernisation Program Land 125: Issues and Requirements for Future Soldier System, in Land Warfare Conference, Brisbane, Australia, 2008.

[10] Soar, R, Dougal, R, Neely, W. Contactless Battery Charging for the Future Soldier, in International Soldier Systems Conference, Brighton, UK, 2006.

[11] Linden, D, Reddy, T. Handbook of Batteries. 3rd edn. New York, USA: McGraw-Hill, 2002.

[12] Gardner, C. Expert Assessment of Advanced Power Sources. Ottawa, Canada: Defence Research and Development Canada, 2007.

[13] Pistoia, G. Battery Operated Devices and Systems - From Portable Electronics to Industrial Products. Amsterdam, Netherlands: Elsevier, 2009.

[14] Cristiani, J. The Current Status of Fuel Cell Technologies for Portable Military Applications, in 25th International Battery Seminar and Exhibit, Fort Lauderdale, USA, 2008.

[15] Lithium Iron Disulphide – Handbook and Application Manual: Energizer Battery Manufacturing Inc., 2009.

[16] Brundage, M. Future Trends and Thrusts for Army Manportable Power Sources, in Joint Service Power Expo, San Diego, USA, 2007.

[17] Hill, I. Presentation on Energy Storage, Portable Batteries, State-of-the-Art Overview, in Soldier Systems Technology Roadmap – Power/Energy/Sustainability Workshop, Vancouver, Canada, 2009.

[18] Browning, D, Pointon, K, Reeve, R. Future trends in dismounted soldier power sources, in Soldier Technology Global Conference, London, UK, 2008.

[19] Polyplus Battery Company. Advanced Lithium Battery Technology - Lithium-Air, 2009. Last viewed 6 January 2011, <http://www.polyplus.com/liair.html>.

[20] Lithium/Air Battery Project (Battery 500), n.d. Last viewed 2 August 2012, <http://researcher.watson.ibm.com/researcher/view_project.php?id=3203>.

[21] Power and Energy Strategy White Paper. Army Capabilities Integration Centre - Research, Development and Engineering Command, 2010.

[22] Defense Update. Battery Supplies and Logistics Lessons Learned in Operation Iraqi Freedom, 2004. Last viewed 2010 30 November, <http://defense-update.com/features/du-1-04/batteries-lessons-iraq.htm>.

[23] Andrukaitis, E, Lemelin, C. Approach to Power for the Canadian Soldier System, in International Soldier Systems Conference, Brighton, UK, 2006.

[24] Cadex Electronics Inc. How to Store Batteries, n.d. Last viewed 20 December 2011, <http://batteryuniversity.com/learn/article/how_to_store_batteries>.

[25] Macklin, W, Liddell, T. Integrated Soldier Power – Presentation to Soldier Modernisation. Presentation by ABSL Power Solutions, 2007.

[26] Best, A. Flexible Integrated Energy Device (FIED), in Land Warfare Conference, Brisbane, Australia, 2008.

[27] Gaune-Escard, M, Seddon, K, eds. Molten Salts and Ionic Liquids: Never the Twain? New Jersey, USA: John Wiley and Sons, 2009.

[28] Illig, J, et al. Studies on $LiFePO_4$ as cathode material in Li-ion batteries. ECS Transactions 2010; 28(30): 3-17.

[29] Jugovic, D, Uskokovic, D. A review of recent developments in the synthesis procedures of lithium iron phosphate powders. Journal of Power Sources 2009; 190(2): 538-544.

[30] Kang, B, Ceder, G. Battery materials for ultrafast charging and discharging. Nature 2009; 458: 190-193.

[31] Ceraolo, M, et al. Lithium-ion: Starting-Lighting-Ignition Batteries: Examining the feasibility, in Vehicle Power and Propulsion Conference, Chicago, USA, 2011.

[32] Cadex Electronics Inc. Types of Lithium-ion - Lithium Iron Phosphate ($LiFePO_4$), n.d. Last viewed 21 December 2011, <http://batteryuniversity.com/learn/article/types_of_lithium_ion>.

[33] Burke, A. Performance, Charging and Second-use Considerations for Lithium Batteries for Plug-in Electric Vehicles. Davis, USA: University of California, 2009.

[34] Garche, J, et al. Encyclopaedia of Electrochemical Power Sources. Oxford, UK: Elsevier Science and Technology, 2009.

[35] Roberts, B. Capturing Grid Power. IEEE Power and Energy Magazine 2009; 7(4): 32-41.

[36] Anderson, D. An Evaluation of Current and Future Costs for Lithium-Ion Batteries for use in Electrified Vehicle Powertrains. Master's thesis, Nicholas School of Environment. Durham, USA: Duke University, 2009.

[37] Super Charge Ion Battery (Datasheet): Toshiba International Corporation, 2010.

[38] Advanved Lithium-Ion Battery Module (Datasheet): Altair Nanotechnologies, 2010.

[39] Agrawal, R, Pandey, G. Solid polymer electrolytes: materials designing and all-solid-state battery applications: an overview. Journal of Physics D: Applied Physics 2008; 41(22).

[40] Manuel Stephan, A. Review on gel polymer electrolytes for lithium batteries. European Polymer Journal 2006; 42(1): 21-42.

[41] Basumallick, I, et al. Organic polymer gel electrolyte for Li-ion batteries. Journal of Power Sources 2006; 162: 797-799.

[42] Kopera, J. Sion Power's Lithium-Sulfur Batteries Power World Record Flight, 2010. Last viewed 20 December 2010, <http://sionpower.com/pdf/articles/Sion%20Power%20Zephyr%20Press%20Release%2029-07-2010.pdf>.

[43] Whiting, I. Portable Power Sources – Status of Near Term Technologies, in International Soldier Systems Conference, Brighton, UK, 2006.

[44] Shim, J, Striebel, K, Cairns, E. The Lithium/Sulfur Rechargeable Cell. Journal of the Electrochemical Society 2002; 149(10): A1321-1325.

[45] Grootjes, A, Ruiter, A, Wit, B. Energy supply for the soldier of the future, research activities 2006. Petten, The Netherlands: Energy Research Centre of the Netherlands, 2007.

[46] Rechargeable $LiFePO_4$ lithium-ion battery - Super-phosphate VL 45E Fe (Datasheet): Saft America Inc., 2010.

[47] Lithium Sulphur Rechargeable Battery Data Sheet (Datasheet): Sion Power Inc., 2009.

[48] Mikhaylik, Y, et al. High Energy Rechargeable Li-S Cells for EV Application. Status, Challenges and Solutions, n.d. Last viewed 27 January 2011, <http://sionpower.com/pdf/articles/SionPowerECS.pdf>.

[49] Cameron, C. Supercapacitor Materials for Soldier Systems. Ottawa, Canada: Defence Research and Development Canada - Atlantic, 2006.

[50] Burke, A. Ultracapacitors: why, how and where is the technology? Journal of Power Sources 2000; 91(1): 37-50.

[51] O'Brien, D. EC Capacitors Deliver High Capacitance in a Small Size. Power Electronics Technology Magazine, March 2001.

[52] Shin, D, et al. Battery-Supercapacitor Hybrid System for High-Rate Pulsed Load Applications, in Design, Automation and Test in Europe Conference and Exhibition (DATE), Grenoble, France, 2011.

[53] Larminie, J, Dicks, A. Fuel Cell Systems Explained. 2nd edn. Chichester, UK, 2003.

[54] Chu, D. Fuel Cells For Future Soldier Power: Lessons Learned and The Road Ahead, in Land Warfare Conference, Brisbane, Australia, 2008.

[55] Fernandes, G, et al. Impact of military JP-8 fuel on heavy-duty diesel engine performance and emissions. Proceeding of the Institution of Mechanical Engineers, Part D: Journal of Automotive Engineering 2007; 221(8): 957-970.

[56] DEFLOGMAN Part 2 Volume 2 Chapter 3. Joint Logistics Command - Australian Department of Defence, 2010.

[57] Fuel Cell Test and Evaluation Centre. Fuel Cell Basics, n.d. Last viewed 21 November 2011, <http://www.fctec.com/fctec_basics.asp>.

[58] Wand, G. Fuel Cell History, Part One, n.d. Last viewed 20 December 2010, <http://www.fuelcelltoday.com/media/pdf/archive/Article_1104_Fuel%20Cell%20History%20Part%201.pdf>.

[59] National Research Council. Energy-Efficient Technologies for the Dismounted Soldier. Washington D.C., USA: The National Academies Press, 1997.

[60] Houston Advanced Research Center - Center for Fuel Cell Research and Applications. Honeycomb SOFC design helps reduce SOFC start up time, 2005. Last viewed 10 January 2011, <http://files.harc.edu/Projects/FuelCell/Reports/QuickBriefs/SOFCDesign.pdf>.

[61] Z.Jiang, Dougal, R. A Hybrid Fuel Cell Power Supply with Rapid Dynamic Response and High Peak-Power Capacity, in Applied Power Electronics Conference and Exposition, Dallas, U.S.A, 2006.

[62] U.S. Department of Energy. Comparison of Fuel Cell Technologies, 2008. Last viewed 12 April 2010, <http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf>.

[63] Fuel Cell Test and Evaluation Center. Proton Exchnage Membrane Fuel Cells (PEMFC), n.d. Last viewed 21 December 2010, <http://www.fctec.com/fctec_types_pem.asp>.

[64] Apanel, G, Johnson, E. Direct methanol fuel cells – ready to go commercial? Fuel Cells Bulletin 2004; 2004(11): 12-17.

[65] SFC Smart Fuel Cell Inc. JENNY 600S – Portable Fuel Cell Power System Technical Data Sheet, n.d. Last viewed 8 June 2010, <http://www.sfc.com/images/stories/sfc/Defense/spec_sheet_jenny.pdf>.

[66] SFC Smart Fuel Cell Inc. SFC Power Manager 3G Technical Data Sheet, n.d. Last viewed 8 June 2010, <http://www.sfc.com/images/stories/sfc/Defense/spec_sheet_sfc_pm_3g_af_bwb.pdf>.

[67] Burnett, H. New Fuel Cell System Reduces Weight for Warfighters, 2012. Last viewed 25 January 2012, <http://www.wpafb.af.mil/news/story.asp?id=123285614>.

[68] XX55 Reformed Methanol Fuel Cell (Datasheet): Ultracell Corporation, 2011.

[69] Nagel, F. Electricity from wood through the combination of gasification and solid oxide fuel cells, Ph.D. Zurich, Switzerland: Swiss Federal Institute of Technology, 2008.

[70] Defence Advanced Research Projects Agency. DARPA Hybrid Small UAS Fuel Cell Quadruples Time on Mission, 2011. Last viewed 22 November 2011, <http://www.darpa.mil/NewsEvents/Releases/2011/09/02_DARPA_hybrid_small_UAS_fuel_cell_quadruples_time_on_mission.aspx>.

[71] Fuel Cell Test and Evaluation Center. Alkaline Fuel Cells (AFC), n.d. Last viewed 14 April 2010, <http://www.fctec.com/fctec_types_afc.asp>.

[72] Samuelson, L. Power Generating (Photovoltaic) Textiles, in International Soldier Systems Conference, Brighton, UK, 2006.

[73] Sorensen, B, Breeze, P. Renewable energy focus handbook. Oxford, UK: Elsevier, 2008.

[74] Corriveau, R. Update on Photovoltaics and CIPI, in Soldier Systems Technology Roadmap - Power/Energy/Sustainability Workshop, Vancouver, Canada, 2009.

[75] Skryabin, I. Highly efficient elongate solar cells for energy generation, in Land Warfare Conference, Brisbane, Australia, 2008.

[76] Blakers, A, Weber, K, Everett, V. Sliver Solar Cell Technology. Canberra, Australia: Australian National University, 2006.

[77] Solar energy for soldier mobility. Defence Science Australia, March 2010.

[78] Grätzel, M. Dye-sensitized solar cells. Journal of Photochemistry and Photobiology C: Photochemistry Reviews 2003; 4(21): 145-153.

[79] Halme, J. Dye-sensitised nanostructured and organic photovoltaic cells: technical review and preliminary tests. Master's thesis. Helsinki, Finland: Helsinki University of Technology, 2002.

[80] Eickhoff, L, Kalbfleisch, K. Graetzel cell, n.d. Last viewed 11 January 2011, <https://www.fh-muenster.de/fb1/downloads/personal/Graetzel_cell.pdf>.

[81] Hoppe, H, Sariciftci, N S. Polymer Solar Cells. Advances in Polymer Science 2008; 214: 1-86.

[82] Rao, C, Thomas, P, Kulkarni, G. Nanocrystals: synthesis, properties and applications. Berlin, Germany: Springer, 2007.

[83] Weiss, P. Quantum-dot leap: tapping tiny crystals' inexplicable light-harvesting talent. Science News, June 2006.

[84] Burnett, B. The Basic Physics and Design of III-V Multijunction Solar Cells, 2002. Last viewed 20 January 2011, <http://photochemistry.epfl.ch/EDEY/NREL.pdf>.

[85] Hecht, J. Photonic Frontiers: Thin-Film Photovoltaics: The key to success is higher efficiency, 2009. Last viewed 16 January 2011, <http://www.laserfocusworld.com/articles/2009/03/photonic-frontiers-thin-film-photovoltaics-the-key-to-success-is-higher-efficiency.html>.

[86] Zin, N S, Blakers, A. Silicon Solar Cells for Tandem High Efficiency Solar Cells. Canberra, Australia: The Australian National University, 2008.

[87] Donelan, M. Energy Harvesting, in Soldier Systems Technology Roadmap – Power/Energy/Sustainability Workshop, Vancouver, Canada, 2009.

[88] Amow, G. A Survey of Sub-10W Thermoelectric Generators for Military Applications. Halifax, Canada: Defence Research and Development Canada - Atlantic, 2010.

[89] Andrukaitis, E, et al. Technology Trends, Threats, Requirements and Opportunities ($T^3$R&O) - Study on Advanced Power Sources for the Canadian Forces in 2020. Defence Research and Development Canada - Directorate of Science and Technology Policy, 2001.

[90] Pickard, D, et al. A Self-powered Field Feeding System. Massachusetts, USA: US Army Natick Soldier Centre, 2006.

[91] Venkatasubramanian, R. Microscale thermoelectric devices for energy harvesting and thermal management, in The 6th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion, Berkeley, USA, 2006.

[92] Venkatasubramanian, R, et al. Thin-film thermoelectric devices with high room-temperature figures of merit. Nature 2001; 413: 597-602.

[93] Carr, P. Summary of the Vision and Future Capabilities Workshop, in Soldier Systems Technology Roadmap - Power/Energy/Sustainability Workshop, Vancouver, Canada, 2009.

[94] Wedlock, L. Solar soldiers power up at ANU, 2011. Last viewed 30 Novemner 2011, <http://news.anu.edu.au/?p=10561>.

[95] Engineering and Physical Sciences Research Council. Solar power systems could lighten the load for British soldiers, 2011. Last viewed 30 November 2011, <http://www.epsrc.ac.uk/newsevents/news/2011/Pages/solarsoldiers.aspx>.

[96] Sookdeo, T. Peformance Measurement, Simulation, and Analysis of the Cox Tee Dee 0.010, the World's Smallest Production IC Engine. Maryland, USA: University of Maryland, 2006.

[97] Decuypere, R, Verstraete, D. Micro Turbines from the Standpoint of Potential Users. Brussels, Belgium: Royal Military Academy of Belgium, 2005.

[98] Annen, K, Stickler, B, Woodroffe, J. High Energy Density Electric Power for UAV/UGV Propulsion Using A Miniature IC Engine (MICE). Billerica, USA: Aerodyne Research Inc., 2003.

[99] Tectonica. Power Generation System (PGS) (Datasheet), n.d. Last viewed 18 April 2011, <http://www.tectonica.net/downloads/PGS-PersGenerator.pdf>.

[100] Annen, K, Stickler, D, J.Woodroffe. Miniature Internal Combustion Engine-Generator for High Energy Density Portable Power. Billerica, USA: Aerodyne Research Inc, 2008.

[101] Ferguson, G. Generette's assault on battery power, 2008. Last viewed 18 April 2011, <http://www.australiandefence.com.au/CE300A50-F806-11DD-8DFE0050568C22C9>.

[102] Epstein, A. Millimeter-scale, MEMS Gas Turbine Engines, in ASME Turbo Expo, Atlanta, USA, 2003.

[103] Epstein, A, et al. Power MEMS and Microengines. Cambridge, USA: Massachusetts Institute of Technology, 1997.

[104] Jacobson, S, Li, H, Epstein, A. Microscale Heat Engines, in ed. Mitsos, A and Barton, P, Microfabricated Power Generation Devcies: Design and Technology. Weinheim, Germany: Wiley-VCH, 2009, pp 81-98.

[105] Cronenberg, G. The Stirling Engine, 2005. Last viewed 10 June 2010, <http://cronenberg.cc/gunther/Skripten/Stirling/stirling.pdf>.

[106] Kongtragool, B, Wongwises, S. A review of solar-powered Stirling engines and low temperature differential Stirling engines. Renewable and Sustainable Energy Reviews 2003; 7(2): 131-154.

[107] Mississippi State University. Micro- Cooling, Heating and Power (m-CHP) Instructional Module, 2005. Last viewed 15 December 2011, <http://microchp.msstate.edu/pdf/m-CHP%20Instructional%20Module.pdf>.

[108] Huth, J, Collins, J. Diesel Fuel-to-Electric Energy Conversion Using Compact, Portable, Stirling Engine-Based Systems. Ohio, USA: Sunpower Inc., 2007.

[109] Complete Guide - Modern Soldier Systems, ed. Biass, E. Zurich, Switzerland: Armada International, 2009.

[110] Lemelin, C. Architecture: Manage Your Power Before It Manages You, in Soldier Systems Technology Roadmap – Power/Energy/Sustainability Workshop, Vancouver, Canada, 2009.

[111] Lemelin, C. Power Challenges for an Integrated Soldier System – The cost of power, in Soldier Technology Conference, London, UK, 2007.

[112] Winterhalter, C. Electronic Textiles and Connectors for Soldier networking, in International Soldier Systems Conference, Brighton, UK, 2006.

[113] Swallow, S. E-Textile Power Distribution Electrically Conductive Textiles, State of the Art Overview, in Soldier Systems Technology Roadmap – Power/Energy/Sustainability Workshop, Vancouver, Canada, 2009.

[114] Hui, S, Ho, W. A New Generation of Universal Contactless Battery Charging Platform for Portable Consumer Electronic Equipment. IEEE Transactions on Power Electronics 2005; 20(3): 620-627.

[115] Heller, C, et al. Power-over-Ethernet for avionics networks, in Digital Avionics Systems Conference, Salt Lake City, USA, 2010.

[116] Yates, S. Power Over Ethernet Blends Distributed Power and Data Management, 2009. Last viewed 7 November 2011, <http://www.cotsjournalonline.com/articles/view/101039>.

[117] Gittlen, S. Power over Ethernet: Promise and problems, 2006. Last viewed 7 November 2011, <http://features.techworld.com/networking/2541/power-over-ethernet-promise-and-problems/>.

[118] Macklin, W. Maturing Portable Power Technologies for Soldier Applications, in Soldier Technology Conference, London, UK, 2007.

[119] STANAG 4619 – Electrical Connectivity Standards for Dismounted Soldier Systems (Edn. 2). North Atlantic Treaty Organisation, n.d.

[120] Soldier Systems Technology Roadmap: Projects and Participants Identified at the Power/Energy/Sustainability Workshop. Government of Canada, 2009.

[121] Protonex Technology Corporation. BPM-602 Battlefield Air Operations Power Manager, 2009. Last viewed 21 January 2011, <http://www.protonex.com/downloads/products/Protonex_BPM602_Spec_Sheet.pdf>.

[122] Atwater, T, Cygan, P, Leung, F C. Man portable power needs of the 21st century: I. Applications for the dismounted soldier II. Enhanced capabilities through the use of hybrid power sources. Journal of Power Sources 2000; 91(1): 27-36.

[123] Canadian Department of National Defence. Integrated Soldier System Project (ISSP) - Related R&D Projects, 2011. Last viewed 9 November 2011, <http://www.materiel.forces.gc.ca/en/issp-rrdp.page?>

[124] Vandeventer, T. Soldier Systems Versatility for Mounted/Dismounted Operations, in Land Warfare Conference, Brisbane, Australia, 2010.

[125] Gibson, L. BMS-D Power Source Study. in possession of the author, Melbourne, Australia: Defence Materiel Organisation, 2009.

[126] UBBL06 (Li-145) Technical Datasheet (Datasheet): Ultralife Corporation, 2010.

[127] Land Warrior in Iraq. Combat and Survival, November, 2008.

[128] Tectonica Australia. Tectonica Awarded Capability Technology Demonstrator Project: Soldier Integrated Power System, 2011. Last viewed 17 November 2011, <http://www.tectonica.net/wp-content/uploads/PN107169-Tectonica-Awarded-CTD-Funding-for-SIPS.pdf>.

[129] Fein, G. Battery Supplies Ran Dangerously Low in Iraq. National Defense Magazine, September 2003.

[130] McLeary, P. Experimental Energy in Afghanistan, 2011. Last viewed 10 November 2011, <http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckScript=blogScript&plckElementId=blogDest&plckBlogPage=BlogViewPost&plckPostId=Blog%3A27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3A4f599cd0-471c-45b2-9b00-3b087b6423d5>.

[131] Francis, P, et al. Defense Acquisitions - Decisions Needed to Shape Army's Combat Systems for the Future. United States Government Accountability Office, 2009.

# Appendix A: TRL Definitions and Summary

The readiness of a particular technology for application in soldier power systems is dependant on its technological maturity, which can be measured using a Technology Readiness Level (TRL). TRLs range from one to nine, each of which is explained in Table 4.

*Table 4 Description of Technology Readiness Levels. Source: [131]*

| Technology Readiness Level | Description |
|---|---|
| 1 | Basic principles of the technology have been observed and reported. |
| 2 | Technology concept and/or application formulated. |
| 3 | Analytical and experimental critical function and/or characteristic proof of concept. |
| 4 | Component and/or breadboard validation in laboratory environment. |
| 5 | Component and/or breadboard validation in relevant environment. |
| 6 | System/subsystem model or prototype demonstration in relevant environment. |
| 7 | System prototype demonstration in an operational environment. |
| 8 | Actual system completed and qualified through test and demonstration. |
| 9 | Actual system proven through successful mission operations. |

The TRLs of various technologies have been provided throughout Section 3 and are summarised in Table 5. TRLs are only provided for technologies where the TRL has been stated in a reference or if sufficient information is available to estimate a TRL.

*Table 5 Summary of TRLs*

| Technology | | TRL |
|---|---|---|
| Primary Batteries | Alkaline Batteries | 9 |
| | Li/$SO_2$ Batteries | 9 |
| | Li/$SOCl_2$ Batteries | 9 |
| | Li/$MnO_2$ Batteries | 9 |
| | $LiFeS_2$ Batteries | 8 |
| | Li/$(CF)_x$ Batteries | 8 |
| | Zn-air Batteries | 9 |
| | Li-air Batteries | 3 - 4 |
| Secondary Batteries | Ni-Cd Batteries | 9 |
| | Ni-MH Batteries | 9 |
| | Li-ion Batteries | 9 |
| | Li-poly Batteries | 8 |
| | Li-$FePO_4$ Batteries | 6 – 8 |
| | LTO Batteries | 6 – 7 |
| | Li-S Batteries | 6 |
| Fuel Cells | Proton Exchange Membrane Fuel Cells | 6 - 7 |
| | Direct Methanol Fuel Cells | 6 - 7 |
| | Solid Oxide Fuel Cells | 2 - 5 |
| Energy Harvesting | Flexible Solar Cells | 8 – 9 |
| | Wearable Solar Cells | 5 – 6 |
| | Passive Kinetic Energy Harvesters | 6 - 7 |
| | Miniaturised Thermoelectric Devices | 5 – 6 |
| Microengines | Micro Internal Combustion Engines | 4 |
| | MEMS-based Microturbines | 2 – 3 |
| | Stirling Engines | 5 – 6 |

## DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
## DOCUMENT CONTROL DATA

1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE

Land 125 - Power Technologies Review

3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION)

| | |
|---|---|
| Document | (U) |
| Title | (U) |
| Abstract | (U) |

4. AUTHOR(S)

Brendan Sims

5. CORPORATE AUTHOR

DSTO Defence Science and Technology Organisation
PO Box 1500
Edinburgh South Australia 5111 Australia

| 6a. DSTO NUMBER | 6b. AR NUMBER | 6c. TYPE OF REPORT | 7. DOCUMENT DATE |
|---|---|---|---|
| DSTO-GD-0710 | AR-015-439 | General Document | November 2012 |

| 8. FILE NUMBER | 9. TASK NUMBER | 10. TASK SPONSOR | 11. NO. OF PAGES | 12. NO. OF REFERENCES |
|---|---|---|---|---|
| 2010/1085954/1 | CDG 07/311 | DGLD | 65 | 131 |

DSTO Publications Repository

http://dspace.dsto.defence.gov.au/dspace/

14. RELEASE AUTHORITY

Chief, Land Operations Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

*Approved for public release*

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CITATION IN OTHER DOCUMENTS Yes

18. DSTO RESEARCH LIBRARY THESAURUS

Army personnel, Electric batteries, Fuel cells, Power equipment, Power supplies

19. ABSTRACT

This review provides an overview of the technologies and issues relevant to future dismounted soldier power systems. The issues with current systems are identified, namely weight, volume, cost and logistics, and power source technologies to address these issues are discussed.