THE APPLICATION OF NEW GENERATION BATTERIES IN OLD TACTICAL RADIOS

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PRETORIA

ABSTRACT

Title:	The Application of New Generation Batteries in Old Tactical Radios
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The power requirement for the soldier's equipment is largely supplied by batteries. Situational awareness is critical for a soldier to perform his tasks. Therefore the radio used by the soldier is a key element in situational awareness and also consumes the most power. The South African National Defence Force (SANDF) uses the A43 tactical radio specifically designed for them. The radios are regarded as old technology but will be in use for about another five years.

The radios still use non-rechargeable alkaline batteries which do not last very long and are not cost effective. The purpose of this study is to research the new generation secondary batteries as a possible replacement for the alkaline battery packs. The new generation batteries investigated in this study are the latest rechargeable batteries, also called secondary batteries. They include nickel cadmium, nickel metal hydride, lithium ion, rechargeable alkaline manganese and zinc air.

The main features of rechargeable cells are covered and the cell characteristics are defined to allow the technology to be matched to the user requirement. Li-ion technology was found to be the best choice. This research also showed that international trends in battery usage are towards Li-ion. A new Li-ion battery was designed based on commercial cells. Tests showed that commercial Li-ion cells can be used in the radio and that they outperform the current battery by far.

The study also examined the design of a New Generation Battery System consisting of an intelligent battery, a charger which uses a Systems Management Bus and a battery "state of health" analyser to assist the user to maintain the batteries. Tests were done to demonstrate that the battery can withstand typical military environmental conditions. Expected military missions for a battery system were defined and used to compare the cost between the existing batteries and the new batteries system. Important usage factors which will influence the client when using a New Generation Battery System were addressed.

To summarise, this study showed that by using a New Generation Battery System, the SANDF could relieve the operational cost of the A43 radio while saving on weight and enabling the soldier to carry out longer missions.

Titel:	Die Aanwending van Nuwe Generasie Batterye op ou Taktiese Radios
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Die kragbehoefte van die soldaat se toerusting word grootliks deur batterye voorsien. Bewustheid van die gevegs situasie is van kardinale belang vir die soldaat om sy take te kan verig. Die belangrikste toerusting is dus die soldaat se radio. Die radio is ook die toerusting wat die meeste krag gebruik. Die Suid-Afrikaanse Nasionale Weermag gebruik die A43 taktiese radio wat spesiale vir hulle ontwerp is. Hierdie radios word reeds as ou tegnologie beskou, maar sal nog in gebruik bly tot en met 'n nuwe aanskafingsproses begin word om hulle te vervang.

Hierdie radios gebruik 'n alkaniese battery wat nie herlaaibaar is nie. Hierdie battery hou nie baie lank nie en is nie meer koste-effektief vir die weermag nie. Die doel van hierdie studie is om die nuwe generasie herlaaibare batterye, as 'n moontlike vervanging van die bestaande battery, na te vors. Die nuwe generasie batterye wat in hierdie studie ondersoek is, was nickel cadmium, nickel metal hydride, lithium ion (Li-ion), rechargeable alkaline manganese en zinc-air.

Die hoofkenmerke van herlaaibare batterye word gedek en met die kliënt se behoeftes vergelyk. Li-ion is as die beste tegnologie vir hierdie probleem bewys. Die studie het ook gewys dat die internasionale tendens in herlaaibare batterye wel Li-ion is. 'n Li-ion battery is ontwerp en met die gebruik van komersiële selle gebou. Toetse het bewys dat die Li-ion battery op die radio kan werk en dat dit baie beter as die bestaande battery funksioneer.

Hierdie studie ondersoek ook die ontwerp van 'n Nuwe Generasie Batterystelsel bestaande uit 'n "slim" battery en 'n laaier met 'n "stelsel bestuur bus", sowel as 'n battery analiseerder om die gebruiker met stelselonderhoud te help. Vêrdere toetse het ook bewys dat die battery onder tipiese militêre omgewingskondisies sal kan funksioneer.

Militêre missies is gedefineer en gebruik om 'n kostevergelyking te doen tussen die ou battery en die Nuwe Generasie Battery. Belangrike faktore wat die soldaat tydens die gebruik van Li-ion battery moet weet, is ook uitgewys.

Om op te som, hierdie studie het bewys dat die Suid-Afrikaanse Nasionale Weermag hulle operasionele koste van die A43 radio drasties kan verminder deur van Li-ion herlaaibare batterye gebruik te maak. Verdere voordele vir die soldaat sluit in die moontlikheid van langer missies en 'n vermindering in die gewig wat hy moet dra.

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LIST OF ABBREVIATIONS

°C	Degrees Celsius
4S3P	Four cells in series and three in parallel
A	Ampere
A43	A43 tactical radio
AA	Cell size
AAA	Cell size
ac	Alternating Current
Ah	Ampere-hour
Amrel EL 1132	Electronic Load
C	Capacity
CD	Compact Disk
CMIS	Command Management Information Systems
dc	Direct Current
D-cell	Cell size
doc	Document
dT/dt	Derivative of temperature over time
dV/dt	Derivative of voltage over time
g	Gram
GP1865L200	Cell with a diameter of 18 mm and length of 65mm. Capacity 2 000 mAh
GPI	A battery company in Hong Kong
H	Height
h	Hour
h/day	Hours per day
IC	Integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
kg	Kilogram
km	Kilometre
kN	Kilonewton
L	Length
LED	Light emitting diode
Li-ion	Lithium ion
m	Metre
m3	Cubic metre
mA	Milli-ampere
mAh	Milli-ampere hour
Mil-STD-810F	Military specifications for environmental tests
mm	Millimetre
Mosfet	Metal Oxide Semiconductor Field Effect Transistor
MP 176065	Li-ion 6Ah prismatic cell
MR	Millions of rand
NATO	North Atlantic Treaty Organisation
Ni-Cd	Nickel-cadmium
Ni-MH	Nickel Metal Hydride
PC	Personal Computer
PDA	Personal Digital Assistant
PPTC	Polymeric Positive Temperature Coefficient
R	Rand
RAM	Rechargeable Alkaline Magnesium
RS232	Serial Connection Standard
s	Second

SANDF	South African National Defence Force
SmBus	System Management Bus
t	Ton
UK	United Kingdom
UK MOD	United Kingdom Ministry of Defence
USA	United States of America
V	Volt
VH-D	Nickel Metal Hydride size D cell
VT-F	Nickel-cadmium size F cell
W	Width
W	Watt
Wh/kg	Watt hour per kilogram

1. INTRODUCTION

1.1 BATTERY USE IN THE MILITARY

The addition of more electronic equipment that the soldier has to carry has led to an increase in the demand for portable power sources. The power requirements for the soldier's equipment are largely supplied by batteries. In the US Army inventory there are currently up to 500 items that depend on batteries. In the late 1990s the expenditure on batteries was around US$100 million. Commonly used battery-powered items include radios, laser range finders, night vision equipment and laptop computers, to name just a few. Radios are being used more frequently to ensure extended connectivity. As an example, the initial procurement of 9 000 multi-band intra-team radios was planned, but the decision was changed and 47 000 radios were ordered [1].

The current battlefield has become an electronic landscape. The soldier of today is much better equipped and is using specialised equipment such as night vision goggles, satellite communications, smart weapons and networked sensors. Due to an increased emphasis on situational awareness, there has been an increase in the capabilities of communication technologies, information technologies, electro-optics and satellite-based positioning. However, this has increased the battery burden on the soldier even more [1].

It is calculated that a squad leader in 2002 used to carry 20 lbs of batteries, and now probably carries 35 lbs of batteries. In total, the weight of batteries required for a 30-man platoon works out to 370 lbs, and the soldier carrying the radios will require the most batteries. When a company carries out three-and-a-half 5-day missions in a period of 21 days, the total weight of batteries will be 1.73 tons at a cost of US$1.5 million [1].

The objective of the US army is to meet the power requirements of a 72-hour mission by 2012. The trend is to use COTS batteries (commercial off-the-shelf) instead of specially designed unique batteries. There are good examples specifically of the use of Li-ion rechargeable batteries and zinc-air batteries. It is expected that future solutions will use battery hybrids. Batteries will be used together with other technologies such as fuel cells, microturbines and thermal electric technologies. The individual solider will essentially complement his personal electronics network with a personal power plant [1].

1.2 INTERNATIONAL MILITARY BATTERY PROBLEMS

As indicated above, batteries are currently the core of soldier-portable electronics. But the acquisition, storage, distribution and disposal of over a hundred different battery types is a logistical problem which adds to the risks already inherent in combat. The great demand for batteries during Operation Iraqi Freedom exceeded manufacturing capacity, and battery supplies would have been exhausted if combat operations in Iraq had lasted another 30 days [2].

The other problem with the soldier battery packs is that they are not interchangeable and each requires its own charger. Furthermore, because they are all dimensioned to deliver peak power for each item of equipment, this leads to a higher battery weight than necessary. It is expected that the system of the future soldier will use a central power source to supply the energy for all the different components [3].

When looking at international soldier modernisation programmes, it is obvious that the soldier's power requirement is a very important aspect. The modern soldier will use increasingly more sophisticated devices such as power-hungry C4I systems (computers, communication, command, control and intelligence), surveillance tools, Personal Digital Assistants (PDAs) and infrared sights. These devices require a reliable mobile power source. Development of more advanced military-standard batteries is therefore ongoing, and the investigation into the use of alternative power generation technologies continues. The French Felin programme, for instance, is investigating the use of lithium-ion batteries that can be recharged using a micro-fuel cell, while other programmes are still looking at fuel cells as a possible alternative to conventional batteries [4].

Currently, future soldier programmes are concentrating mostly on the soldiers' uniforms, weapons systems, sensors and communication capabilities, and these are going through a period of revolutionary development. The most critical of these new developments are power supply systems [5]. The requirement is to allow the new electronics-based equipment to function effectively for missions up to 72 hours in length.

The physical load carried by a dismounted soldier of the United States of America (USA) can exceed 100 pounds for certain missions. The USA has developed a new Landwards System [5] for its soldiers which may add 30 pounds of weight, not counting any extra batteries needed to guarantee power for the mission, which would clearly impact on the soldier's combat effectiveness [5].

Since batteries are the generic solution for soldier power, they will be an integral part of hybrid and stand-alone energy sources for the foreseeable future. The challenge is to make them smaller, lighter, cheaper, more reliable and more energy-dense without sacrificing safety [5].

When designing any new electronic equipment for a soldier, one of the important inputs as part of the specification is the power consumption. For instance, in the design of a radio network for tactical operations, the company Rohde & Schwarz stated that energy consumption is not a problem with vehicle-based radio systems. However in the case of man-pack radios, and particularly hand-held radios, it is absolutely essential to take limited battery capacity into consideration [6]. The equipment needs more capacity from the batteries but the soldier wants to carry less weight. The US military has primary batteries that max out at 250 to 300 Wh/kg. The capacity could be sufficient but the military wants to reduce the weight by a factor of five [7].

1.3 SANDF BATTERY PROBLEMS

In a required operational capability [8], the South African National Defence Force (SANDF) pointed out that they carry sixteen different batteries for a specific mission. This is also a logistical problem as well as a compatibility problem for the SANDF. The main problems stated in this document are firstly, that batteries are expensive and the funds for a mission are limited. Secondly, the batteries in the stores seem to have a limited shelf life. For a long deployment the weight added by the batteries is unrealistic. Lastly, the rechargeable batteries lose their charge over time and have to be recharged in the field, which is a problem for certain missions.

In 1993 battery manufacturers started eliminating the use of mercury in alkaline manganese and zinc carbon batteries [9]. The alkaline battery packs for the A43 military radio were qualified in 1993 [10]. Since then, the general feeling among the users is that the alkaline battery packs of today no longer have the same capacity. The question that now arises is whether this change has affected the capability of the SANDF's alkaline battery packs to deliver relatively high currents. Tests described in this report confirm that the current alkaline battery pack will not pass the original qualification tests.

In a work breakdown statement [11] and a project requirement [12], the SANDF "Functional Operational Requirement/Motivation" stated that currently the A43 radio (SANDF tactical radio) uses alkaline batteries. One alkaline battery per A43 under normal field operations lasts a maximum of ±8 hours. The alkaline cells are no longer cost effective, and due to some technology changes the cells are not suitable for high-current applications as required by the A43 radio. The present alkaline batteries are manufactured locally with cells procured overseas. These batteries are primary batteries and are disposed of after use. As a result of the exchange rate, these batteries are no longer cost effective for operational use. It is therefore necessary to investigate alternative cell technologies.

The number of batteries required per year by the SANDF for the A43 radio is around 44 000 [13]. The A43 battery consists of 11 size D cells, in other words the battery manufacturers must import about 500 000 D cells for just one piece of equipment used by the SANDF. Batteries therefore make up a big proportion of their budget for consumables. The SANDF is not involved in a conventional war now, but apart from training when batteries are used, the SANDF is involved in peace-keeping operations in Burundi and other parts of Africa. It has been calculated that in the case of a two-year conventional war, the SANDF would probably spend R11.27 million on batteries for only one battalion. This is confirmed by the fact that the US Army in 1996 spent approximately $100 million on batteries [14].

1.4 PURPOSE OF THIS STUDY

The A43 is a tactical radio used by the SANDF (Figure 1) as an inter-platoon radio. It is a VHF radio with a range of 3 km in the lower power mode and 6 km in the high-power mode. The range depends on the antenna used. The radio has full encryption capabilities and can also be used to send data. It is powered by an alkaline battery pack that clips onto the bottom of the radio. The radio is carried in a dedicated pouch which is big enough for the radio with the battery plus two extra batteries [15].

Figure 1: A SANDF soldier with his radio

The full specifications of the radio as shown in Figure 2 are restricted information [16]. This is a radio developed for the SANDF and is only used by the SANDF. It is therefore obvious that a replacement battery cannot be bought, but must be specifically designed for this radio.

Figure 2: The A43 tactical radio and battery pack

A non-rechargeable battery is also referred to as a primary battery. This study investigates new generation batteries as a possible cost-effective replacement for the current alkaline battery. New generation batteries considered in this study are the latest rechargeable batteries, also called secondary batteries. They include nickel cadmium, nickel metal hydride, lithium ion, rechargeable alkaline manganese and zinc-air. This battery technologies are summarised in the next section.

1.4.1 Lithium Ion (Li-ion)

As a rechargeable battery, Li-ion technology is very promising and has a big market capitalisation. Li-ion has many advantages, the most important of which are listed here. The Li-ion cell has a high operating voltage, namely 3.6 V. Due to its low weight and high capacity, this technology has a high energy density, typically 600 mAh/g. Depending on the usage conditions, a Li-ion battery should have an excellent cycling ability (500 – 1 200 cycles). It has a moderate self-discharge rate (less then 8%/month stored at 20°C). This technology has no memory effect and has unrestricted transportation requirements for low-capacity commercial cells. Li-ion is considered to be environmentally friendly since it contains no heavy metals.

There are some safety concerns regarding Li-ion, but these are addressed by both the cell manufacturer and the battery designer [17]. The application of Li-ion is very similar to that of other rechargeable products such as Ni-Cd and Ni-MH. There are three markets in which Li-ion batteries enjoy wide acceptance, namely cellphones, digital cameras and laptop computers [17]. Other markets, which are smaller but growing, are military radio communications, outer space equipment and electrically driven vehicles.

1.4.2 Nickel Metal Hydride (Ni-MH)

Ni-MH technology is similar to the well-known Ni-Cd, but with added advantages. This technology is less prone to memory effects than Ni-Cd, therefore periodic exercise cycles are required less often. Ni-MH has no special storage or transportation requirements. The technology is considered to be environmentally friendly (contains only mild toxins). Ni-MH cells exhibit a high capacity, up to 700 mAh (AAA cell size) or 2 200 mAh (AA cell size) and can deliver 70% of their rated capacity when subjected to a high discharge rate. The biggest disadvantage of Ni-MH is the self-discharge rate of about 15% per month at 20°C [19]. Typical applications of Ni-MH include digital cameras, portable electronic devices, remote controls and emergency lighting [20].

1.4.3 Nickel Cadmium (Ni-Cd)

A Ni-Cd battery is one of the most rugged rechargeable batteries. Economically priced, the Ni-Cd is the least expensive battery in terms of cost per cycle. Ni-Cd batteries are available in a wide range of sizes and performance options. Ni-Cd has simple charge requirements and can be charged quickly even after prolonged storage. It can also be charged at low temperatures. If properly maintained, the Ni-Cd provides in excess of 1 000 charge/discharge cycles. But if not properly maintained, the cells lose capacity due to the memory effect. This technology can supply very high currents. The cells are considered to be robust and have a long shelf life in any state of charge. Their biggest disadvantage is that they contain cadmium which is very toxic [14]. Over 50% of all rechargeable batteries fitted to portable equipment are of the Ni-Cd type. Amongst rechargeable batteries, the

Ni-Cd battery remains a popular choice for applications such as two-way radios, emergency medical equipment and power tools. Ni-Cd is widely used for critical standby power applications where its reliability and long life count [22].

1.4.4 Rechargeable Alkaline Manganese (RAM)

The rechargeable alkaline battery combines the high capacity and long shelf life of primary alkaline batteries with the cost saving of rechargeable batteries. Although the performance of RAM batteries may be slightly less than that of primary alkaline, their rechargeability allows a single cell to provide cumulative benefits [23]. Typical applications of RAM batteries include portable radios, cassette/CD players, torches, garden lights, calculators and remote control units [24].

1.4.5 Zinc-air

Zinc-air cells function in the same way as conventional batteries in that they generate electrical power from chemical reactions. Instead of containing the necessary ingredients inside the cell, zinc-air batteries use a main reactant, oxygen, from the outside air [25]. At this stage, zinc-air cells are not rechargeable but they could be in the near future. Studies have also shown that zinc-air batteries combined with rechargeable batteries could also be a solution.

Zinc-air cells have the highest energy density amongst all primary cells. They are capable of providing up to three times the energy of common alkaline batteries in a more compact package. Zinc-air cells are environmentally friendly, they can be disposed of safely in landfills with no toxic material concerns and transportation is unrestricted. In general they have good safety properties [26][27].

The current applications of zinc-air cells include navigational aids and hearing aids. There are some applications in hand-held electronics, such as cellphones, PDAs, digital still cameras and video cameras. New markets for zinc-air cells include electrically driven vehicles and military applications [26][27].

1.4.6 Methodology used

The purpose of this study is to research the new generation secondary batteries as a possible replacement for the alkaline battery packs used in the A43 tactical radio. To find a solution, research should first be done into battery cell technology to ensure that the capabilities and limitations of the different technologies are well understood. The study then examines the design of a New Generation Battery System, namely a rechargeable battery, a charger and the maintenance concept. Cost comparisons of the new batteries are made since cost is important for the user. Lastly, the use of the New Generation Battery System in a military environment must be investigated.

Figure 3 shows that the approach for designing a mobile battery system must involve all system components, including the user and the environment. Questions must be addressed such as: What are the critical operational parameters and how do they change with time and environment? What are the effects of extremes of temperature, pressure and impact? The goals of reliability and positive user experience require that design should address the correct user problems and operational concepts [18].

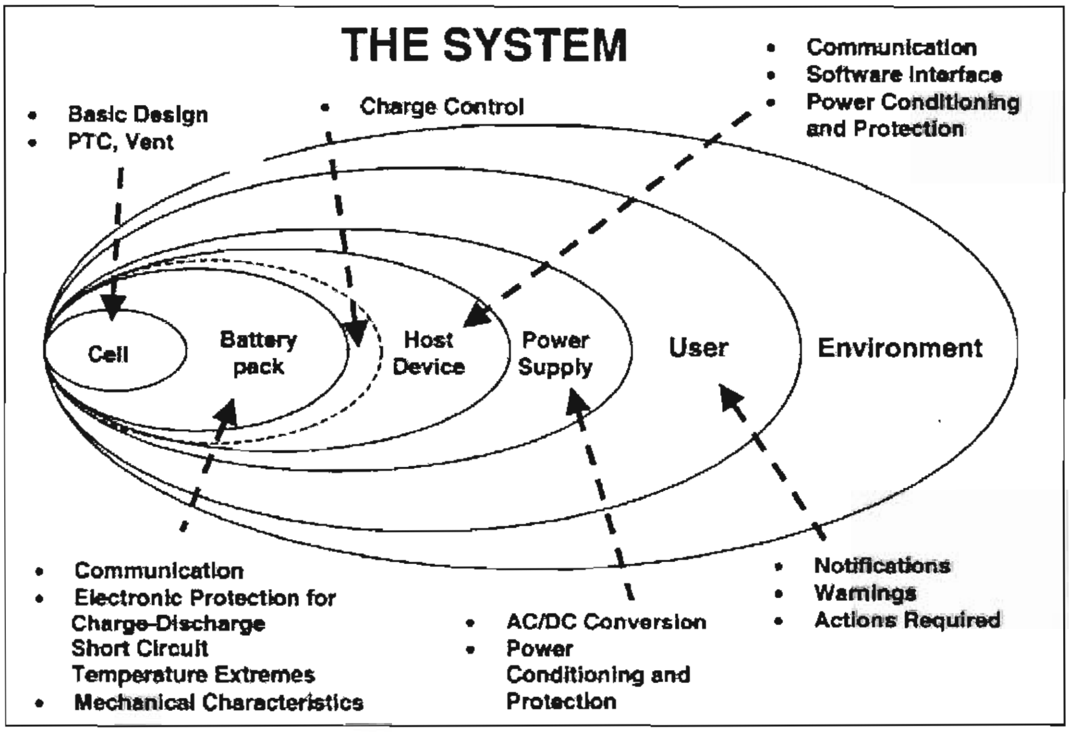

Figure 3: Conceptual diagram of a mobile device and its user

The SANDF is the main stakeholder and for them to benefit from this study the following factors must be addressed: the solution should be cost effective and should be based on mature and stable battery technologies. The output of this study should lead to a product design phase and the information could be used in future product requirements for the acquisition of batteries.

Command Management Information Systems (CMIS) is responsible for the operational logistic budget of the SANDF. A new generation battery will require a new logistic and maintenance concept from the SANDF, but they could save millions of rand in the long term.

A New Generation Battery System should relieve the operational cost of military units in general, but units responsible for training will benefit the most. When a New Generation Battery System is in place, the cost of maintaining it will be a great deal less. The more these type of batteries are used the better the financial return will be.

The infantry soldier cannot throw away spent batteries as he is now used to doing. However, new generation batteries will save him weight and will allow him to carry out longer missions.

What is learned from using new generation batteries in the old tactical radios will be used as important inputs to the projects for designing new tactical radios.

1.5 OUTLINE OF THIS STUDY

A schematic presentation of the work done in this study is presented in Figure 4.

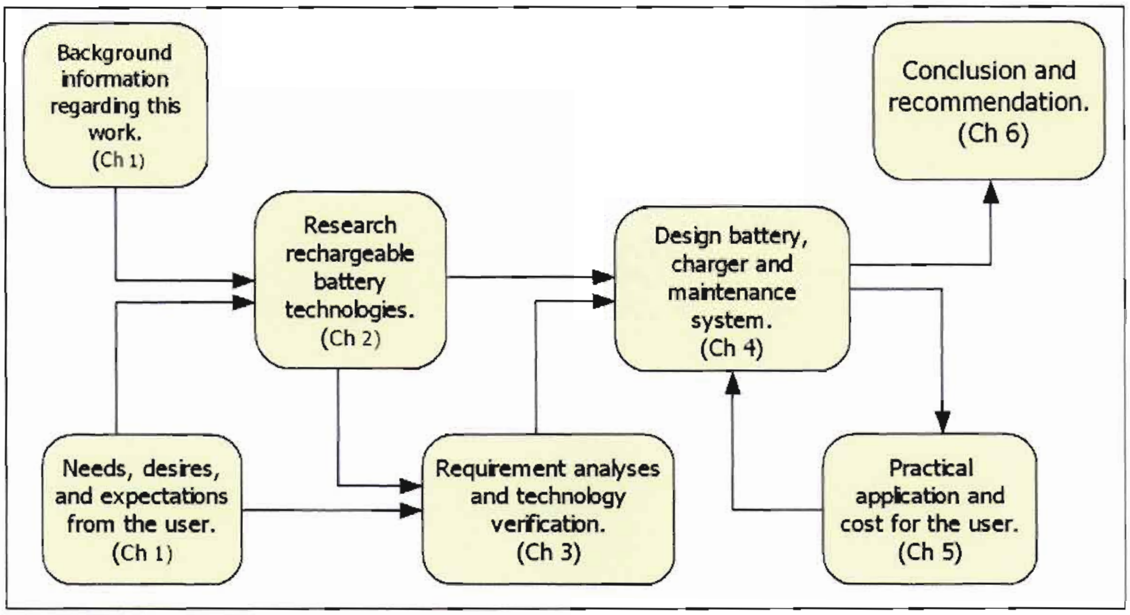

Figure 4: Schematic layout of this study

Chapter One looks at the global problem of batteries in the defence environment and the problems in the SANDF regarding batteries. Some details of the SANDF requirement are given and the A43 tactical radio is described.

To address the problem, *Chapter Two* contains a detailed literature survey of the different battery cell technologies. The main features of rechargeable cells are covered and the cell characteristics are defined to allow the technology to be matched to the user requirement. For a complete system solution, battery charging was also taken into consideration. A user criteria and value system was defined and the technology was mapped onto the value system.

In *Chapter Three* the final decision on which battery technology to use was made. Part of the decision input was to look at batteries for similar devices, namely laptops and hand-held devices as well as world trends for military batteries. Li-ion cells came out as the best option for this application. Li-ion prototype batteries were then compared with the current battery pack by carrying out suitable tests.

Selection of the appropriate battery cell is just part of the solution. In *Chapter Four* a New Generation Battery System is described which is designed to include charging and maintenance. Some of the design concepts were verified by tests. The system requirements are defined as well as the required verification tests.

Chapter Five covers the important factors which will influence the client when using a New Generation Battery System. User guidelines are addressed based on an understanding of Li-ion technology requirements, the impact on users of the New Generation Battery System and safety precautions. The operational and maintenance concepts were defined and were used to do a tactical cost analysis.

Chapter Six summarises the key findings of the study and shows the value gained for the customer. Recommendations regarding future studies are included.

2. BATTERY CELL TECHNOLOGIES

2.1 INTRODUCTION

This section investigates the new generation secondary batteries as a possible replacement for the alkaline battery packs used in the A43 tactical radio. The choice of the best battery technology for this application is not obvious, as the A43 military radio uses a variable load with high current peaks (2 A) in transmit mode [16] and the military in general has unique user requirements. The present available and mature cell technologies were investigated to gain an understanding of both the technology and characteristics of rechargeable cells. This chapter also matches the user requirements to the cell technologies with the intention of identifying a technology that will suit most requirements. Chargers and charging techniques also played a role in identifying the most suitable rechargeable technology.

All values used in the comparison of cell technologies were based on commercially available cells. It is obvious that different manufacturers have different values, but this should not cause a significant comparison difference in the final choice.

The way in which the user will eventually use the batteries is very important in making a choice. For instance, how long will the batteries lie on a shelf between missions? This chapter concentrates on general use until a rather more detailed user scenario has been defined. All the values have been theoretically calculated and have not yet been verified in the laboratory.

The study concentrated on the following technologies: Nickel cadmium (Ni-Cd), which is a fairly old but reliable technology. Nickel metal hydride (Ni-MH), which is the successor of Ni-Cd. Lithium ion (Li-ion), which is a relatively new technology for radios but a well-known technology used in cellphones. Rechargeable alkaline manganese (RAM) was also investigated since this alkaline technology could be a direct replacement for the current alkaline battery with the advantage that it is rechargeable. Zinc-air cells were included in the comparison stage even although they are not strictly rechargeable. Zinc-air cells can only be recharged in a laboratory. It is not clear whether a rechargeable technology is the best solution, especially for critical missions. Fuel cells were not used in the comparison as it was felt this is still a new technology, and if they were included, they could be a clear-cut winner. In essence, we would then not be comparing apples with apples.

2.2 BATTERY CELL CHARACTERISTICS

This section compares the typical characteristics of the different rechargeable cell technologies. Cells are compared according to each characteristic without yet directly linking it to the user requirement. The characteristics covered in this section are summarised in Table 1.

Table 1: Battery cell characteristics

Characteristic	Description
Voltage window	Different technologies produce a different voltage per cell
Battery capacity	This gives an indication of how long a battery will last
Energy density	This gives an indication of the weight and size of a battery
Ageing effect	Describes the reasons why batteries do not last forever
Capacity fading	Explains why the capacity of batteries reduces over time
Self-discharge	What happens if a battery is left unattended
Cycle life	How many times a battery can be charged and discharged
Internal resistance	This is directly related to the battery's ability to provide high currents
Temperature characteristics	The performance of batteries at high and low temperatures
Balancing requirements	This is needed because a battery is built up of a number of cells which can influence each other
Electronic protection	High-capacity batteries must be protected from misuse
Short circuit	How batteries can be protected from a short circuit
Battery safety	How a battery can be used under various circumstances
Disposal of batteries	Whether the battery is toxic to the environment
Smart batteries	Smart batteries can communicate with their host and their charger for optimum power management

Cost factor	Usually an important consideration for a user
Transportation regulations	High-capacity batteries will have regulations to guarantee safe transport
Battery packs	To build a battery it is necessary to connect cells in series and parallel combinations
Battery charging requirements	Different technologies requires different chargers

2.2.1 Voltage window

The voltage window of a cell plays a role in the design of the battery pack. It will influence the maximum and minimum voltage of the battery pack acceptable for the equipment. When discharging the battery pack, the cell voltage should optimally be taken quite low to have an economic and efficient battery pack. All these voltage limits will change depending on the type of cell used.

Li-ion cells have a voltage window of 4.0 - 4.3 V during charge and 2.5 - 2.75 V during discharge. This voltage window should be adhered to in accordance with the precise and specific requirements of the manufacturer. Discharging Li-ion cells below 2.5 -2.75 V leads to electrochemical corrosion of the copper carrier of the negative electrode. Overcharging of Li-ion cells above the 4.0 - 4.3 V upper limits would be even riskier and could lead to thermal runaways with possible fire and explosion [17].

Ni-Cd and Ni-MH cells have a cell voltage of 1.2 V. Neither cell condition nor state of charge can be determined by open circuit (no load). Within a short while after charging the voltage may be above 1.4 V. It will fall shortly thereafter to 1.35 V and continue to drop as the cell loses charge. At normal discharge rates, the voltage drop is nearly flat until the cell approaches complete discharge. The battery provides most of its energy above 1.0 V per cell. Ni-Cd and Ni-MH cells are normally charged to 1.40 - 1.42 V per cell to avoid gassing. Gassing begins at about 1.47 V, and charging at this rate should be avoided as water usage becomes excessive [22] [20].

Alkaline batteries have open circuit cell voltage ranges of 1.5 - 1.6 V. Nominal voltage is 1.5 V. Operating voltage is dictated by the state-of-discharge and the actual load imposed by the equipment. The voltage profile under discharge is a sloping curve. In most instances, 0.8 V is considered the end-voltage. RAM batteries can be charged in a constant voltage or pulse charger. The end voltage must be limited to 1.65 ±0.05 V. With pulse charging, a 1.7 V pulse is applied to the cell for a very short period [23] [24].

The nominal voltage for most makes of zinc-air cells is 1.4 V and the end voltage is 0.9 V. Some cells have voltages from 1.9 V up to 4.5 V depending on the cell design [26] [27].

The maximum voltage specification of the system will determine the number of cells used in series. The minimum voltage of the equipment will define the actual cut-off voltage of the cells. If this cut-off voltage is higher than the mentioned low voltage, the actual capacity of the battery will be lower than the manufacturer's specified capacity. In other words, the equipment does not use all the power of the battery. In the case of Ni-Cd and Ni-MH batteries, a periodic full discharge is necessary to prevent a memory effect.

2.2.2 Battery capacity

Capacity is calculated by obtaining the product of the discharge current and the discharge duration in case of discharge at constant current. In the case of a constant load, the integration of the cell voltage versus time curve must be obtained [17].

The initial capacity can further be defined as the electrical output, expressed in ampere-hours, which the fresh, fully charged battery can deliver to a specified load. The rated capacity is a designation of the total electrical output of the battery at typical discharge rates. For example, for each minute of radio operation, 6 seconds shall be under transmit current drain, 6 seconds shall be under receive current drain and 48 seconds shall be under standby current drain [28].

Many parameters may interfere with the capacity [17]:

- State of charge.
- Storage conditions.
- Number of charge/discharge cycles.
- Discharge current. Normally limited by the manufacturers.
- Minimum acceptable end-of-discharge voltage.
- Maximum acceptable end-of-charge voltage.
- Temperature.

Capacity is therefore an average value under standard conditions. In the comparison of the capacity of cells, it is important to consider the current drawn from the equipment. If a cell is not designed for high-current applications, the cell capacity will dramatically drop off when drawing higher currents. The difference is illustrated in Figure 5 and Figure 6. In Figure 5, the graph illustrates the voltage drop when a current was drawn within the cells' specification.

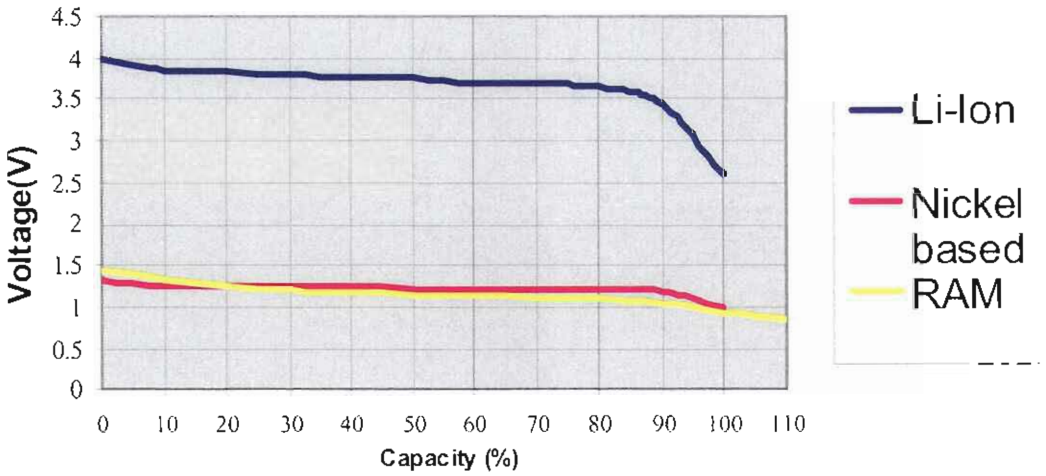

Figure 5: Voltage versus capacity with a low current draw

In Figure 6, higher currents were drawn and a big reduction in capacity can be noted in the RAM cells, which are not designed for high currents.

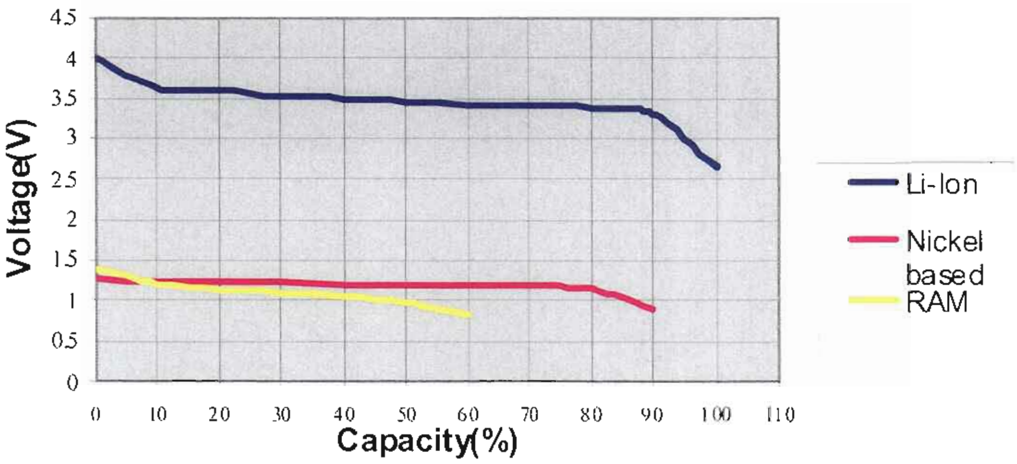

Figure 6: Voltage versus capacity with a high current draw

The graphs in Figure 5 and Figure 6 are produced from cell specification values found in [23], [27], [29], [30] and [31].

The electronic protection circuit associated with high-capacity cells induces some voltage drop, which may impact on the capacity at high currents. It is advisable to check if the rated capacity applies to the cell without the electronic protection [19].

The standard cell rating, often abbreviated as C, is the capacity obtained from a new, thoroughly conditioned cell subjected to a constant-current discharge at room temperature after being optimally charged. Since cell capacity varies inversely with the discharge rate, capacity ratings depend on the discharge rate used. The rated capacity is normally determined at a discharge rate that fully depletes the cell within five hours. In other words, a capacity measured when drawing a current of 0.2C [20].

The published C value may reflect either an average or a minimum value for all cells. Typically, Ni-Cd cells are rated on the basis of minimum values, while nickel-metal-hydride cells are rated on average values. The difference between the two values may be significant (~10%) depending on the variability in the manufacturing process [20].

The new generation of zinc-air cells have a capacity of 8 Ah at 0.5 A (+25 °C). With recently developed battery pack configurations, capacities of up to 60 Ah and above have been achieved. Even larger capacities are dealt with in electrically driven vehicle zinc-air battery packs [32].

2.2.3 Energy density

The energy density of a battery is a measurement of how much energy the battery can supply relative to its weight or volume. These two concepts combine the cell operating voltage and the capacity delivered per weight or volume unit. The energy density is expressed in watt-hours per kilogram or litre. The power density is expressed in watts per kilogram or litre [28]. As Li-ion is light and operates above 3 V, it easily outclasses the traditional rechargeable products such as lead-acid, Ni-Cd and Ni-MH (see Figure 7).

Alkaline cells have a good energy density when operating at less than 1 A draw rates. Rechargeable alkaline cells have a greater internal resistance than Ni-Cd and Ni-MH batteries and are therefore able to deliver energy as efficiently at high rates of discharge. A rechargeable alkaline battery will provide significantly higher capacity than a Ni-Cd battery at low currents, but this advantage diminishes with increased loads [30].

The zinc-air cell has the highest energy density because of the metallic zinc as its negative electrode, oxygen in the air as its positive electrode and aqueous potassium hydroxide as its electrolyte. The "air breathing" nature of the zinc-air battery is directly responsible for the high energy density of the technology as it avoids the need to include heavy, bulky metal oxidisers as part of the battery [33]. This translates into more energy per kilogram and more energy per litre than traditional technologies as detailed in Figure 7.

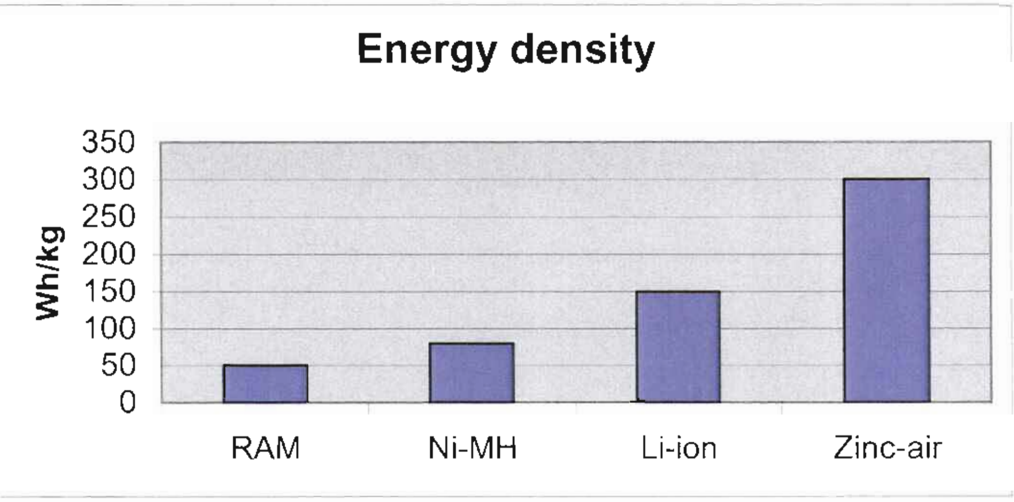

Figure 7: Energy density comparison

The graphs in Figure 7 are produced from cell specification values found in [23], [27], [29], [30] and [31].

2.2.4 Ageing effect

Ageing is the capacity lost from cycle to cycle rather than self-discharge [17]. A battery is a perishable product that starts deteriorating right from the time it leaves the factory. Lithium-ion batteries have many advantages over Ni-Cd and Ni-MH batteries, but the biggest disadvantage of Li-ion batteries is ageing. Capacity deterioration is noticeable even after one year, whether the battery is in storage or in use, and after two years the battery frequently fails. This poses a problem in defence applications where storage of batteries for operational readiness is important. It is not recommended that Li-ion batteries be kept in storage for a long time. When buying Li-ion batteries, the manufacturing date must be verified [19].

The Ni-Cd battery is very robust and can be charged even after prolonged storage. The biggest disadvantage is a possible memory problem when the capacity of the battery diminishes because of the formation of crystals inside the battery [34].

Alkaline cells can be stored for months on the shelf as they have a low self-discharge rate. RAM batteries show a very high capacity on the first discharge but the capacity diminishes rapidly with each cycle, especially if the battery has gone through a deep discharge cycle [23].

Zinc-air cells have a shelf life of two years in their original packaging. They have an active life of about two months after being removed from the packaging if stored in the re-closable pouch [27].

2.2.5 Capacity fading

During repeated cycles, all cells tend to have less and less capacity. The degree of capacity fade will not be the same in all applications. It depends on factors such as the rate of discharge and the end-point voltage at which the discharge is terminated. These relate to the "depth of discharge" or the amount of energy withdrawn from the battery prior to recharge for each cycle.

Most cells are damaged by deep cycling. This occurs if a battery is discharged completely (or nearly so) before recharging. Leaving a battery in a discharged state even for a week also damages it [19].

The capacity fading of Li-ion cells is due to oxidation, which occurs naturally as a result of ageing. Usage does not contribute much to capacity fading as the typical lifespan of a Li-ion cell is two to three years, whether in use or not [19].

Ni-MH and Ni-Cd batteries are considered high-maintenance batteries which require regular discharge cycles to prevent "memory" effects. Although the Ni-MH battery was originally advertised as "memory-free", both Ni-Cd and Ni-MH batteries are similarly affected by "memory". "Memory" may not be as apparent in the Ni-MH battery because of its shorter cycle life as compared to the Ni-Cd's cycle life [48].

Charging RAM batteries after partial discharge will extend their service hours. On each successive discharge, the capacity of the battery will be lower in comparison to the previous cycle. Under deep discharge conditions, the capacity of the 25th cycle is about half of the initial capacity. Under partial discharge conditions, the reusable alkaline cell can last for several hundred cycles. The standard claim of 25 cycles for RAM batteries is based on typical consumer use products [30].

It should be kept in mind that if a cell is terminated at a higher end-point voltage it will not deliver as much energy during each discharge cycle. As a result, the benefits of reduced capacity fade may not be as significant when the total run-time of the device over the total useful lifetime of the battery is considered [30].

2.2.6 Self-discharge

The self-discharge rate is the rate at which the battery will lose charge during storage or other periods of non-use [28] (see Figure 8).

Li-ion batteries have a low self-discharge rate compared to Ni-Cd and Ni-MH batteries. However, the Li-ion's capacity is only partly reversible. As described under ageing, capacity deterioration is noticeable after one year, whether the battery is in storage or in use. Self-discharge is markedly affected by the cell's state of charge, temperature and the electronic protection circuits. Self-discharge specifications do not usually include the current drawn by the electronic circuits [17].

At room temperature, Ni-MH batteries not in use will self-discharge in around 30 to 60 days, depending on environmental conditions (see Figure 8). In other words, if the batteries are left on the shelf for more than 30 to 60 days, they should be recharged before use. It is normal that batteries are fully discharged after long-term storage [31].

At room temperature (25 °C), RAM batteries retain 80% of their energy for up to five years. Under the same conditions, a consumer-type Ni-Cd battery will retain 80% of its energy for less than one month [24]. Even at elevated temperatures, RAM batteries have superior capacity retention [23].

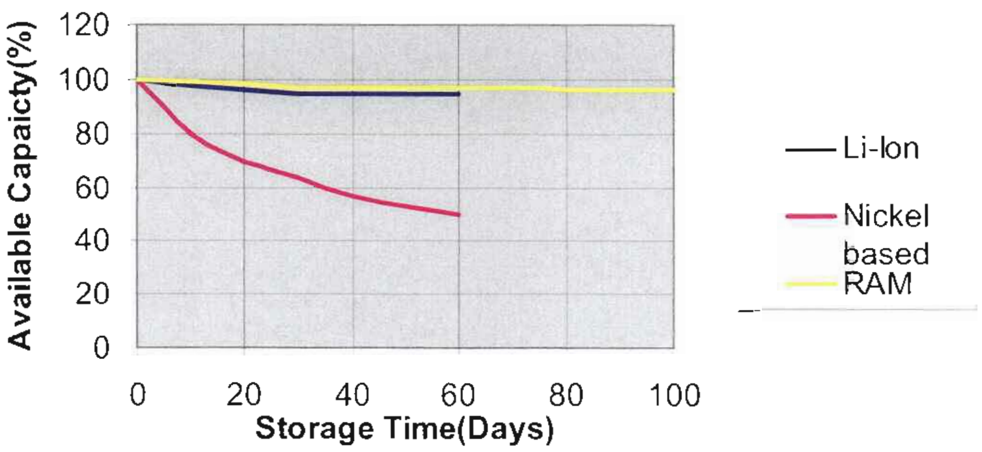

Figure 8: Capacity versus storage time

The graphs in Figure 8 were produced from cell specification values found in [23], [27], [29], [30] and [31].

2.2.7 Cycle life

The cycle life is the number of cycles that the rechargeable battery can be charged and discharged before it no longer holds or delivers any useful amount of energy [28]. The retained percentage of the cell's nominal capacity, considered as an acceptable minimum, is 60%. The minimum number of cycles usually specified is 500. This would imply an average capacity fade of below 0.08% per cycle. The number of cycles will depend on [29]:

- The cell design (manufacturer).
- The depth of discharge, which if limited, will increase the cycles.
- The charge end-voltage (the lower the better if it is a nickel-based cell).
- The temperature (which accelerates cell ageing).

2.2.8 Internal resistance

A cell's internal resistance under load leads to a voltage drop. The lower the internal resistance, the higher the cell's available voltage and capacity will be. This is important when drawing higher currents. The protection electronics must be borne in mind as this also contributes to the total internal resistance [17].

The internal resistance is the gatekeeper of a battery and largely determines the performance and run-time [48]. High impedance curtails the flow of energy from the battery to the equipment. When a heavy current is drawn from a high-impedance battery, the voltage drops, triggering the "low battery" indicator. The battery may hold sufficient capacity although the equipment cuts off and the residual energy remains undelivered [19].

Maintaining low impedance in a battery is important, especially with devices requiring high-surge current. The impedance of a nickel-based battery can increase drastically if not properly maintained [19]. In general, RAM batteries have a high internal resistance and are not suitable for high-current applications [30].

The discharge curve of zinc-air cells used in hearing aids is relatively flat. Their internal resistance is only moderately low and they are not suitable for heavy or pulsed discharging [35].

2.2.9 Temperature characteristics

Chemical reaction rates decrease as temperatures drop. All batteries suffer from a loss in performance at lower temperatures. Similarly, at slightly elevated temperatures, a greater capacity can be delivered by the cells (see Figure 9). However, if the temperature increases beyond a certain level, internal gas pressures build up and may cause cell failure [30].

In general, Li-ion, Ni-MH and Ni-Cd batteries have to be stored cool between -20 °C and +30 °C. Their operational temperature is between -20 °C and +60 °C. Charging below 0 °C or above 60°C is not recommended [17].

The use of RAM cells in cold environments leads to a significant capacity degrading. These cells operate adequately at higher temperatures. The excellent high-temperature charge retention [23] and charge acceptance of RAM batteries allow for effective use of solar energy for recharging [24].

Charging Ni-Cd cells below the recommended temperature can cause oxygen pressure build-up and activate the resetable safety vent. Multiple vent activations will reduce cell capacity [19].

The larger versions of zinc-air cells can operate in temperatures as low as -20 °C and as high as +60 °C [32].

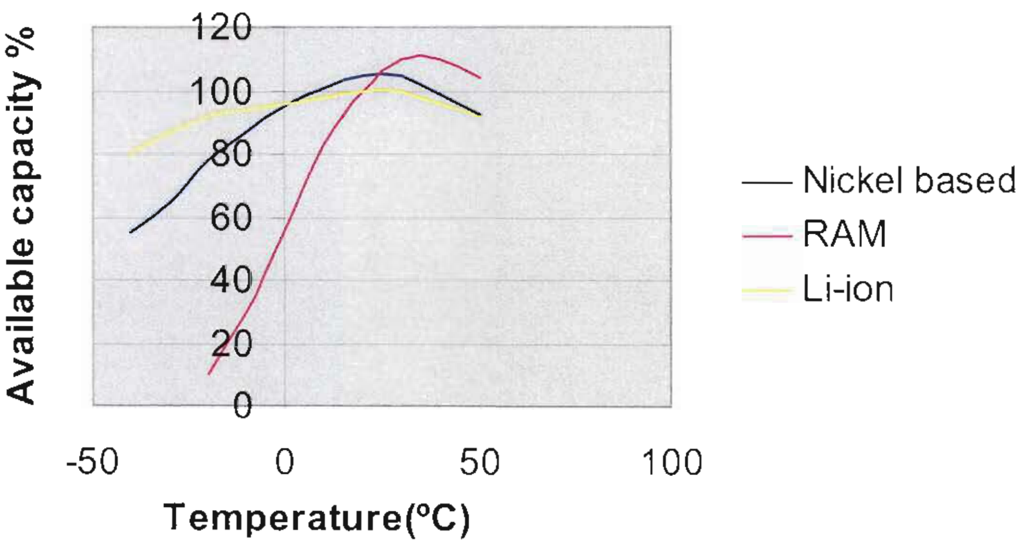

Figure 9: Capacity versus temperature

The graphs in Figure 9 were produced from cell specification values found in [23], [27], [29], [30] and [31].

2.2.10 Balancing requirements

In the manufacture of a battery consisting of more than one cell, special electronics are included to ensure that all cells are evenly charged. Charge balancing electronics achieve cell equalisation by electronically altering the state of charge of individual cells within the series string. Individual cells may require periodic state of charge adjustments due to drift caused by changes in internal impedance, changes of cell capacity due to ageing, increased self-discharge and exposure to thermal gradients. Without cell balancing, charging or regenerative performance of the pack is limited by the highest charged cell. High power discharges are limited by the lowest-charged cell [36].

There are two built-in balancing functions for equalising the power distribution on each cell in a battery pack. This is normally carried out via electronic components which are fitted either on the instrument's printed circuit board or its charger. When the instrument uses an amount of power from its battery pack, each cell inside the battery pack must supply equal amounts of power. In addition, when the battery pack is charging, each cell must collect the same amount of charge in the charging period [36].

To reduce the electronic sophistication of cell balancing, a battery pack with cells that has the needed capacity rating (at the required peak current) should be built, instead of paralleling a number of small cells. Ni-Cd, Ni-MH and Li-ion technologies have very high-capacity cells available [31].

Cell balancing improves battery performance, but because of the extra current needed for the electronics, high-capacity batteries are more suited for balancing circuits. Li-ion cells must have protection circuits and the balancing electronics are usually combined with the protection circuits.

Extra electronics on RAM cells must rather be relatively simple and inexpensive to suit this low-priced technology which has a limited number of discharge cycles [30].

A number of zinc-air cells can be configured in series to form a battery pack. The zinc-air battery comprises cells connected in series within modules and modules can be connected in parallel or in series to make up a battery with the required voltage and capacity. Zinc-air batteries are highly dependant on a good diffusion air management system, and thus proper provision in this regard should be made to guarantee good operation of a battery pack [25].

2.2.11 Electronic protection

Cells have to be protected on an individual basis from current and voltage excursions outside strictly defined ranges [17]. Most of the major electronic chip manufacturers sell protection circuits for the different types of cells. The function of these protection circuits is [19]:

- Cell balancing to get evenly charged cells.
- Smart management bus systems to communicate with the host equipment.
- Gas gauges.
- Over-voltage protection during charge.
- Under-voltage protection during discharge.
- Over-current protection.

The most important factor in maintaining rechargeability is to avoid over-discharge or cell reversal. When multiple cells are connected in series, there will be some degree of mismatch between the cells. One cell in the set will reach the low voltage point first and then rapidly drop to zero (or negative) voltage, while the other cells are still delivering energy to the load. In systems operating from primary batteries, the end voltage is not a concern. Once the batteries have been depleted, they are replaced with new cells. With rechargeable batteries, however, the repeated or extended reversal of cells will reduce the performance of the battery after subsequent recharges.

Battery management circuitry can sense cell voltages and automatically shut off the load (or indicate a low battery warning) when a low cell voltage is observed. When cells are connected in series, voltage sensing is most effective when the voltage of each individual cell is sensed rather than the sum of all cells. This accounts for any cell variation that may exist. If this is not possible, the voltage cut-off for the series stack should be set high enough so that cell reversal is unlikely. The goal of battery management circuitry is to optimise the trade-off between single-cycle capacity and multiple-cycle battery life [30].

Some battery management circuits, for instance Ni-Cd and Ni-MH systems, have operating currents in the range of a few hundred micro amps. This current could fully drain a small cell in one or two months. Background currents at this level are not a problem with these chemistries, since their self-discharge rate can drain the cells in a few weeks even with no load connected [30].

Rechargeable alkaline may be preferred in many applications because of its excellent charge retention in storage. The load current placed on the cells by the battery management circuit must be very low in order to maintain the low self-discharge rate after weeks or months of storage [30]. Circuitry connected to the batteries should not place a continuous load on the cells during periods of storage, as this could deep-discharge them (this is referred to as a "loaded storage" condition that is considered undesirable for any New Generation Battery System). For example, a load placed on the battery terminals as part of a battery monitoring circuit should be disconnected when the device is not in use or it could eventually deep-discharge the cells. This will reduce the rechargeability of the cells [30].

Zinc-air cells and batteries are not manufactured with any special electronic protection in their packaging. The only design considerations that are taken into account during design and packaging are concerned with airflow and air control. No special electronic protection is incorporated into the existing zinc-air cell or battery packages [27].

2.2.12 Short circuit

Short circuit will translate to a quick temperature increase and might lead to fire. Li-ion batteries are protected from this by a positive temperature coefficient resistor that undergoes a large change in resistance when internal temperature rises or internal non-resetable thermal fuses are placed against the cells [17].

Most rechargeable battery packs use a series diode against reversed polarity mistakes. In low-voltage systems, however, the forward voltage drop of the diode can be excessive.

Li-ion cells whose nominal capacity exceeds 1 Ah are fitted with a circuit breaker. This circuit breaker's function is to interrupt, irreversibly, the current flow in case of excessive internal temperature or pressure [17].

Ni-Cd, Ni-MH and Li-Ion battery packs have different protection requirements. Polymeric Positive-Temperature-Coefficient (PPTC) resistors are available that address different technology needs [20]. Power Mosfets and ICs provide very effective battery pack protection. Thermal fuses and bi-metal breakers are another method of protection. Some of these devices are also used in combination. The thermal fuse is a one-time device, and once it blows, it must be replaced. The Mosfets and ICs normally work in combination with a linear thermistor sensor, which provides feedback to its silicon-based current-limiting circuits. PPTCs and bi-metal circuit breakers are resetable units; once the fault is cleared, they allow normal battery operation [37].

2.2.13 Battery safety

The safety of a battery can be defined as its ability to be used under various circumstances without electrolyte leakage, fumes, fire or an explosion. This should include mishaps such as exposure of the battery to vibration and mechanical shocks, for instance if the battery is dropped. There should be protection against accidental heating (in a car for instance) and protection against overcharge or over-discharge. Batteries must also be protected against crushing and piercing, which could be very dangerous for the user [17]. Li-ion has passed the safety test as set out in "Standards for lithium batteries UL 1642 – Third Edition 1995" but it is still considered to be a dangerous battery [17].

Ni-Cd and Ni-MH battery packs, like all rechargeable batteries, require special safety procedures during handling. Do not disassemble batteries or cells as they can cause respiratory damage. Do not allow electrolyte to contact skin or eyes. Do not short battery terminals together because the battery can explode, especially high-energy batteries. The "No Smoking" rule must be strictly applied during charging, installation and use of Ni-Cd and Ni-MH batteries. Damaged Ni-Cd and Ni-MH batteries may vent the explosive gas, hydrogen, which can ignite on exposure to any naked flame or spark. Store batteries in a cool, dry, well-ventilated area away from sources of heat or ignition. Batteries must never be stored with explosives, flammable materials/liquid chemicals or food [38].

RAM batteries have demonstrated consumer safety in actual use since 1993, with no reported accidents [24].

In the case of zinc-air cells and batteries, accidental short circuit for a few seconds will not seriously affect the battery. Prolonged short circuit will cause the battery to lose energy, and can cause the cell to vent and possibly break down [39].

2.2.14 Disposal of batteries

The disposal of Li-ion batteries is not regulated. These products do not contain heavy/toxic metals such as lead, mercury or cadmium [17].

Ni-MH is environmentally friendly and contains only mild toxins, profitable for recycling. Although disposal procedures for Ni-MH cells are still evolving, observe the following precautions: discharge the batteries fully prior to disposal, and do not incinerate, open or puncture the cells [21].

Proper disposal of Ni-Cd batteries and battery packs is necessary because of the cadmium component in the battery, which is very toxic. Cadmium is an expensive metal and is toxic. Recent regulations limiting the disposal of waste cadmium (from cell manufacturing or from disposal of used batteries) has contributed to the higher costs of making and using these batteries [28].

The disposal of primary alkaline cells and batteries is not regulated. These products do not contain heavy/toxic metals such as lead, mercury or cadmium. They can be disposed of as normal household waste [41].

Zinc-air batteries do not contain any toxic or hazardous materials and they are considered as dry batteries, thus rendering them safe for unregulated disposal [32].

However, one should be aware that there may be local rules and regulations for disposal of rechargeable cells.

2.2.15 Smart batteries

"Dumb" batteries just supply energy and power. The "smart" ones, in addition, do the talking. For instance, they can tell their "system host" (the one they are connected to) what their voltage, temperature and remaining running time are. Smart batteries may participate in the complete system power management and help control their charger [17].

The "System Management" bus (SMbus) is defined in specifications issued in 1995 by Intel and Duracell to standardise interfaces to battery subsystem components. The SMbus is an attractive concept, which provides accurate tracking of battery use and battery parameters. The SmBus for instance allows the simultaneous management of two batteries (one in operation and one in back-up mode). The SmBus is applicable to Li-ion as well as Ni-Cd or Ni-MH batteries [17].

The disadvantage is cost and power consumption. A more important factor is the maintenance requirement of recalibrating the SMbus capacity readings. If the load is uneven and varies quite a lot, the true capacity is no longer synchronised with the fuel gauge. A full charge and discharge cycle are needed to calibrate the battery. This could be described as adding a digital memory to a battery, which was described as having no memory effect, in the case of Li-ion [19].

Some batteries claim to be smart if they only provide functions for protection from overcharging, undercharging and short-circuiting. For the purposes of this study, a "smart" battery is a battery pack that includes built-in electronics for state-of-charge monitoring, recharging or other functions, with the ability to communicate with the host system.

There are also integrated circuits available specifically for use with rechargeable alkaline battery technology. The circuits manage the charge and discharge control of two cells in series and work with 3-cell and 4-cell battery packs. They also generate drive signals for optional external LEDs to indicate charge status. The IC also switches itself into a low-power "sleep" mode after discharge termination [30].

2.2.16 Cost factor

For overall comparison of rechargeable battery characteristics, a cost factor should also be included, since raw material costs vary widely among the various electrochemical companies. Ni-Cd and Ni-MH batteries suffer higher costs due to their high raw material cost, and rechargeable alkaline and zinc-air suffer higher costs due to their poor cycle life. Lithium systems suffer higher costs due to high processing costs combined with high raw material costs.

The initial cost is the relative cost of purchasing the battery. The life-cycle cost is the per-use relative cost of the battery [28].

2.2.17 Transportation regulations

The regulations that govern the transportation of rechargeable lithium ion cells and batteries are included in the International Civil Aviation Organization (ICAO) Technical Instructions and the corresponding International Air Transport Association (IATA) Dangerous Goods Regulations, and the International Maritime Dangerous Goods (IMDG) Code. Restrictions are based on the lithium content, for example a lithium content of 1.5 g/8.0 g battery is exempt from transport regulations [40].

Most airfreight companies accept the nickel-based batteries without special conditions [53]. No special transport regulations were found for zinc-air or alkaline batteries.

2.2.18 Battery packs

As a single cell cannot supply higher voltages or a higher capacity; it is necessary to connect cells in series and/or parallel combinations. Cells in series increase the voltage and cells in parallel increase the capacity.

A Li-ion battery pack for instance must fulfil several key functions: there should be protection against excessive charge/discharge currents; cell balancing is important to minimise imbalance between cell capacities; and the battery pack should have the ability to handle the communication between battery and charger for identification and adjusting of charger parameters [17].

Generally, cells are installed in battery packs for use in products. When these batteries are used, the type of battery, number of cells, shape of the pack, constituent parts of the pack and the space available must be considered.

Typical and standard types of battery packs can be seen in Figure 10.

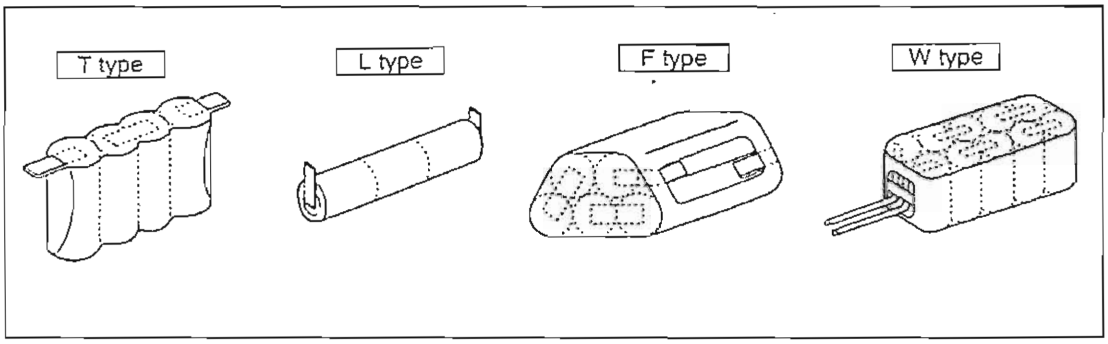

Figure 10: Types of battery packs

2.3 BATTERY CHARGING REQUIREMENTS

As an increasing amount of electronic equipment is becoming portable, and there is an increasing urgency to find better batteries with higher capacity, smaller size and lower weight. The continuing improvements in battery technology call for more sophisticated charging algorithms to ensure fast and secure charging. Higher-accuracy monitoring of the charge process is required to minimise charge time and utilise the maximum capacity of the battery while avoiding battery damage [42].

2.3.1 Safe Charging of Batteries

Modern fast chargers (i.e. battery fully charged in less than three hours, normally one hour) require accurate measurements of the cell voltage, charging current and battery temperature in order to fully charge the battery without overcharging or otherwise damaging it [42].

2.3.2 Charging Methods

Li-ion batteries are charged with constant voltage (current limited). Ni-Cd and Ni-MH batteries are charged with constant current and have a set of different termination methods [53]. Rechargeable alkaline manganese cells use a constant current charge source and the charge current is limited to 100 to 150 mA [23].

2.3.3 Maximum Charge Current

The maximum charge current is dependent on the battery capacity (C). The maximum charge current is normally given as a ratio of the battery capacity. For example, a battery with a cell capacity of 750 mAh charged with a charging current of 750 mA is referred to as being charged at 1C (1 times the battery capacity) [42].

2.3.4 Overheating

The battery is charged by transferring electrical energy into it. This energy is stored in a chemical process. However, not all the electrical energy transferred to the battery is transformed in the battery as chemical energy. Some of the electrical energy ends up as thermal energy, thereby heating up the battery. When the battery is fully charged, all the electrical energy applied to it ends up as thermal energy. With a fast charger, this will rapidly heat up the battery, causing damage to the battery if the charging is not terminated. Monitoring the temperature to terminate the charging is an important factor in designing a good battery charger [42].

2.3.5 Termination Methods

The application and environment in which the battery is used sets limitations on the choice of termination methods. It might be impractical to measure the temperature of the battery and easier to measure the voltage, or the other way around. Other termination methods are as follows [42]:

Time - This is one of the simplest methods to measure when to terminate charging. This is normally used as back-up termination when fast-charging, but also as a primary termination method in normal slow charging (14 – 16 h). This method applies to all batteries.

Voltage - Charging is terminated when the voltage rises above a preset upper limit. This is used in combination with constant current charging. Voltage level is used for Li-ion as the primary charging algorithm/termination method. Li-ion chargers usually continue with a second phase after the maximum voltage has been reached to safely charge the battery to 100%. It is also used in Ni-Cd and Ni-MH batteries as back-up termination.

Voltage Drop (dV/dt) - This termination method utilises the negative derivative of voltage over time, monitoring the voltage drop occurring in some battery types if charging is continued after the battery is fully charged. It is commonly used with constant current charging and applies to fast charging of Ni-Cd and Ni-MH batteries.

Current - Charging is terminated when the charge current drops below a preset value. It is commonly used with constant voltage charging and applies to Li-ion to terminate the top-off charge phase usually following the fast-charge phase.

Temperature - Absolute temperature can be used as termination (for Ni-Cd and Ni-MH batteries), but is preferred as a back-up termination method only. Charging of any battery should be terminated if the temperature rises above the operating temperature limit set by the manufacturer.

Zero Delta Voltage (dV/dt = 0) - This termination method is very similar to the dV/dt method, but pinpoints more accurately when the voltage no longer rises over time. This method applies to Ni-Cd and Ni-MH batteries.

2.3.6 Fast charging of Ni-Cd and Ni-MH cells

The fast-charge and termination methods used depend on cell chemistry and other design factors. Fast-charge rates in excess of 2C are possible, but the most common rate is about C/2 because charging efficiency is somewhat less than 100% and a full charge at the C/2 rate requires slightly more than two hours. While constant current is applied, the cell voltage rises slowly and eventually reaches a peak (a point of zero slope, see Figure 11). Ni-MH charging should be terminated at this peak. Ni-Cd charging, on the other hand, should terminate at a point past the peak, when the battery voltage first shows a slight decline. Cell damage can result if fast charge continues past either battery's termination point [51].

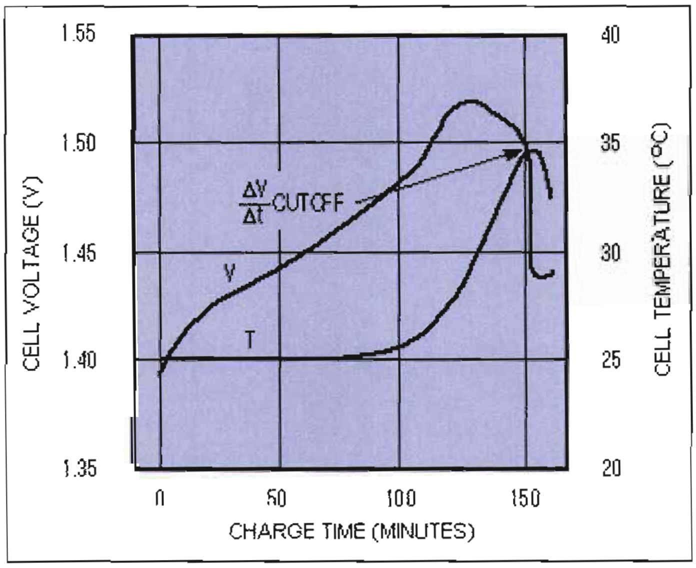

Figure 11: Ni-Cd battery-charging characteristics at C/2 rate

2.3.7 Fast charging of Li-ion cells

Li-ion battery charging differs from the nickel chemistry charging methods. A top-off charge can follow to ensure maximum energy storage in a safe manner. Li-ion chargers regulate their charging voltage to an accuracy of more than 0.75%, and their maximum charging rate is set with a current limit, much like that of a bench power supply. When fast charging begins, the cell voltage is low, and charging current assumes the current-limit value (Figure 12) [51].

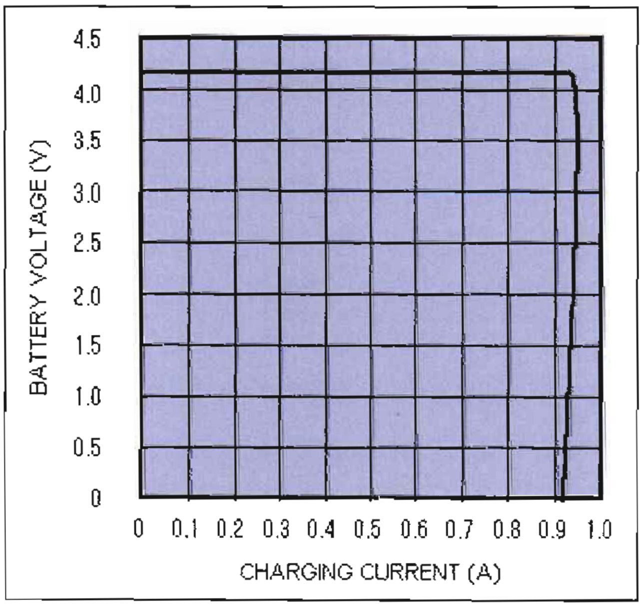

Figure 12: Li-ion battery voltage versus charging current

Battery voltage rises slowly during the charge. Eventually, the current tapers down, and the voltage rises to a float-voltage level of 4.2 V per cell (Figure 13).

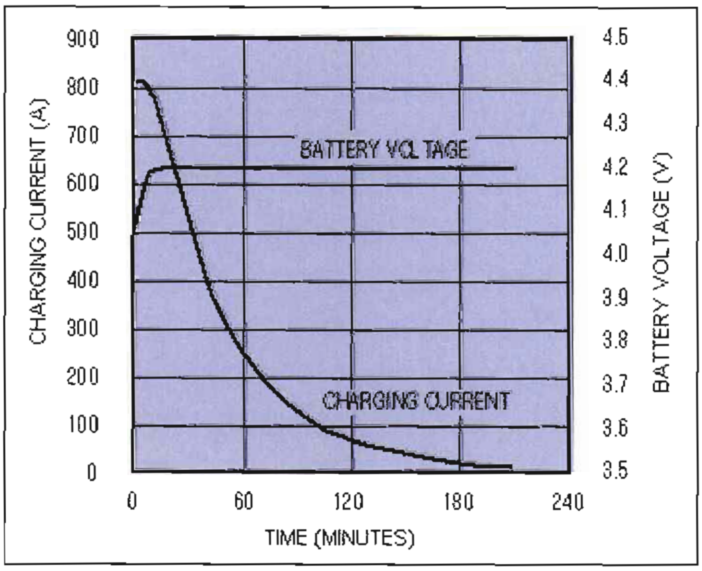

Figure 13: Li-ion battery-charging profile

The charger can terminate charging when the battery reaches its float voltage, but that approach neglects the topping-off operation. The charging current is monitored and terminated at a sufficiently low level (typically 5% of the charging current) specified by the manufacturer. A top-off cycle often follows this method as well [51].

2.3.8 Optional top-off charge (all chemistries)

Chargers for all chemistries often include an optional top-off phase. This phase occurs after fast-charge termination and applies a moderate charging current that boosts the battery up to its full-charge level (the operation is analogous to topping off a car's fuel tank after the pump has stopped automatically). The top-off charge is terminated on reaching a limit with respect to cell voltage, temperature or time. In some cases, top-off charge can provide a run life of 5% or even 10% above that of a standard fast charge. Extra care is advisable here as the battery is at or near full charge and is therefore subject to damage from overcharging [51].

2.3.9 Optional trickle charge (all chemistries except Li-ion)

Chargers for all chemistries often include an optional trickle-charge phase. This phase compensates for self-discharge in a battery. The Li-ion self-discharge rate is so low that trickle charging is not required or recommended. Ni-Cd can usually accept a C/16 trickle charge indefinitely. For Ni-MH cells, a safe continuous current is usually around C/50, but trickle charging for Ni-MH cells is not universally recommended [51].

2.3.10 Fuel cells to charge batteries

The major advantage of using fuel cells to charge batteries is that an electricity outlet is not required, making it possible to charge devices at remote locations. The high capacity of zinc-air batteries makes them very suitable as a field charger. Figure 14 shows a cellphone charger [27].

Figure 14: Zinc-air cellphone charger

2.3.11 Battery analysers

When a battery is charged the ready light will eventually switch on to indicate that the battery is charged. However, this does not guarantee sufficient capacity, and neither is this an indication that the battery is in a good "state of health". Rechargeable batteries gradually lose their ability to hold a charge. In routine use, this might not be noticed but in case of an emergency, the radio system might collapse, because full performance is required. Weak batteries are charged quicker and remain on "ready" longer than strong batteries. This means that the unsuspecting user will probably choose the weak battery above the strong one [19].

It is important to know both the capacity of a battery pack as well as the "state of health" of the battery pack. Part of a New Generation Battery System must include a battery analyser. An analyser can also be used to restore a battery in the case of a nickel-based battery. A battery analyser can be used to determine the internal resistance of a battery, which in the case of a lithium battery will give a good indication of the current state of the battery. A battery analyser's primary function is to weed out the poor batteries, but it could also be used as a quality control tool for new batteries.

Before an important mission, a battery analyser can be used do a quick test on a battery by simulating the radio as a load. This is more useful than measuring the voltage of a battery. Modern battery analysers use artificial intelligence to test and evaluate batteries. When using a rechargeable system, a battery maintenance programme is very important and it is something that must not be left until a crisis develops. Batteries placed on prolonged standby commonly fail and this is where a battery analyser can help to maintain a fleet of batteries [19].

2.4 VALUE SYSTEM FOR CHOOSING THE BEST TECHNOLOGY

Many different parameters can be used to judge the performance of battery systems. Different cell technologies have been developed which optimise one or more of these parameters, but each technology has limitations. The criteria that will be used as part of a value system to determine the best technology for the SANDF radio application requirements are described below.

Table 2: Value system criteria

Criteria	Description
Talk time	How long a soldier can use his radio before he needs to change batteries is an important criterion.
Size and weight	A soldier carries a lot of equipment and therefore there must be a limitation on the size of the batteries as well as the weight.
Temperature capability	A soldier's equipment must function in extreme temperature conditions.
Charge time	Quick charging of batteries is important for a soldier especially if field charging is required.
Charge requirements	It cannot be expected from a soldier to be a battery expert, therefore his chargers must be able to fully handle all charging requirements.
Cost of ownership	Cost of batteries is always a factor, but for secondary batteries, the cost of maintaining the batteries must also be included.
Capacity fade	Rechargeable batteries lose their capacity over time, and for maintenance considerations the soldier needs batteries that will last a long time.
Shelf life and storage	Soldiers cannot always plan when they need to use their equipment. Therefore batteries will be stored and must be ready for use.
Battery complexity	Less complex batteries should be more reliable. Batteries must never be the weakest link of a radio system.
Safety requirements	The functions of a soldier could lead to the mishandling of the batteries. It is therefore important to know what could happen is such cases.
Disposal of batteries	Soldiers operate according to strict environmental regulations.

To do the required theoretical calculations, the specifications of a range of commercial cells as supplied by the manufacturers [24] [31] [32] were used. These calculated values could change if a different manufacturer were identified, but for comparison purposes any possible changes would not have a major effect. Since the current alkaline batteries in use are very similar to RAM cells, so their theoretical values were not calculated separately. The technologies compared were alkaline and zinc-air as primary cells, and RAM, Li-ion, Ni-MH and Ni-Cd as secondary cells.

2.4.1 Talk time (energy density)

Capacity affects the radios' continuous run-time and the minimum required capacity is 6 Ah [12]. Standard conditions were used to compare technologies, namely: new cells (first charge discharge cycles), typical operating temperature range (20 °C) and the discharge limit voltage determined by the radios. The chosen technology must have the ability to supply peak currents of up to 2 A. To produce these relatively high currents, cells with a low internal resistance are the better option. Although extra electronics in a battery pack will have an influence on the capacity and the internal resistance, in this application all types of batteries will have some electronics in them. It should be noted that weight limitations have a direct effect on the maximum possible capacity, therefore the energy density described in paragraph 2.2.3 was chosen as the criterion.

The cells which were selected had the required capacity of at least 6 Ah (if not, they were connected in parallel to obtain the required capacity). Secondly, sufficient cells must be connected in series to get as close to 18 V as possible. Energy density is the number of cells in series multiplied by the capacity of the parallel combination divided by the weight of all the cells in kg. The answer is given in Watt-hours per kilogram [17] (Table 3).

Table 3: Capacity comparison

Characteristics	**Zinc-air**	**RAM/ Alkaline**	**Nickel-Cadmium**	**Nickel Metal Hydride**	**Lithium ion**
Capacity selected for the A43 radio. Specified at 0.2C rate	*High-capacity battery = 14 Ah*	*3 cells in parallel = 4 Ah* 5 cells in parallel = 6.6 Ah (to be tested)	Saft VT-F cell = 7.6 Ah	Saft VH-D = 8.5 Ah	Saft MP 176065 = 6 Ah
Energy Density [Wh/kg]	12 V * 14Ah / 0,9kg = 186 Wh/kg	12* 1.5V * 4Ah / (36 * .021kg) = 95 Wh/kg 12* 1.5V * 6.6Ah / (60 * .021kg) = 94Wh/kg	15 cells * 1.2V * 7.6 Ah/ (15*0.21 kg) = 43 Wh/kg	15 cells * 1.2 V * 8.5 Ah/(15 * 0.16 kg) = 64 Wh/kg	5 cells * 3.6 V * 6 Ah /(5 * 0.15kg) = 144Wh/kg

Of the secondary cells, Li-ion is the best (see green block) due to the higher voltage per cell. Zinc-air is a primary cell with a spectacular energy density value but this depends on the current drawn.

2.4.2 Size and weight

The voltage and capacity of the cells will determine the number of cells to be used in a battery pack. The number of cells translates to the battery size and weight (Table 4). The battery size specification is fixed as the battery must fit into the existing carry pouch [12]. The weight is specified as 900 g maximum [12]. High energy density batteries are considered the better option. It should be noted that to keep within the required weight limitation, a smaller capacity battery must be built for some battery technologies. For the A43 radio the supply voltage is specified at 12.5 V with a range of 10 V – 18 V [16].

Table 4: Weight comparison

Characteristics	Zinc-air	RAM/ Alkaline	Nickel-Cadmium	Nickel Metal Hydride	Lithium ion
Number of cells	Calculation based on a battery and not single cells.	12 * 1.5V = 18 V	15 * 1.2 V = 18 V	15 * 1.2 V = 18 V	5 * 3.6 V = 18 V
Radio cut-off voltage/ cell	10 V	0.8 V	0.67 V	0.67 V	2 V
Weight limit specified = 900 g	0.9 kg	60 * 0.021 kg = 1.26 kg	15 * 0.21 kg = 3.15 kg	15*0.16 kg = 2.4 kg	5 * 0.15 kg = 0.75 kg
Volume required for the A43 is 484 mL	180 X 90 X 5 = 81 mL	(10*14) X (6*14) X 49.9 = 587 mL	(5*32.4) x (3*32.4) x 91.1 = 1 435 mL	(5*32.3) x (3*32.3) x 89.1 = 1 394 mL	(5*18) x 59.8 x 65 = 350 mL

The only cells close to the specified weight and volume are zinc-air and Li-ion (see green blocks). The zinc-air battery is the smallest and the Li-ion battery weighs the least.

2.4.3 Temperature capability

Since temperature will reduce the capacity of the batteries (paragraph 2.2.9), a capacity reduction of not more than 60% should be acceptable (Table 5). The radio has a functional temperature range of –10 °C to 55 °C and a storage temperature range of –20 °C to +73 °C [16].

Table 5: Temperature comparison

Characteristics	Zinc-air	RAM/ Alkaline	Nickel-Cadmium	Nickel Metal Hydride	Lithium ion
Operating temperature % capacity at –10°C	> 60%	14%	80% (VT series is designed to work at 55°C)	80%	85%
Operating temperature % capacity at 55 °C	>60%	100%	90%	85%	98%
Storage temperature		15°C to 35°C	5°C to 25°C	5°C to 25°C	0°C to 25°C
Charge temperature	Not applicable	15°C to 35°C	0°C to 50°C	-5°C to 40°C	0°C to 50°C

At temperatures below freezing all technologies (see green blocks) except for the alkaline-type batteries will have at least 60% capacity. None of the batteries meets the storage temperature range of the radio.

2.4.4 Charge time

For military applications, quick charging (paragraph 2.3.7) is an important factor. Both the base chargers as well as the field charger must have the ability to charge a battery pack within two hours [12].

Table 6: Charge time comparison

Characteristics	RAM	Nickel-Cadmium	Nickel Metal Hydride	Lithium ion
Charging current and time (A43 radio)	Standard: 8 h – 16 h Quick: ~2 h	Standard: 700 mA for 16 h Permanent: 350 mA indefinitely Quick charge: ~1 h	Standard: 850 mA for 16 h Quick: 4 000 mA for ~2.3 h	Standard: 1 200 mA for 7 h Quick: 6 000 mA for ~3 h

With the right charger most technologies can be charged quickly, but Ni-Cd (see green block) is a lot quicker and the only one which meets the two-hour requirement. Note: the field charger must be able to produce the required high currents for charging which might exclude small solar chargers.

2.4.5 Charge requirements

It will be acceptable to have an intelligent base charger that can keep the battery in optimum condition (paragraph 2.3.5). In other words, the charger will compensate for self-discharge of the cells, discharge if required, will not trickle charge if not beneficial to the battery and will prevent overcharging (Table 7).

The battery could keep track of the number of charge and discharge cycles to assist in predicting the remaining capacity (paragraph 2.2.15). Standard charge time is defined as 10 hours and quick charge is defined as two hours. High-maintenance batteries (memory effect) are considered a disadvantage but not a disqualifying factor.

Table 7: Charging requirement comparison

Technology	Charge requirements
RAM	1.65 V ±0.05 V. Could be a simple constant voltage charge or a more complicated pulse charger for quick charging.
Nickel-Cadmium	Slow charging-simple-constant current over a predetermined period. Rapid charging at 1C. The cell voltage rises slowly and should be terminated at a point past the peak: when the battery voltage first shows a slight decline (-ΔV).
Nickel Metal Hydride	Fast-charging procedures for Ni-Cd and Ni-MH batteries are very similar. While constant current is applied, the cell voltage rises slowly and eventually reaches a peak (a point of zero slope). Ni-MH charging should be terminated at this peak (the ΔV point).
Lithium Ion	External conditions need to be monitored – temperature must not exceed 5 °C to 45 °C before charging begins. Battery is fully charged by constant current then constant voltage. Constant voltage must not fluctuate by more than ±1%.

The nickel-based technologies have the characteristics of memory effect, and in general their charging procedure is more complicated. Li-ion has the requirement of strict limits, which the charger must adhere to for safety reasons. For fast charging Ni-mH could be the best choice (see green block).

Under these criteria, the primary cells could be seen as an advantage since they have no requirement of buying and maintaining expensive chargers.

2.4.6 Cost of ownership

The initial cost is the cost of purchasing the battery (paragraph 2.2.16). The cost per cycle is the derived from the initial cost divided by the number of cycles. The acceptable battery will have the lowest cost per cycle.

Current cost was obtained from a local battery supplier and could fluctuate depending on the exchange rate (Table 8). The values shown were calculated by multiplying the number of cells by the cost of one cell.

Table 8: Cost comparison

Characteristics	Zink Air	RAM/ Alkaline	Nickel-Cadmium	Nickel Metal Hydride	Lithium ion
Budgetary price (No protection electronics)	R850	RAM = R504 Current alkaline battery in use = R90	R1 343	R1 750	R2350
Cost per cycle (until 80% if initial capacity)	R850	504 / 25 = R20	1343 / 1000 = R1.34	1 750 / 1000 = R1.75	2 350 / 1000 = R2.35

The cost per cycle of Ni-Cd (see green block) could probably be lower since a well-maintained battery could last up to 1 500 cycles. The cost of the Li-ion battery could be greater due to the fact that the battery's life cycle is three years and it would be difficult to obtain 1 000 cycles if it is not used everyday. The cost of RAM cells would probably be reduced significantly due to mass manufacturing. The cost of primary cells per cycle is very high, but there is no need for expensive chargers and battery analysers. Disposal cost is not taken into consideration, but this could have the biggest effect on Ni-Cd batteries (paragraph 2.2.14).

2.4.7 Capacity fade

The cycle life is the number of times that a rechargeable battery can be charged and discharged before it is no longer able to hold or deliver any useful amount of energy (paragraph 2.2.5). The retained percentage of the cell's nominal capacity, considered as an acceptable minimum, is 60%. The minimum number of cycles specified is 800 [12]. To compare technologies it is assumed that all technologies will be used and charged within their specifications. This will include: depth of discharge, charge end voltages and operational temperature (paragraph 2.2.5). The technology with the least amount of capacity fading will be considered the best option (Table 9). Note: cycle life falls under ageing (paragraph 2.2.4) and is the capacity lost from cycle to cycle, excluding self-discharge.

Table 9: Cycle life comparison

Characteristics	RAM/Alkaline	Nickel-Cadmium	Nickel Metal Hydride	Lithium ion
Best cycle life Up to 60% ideal environment [Years]	10 – 25 cycles (Depending on the depth of discharge)	1 000 (20 – 25 years) Discharge at 0.2C	1 000 Discharge at 0.2C	1 000 or 2 years Discharge at 1C

To reach the maximum number of cycles of a battery depends on how the battery is maintained. Except for RAM, all other technologies can reach the 800 cycles requirement. Ni-Cd can last up to 25 years (see green block).

2.4.8 Shelf life and storage

The self-discharge rate is the rate at which the battery will lose its charge during storage or other periods of non-use (no external load connected) (paragraph 2.2.6). It will be considered a superior technology if it has a long shelf life, independent of the charge state of the cell (Table 10). Batteries are considered perishable and therefore should not necessarily last for years. A battery with at least a 5-year life cycle will be considered the acceptable battery. For comparison purposes, it is assumed that batteries will be stored under normal conditions (20 °C). Usually self-discharge specifications exclude any current drawn by external electronic circuits. It is normal for batteries to be fully depleted of their power after long-term storage. However, for this comparison a battery must still have more than 60% charge after one month.

Table 10: Self-discharge comparison

Characteristics	Zinc-Air	RAM/ Alkaline	Nickel-Cadmium	Nickel Metal Hydride	Lithium ion
Self-discharge per month at 20 °C	Shelf life 5 years. 1 month if left open. 3 months if re-sealed	0.6%	10% high-temperature cells	30%	5%

Li-ion batteries have a low self-discharge rate compared to Ni-Cd and Ni-MH. However, the Li-ion capacity is only partly reversible. Capacity deterioration is noticeable after one year, whether the battery is in use or in storage. RAM, primary alkaline (see green block) and zinc-air are superior if batteries need to be stored for a long time. After opening a zinc-air battery, it must be used within three months.

2.4.9 Battery complexity

To make provision for the balancing of cells (paragraph 2.2.10), charging and protection electronics (paragraph 2.2.11), the preferred battery will have fewer cells (paragraph 2.2.18). The more links the greater the odds of one breaking. Packs with fewer cells in series perform better. Batteries with many built-in electronics (protection circuits, etc.) will be considered less reliable (Table 11). An indication of the remaining capacity is considered essential [12], therefore, batteries must have some integrated electronics. Other environmental specifications such as shock, humidity, fungus, sand, dust and salt fog will play a role in choosing the battery enclosure but cells should also be rugged. It is also important to know if the cells are sealed or not.

Table 11: Complexity comparison

Technology	Complexity
Zinc-air	Very simple concept. Use battery and when finished throw it away. No charging requirements.
RAM/Alkaline	Will need many cells (60). Cell reliability will be a factor; one defective cell out of 60 will reduce the functionality of the battery pack. Charging of multiple cells and associated electronics will play a role.
Nickel-Cadmium	No need for cell balancing and protection electronics.
Nickel-Metal-Hydride	No need for cell balancing and protection electronics.
Lithium ion	No need for cell balancing but protection electronics is a must.

Li-ion and RAM cells are considered well suited for parallel connection. However, the more cells connected in series, the more complex the protection circuits. It is very difficult to predict the reliability of connecting a couple of cells to build a battery, and should rather be tested. It is expected that building a RAM battery will require a lot of cells and building a Li-ion battery will require reliable protection electronics. Ni-Cd and Ni-mH does not require protection electronics (see green block).

2.4.10 Safety requirements

When designing a battery for a specific application, the chemical stability and toxicity of the battery system are primary concerns (paragraph 2.2.13). One of the desirable traits of a battery's chemical make-up is a solid cathode material rather than a liquid. Compared to a liquid cathode system, a solid cathode is less volatile in the event that the battery is subjected to abusive conditions. Furthermore, all batteries are inherently dangerous, but the high-capacity batteries are generally considered more dangerous. The preferred battery could be the one that needs less electronic protection (Table 12).

Table 12: Safety comparison

Technology	**Safety**
Zinc-air	Similar to any sealed container, battery cells may rupture when exposed to excessive heat; this could result in the release of flammable or corrosive materials. Accidental short circuit for a few seconds will not seriously affect this battery.
RAM/ Alkaline	Care must be taken during handling. Electrolyte will leak if the cell is pierced or ruptured. Can be harmful on contact with skin. These cells are fitted with a safety vent to relieve pressure before explosion.
Nickel-Cadmium	Can pose a fire hazard during venting and should therefore be kept away from sparks and flames.
Nickel-Metal-Hydride	Can pose a fire hazard during venting and should therefore be kept away from sparks and flames.
Lithium ion	Very high energy density. Exercise caution when handling and testing. Do not short circuit, overcharge, crush, mutilate, nail penetrate, apply reverse polarity, expose to high temperature or disassemble. Abuse of the cell could cause physical injury.

Li-ion is a dangerous battery but it should be realised that manufacturers are striving to produce safer batteries. New technology Li-ion batteries are safer than old generation Li-ion batteries and are used extensively in cellphones. Due to lower energy density the RAM batteries could be seen as a safer option (see green block).

2.4.11 Disposal of batteries

Batteries that are more suitable do not contain heavy/toxic metals such as lead, mercury or cadmium (paragraph 2.2.14). This should not be considered a disqualifying factor if disposal processes and procedures are required and are in place. A battery containing cadmium is classified as hazardous waste by the Environmental Protection Agency and is subject to legislation in many states in the USA. This could eventually affect the sale and collection of products that include heavy metals (Table 13).

Table 13: Disposal comparison

Technology	Safety
Zinc-air	Zinc-air batteries do not contain any toxic or hazardous materials and they are considered dry batteries, thus rendering them safe for unregulated disposal.
RAM/ Alkaline	These products do not contain heavy/toxic metals such as lead, mercury or cadmium. They can be disposed of as normal household waste.
Nickel-Cadmium	Proper disposal of nickel-cadmium batteries and battery packs is necessary because the cadmium component in the battery is very toxic.
Nickel-Metal-Hydride	Ni-MH is environmentally friendly, contains only mild toxins; is profitable for recycling.
Lithium ion	Li-ion batteries are not regulated. These products do not contain heavy/toxic metals such as lead, mercury or cadmium.

Most designers avoid using Ni-Cd. Although it will still take a long time before this type of battery is phased out, it will eventually happen. RAM and Li-ion contains no heavy metals (see green block).

2.4.12 Matching of technologies to the user value system

A software package called Trade-Off was used to assist in obtaining a weight allocated to the chosen criteria. Trade-Off was used as a group decision support system by using the input of a number of people from both the SANDF and Armscor [20]. The results, in order of importance, can be seen in Table 14.

Table 14: Criteria used for user value system

Criteria	Weight
Talk time (Energy density)	24.2%
Size and weight	16.9%
Temperature capabilities	11.3%
Charge time	8.9%
Charger requirement	8.1%
Cost of ownership	7.8%
Ageing (Capacity fade)	5.6%
Battery complexity	5.3%
Shelf life and storage	5.2%
Safety requirements	4.2%
Disposal of batteries	2.6%

Each technology was match to each one of the criteria (Table 15 and Figure 15). A logarithmic scale was used:

☺ Indicates a value of 9 and it is used for a "very good" match.

± Indicates a value of 3 and it is used for a "not too bad" match.

* Indicates a value of 1 and it is used for a technology that can hardly be used for the specified criteria.

_ A blank gets a value of 0 and it is used for a technology that cannot be used for the specified criteria.

Table 15: Matching user requirement to cell technologies

Characteristic	Weight	RAM	Ni-Cd	Ni-MH	Li-ion
Talk time (Energy Density)	24.2	±	*	±	☺
Size and weight	16.9	±	*	*	☺
Temperature	11.3		☺	☺	☺
Charge time	8.9	±	☺	±	±
Charge requirements	8.1	☺	*	☺	±
Cost of ownership	7.8	±	☺	±	*
Ageing / Capacity fade	5.6	*	☺	±	☺
Battery complexity	5.3	*	☺	☺	±
Shelf life and storage	5.2	☺	±	*	±
Safety	4.2	☺	±	±	*
Disposal	2.6	☺		☺	☺
Total value		365	428	420	640

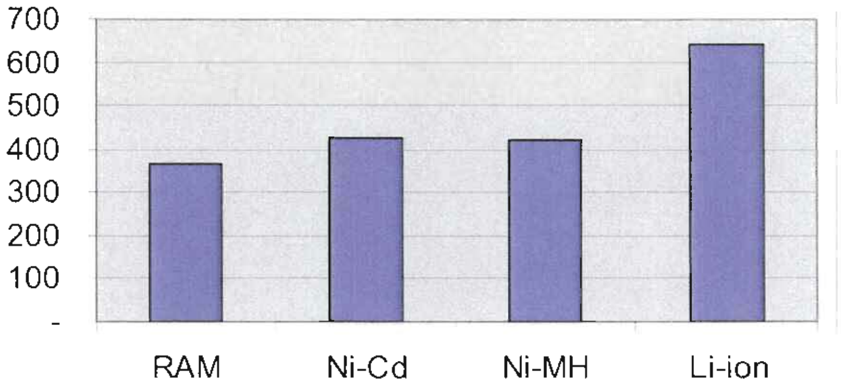

Figure 15: Indication of technology matches to the user requirement

2.4.13 Interpretation

It is important to realise that this result must be tested in a more holistic way. In other words, military operational scenarios must be formulated and then it must be determined if the user can adapt to the chosen battery technology requirements. It must also be determined if this technology will cause a change to the user requirements and if the requirement change is acceptable to the user. This will be discussed in paragraphs 5.2 and 5.3

2.5 SUMMARY

The intention of the research in this chapter is to gain an understanding of rechargeable battery technology. The best technology for a New Generation Battery System for the A43 radio must be chosen.

Aspects of Ni-Cd technology, which are important for this application, can be summarised as follows. Ni-Cd is a rugged and reliable technology and it performs well under rigorous working conditions. Ni-Cd batteries have a long life and long shelf life. A Ni-Cd battery could easily handled the required discharge rates. But Ni-Cd has a low energy density and the cells contain toxic metals. There are already regulations in place to prevent the use of these batteries. Ni-Cd has demanding maintenance requirements due to its memory effect [19]. This technology is therefore not seen as a suitable battery for the A43 radio.

Aspects of Ni-MH technology, which are important for this application can be summarised as follows. Ni-MH is a replacement for Ni-Cd and has a higher energy density. Ni-MH does not have the same memory problems compared to Ni-Cd, but the battery has a reduced cycle life compared to Ni-Cd. The disadvantages of Ni-MH are high self-discharge and performance degradation if stored at high temperatures. The cycle life cold be shortened when used in a high-current application [19]. This technology is therefore not fully suited for the A43 radio.

Li-ion technology can be summarised as follows. Li-ion has a high energy density and is used where light weight is important. Li-ion has a relatively low self-discharge and no memory effect. The technology is economical if used every day, but it is not economical for the occasional user. Li-ion is subject to ageing even when the battery is not in use and has a lifespan of two to three years. The disadvantage if used in radios is the replacement cost and restrictions because of the safety requirements [19]. Technically speaking, this technology has improved in such a way that makes it well suited for use in the A43 radio.

Aspects to consider in RAM technology can be summarised as follows. RAM is more suited for low-power applications. RAM has a limited cycle life but very low self-discharge. The longevity of RAM is a direct function of depth of discharge. The biggest disadvantage is a low load current capability and limited capacity at sub-zero temperatures [23]. RAM technology is definitely not suited for the A43 radio.

Zinc-air is a primary battery and at this stage it cannot be re-charged. Zinc-air has an incredibly high energy density (at relative low currents), but after opening, the battery cannot be stored for more than three months. At present, zinc-air out-performs all primary batteries.

Matching the user value system to the characteristics of the different cell technologies points to the best solution for the radio application, namely Li-ion technology. Today's soldier places a high premium on light-weight equipment and Li-ion has the best energy density of all rechargeable cells. Li-ion is an expensive technology, but with increasing commercial use, cells are already available which are less expensive. Li-ion technology has improved a lot and many of the changes have enhanced the safety record of Li-ion cells. Li-ion chargers need more stringent specifications, but in general, the downfall of any rechargeable system is usually a poor charger. Li-ion is not a technology for occasional use, and to make it cost effective the batteries must be used every day. Li-ion has a small capacity fade due to the re-charging cycles and a larger capacity fade due to aging. In a way, this is an advantage since the capacity retention ability could be predicted by looking at the battery's date of manufacture.

Manufacturers of Li-ion cells dictate very strict guidelines for charge procedures. The charge time for most chargers is about three hours. The battery should remain cool, hence the need for temperature monitoring. Increasing the charge current does not shorten the charge time. The two common battery killers are high temperature during charge and incorrect trickle charge after charge.

To confirm the findings discussed in this section, it is necessary to investigate international battery trends. We have to look for similar military radio projects as well as what technology is used in other mobile devices. Lastly, we need to test Li-ion technology to verify the manufacturer's specifications and to understand the technology.

3. VERIFYING THE CHOICE OF LI-ION

3.1 INTRODUCTION

By matching the different rechargeable battery technologies with the requirements of the SANDF, Li-ion technology was chosen as the best solution. To verify this choice it is important to look at what the international trends are and at the same time to test the Li-ion technology.

At this stage the SANDF wishes to improve the batteries of their tactical radio. Wireless communications is the most power-hungry of soldier electronics applications and offers the best chance to reduce future warrior energy requirements, or in other words, it is important to have energy-efficient radios [5]. However, a new generation radio for the SANDF is still a future project, and for now, improving the batteries is the best option.

The success of the Ni-MH has been driven by its high energy density and the use of environmentally friendly metals. In many parts of the world, the buyer is encouraged to use Ni-MH rather than Ni-Cd batteries due to environmental concerns about careless disposal of the spent battery. It is widely accepted that Ni-MH is an interim step to lithium battery technology [19].

Among portable secondary batteries, lithium ion shows the most promise. Lithium ion will lead the demand in the powering portable devices (Figure 16). The market for nickel-cadmium, on the other hand, is shrinking. This chemistry will be replaced with nickel metal hydride.

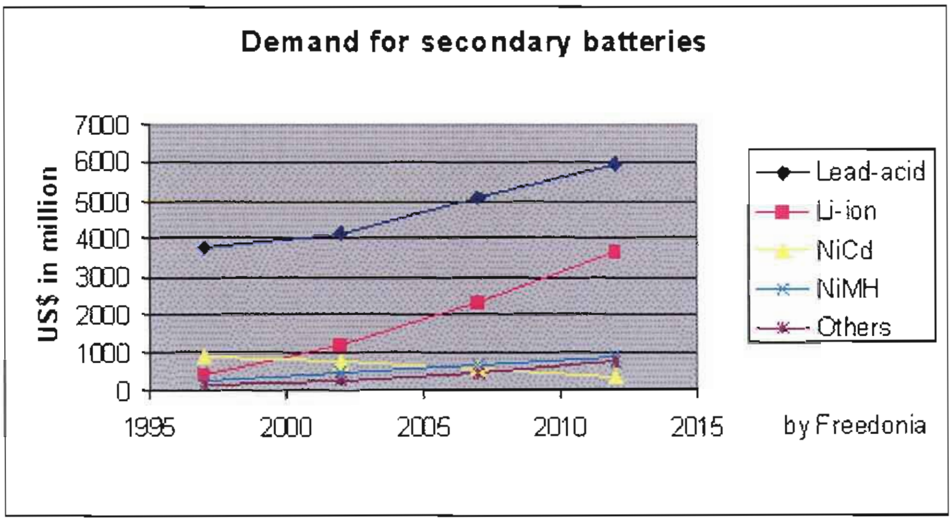

Figure 16: Demand for secondary batteries

It is possible to predict the characteristics of a cell, but when cells are combined to form a battery pack additional factors start playing a role. Tests must be conducted under real usage conditions which should include the current alkaline battery as a baseline. In this application a radio draws a transmit current for a certain period and receives and a standby current for another period. Different currents will place different demands on the battery. In this section, prototype Li-ion batteries were tested and compared to the current alkaline battery.

3.2 WORLD TRENDS IN RECHARGEABLE BATTERIES

To verify the choice of Li-ion technology, examples found in the literature are listed in this section.

Dr Robin Tichy from Micro Power Electronics stated: "Power tools are actually one of the biggest battery markets, period, but power tools require very high currents and Li-ion is now addressing those types of needs".

Bren-tronics in the USA designed a special Li-ion battery to be tested in their Land Warrior programme [44]. This design is very similar to the battery design described in Chapter 4.

The UK MOD's Bowman communication system (man-portable radios) uses the revolutionary Kaizen cell. These batteries are an enhanced extension of Li-ion technology and can operate in temperatures ranging from –51 °C to +75 °C [45].

COM DEV in Canada assembles commercial 1.5 Ah Sony 18650-HC Li-ion cells into spacecraft batteries. In tests, these cells completed 3 200 cycles at 60% depth of discharge. This is equivalent to 30 years of cycling in orbit [47].

The prismatic Li-ion cell produced by Yardney was adopted for the Mars Exploration Rover mission. It has a cycle life of over 1 000 cycles. At –20 °C it delivers over 65% of its capacity [47].

Li-ion batteries with a new electrolyte were developed by SAFT America, which delivers 70% capacity at –40 °C [47].

Man-portable applications in the US army describe a new power source that has a 35 watt proton exchange membrane fuel cell stack. This is used in parallel with Li-ion batteries to assist with delivering peak loads [47].

The new soldier system in the USA, called the Objective Force warrior, will have a hybrid consisting of a Li-ion battery and a direct methanol fuel cell delivering 200 Wh/Kg [47].

Batteries for laptops and other small portable devices must be small and lightweight. Generally, the size and weight is more important than run time. Users have accepted that a laptop only runs for an hour or two before recharging is required. Laptops are power hungry and this will probably increase as they become more advanced. The inside temperature of a laptop will also effect the battery's life expectation. The best solution at this stage is the Li-ion battery, and if a very small battery is needed the battery choice will be the Li-ion polymer battery [19].

The Dell computer company and Apple Computer Inc had to recall millions of Li-ion batteries manufactured by Sony Corp subsidiary in Japan. This was due to laptops catching fire as illustrated in Figure 17.

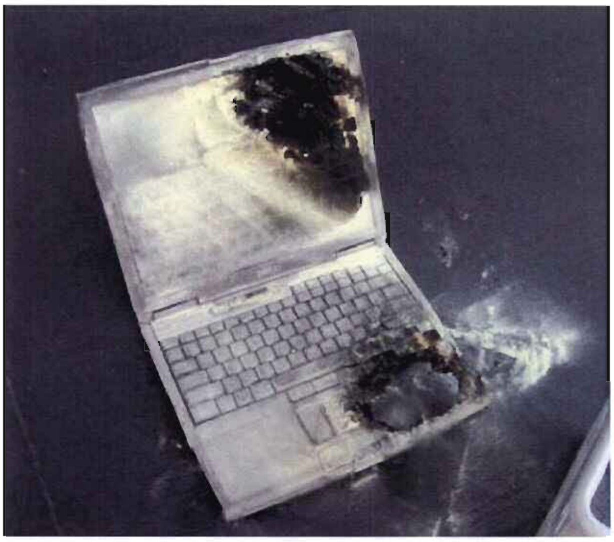

Figure 17: Dell laptop fire

Sony said the problems arise "on rare occasions" when microscopic metal particles hit other parts of the battery cell and lead to a short circuit [54]. From this incident it is obvious that safety is a concern when using Li-ion batteries. It is important to acquire good quality cells and to design the system in such away that the batteries cannot overheat.

The problem encountered with other handheld devices, which usually work with standard 1.5 V AA cells, is that Li-ion cells are 3.6 V. Ni-MH (1.2 V) cells are a better option, but an important drawback is that nickel-based batteries need occasional exercise to prevent a memory effect, especially when the equipment does not fully drain the battery.

The ability to produce large Li-ion batteries from small cells with high reliability has been demonstrated with a proprietary electronic architecture. The technology has been proven with the construction and demonstration of battery modules having 700 – 1 100 Wh of energy. The potential usefulness of these batteries as safe and cost-effective replacements for lead-acid and nickel-cadmium batteries has been demonstrated [49].

The findings of this research were discussed at a battery workshop at Graz University of Technology, which specialises in battery technologies. The main points discussed in these workshops can be found in Appendix A. Considering the information received at the workshops and the current battery requirements for the A43 radio, it still makes sense to concentrate on Li-ion technology as the solution. Li-polymer could be the better choice if a lightweight battery is important, but the technology must still prove itself. The advantages of the Li-ion are as follows:

- Commercial battery packs are available in configurations which supply 14.5 V 6 Ah.
- These batteries are relatively inexpensive at about R650.
- A battery built up from smaller cells (2 Ah) should be safer than a battery built up from 6 Ah cells.
- It is possible to use the same chargers for Li-ion and Li-polymer.
- Charging requirements of Li-ion are less complicated than those for Ni-MH.

3.3 LI-ION BATTERY CELLS AS THE BEST CHOICE

Lithium has the lightest weight, highest voltage and greatest energy density of all metals. Rechargeable lithium batteries were developed during late 1970s and the 1980s. Since then a lot of work has been done on all aspects of Li-ion chemistry. The word Li-ion battery can imply dozens of different combinations of chemistry at the anode, the cathode and the electrolytes [46]. Although there can be many differences in the different Li-ion cells, the basic operation is the same. Manufacturers will keep on improving the technology and eradicating the negative aspects, for instance bad safety will be addressed as the technology improves. Li-ion cells are described by the letters on the cell [46], for instance an ICP18650 cell is described as in Table 16.

Table 16: Describing a Li-ion cell

First letter	I – Li-ion chemistry
Second letter	C – cobalt, N – nickel, M – manganese
Third letter	C – cylindrical, P – prismatic
First numbers	Diameter - 18mm
Middle numbers	Height – (Only used for prismatic cells)
Last numbers	Length - 65.0mm

Li-ion batteries will not fulfil all user requirements; the future solution will probably be a fuel cell Li-ion hybrid. In most instances, the batteries will be used to supply the high currents and the fuel cells will be used to charge the batteries [1].

Batteries cared for by a single user generally last longer than batteries in a fleet system where nobody is accountable for the batteries' performance. When using Li-ion batteries it would make sense to issue a battery to a soldier and then the battery pack becomes part of the soldier's personal equipment. The reason for this is that a Li-ion battery must be used daily to make it economical (the batteries lose their ability to hold a charge because of ageing and not because of recharging). The soldier can use his battery pack to power other equipment as well, and thereby save on battery costs. A personal battery pack should reduce battery waste and improve reliability. A soldier will get to know the irregularities of the battery and will adjust to the performance and lower his expectations as the battery ages [19].

The proper user procedures of the battery must be defined to assist the user in making a final decision. The important factors which will influence the choice of the user are the cost of a Li-ion rechargeable system and the lifespan of the batteries. A Li-ion battery must be used regularly to make it cost effective. If the user requires 1 000 charge cycles of the battery and the battery's lifespan is three years, he must literally use it every day. It would therefore make more sense to design a battery with outputs of 3 V, 6 V, 9 V and 12 V. This will enable the user to use it in other equipment even when the capacity has reduced to a value where the battery cannot be used in the radio.

A good battery charger is important and a battery analyser is indispensable equipment. A balance between cost and the amount of electronics necessary in the battery must be found. A quality charger is especially important when considering the high cost of battery replacements and the frustration of poorly performing batteries. In most cases, the money invested in a more advanced charger is recovered by a longer lifespan and higher performance of the batteries [47].

Battery technologies advance each year and committing to a certain battery or even a certain technology would be senseless. The best approach is to scan the market on a yearly basis and to identify new technologies or upgrades of the technologies. Li-ion is a new technology and it is expected that the manufacturers would address the current disadvantages in due course.

3.4 VERIFICATION TEST AGAINST THE USER REQUIREMENT

The A43 tactical radio currently uses alkaline primary batteries. The alkaline battery pack was tested as a baseline and some Li-ion battery packs were tested to verify if this technology would be a suitable replacement. In Figure 18 the alkaline battery pack is shown on the left and the Li-ion battery pack is shown on the right. The Li-ion battery pack was manufactured based on the requirement specifications [12] and on the radio requirement for batteries [16].

Figure 18: Current alkaline battery and a prototype Li-ion battery

The test done on the battery packs was designed to get an indication of the rated capacity of the battery packs (paragraph 2.2.2). The capacity of battery packs depends on the current being drawn by the equipment and the temperature of the environment (paragraph 2.2.9). Another factor which is important for rechargeable batteries is the cycle life. Due to ageing and recycling, the capacity of a battery will deteriorate (paragraph 2.2.5) and this can be tracked by looking at the changes in the internal resistance of the battery.

3.4.1 Test setup

Measurements were done with an Amrel Electronic Load (Figure 19). A software program was developed to simulate the radio as a load and to log the battery voltage on a spreadsheet. The program runs on a personal computer and it controls the Electronic Load via the serial port.

Figure 19: Amrel Electronic Load

The Electronic Load, via the PC, was set up in constant current mode for discharge testing Figure 20. The PC was also used to log the battery voltage and current.

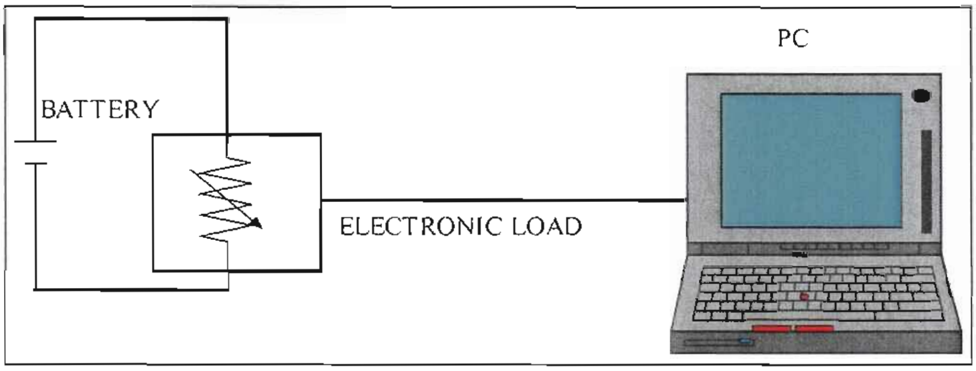

Figure 20: Discharge set-up

The Electronic Load, via the PC, was set up in constant resistance (very low resistance) mode during the battery charging Figure 21. The PC was also used to log the battery voltage and tracked the current to determine when the battery was fully charged.

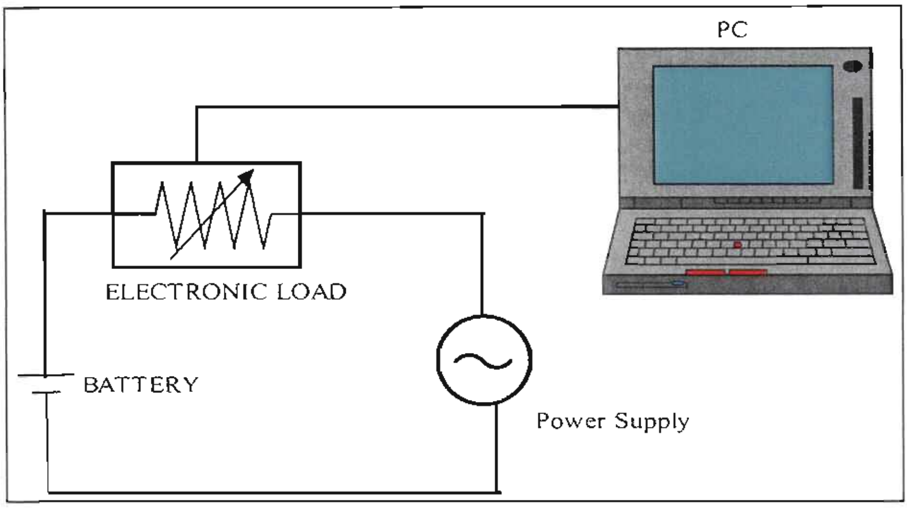

Figure 21: Charge set-up

Temperature tests were conducted in a Specht Scientific temperature chamber. Batteries were also fitted with a Davis Weather Wizard III temperature sensor. Tests were done in accordance with Mil-STD-810F [50].

The current alkaline battery pack used by the SANDF was tested as a baseline. This alkaline battery pack consists of 11 D cells in series. The nominal voltage of the battery pack is 16.5 V. The expected capacity, according to the user, is 6 Ah.
The Li-ion battery used was the GP1865L200-4S3P from GPI. These are commercial batteries. The nominal voltage is 14.8 V, but this can be charged to 16.4 V. The capacity of the battery pack is 6 Ah. The battery pack consists of 2 000 mA/h cells of which three are in parallel and four in series (indicated by 4S3P). Specifications from the manufacturer included the following: The battery packs without the protection circuit can be discharged by 1.5C (9 A) continuously. However, with the protection circuit the discharge current must be limited to 5 A continuously. It was important to keep the operating temperature between –20 °C and 60 °C.

The manufacturer stated that this battery pack had no transport restrictions if the packs were not fully charged. Currently, the standard from the manufacturer is to charge the packs to around 30% state of charge before shipping. For the safe use of Li-ion batteries, always follow the instructions provided by the manufacturer (paragraph 2.2.13). Improper handling of Li-ion batteries may result in injury or damage from electrolyte leakage, heating, ignition or explosion.

The battery pack can be charged to 4.2 V per cell but the voltage must be controlled accurately for safety reasons, as well as to prevent unnecessary stress on the battery. If the battery pack is, for example, only charged up to 4 V per cell, it has the advantage of a higher margin of error, as well as the possibility of lasting longer. The only disadvantage is a lower capacity, but as found in the tests, the remaining capacity is more than enough for this application. It was decided to charge the battery pack only up to about 4 V per cell for most tests, with the option of advising the user that charging up to only 4 V has a lot of advantages. The radio's cut-off voltage is 9 V [16], therefore all tests were stopped when the battery voltage dropped below 9 V.

3.4.2 Test Procedures and Results

A full description of the test procedures can be found in [62] and are summarised in Appendix B. All tests were chosen with the goal of learning about and better understanding the Li-ion battery technology. Some of the tests are summarised in this section.

Size and weight of the battery

The battery size specification [12] is fixed, as the battery must fit into an existing radio pouch. The weight is specified as 900 g maximum [12], and this is probably an arbitrary value, but it is a very important factor for today's soldier who is already overloaded with equipment. Due to the energy density (paragraph 2.2.3) of Li-ion cells, the weight of the prototype battery was 774 g, which is well inside this weight limit. The current alkaline battery with the enclosure weighs 980 g.

Battery internal resistance

Internal resistance should give a good indication of the state of health of the battery (paragraph 2.2.8). To get an indication of the internal resistance, the formula in Figure 22 was used on the voltage drop which happens when the radio transmits.

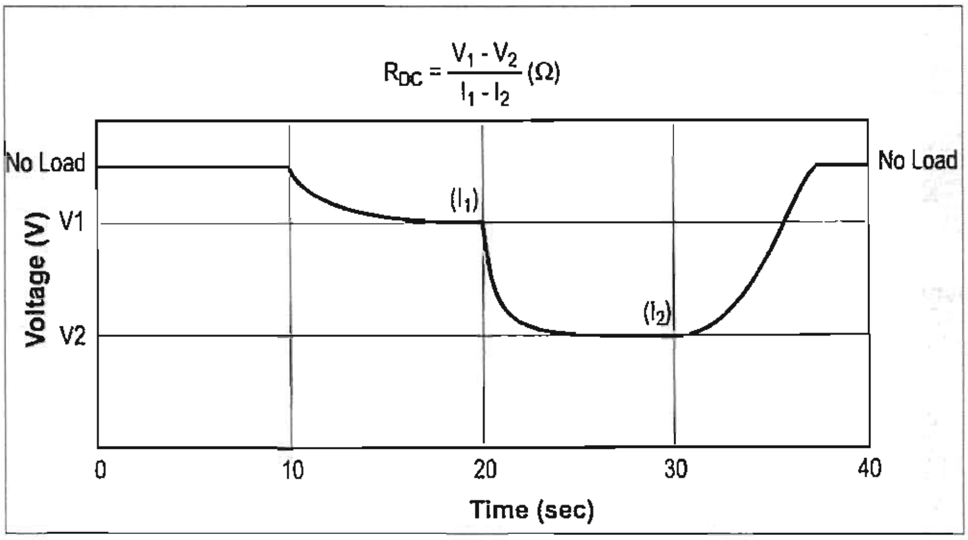

Figure 22: Internal resistance

This method was found to be very inaccurate and over a period of 35 cycles no trend in the internal capacity could be seen Figure 23.

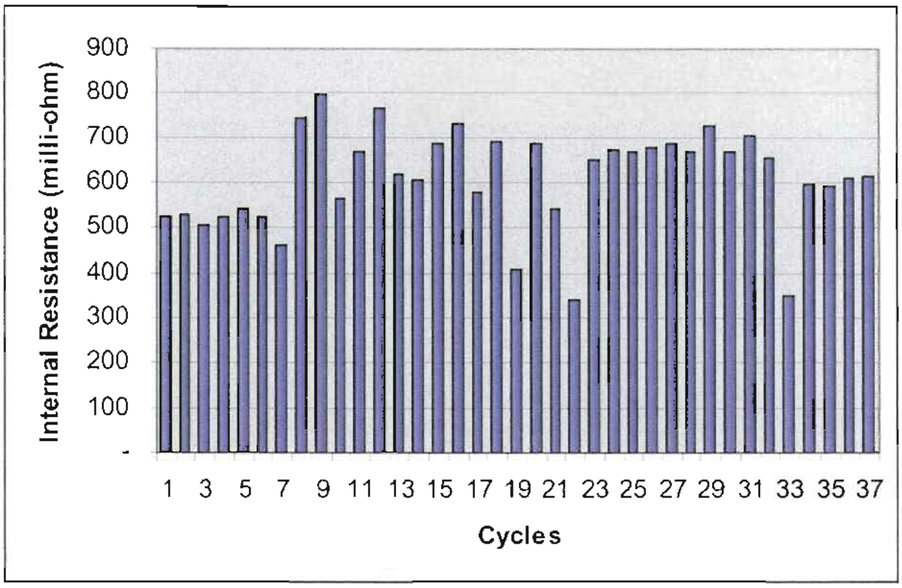

Figure 23: Internal resistance test

It should be noted that the electronic load might not be accurate enough to measure small current values, but in any case, 37 cycles should not affect the internal resistance of a battery which could easily last for more than 500 cycles.

Initial capacity test

The minimum expected required capacity is 6 Ah at 20 °C [12]. The IEEE standard capacity test is specified at 0.2C which works out to a test current requirement of 1.2 A (paragraph 2.2.2). This test was done to verify the manufacturer's specification of the battery capacity. In Figure 24 the Li-ion only lasted about four hours, but that was due to the fact that it was only charged to 4 V per cell. The alkaline battery only lasted 2.5 hours at 1.2 A.

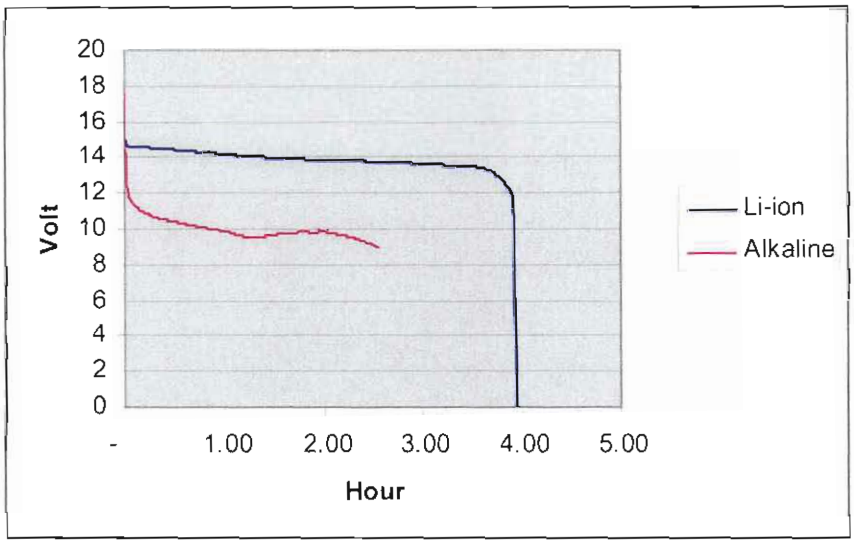

Figure 24: Initial capacity tests

The calculated capacity of the alkaline battery was 3.06 Ah and the initial capacity of the Li-ion battery was 4.6 Ah when charged to 16 V.

Discharge time test

This test was designed to simulate the variable load of the A43 radio. For this test the Electronic Load was used to simulate four different cycles. Cycle A (Radio receive mode) consisted of a discharge at 950 mA for 1 minute then 250 mA for 29 minutes. Cycle B (Radio transmit mode, low power) consisted of a discharge at 1 500 mA for 1 minute then 250 mA for 29 minutes. Cycle C (Radio transmit mode, high power) consisted of a discharge at 2 000 mA for 1 minute then 250 mA for

29 minutes. Cycle D (Radio standby mode) consisted of a discharge at 250 mA continuously.

As discussed in this document, the alkaline batteries do not pass the original qualification test [10]. One of qualification requirements, for instance, was based on Cycle B. The alkaline batteries were received from the SANDF and might not have been stored under optimum conditions. But as shown in Figure 25, the alkaline battery tested to a discharge time of only two hours, which, from a soldiers view point, is totally unacceptable. In comparison, the Li-ion battery tested to a discharge time of twenty hours, which could translate to about one battery every twenty four hours.

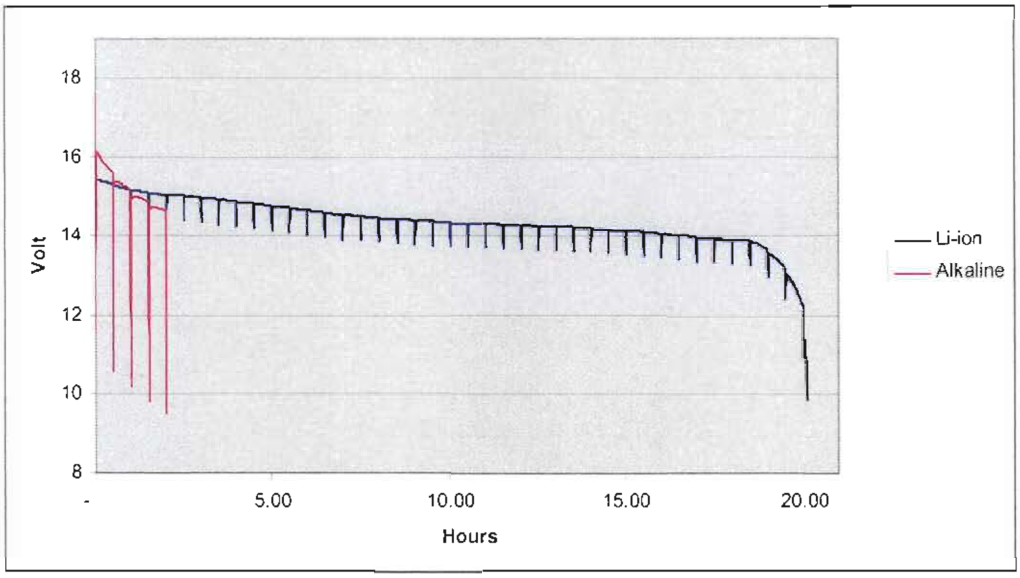

Figure 25: Batteries discharged at 1.5 A for 1 minute and 0.25 A for 29 minutes

Note that the alkaline battery was not fully discharged after the tests. The higher internal resistance of the battery caused a bigger voltage drop at 1.5 A which will trigger the low-voltage sensor of the radio, which will then switch off.

The values for the discharge time tests for the alkaline battery are summarised in Table 17.

Table 17: Alkaline battery results

Test	Result
Average discharge time Cycle A	9 hours
Average discharge time Cycle B	4 hours
Average discharge time Cycle C	1 minute

As Table 17 shows, the battery lasted 9 hours in the receive test (Cycle A) and 4 hours in the low-power transmit mode (Cycle B). The battery is not suitable at all for the high-power transmit mode (Cycle C).

The values for the discharge time tests for the Li-ion battery are summarised in Table 18.

Table 18: 6 Ah Li-ion results

Test	Result
Average discharge time Cycle A	20.1 hours
Average discharge time Cycle B	20 hours
Average discharge time Cycle C	18.8 hours
Average discharge time Cycle D	25.9 hours

As Table 18 shows, the battery lasted 20.1 hours in the receive test (Cycle A) and 20 hours in the low-power transmit mode (Cycle B), which is up to five times longer compared to the alkaline battery. The battery lasted 18.8 hours in the high-power transmit mode (Cycle C) and 25.9 hours when in standby mode (Cycle D).

Voltage versus capacity test

The Li-ion battery packs are designed to be charged to a maximum of 4.2 V/cell. In a military environment, operational temperatures could be quite high. For safety reasons, the battery packs should not be fully charged. This test determined what the capacity difference was between charging to 4.1 V/cell and 4.0 V/cell. If the discharge time at 4.0 V per cell is still acceptable to the user, it translates to a safer battery which should last longer. This is due to the fact that the battery does not operates at maximum charge levels and is therefore not subject to maximum stress factors. According to the Cycle B test, the discharge time when the battery was charged to 4.1 V was 23.2 hours and when charged to 4 V the discharge time was 18.8 hours.

Temperature tests

Tests were done as described in MILL-STD-810F method 501,4 procedure I & II based on similar requirements for the radio [16]. A few temperature tests were done on the battery, namely the high temperature operational test (55 °C), the low temperature operational test (-10 °C), the high temperature storage test (73 °C) and the low temperature storage test (-20 °C).

The Cycle B test was done, and from Figure 26 it can be seen that at -10 °C the discharge is very close to the 20 hours measured at room temperature. At 55 °C the discharge time was actually longer and this is due to a reduction in internal resistance caused by the increase in temperature.

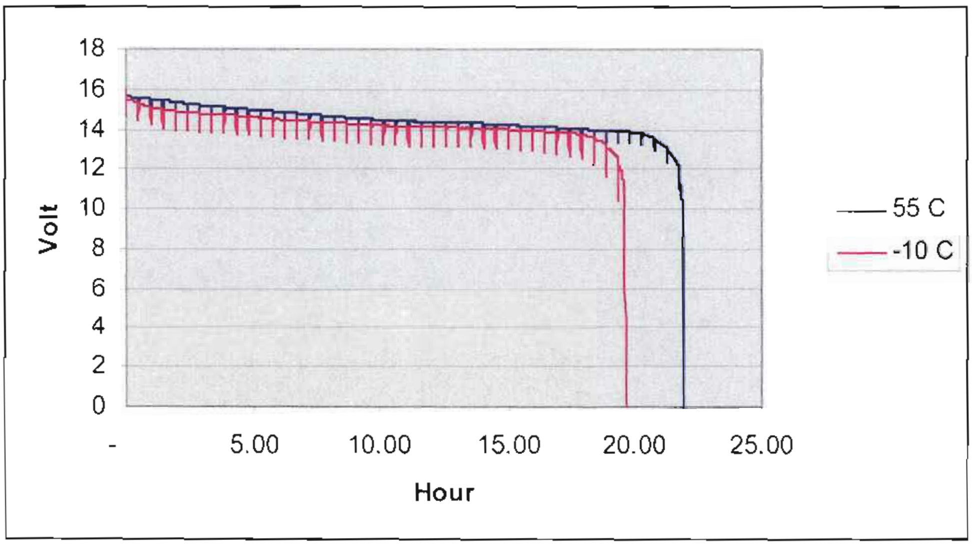

Figure 26: Temperature effect on the Li-ion battery

For the high temperature storage test the battery was stored at 73 °C for 24 hours and then immediately tested. The Cycle B discharge was applied and the discharge time was 22.5 hours. When the battery was stored at -20 °C for 24 hours and then tested, the discharge time was 17 hours. Regarding the temperature tests on the alkaline battery pack, the battery started leaking at the high temperature (55°C) and could not be tested.

Cycle life

The cycle life is the number of times that the rechargeable battery can be charged and discharged before it is no longer able to hold or deliver any useful amount of energy (paragraph 2.2.7). The retained percentage of the cell's nominal capacity, considered as an acceptable minimum, is 70%. The minimum number of cycles specified is 800 [12]. For this test the battery was discharged at 5 A continuously to drain the battery quickly and to see if the test could put some stress on the battery (see Figure 27).

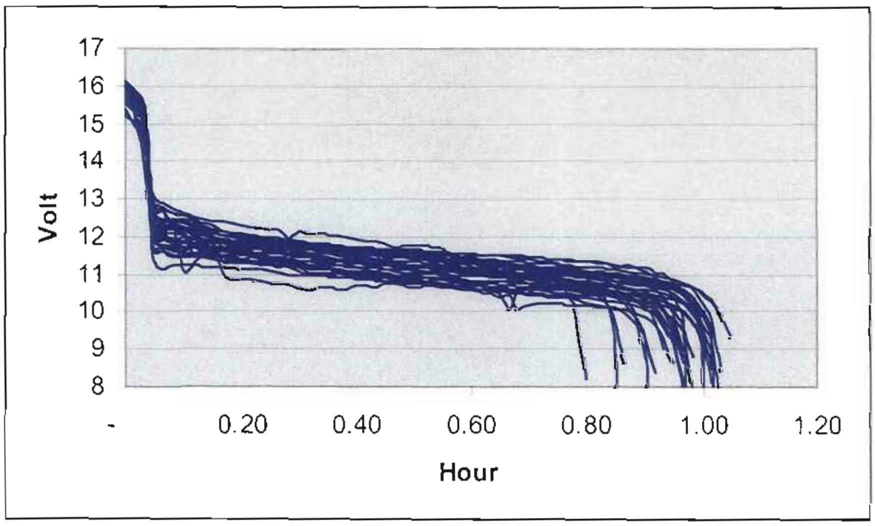

Figure 27: Cycle life tests

The discharge time varied from 0.8 hours to 1 hour depending on how well the charging cycle was completed. No trend was noted after 40 cycles.

Safety tests

High energy density batteries are dangerous. Exercise caution when handling and testing them. The following safety test must be done in a controlled environment:

Crush test

Apply about 13 kN of force when crushing the cells. Figure 28 shows two Li-ion cells after they had been crushed.

Figure 28: Crushed Li-ion cells

Nail penetration test

Penetrate a 4 mm nail into the cell body. Figure 29 shows from left the Li-ion cell under a protection plate with a nail on top. The next frame shows the mini explosion and the last frame shows the last bit of smoke coming from the cell.

Figure 29: Nail penetration resulting in fire

Bullet penetration test

Place the battery pack in an aluminium box, and shoot at it with a 5.56 x 45 NATO calibre round. Figure 30 shows from left a Li-ion battery on a brick, the next frame shows the battery flying through the air and the last frame shows the battery burning.

Figure 30: 5.56 x 45 Nato calibre fired at the battery

3.4.3 Interpretation of the results

For the weight test, and taking in consideration that the final enclosure could be heavier than the prototype enclosure, the Li-ion battery pack should pass the weight limit test of 900g.

The alkaline battery pack turned out to have a lot less capacity than expected. This battery pack was qualified in 1993 [10], the same year when battery manufacturers were forced to start eliminating the use of mercury in alkaline manganese and zinc carbon batteries [9]. The alkaline battery pack might have lasted 8 hours in the 1.5 A discharge test (Cycle B) then, but with the same test now, the battery pack only lasted an average of 4 hours and could not handle the 2 A discharge (Cycle C) at all.

The 6A/h Li-ion battery pack lasted close to 20 hours in the 1.5 A discharge tests (Cycle B), which is a dramatic improvement. Even in both the high-temperature test and the low-temperature test the Li-ion battery lasted up to 20 hours. As expected, the alkaline battery cannot be used at sub-zero temperatures. From the literature it will be noted that Li-ion batteries can be designed to work at a specified temperature, for instance Li-ion batteries with a new electrolyte were developed by SAFT America, which deliver 70% capacity at -40 °C [1]. This means that the Li-ion battery is a good choice if temperature and capacity are important for the user.

It was not possible to learn much from the 30 days' storage test, since any variation was too small to notice. Neither did the 5 A discharge cycle test show any problems with the battery. To carry out the 800 expected charge-discharge cycles would have taken too long. The battery was discharged 37 times at a load of 5 A, which should be quite tough on the battery. No noticeable difference could be detected at the 40th cycle. These tests take a very long time and it is not easy to control all the conditions over such a long period. From the test results there was no reason to doubt the manufacturer's cell specifications for self discharge and cycle life.

Lastly, the internal resistance calculations were not very accurate and varied quite a lot. A better way of determining the state of health of the battery must be found. The Li-ion battery pack lasted 19 hours with a charge of 4 V per cell and 23 hours with a charge of 4.1 V per cell. Taking into consideration that a typical mission is probably 24 hours, it might be better to charge the battery up to 4.1 V per cell which is still below the upper limit of 4.2 V per cell.

In both the nail penetration test and the bullet penetration test the battery started to burn. This burning effect was not like an explosion but it emphasises the fact that high-energy batteries are dangerous and should not be mishandled. It might be necessary to design a pressure release valve in the battery enclosure. The concept of a pressure release valve is discussed in [63] and is based on the fact that an explosion could occur if the pressure inside a battery is not allowed to escape.

3.5 SUMMARY

When looking at world trends regarding rechargeable batteries for military use, it becomes obvious that the Li-ion technology is a good choice. For laptops and handheld devices, Li-ion is also the preferred choice.

However, if Li-ion is chosen instead of the current alkaline technology, the user would have to spend more time on maintenance. To do this the user would need good chargers and battery analysers. It is also important for the user to realise that for the Li-ion batteries to be cost effective, they must be used as often as possible.

During tests on a prototype Li-ion battery the following were noted: the Li-ion pack has the ability to provide larger currents than the alkaline battery packs, the Li-ion battery pack is bit smaller and it is 26% lighter in weight compared to the alkaline battery pack.

It is important to realise that the initial capacity depends a lot on the load current. In the case of alkaline batteries, the stated capacity usually relates to a low current drain, typical of the low currents required for commercial equipment. When the alkaline battery pack was measured at 1.2 A, the capacity worked out to only 3 Ah. The Li-ion battery pack capacity depends on the charge. The capacity specified (6A h) is with a full charge. In a military environment where extreme conditions exist, it will be safer not to fully charge the battery. Tests have shown that a charge of 16.0 V instead of 16.4 V still gives a capacity of 4.6 Ah.

For most of the tests where the A43 load was simulated and the discharge time was measured, the Li-ion battery pack lasted up to five times longer than the alkaline battery. For instance, with a 1.5 A load the alkaline battery lasted four hours compared to the Li-ion battery pack which lasted 20 hours.

Regarding the temperature tests on the alkaline battery pack, the battery started leaking at very high temperatures (55°C) and could not be tested. The Li-ion battery was successfully charged and discharged at 55°C. The discharge time at this temperature was actually a bit longer. Even when the Li-ion battery was stored at 73 °C and tested at room temperature, there was still no reduction in discharge time. At –10 °C there was still no indication of a reduction in discharge time. When the battery was stored at –20 °C and then tested at room temperature there was only a 10% reduction in discharge time.

Crushing the cells did not lead to an explosion either, but this could depend on how much they are crushed. As expected, the battery started to burn when the cells were penetrated.

To summarise, the Li-ion battery pack was built with commercial cells, which are a lot less expensive than military-specification Li-ion cells. However, functionally they outperformed the alkaline battery pack by far.

The results from this test and the knowledge obtained from working with Li-ion batteries confirmed that Li-ion is the best choice for the A43 radio. However, rechargeable cells on their own cannot fulfil the user requirement. A battery system using Li-ion cells must be designed and the battery should have an accompanying charger. Maintaining the battery system should also be addressed as part of the complete system.

4. DESIGNING A NEW GENERATION BATTERY SYSTEM

4.1 INTRODUCTION

Selection of the appropriate battery cell is just part of the solution. To ensure that the technology can be used as required, a New Generation Battery System must be designed. The stated user requirement must be validated since the type of technology used will influence what the user can expect from a new battery. Some of the design concepts must be verified by tests to ensure that the specifications for building a New Generation Battery System can be met. In this section a battery system is designed based on the user requirement [12] and information obtained from the technology study (Chapter 2), as well as what was learned from the verification test (paragraph 3.4). This design and specification do not cover everything but can be seen as a minimum requirement.

The A43 radio requires a battery pack with a voltage of between 10 and 18 V [16]. The capacity of the battery should be about 6 Ah [12]. The A43 battery system design is shown in the schematic block diagram in Figure 31.

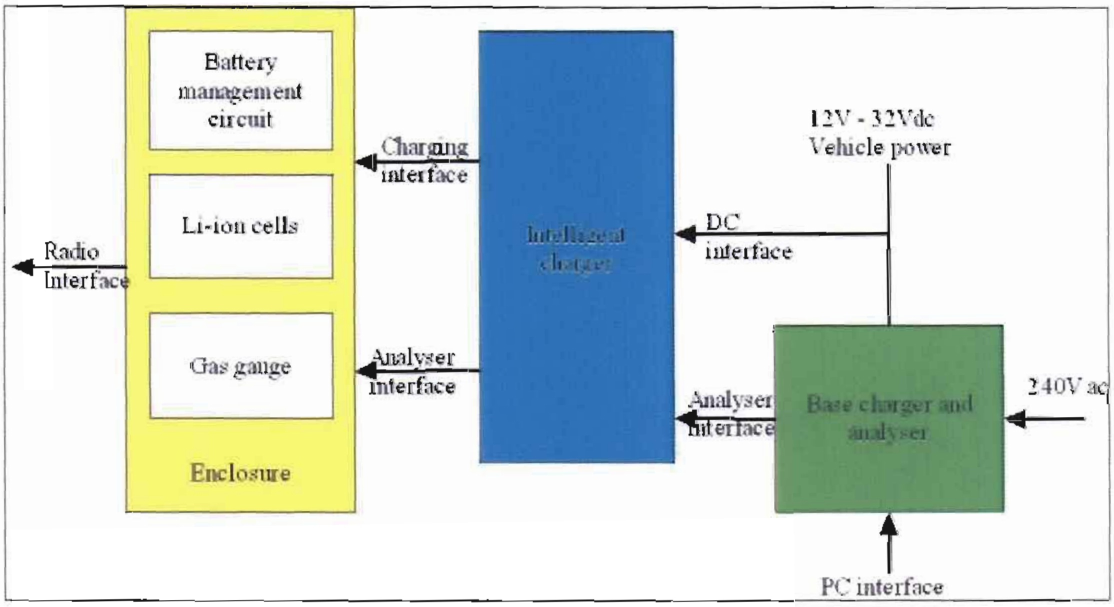

Figure 31: A43 Battery system

From this battery system design the items identified for a battery system are listed in Table 19.

Table 19: Battery system items

Item	Description
Li-ion cells	The battery is made up of the appropriate number of cells.
Battery management circuit	This circuit is responsible for functions such as protection, gas gauge control, System Management Bus (SmBus) and cell balancing.
Battery enclosure	An enclosure designed to fit the radio and withstand the environmental conditions.
Charging interface	An interface, where the charger connects, which for safety reasons should not be the same as any other charger already in use by the SANDF.
Radio interface	The connectors required to connect the battery to the radio.
Analyser interface	An interface used for SmBus communication.
Intelligent charger	A charger which uses the SmBus to interrogate the battery and control the charging cycle for optimum charging. This is a field charger with a dc input.
Base charger and analyser	The base charger connects to 220 V and supplies the field charger with the required dc input. The base charger contains an analyser which is used for battery management.
DC interface	The dc interface will be used to connect to vehicles used in the SANDF.
PC interface	The PC interface is required when the SmBus parameters of the battery must be changed. But it could also be used for a higher level battery database.
AC interface	At a base the charger will work from 220 V ac.

To enable better understanding of how the New Generation Battery System should look, full-scale CAD drawings were made. The complete battery system will include a smart Li-ion battery as suggested in Figure 32, a field charger as suggested in Figure 33 and a base charger with analyser as in Figure 34.

The battery should be fitted with a safety circuit and a fuel gauge to indicate the remaining capacity. The fuel gauge can be seen on the side of the battery in Figure 32. The fuel gauge LEDs are activated when the button is pressed. The connections for the SmBus and charger can be seen on the top right-hand side of the battery. The SmBus will assist the user to test, maintain and manage the battery system.

Figure 32: A43 Li-ion battery pack

The charger connects to a cable which connects to an applicable vehicle to supply the charger with a dc source. The charger also connects to the SmBus on the battery and LEDs on the side give an indication of the status of the charging cycle Figure 33.

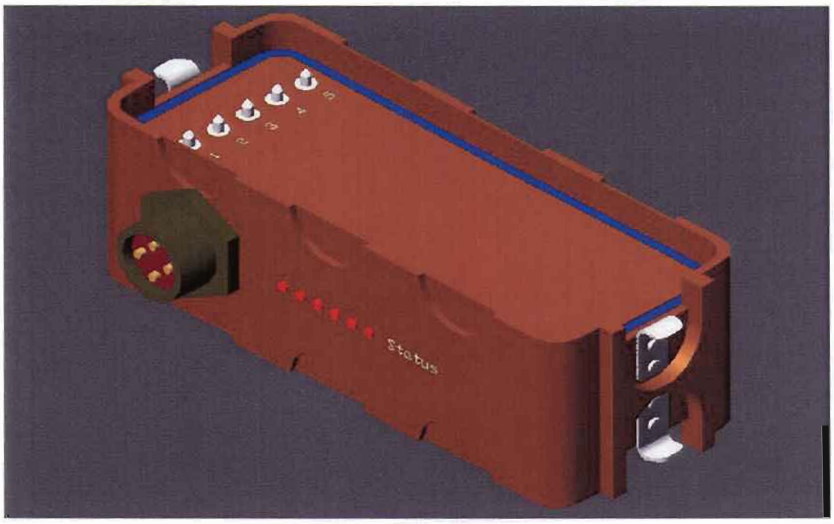

Figure 33: A43 Li-ion field charger

The analyser should be part of the base charger (Figure 34). The analyser should have a LCD that will give an indication of the state of health of the battery. The base charger can connect up to three field chargers.

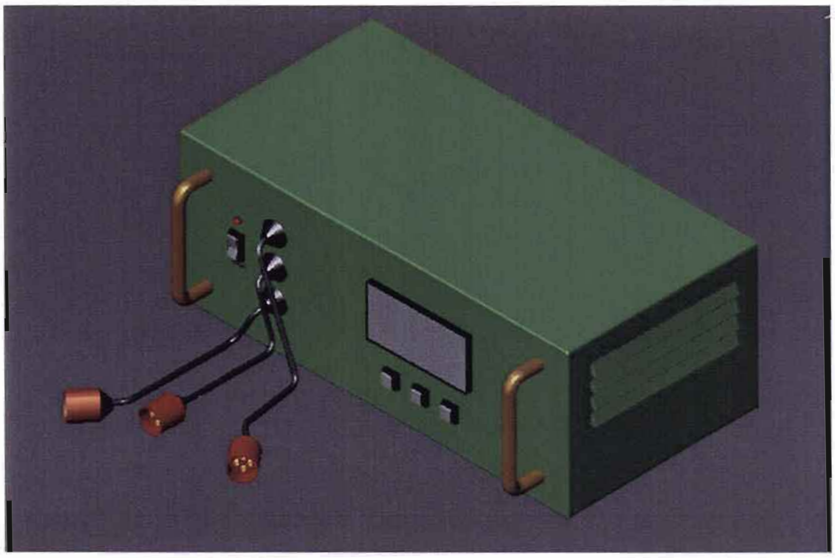

Figure 34: A43 Li-ion base charger/analyser

The main purpose of the battery analyser is to interrogate the SmBus to make "go/no-go" decisions regarding the battery's state of health. The SmBus will also supply the charger with the necessary charging and control information and help the user to maintain the battery.

An example of a typical charging block diagram is given in Figure 35.

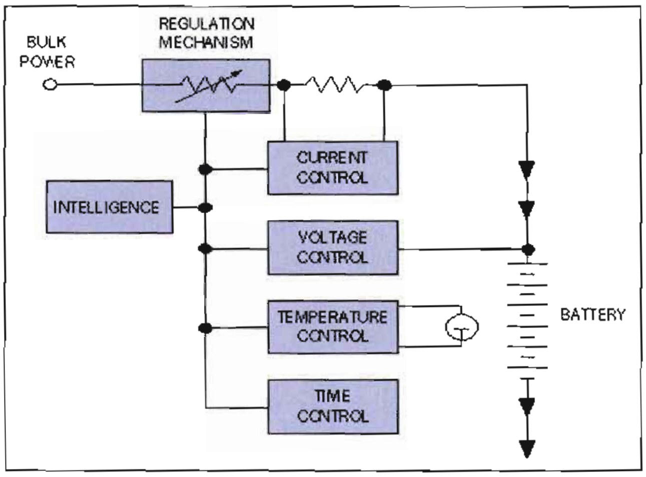

Figure 35: Li-ion charger block diagram

From this diagram it can be noted that the charger concept is very similar to that of a lead-acid battery, with the difference that the Li-ion battery has much tighter tolerance on the voltage level. Temperature is also an important input to the charger as discussed in paragraph 4.2.5. Time control is usually used as a safety back-up when the monitoring function fails. Intelligence will be provided by the circuitry which provides the SmBus properties.

4.2 BATTERY SYSTEM FUNCTIONAL AND PERFORMANCE REQUIREMENTS

Important functions required by the battery system are highlighted in this section and where possible the measurable performance requirements are also listed.

4.2.1 Battery system states and modes

When designing a battery system for military use the following phases in the life of the battery must be considered: Packaging of the batteries as well as the charger during transportation to ensure compliance with road and air transportation regulations. Safe handling procedures for high energy batteries, which should be part of soldier training. Storage of the batteries when not in use, especially since these batteries cannot be stored for a long time without maintenance. Integration into the current radio as well as existing pouches used by the soldier. How will the battery be used in the field, especially regarding charging requirements? How will the battery be maintained, including the determination of the battery's state of health? Finally, what will happen when the system comes to the end of its life, namely disposal and recycling of the battery?

4.2.2 Voltage and current requirements

The Li-ion cells should be connected in a configuration such as to provide a voltage smaller than 18 V and greater than 10 V, which is a requirement by the radio [16].

Since the radio is not specifically designed for new generation batteries, it is important to note that the radio will only switch off at 10 V. Therefore the radio will try to discharge the cells down to 2.,5 V per cell. Li-ion cells must not be discharged below 2.5 V per cell (paragraph 2.2.1) so the protection circuit must ensure this.

The maximum current required by the radio is 2 A, but during tests it was established that the radio requires a current spike of 6.5 A during switch-on. The battery protection circuit should allow for this spike.

The charger should be intelligent enough to be able to set the required charging voltage as indicated by the battery. This information transfer will be done via the SmBus, typically up to 16.4 V ±0.1 V at maximum charge current (1C). It is suggested, as discussed in paragraph 3.4, to charge the battery only to 4.1 V per cell. This will help to minimise possible stress on the battery when it is used at the high temperatures typical of a military environment.

The base charger should run off 210 V – 250 V AC at 50 Hz. Any overload protection should have automatic recovery ability. The base charger should have an indefinite short circuit protection. The aim of these requirements is to give the soldier a more reliable system.

The maximum charging current should be 6 A per battery based on the fact that a Li-ion battery of 6 Ah could be charged at 1C (paragraph 2.3.1). The charger should be able to charge two batteries simultaneously. The minimum charging current should be 2 A to ensure that the battery can be charged within three hours (paragraph 3.4.3).

The charger should terminate (no trickle charge) the charge when the charging current is less than 200 mA (the exact value will be supplied by the battery manufacturer). The charger should also stop charging if full charge is not reached within a pre-determined number of hours or when a faulty battery is detected. The charger should always monitor the battery temperature, since temperature is a good indication of fault conditions (paragraph 2.3.4) and Li-ion cells must not be charged outside the specified temperature range (see paragraph 4.2.5).

4.2.3 Capacity requirements

The cell configuration should have an initial capacity (measured at 0.2 C to a cut-off voltage of 10 V) of better than 6 Ah. 6 Ah capacity was a requirement from the user which was validated by the cycle tests done in paragraph 3.4. Since talk time was the most important factor in the value system, it is expected that the higher the capacity the better. The problem is that only batteries with a maximum equivalent lithium content of 8 g are currently exempted from the U.S. hazardous materials regulations. This also applies to shipments that are transported by motor vehicle.

Batteries must be packed in such a way as to prevent short circuits or generating a dangerous quantity of heat. Equivalent lithium content for Li-ion batteries is calculated as 0.3 times the rated capacity in ampere-hours. The equivalent lithium content for a battery pack is the rated capacity in ampere-hours for a single cell multiplied by 0.3 and then multiplied by the number of cells in the battery [64]. To stay within the transportation regulations, the highest capacity battery allowed is 12 cells with a 2.2 Ah capacity, which works out to a battery of 6.6 Ah. The 2.2 Ah cells are still quite new and it might be more cost effective to use the 2 Ah cells for now.

For maintenance purposes the analyser should warn the user if the battery has less than 80% of its original capacity left. This is one of the indications to the user that new batteries are required and the old batteries need to be taken out of service. The value of 80% should still be validated by closely monitoring battery performance when the battery is used in military applications.

4.2.4 Battery discharging requirements

The analyser should be able to discharge a battery in the case where the battery must be stored (50% charge) or disposed of (0% charge). To re-calibrate the SmBus capacity measuring function, the battery should be fully discharged if deemed necessary [19].

4.2.5 Temperature requirements

Cells should have a discharge temperature range from -20 °C to 70 °C as specified by the user requirement [12]. At -10 °C the capacity must be equal to or more than 60% of the initial capacity. At 0 °C the capacity must be equal to or more than 70% of the initial capacity.

At 70 °C the capacity must be equal to or more than 90% of the initial capacity. Cells should have a charge temperature range of at least 0 °C to 45 °C. This temperature range was verified during the verification tests discussed in paragraph 3.4.3.

The charger should monitor the battery temperature and should function as indicated in Table 20 [51]

Table 20: Charging temperatures

Battery Temperature	Function	Display
Below 0 °C	Don't charge.	Outside charging temperature
0 °C – 45 °C	Charge	Charge state
45 °C – 69 °C	Slow charge	Charge state
70 °C	Don't charge	Outside charging temperature

4.2.6 Battery charging/discharging cycles

Cells should have a minimum of 70% of the initial capacity after 500 cycles as specified in the user requirement [12]. This requirement was not validated but it should be possible, as indicated by the cell specifications supplied by the manufacturers [31].

4.2.7 Battery Storage

Cells should not lose more than 6% of their capacity when stored for a month at 15 °C. This figure is based on the manufacturer's cell specification (paragraph 2.2.6). This type of specification is usually achieved by buying better quality cells.

4.2.8 Battery pack weight and dimensions

After discussions with the user [13], the importance of a battery enclosure which can withstand the environmental conditions was pointed out. The minimum weight

value for the battery pack was adjusted to less than 1 400 g. The validity of the requirement was verified by weighing the prototype batteries (paragraph 3.4).
The cells plus the electronic circuits must fit in an enclosure where the outer dimensions of the enclosure are 155 mm (L) x 59 mm (W) x 80 mm (H). This requirement is necessary to ensure that the new batteries still fit into the existing pouches used by the soldier [13].

4.2.9 Safety requirements

Li-ion batteries are dangerous due to their higher energy capability (see penetration tests in paragraph 3.4). All relevant safety tests that were done on the cells by the manufacturers must be provided. Cells with the best safety specifications will be considered as superior.

The cells must be packaged in such a way that no pressure build-up is possible in the case of damaged cells [18]. For instance the cells should not be potted [63].

The protection circuits of the battery must be able to reset themselves when the abnormal electrical condition is removed. The charger should never exceed a charging voltage of 16.8 V (paragraph 2.2.1) due to the danger of overcharging.

4.2.10 SmBus requirements

The battery system should support the 2-wire SmBus v1.1 specification interface as a minimum requirement. This was not part of the user requirement, but from the literature study it became obvious that maintaining the battery is very important and that the SmBus will play a major role in assisting to maintain the battery. The SmBus will mainly be used to assist with determining the state of health of the battery.

For maintaining the battery, the following information could be used by the analyser to determine whether a battery must be replaced. Firstly the battery's age: usually batteries older than two years should be replaced, but this might change as the technology improves. The charger should warn the user if defective cells are detected and the battery should be replaced. Usually, batteries with a cycle count of more than 500 should be replaced, but this might also change as the technology improves. The user must be warned if a battery has been exposed to high temperatures, as high temperatures could shorten the life of the battery or have a effect on the battery's performance.

4.2.11 Capacity indication (gas gauge)

The battery should have an external capacity indication, relative to the initial capacity, showing the capacity left in the battery in percentage as follows: 100%, 80%, 60%, 40%, 20%. This is a useful tool for the soldier to get a quick indication of the charge left in his batteries.

4.2.12 Maintainability of the system

On the level at which the SANDF operates, maintaining fairly complex equipment repairs will not be done in house [58]. The pack should have no built-in user-replaceable or user-serviceable parts. In the case of a defect, the user should only have to replace the equipment and should not need to do any board-level replacements or board-level adjustments.

The charger should be able to do a reconditioning charge in the case of batteries that are over-discharged. This consists of a slow charge of 100 mA until the battery electronics have enough power [51]. This is a requirement specifically for Li-ion cells which, if left unattended too long, would cause the voltage to be too low to switch on and drive the protection circuit.

4.2.13 Environmental conditions

The battery should be operational and perform according to specification under all reasonable battlefield environments. The battlefield environment covers the environmental conditions found in South Africa up to sub-Saharan Africa. Design test requirements to withstand these conditions can be found in MIL-STD-810F [50] and the required test is described in paragraph 4.3.

4.2.14 System interface

The input voltage to the charger should be 12 V – 32 V dc, based on expected voltages of vehicles used by the SANDF. The base charger should work from an AC input of 220 V - 250 V at 50 Hz as found in a military base.

The charger should provide an interface to the battery analyser. This interface allows the analyser to interrogate the battery. The analyser should connect to a PC via an RS232 or a USB port. A software application will be used to configure the SmBus parameters.

4.3 MILITARY ACCEPTANCE TESTS FOR THE BATTERY SYSTEM

A military system must be qualified before it can be used in the field. A soldier mostly operates in life-threatening situations and cannot be expected to field trial new equipment while busy with an operation. New equipment must be tested in such a way that the soldier can be assured that the equipment will work in all expected environments.

MIL-STD-81OF [50] is a military standard document on environmental testing. This document lists test methods for determining the effects of natural and induced environments on equipment used in military applications. This standard shall not be invoked on a blanket basis, but each test will be assessed in terms of the need. Application of this standard early in the development phase of the acquisition process is encouraged.

Based on the required qualifications test for the A43 radio, a test list was defined in support of the following objectives: to disclose deficiencies, to assess equipment suitability for the expected environmental conditions and to verify contractual compliance when a specification for a battery system goes out on tender. The complete list can be seen in Appendix C.

In the previous section (paragraph 3.4) a test was described which is done to insure that the Li-ion battery can handle the required currents and to determine the expected talk time. The next section (paragraph 4.4) describes a test was done with the following two objectives in mind: firstly to test whether the protection circuits in the battery can handle a certain amount of misuse by the soldier, and secondly to get an opportunity to discuss the complete test list with experts at the facilities which do these types of environmental tests.

The batteries tested were prototypes manufactured by two different companies (refer to Figure 36). The brown battery was an 8 Ah battery with a locally manufactured protection circuit. The intention was to verify that the protection circuit would pass the required test. The black battery was built by Varta in the UK and since their Li-ion cells are reputed to be of good quality, the intention of the test was to see whether it would be possible to get a impression of the quality of cells used to build the battery.

Figure 36: Two prototype Li-ion batteries

4.4 DESIGN VERIFICATION RESULTS

The test was done at Gerotek, which is an accredited test facility specialising in environmental testing for military equipment. The full test report can be found in Appendix D.

From this report it was noted that it is not really possible to verify the quality of the cells with these tests. Quality differences will probably only be noted during the ageing process which only becomes noticeable after two years or during about 500 charge and discharge cycles. In the capacity test the black battery's capacity was found to be the same as specified and the brown battery's capacity was found to be less than specified. The question is whether this could be an indication that the cells in the black battery were of better quality or whether the electronics in the brown battery added to a capacity reduction. This could happen if the internal resistance of the battery pack increased due to the protection circuit.

Shorting the batteries was not a problem for the protection circuit in the batteries. Reverse charging showed that the protection circuit in the brown battery did not automatically reset when the fault condition was remove. This is an important function for the soldier, as the soldier would not want to lose the battery due to human error. A soldier's battery must be very reliable and new electronic technologies should be able to protect the battery and to reset the protection circuit if the fault condition is removed.

With the temperature test it was noted that the temperature protection setting of the brown battery, which can be set via the SmBus, was lower than the black battery's settings. This brings out the point that the SmBus protection settings must be set at a value which protects the battery but takes into consideration the expected operational environment of the soldier.

A second battery workshop was attended at the Technical University in Graz and the objectives of the workshop were to:

- Get an up-to-date overview of the latest battery technologies for application in defence communication systems.

- To assess the viability of these technologies from an academic and industrial perspective.
- To discuss the implementation of the lithium ion programme for the A 43 radio with potential suppliers and qualification authorities.

Some of the points discussed in this workshop which are not covered in the above sections can be found in Appendix E.

4.5 SUMMARY

The New Generation Battery System consists of three main components, namely an intelligent battery, a field chargers and a base charger with a built-in analyser. The battery consists of a fuel gauge, an SmBus, the required protection of the Li-ion cells and an enclosure which can withstand the required environmental conditions. The fuel gauge gives the soldier an indication of the capacity left in the battery. The SmBus keeps track of the state of health of the battery as part of the maintenance process and can provide the charger with the required parameters for optimum charging. The field charger will be connected to a vehicle to charge the batteries. The base charger works off 220 V and has a LCD to display the state of health of the battery.

The recommended battery consists of three cells in parallel and four cells in series. The capacity of the battery should be between 6 Ah and 6.6 Ah, which is still within the transport regulations. It is important to build the battery with good quality cells. This will not only improve the performance of the battery, but is essential for safety requirements.

The Military Standard document on environmental testing (MIL-STD-81OF) describes the tests needed to qualify the battery system before it can be used in the field. New equipment must be tested in such a way that the soldier can be assured that the equipment will work in all expected environments.

Some of these environmental tests were done on two different Li-ion batteries to ensure that the electronic circuits in the battery functioned as specified. The important points to note from this test were that the battery enclosure is an important factor in protecting the battery cells. It is also important to have protection circuits that can reset after the fault condition has been removed, as this will improve the reliability of the system. Lastly, when building a battery pack, one should start by using good quality cells. It is very difficult to test the battery in such a way that the expected quality over the battery's lifetime is demonstrated.

This tests simulate the environment in which the battery may be used, but it is also important to do tests where the user is in the loop and is engaged in a military mission. It is important to determine the effect of the technology on how the user operates and what standard operating procedures (doctrine) need to change when using this technology.

5. PRACTICAL APPLICATION OF THE BATTERY SYSTEM

5.1 INTRODUCTION

In the previous chapter a proposed design for a New Generation Battery System was presented and some of the design factors were verified. The new concept in defence forces is to regard the "Soldier as a System" [61]. This holistic approach immediately helps to recognise the fact that a New Generation Battery System cannot operate on its own. The New Generation Battery System will have an influence on the soldier, his doctrine, his training and the equipment he is using. This section explores the influence which Li-ion battery technology could have on the soldier.

From the user requirement [12], firstly, the current cost of alkaline batteries was defined as one of the bigger problems regarding the current alkaline batteries in use. Secondly, the low energy of the alkaline battery forces the soldier to carry more batteries which adds to overloading of the soldier. In Figure 37 the concept of using new technology to resolve the conflict between battery cost, an overloaded soldier and the current low-energy batteries is illustrated.

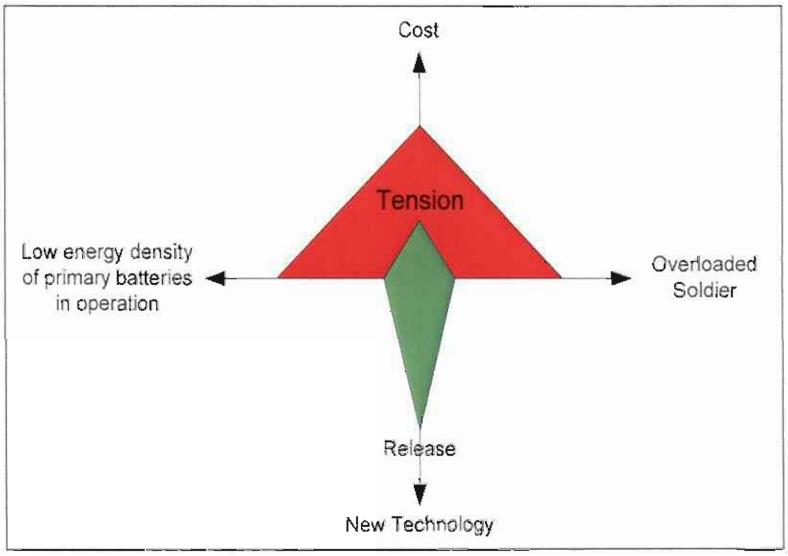

Figure 37: Current conflict within the alkaline battery system

All decisions have an associated relative cost consequence, both in the short and long term. We combat this by trying to impose a "systems" and/or "life cycle" view and attempt to apply informed disciplines of managing the "life cycle" of a system. The systems view recognises the fact that accomplishing the mission is the main goal of a system [55]. As a starting point, two typical military scenarios will be defined.

The objective of this section is also to determine the life cycle cost of a rechargeable battery system for the A43 radio. The life cycle cost of the current alkaline batteries is used as the baseline. This information is intended to support a decision to move to a New Generation Battery System.

5.2 MILITARY OPERATIONAL SCENARIOS FOR A BATTERY SYSTEM

The operational scenarios are important for understanding the problem. These scenarios also help to size the New Generation Battery System, which then directly influences its life cycle cost. Two operational scenarios are considered, namely the conventional scenario and the more current border protection scenario.

5.2.1 Conventional scenario

The conventional scenario is a full-scale war and represents the worst case. Conventional operations are conducted within the command structure, possibly with some small variations as indicated in Figure 38. This scenario considers A43 battery requirements up to battalion level. The nominal number of radios is indicated in parentheses [58].

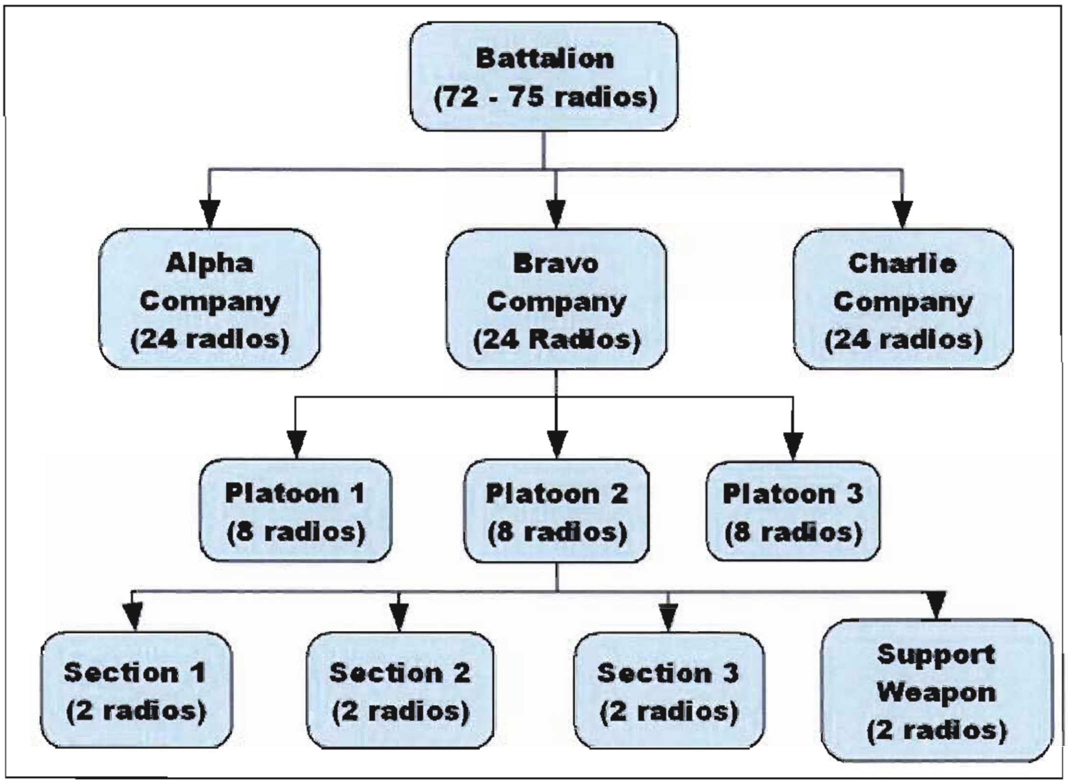

Figure 38: Command structure used for conventional maintenance context

The maintenance levels, as required for the conventional scenario, are indicated in Figure 39. The maintenance concept consist of a supply units named F Echelon which operates at the front line, A Echelon which operates from the Brigade headquarters to the front line, and B Echelon which operates at the Brigade administration area [58]. F Echelon, A Echelon and B Echelon can be seen as the user level, the intermediate level and the supply level respectively.

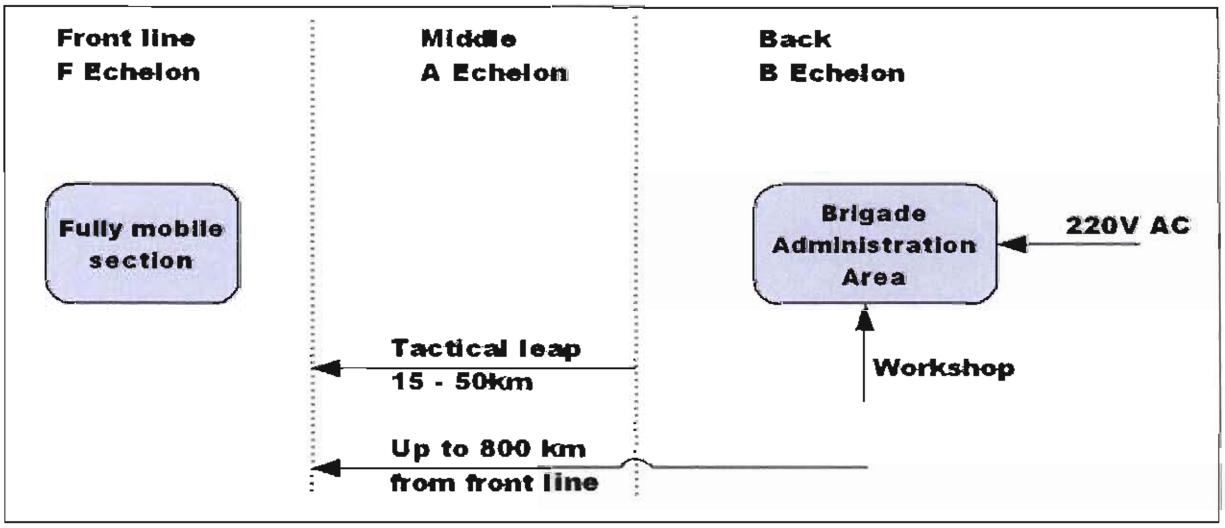

Figure 39: Maintenance levels in a conventional role

For calculation purposes the following schedule is used for the A43 radio. The A43 receives 24 h/day, with one-minute transmit time per half-hour (primary battery usage is estimated at 4 batteries/day) [12]. A company must be self-sufficient for the first 14 days of an operation according to current doctrine. Section level is replenished from the company after 7 days. The company is replenished after 14 days depending on the situation. After the first replenishment the replenishment interval is a maximum of 14 days. During a contact the logistics delay is less than 3 hours [58]. Batteries can be charged 24 h per day, i.e. personnel and battery chargers are available at the maintenance levels indicated by the maintenance concept defined in Table 21.

Table 21: New Generation Battery System Maintenance Concept (Conventional Scenario)

Item	**User Level F Echelon**	**Intermediate Level A Echelon**	**Supply Level B Echelon**
Battery	Exchange flat and partially used batteries with operational batteries	Exchange flat and partially used batteries with operational batteries Charge flat and partially used batteries Do a "Go/no go" battery test Failed batteries that do not charge successfully are separated	Exchange flat and partially used batteries with operational batteries Charge flat and partially used batteries Do a "Go/no go" battery test Failed batteries that do not charge successfully are separated Dispose of failed batteries
Battery Charger	Not applicable	"Go/no go" charger test Exchange faulty unit	"Go/no go" charger test Exchange faulty unit Diagnose to module level and exchange modules

This maintenance concept is based on a New Generation Battery System as described in Chapter 4. The soldier at the front line will carry enough batteries for the mission and not a battery charger. This is because the soldier may not have access to a vehicle to charge his batteries. At A Echelon the vehicles will have a field charger which is intelligent enough to do a "Go/no go" test on the batteries. A "Go/no go" test is basically an indication to the soldier not to use this battery any more, and is based on the state of health of the battery. Depending on the set-up there could be a base charger at A Echelon and B Echelon.

5.2.2 Border patrol scenario

A common scenario during peacetime is the detection of illegal border crossings. The example of the Kruger Park is used. The maintenance levels are shown in Figure 40. The maintenance concept is the same as described in Table 21. Observation posts are replenished every 1 to 2 weeks and operate 365 days/year.

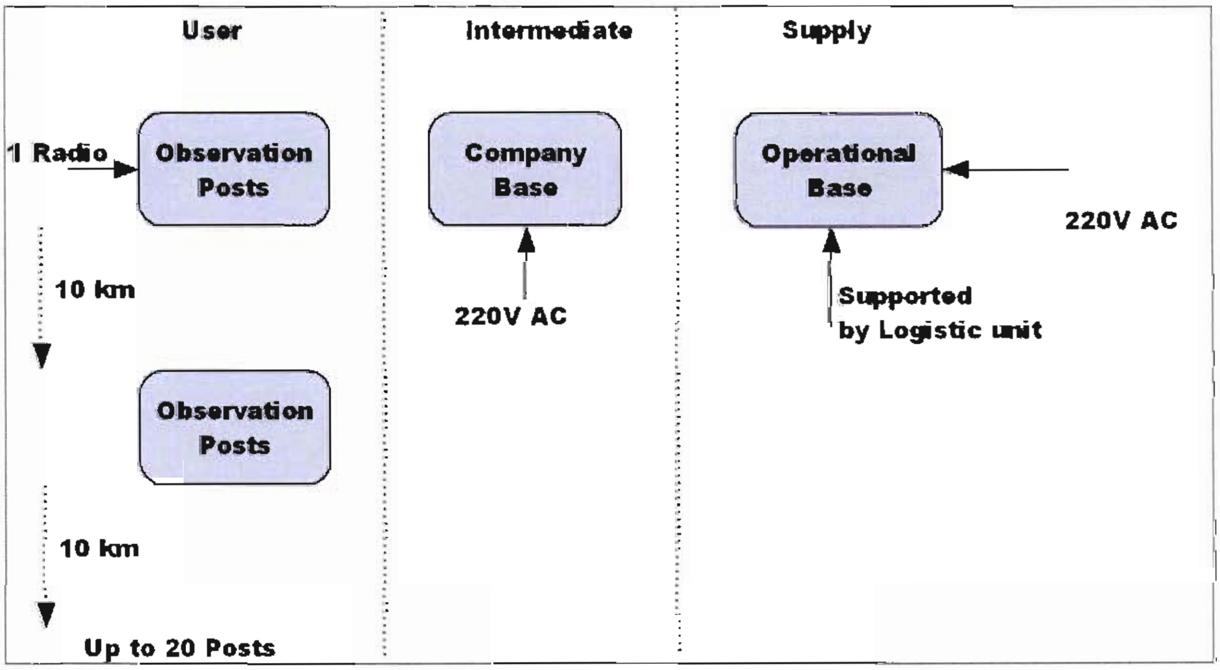

Figure 40: Maintenance levels for border patrol (Kruger Park example)

A typical observation post, consisting of three tents protected by a branch fence in the Kruger park, can be seen in Figure 41. This group of soldiers is referred to as a half section [59].

Figure 41: Observation post in the Kruger park

Again the A43 receives 24 h/day, with 1 minute transmit time per half hour (primary battery usage is estimated at 4 batteries/day). Batteries can be charged 8 h/day, i.e. personnel and battery chargers are available at the maintenance levels indicated by the maintenance concept.

5.3 DOCTRINE CHANGES WHEN USING A NEW GENERATION BATTERY SYSTEM

Doctrine is define as that which the military believes is best way to conduct military affairs. This paragraph deals with the issues involved in changing from an alkaline battery system to a New Generation Battery System for the A43 radio from a soldier's point of view. It considers not only the direct users of the batteries but also the mission planners and product system managers. The objective of this report is to identify issues involved in changing to a New Generation Battery System so that they can be dealt with in terms of supporting models, operating procedures and training materials.

Perhaps the most significant change will be one of attitude. The alkaline battery system is a consumable system. The New Generation Battery System, on the other hand, is a reusable system. The soldier is used to carrying a certain load of batteries which gets lighter as he throws away the spent batteries. Now he is expected to bring all the batteries back.

5.3.1 Understanding Li-ion requirements

Rechargeable Li-ion batteries have some important requirements and characteristics that the soldier must understand.

The Li-ion battery has a time clock that starts ticking as soon as the battery leaves the factory. The ageing of the battery will cause its internal resistance to increase. In time, the cell resistance raises to a point where the battery can no longer deliver the energy, although it may still be retained in the battery [19]. The radio, which requires bursts of high current, is affected most by the increase in internal resistance, in other words the low battery sensor will be triggered sooner when the radio transmits and there is a higher voltage drop due to the increase in internal resistance.

A periodic full discharge is not required because the lithium-based battery has no memory. The batteries prefer a shallow discharge and therefore regular charging is encouraged [19]. For best results, the battery should be kept cool. Keeping the battery cool is probably the least important thing on a soldier's mind. In addition, the battery must be stored at about 40% charge level, and it should never be fully charged or discharged before storage. The Li-ion battery does not like prolonged storage. Irreversible capacity loss occurs after 6 to 12 months, especially if the battery is stored at full charge and at warm temperatures [19]. This type of system therefore needs good maintenance procedures.

The SANDF should try to avoid purchasing spare Li-ion batteries for later use. The manufacturing date must be observed when purchasing and old stock should not be purchased. This could be a major problem if the current doctrine dictates that there should be an emergency stock of batteries in case of war.

Smart batteries should not be deep discharged. Discharging the batteries below a certain voltage point will put the battery to sleep, and a recharge often fails to wake it up. The self-discharge of the Li-ion battery is 5% in the first 24 hours after charge and averages 1 to 2% per month thereafter. In addition to the natural self-discharge through the chemical cell, the safety circuit could draw as much as 3% per month [19]. A soldier should not leave discharged batteries uncharged until the next mission, as batteries lying somewhere in a cupboard could easily become unserviceable.

Some of the safety features of lithium-based batteries are one-way, which means that once activated, the cells are inoperable thereafter. In the design of the battery it is important to try to have resetable safety protection. Not misusing the battery is still very important and must be addressed by appropriate training.

5.3.2 Impact on users of the New Generation Battery System

The main aim of the New Generation Battery System is to provide sustainable power to the A43 radio. Six main functions required to provide sustainable power to this radio, namely acquisition, operation, maintenance, disposal, management and monitoring [56]. In this section the impact of these functions on users is considered [56].

Acquisition and transition of New Generation Battery System components

The first step is to acquire batteries and battery chargers and train new personnel as required from time to time. This is followed by the transition of the batteries and battery chargers into operation, which includes the distribution of batteries and battery chargers and their installation (Figure 42).

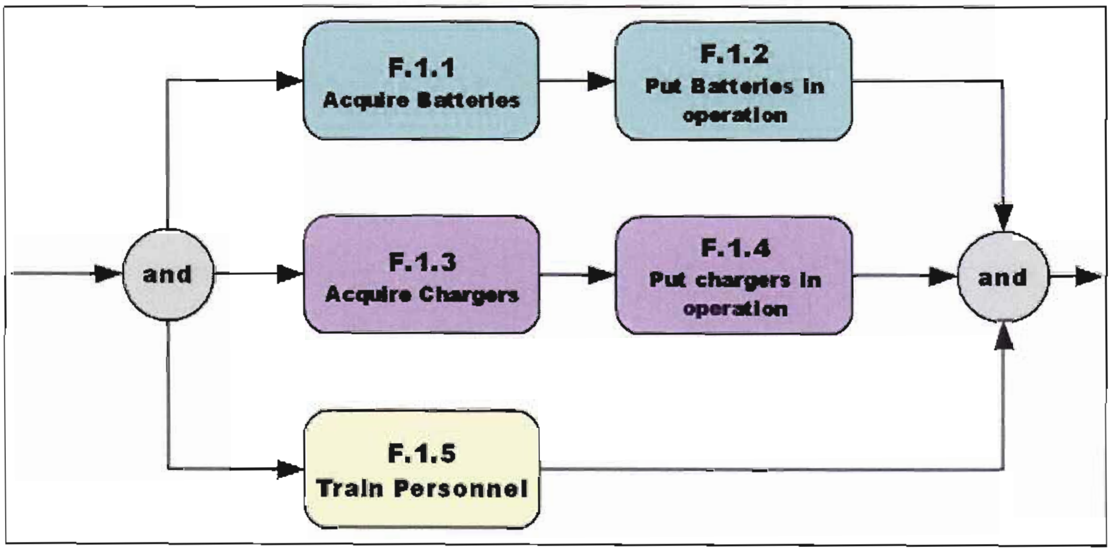

Figure 42: Acquisition functions of the New Generation Battery System

The acquisition of batteries (Figure 42: F1.1 and F1.2) relates to all activities, which range from sending a request to the supplier, negotiating an agreement, receiving the batteries and paying the supplier.

Acquiring batteries and battery chargers (Figure 42: F1.1 and F1.3) and installing chargers relates to all activities, ranging from sending a request to the supplier, negotiating an agreement, receiving the battery chargers and paying the supplier.

Training (Figure 42: F1.5) involves instructing personnel on procedures relating to operating, charging and storing the batteries.

Operation of the New Generation Battery System

The purpose of the New Generation Battery System is to provide power to the A43 radio. From the point of view of the soldier, a visual indication of the remaining charge (Figure 32) is important for planning battery use. In this set-up it is important to have batteries which provide longer talk time. The soldier will never accept a new system which does not have obvious advantages.

Maintenance of the New Generation Battery System

Functions related to maintaining batteries and battery chargers are displayed in Figure 43.

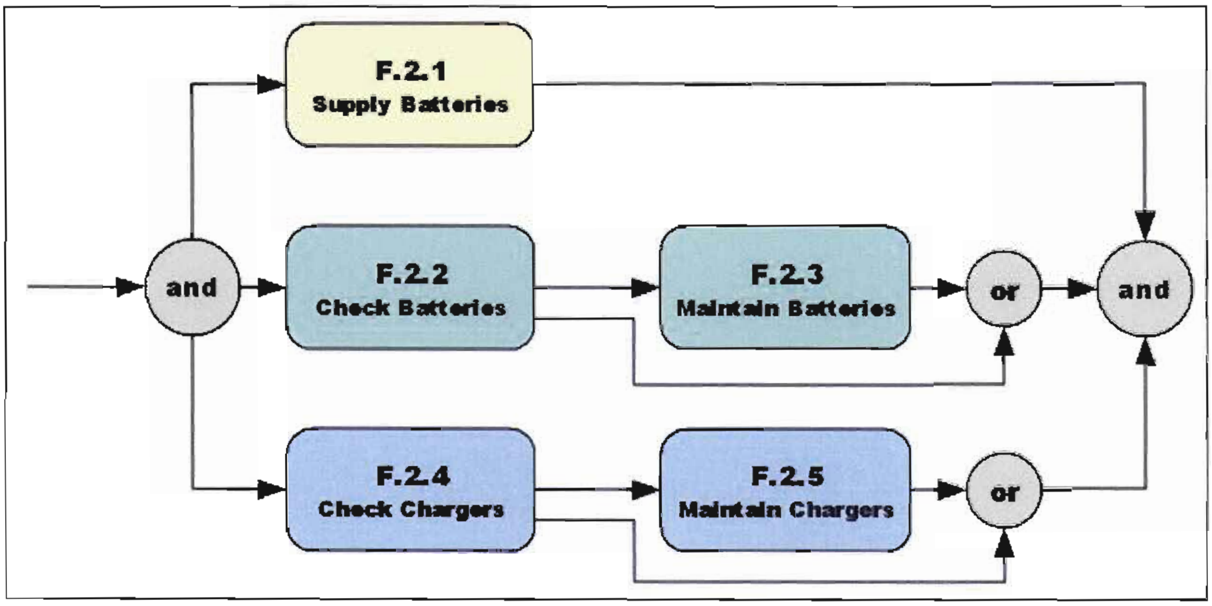

Figure 43: Maintenance function of the New Generation Battery System

Supplying batteries (Figure 43, F.2.1) includes the stores function and the distribution of batteries. Since these supply chains already exist in the SANDF, this should not be a problem for the current batteries. A rechargeable battery system must be based on an exchange principle. Flat and partially used batteries are replaced with charged batteries on a one-to-one basis. The only issue of concern here is that soldiers in the field may simply discard the rechargeable batteries.

The battery charger (Figure 43, F.2.4) will perform a self-test at power on, indicating its serviceability to the user. Battery maintenance (Figure 43, F.2.3) starts with visual inspection. If the battery is obviously damaged, it is put into the disposal store; otherwise it is inserted into the charger(Figure 43, F.2.3).

Maintenance of the battery chargers (Figure 43 F.2.5) will require training of maintenance personnel. At this stage, it appears that repair will consist of detecting the fault to module level and replacing the module.

Disposal of the New Generation Battery System

Batteries are issued for final disposal from the disposal store. To reduce the safety risk, all batteries are completely discharged before disposal. The SANDF will contract a waste company to dispose of the batteries. The disposal method is recorded for environmental management reasons. Sensitivity to safety and the environment will be critical.

Management of the New Generation Battery System

An important function relating to battery life, based on battery age and expected battery life, will be to make a decision to dispose of all old batteries. A cost model and a battery capacity model could be used to make the disposal decision. Because of battery capacity loss over time, more batteries and battery chargers will be needed to accomplish the same mission at the end of the battery's life than at initial purchase. The batteries are replaced when the increase in cost due to loss of capacity over time equals the cost of new batteries. The control should be based on a model, taking into account usage, maintenance and battery failure rates. In addition, when the number of trained maintenance personnel drops below a certain level, training must be initiated [56].

Tactical management relates to mission-level planning and scheduling of logistic support. At this level of planning, a pool of rechargeable batteries is available. Based on the mission duration, replenishment interval and the number of A43 radios, the number of batteries and battery chargers for a specific mission can be determined. It is suggested that a computer model be used for planning. This is important because of capacity loss effects [56] and the fact that batteries cannot really be stored for a long time due to the ageing effect.

5.3.3 Safety and performance precautions

High-energy batteries are always dangerous and strict safety precautions must be followed. Most manufacturers will provide a list of safety precautions, for example as seen in [57]. Most safety precautions are obvious, but some of them that relate directly to how a soldier operates are discussed here.

Using the battery

Heat is one of the biggest enemies of a battery. Be sure to prevent batteries from being dropped. When carrying extra battery packs, make sure that the terminals are not shorted out by any metal objects.

Avoiding misuse of the battery

Misusing the battery may cause it to get hot, rupture or ignite and can cause serious injury. Do not heat the battery or place it in a fire. Do not crush or pierce the battery as this can lead to fire. Do not disassemble or modify the battery. The battery contains safety and protection devices which, if damaged, may cause the battery to generate heat, rupture or ignite. Immediately discontinue use of the battery if, while using, charging, or storing, it emits an unusual smell, feels hot, changes shape, or appears abnormal in any other way.

Charging the battery

Be sure to follow the rules listed below when charging the battery. Failure to do so may cause the battery to become hot, rupture, or ignite and cause serious injury. When charging the battery, use the specified battery charger. Do not continue charging the battery if it does not recharge within the specified charging time. Doing so may cause the battery to become hot, rupture, or ignite. The temperature range over which the battery can be charged is 0 °C to 45 °C. Charging the battery at temperatures outside of this range may cause it to become hot or to break, and may also harm its performance or reduce its life expectancy.

Discharging the battery

If the battery is used in devices other than the radio, its performance may be damaged or its life expectancy reduced. If the device causes an abnormal current to flow, it may cause the battery to become hot, rupture or ignite and cause serious injury. The temperature range over which the battery usually can be discharged is –20 °C to 60 °C. Use of the battery outside of this temperature range may damage its performance or reduce its life expectancy.

5.4 NEW GENERATION BATTERY SYSTEM TACTICAL COSTING MODELS

The purpose of this section is to determine the differences in cost between a New Generation Battery System and the old alkaline batteries.

5.4.1 Tactical cost process model

New Generation Battery System models were built in Mathlab, and for more information on these models see [52] and Appendix F. The model deals with two main aspects, namely effectiveness and life cycle cost. The measures of effectiveness for both the alkaline battery system and the New Generation Battery System are the operational availability of the battery system, the mass of the batteries carried at section level and the cost of the battery system.

The New Generation Battery System effectiveness model is intended to determine when an operational availability of 100% has been achieved given the number of radios and the operational and logistics scenarios. The problem is complicated by the distributed nature of the system as described in Table 21. Operational availability is defined here as being able to provide an operational battery for each radio at given geographic locations for a predetermined period of time. Once the system has been shown to offer the required availability, the life cycle cost can then be calculated. The New Generation Battery System life cycle is defined using ISO 15288 *Systems Engineering – System Life Cycle Processes* [60]. The New Generation Battery System process model is graphically presented in Figure 44.

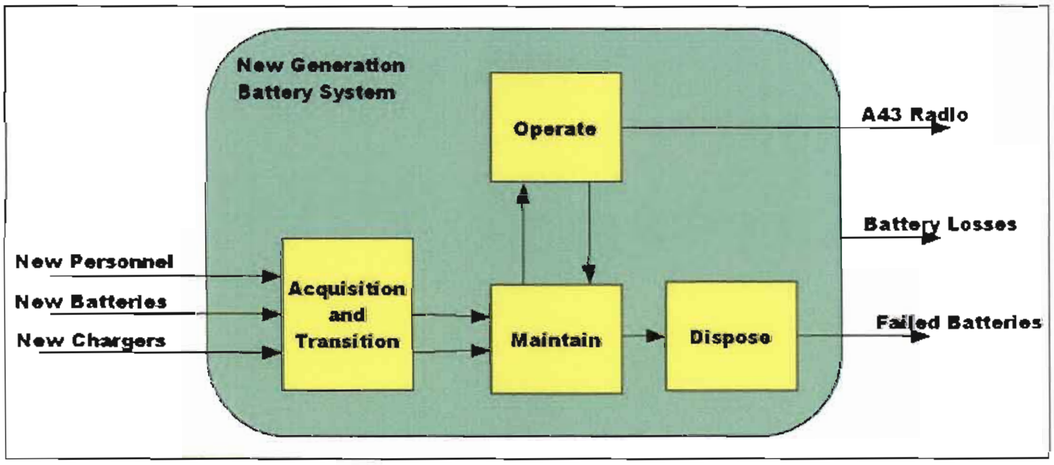

Figure 44: New Generation Battery System process model

In Figure 44, new personnel enter the system via the transition process in which they are trained. New batteries also enter the system via the transition process for inspection and placement in the maintenance store. The maintenance process interacts with the operation process - flat batteries are charged to render them operational. Flat or partially flat batteries are returned to the maintain process. Occasionally, a battery may fail during operation or maintenance and is sent to the disposal process [52].

5.4.2 Battery cost results

Results for the alkaline battery system and the New Generation Battery System are presented for a two-year mission period which corresponds to the battery life of a rechargeable battery. The number of radios considered is for one company or seventy-five A43 radios. The scenario is described in paragraph 5.2.1.

In all cases the number of batteries and number of battery chargers was chosen to provide 100% operational availability. It should be remembered that with short replenishment intervals, operational availability is sensitive to logistics delays. Calculations are based on 24-hour operation and maintenance. A 20% loss of usage time was taken into account. Thus these results represent worst-case costs, but do not include "losses" [52].

The results are summarised in Table 22. For all the results see Appendix F.

Table 22: Battery system cost for 75 A43 radios over 730 days

Battery Type	Parameter	Replenishment Interval (days)		
		1	7	14
Alkaline Battery System	Number of batteries	187 715	187 715	187 715
	Mass of batteries - section level (kg)	8.8	49.0	96.0
	Total present cost (MR)	11.27	11.27	11.27
New Generation Battery System	Number of batteries	476	1 880	3 518
	Mass of batteries - section level (kg)	4.0	18.4	35.2
	Total present cost (MR)	1.52	4.76	8.54

The number of batteries needed in the alkaline battery system does not depend on the replenishment interval; 187 715 batteries are required over a period of 730 days. But in the case of the New Generation Battery System, if the situation allows the batteries to be charged every day, the number of batteries required is only 476. In this scenario the cost of the primary batteries is roughly R11.27 million and the cost of the secondary batteries including charging and labour costs is roughly R1.52 million. The worst case is when the rechargeable batteries can only be recharged every 14 days. The cost then for the rechargeable system is R8.54 million. From this it can be seen that the New Generation Battery System should have a dramatic savings on battery costs, but the amount saved will depend on the replenishment interval and the maintenance of the system.

5.5 SUMMARY

It is not expected that the typical military environment will be trouble-free for the batteries. However, it should be possible to manage this taking into consideration that Li-ion technology still seems to be by far the best choice. It is clear from the preceding sections that use of the New Generation Battery System will be quite complex and involve more user effort across the ranks. The most significant issue concerning the New Generation Battery System is the loss of capacity over time. This loss must be detected and managed, which in a sense might be seen as a disadvantage for a New Generation Battery System.

The New Generation Battery System is in all cases more effective in terms of mass and volume compared to the alkaline battery system. The New Generation Battery System is more cost effective than the alkaline battery system but it becomes less and less cost effective with an increasing replenishment interval. The energy cost of charging the batteries is negligible in terms of the total cost, and regarding transporting of the batteries, there should be a huge saving due to fewer batteries needing to be transported.

Scenarios in which the battery can be charged every day will be both cost effective and ideal for the Li-ion technology requirement. Training scenarios and the border patrol scenario could fall into this category.

The New Generation Battery System includes the SmBus specifically to assist the soldier to maintain the system. It could also be deduced from the models that at some stage the battery will lose some capacity due to aging and therefore it has to be charged more often. This will require additional batteries and additional chargers and at some point the system becomes non-cost-effective. It is therefore important to have a maintenance set-up which could weed out the batteries which have lost too much of their capacity.

It is recommended that the implications of changing to a New Generation Battery System be clearly understood and that the necessary people be trained to manage the battery system. By monitoring the battery system over time it should be possible to develop supporting software models which use the data from the battery's SmBus. Operation planners could use software models which assist them to determine the required number of batteries and chargers for a specific mission.

6. CONCLUSION

6.1 KEY FINDINGS FROM THE STUDY

The A43 is a tactical radio used by the SANDF as an inter-platoon radio. It is expected that this radio will still be in use for the next five years. The radio uses an alkaline battery pack which lasts about 8 hours during typical radio usage. The SANDF has found that these batteries are no longer cost effective anymore and that a typical mission requires too many batteries, which overloads the soldier.

This study researched new generation batteries as a possible cost-effective replacement for the alkaline battery. New generation batteries considered in this study was nickel-cadmium, nickel metal hydride, lithium ion, rechargeable alkaline manganese and zinc-air.

Ni-Cd is a rugged and reliable technology and it performs well under rigorous working conditions. But Ni-Cd has a low energy density and the cells contains toxic metals. Ni-Cd has also a demanding maintenance requirement due to its memory effect.

Ni-MH is a replacement for Ni-Cd and has a higher energy density. Ni-MH does not have the same memory problems compared to Ni-Cd, but the battery has a reduced cycle life compared to Ni-Cd. The disadvantages of Ni-MH are high self-discharge and a performance degradation if stored at high temperatures.

Li-ion has a high energy density and is used where light weight is important. Li-ion has a relatively low self-discharge rate and no memory effect. The technology is economical if used every day, but not for the occasional user. This technology requires protection circuits and must not be misused.

RAM is more suited for low-power applications. RAM has a limited cycle life but very low self-discharge. The longevity of RAM is a direct function of depth of discharge. The biggest disadvantage is a low load current capability and limited capacity at sub-zero temperatures.

Zinc-air is a primary battery and at this stage it cannot be re-charged. Zinc-air has an incredibly high energy density (at relatively low currents), but after opening, it cannot be stored for more than three months. At present, zinc-air out performs all primary batteries.

Matching the user value system to the characteristics of the different cell technologies points to the best solution for the radio application, namely Li-ion technology. Today's soldier places a high premium on light-weight equipment and Li-ion has the best energy density of all rechargeable cells. Li-ion is not a technology for occasional use, and to make it more cost effective the batteries must be used every day. The charge time for Li-ion is about three hours.

When looking at world trends towards rechargeable batteries for military use, it becomes obvious that Li-ion technology is a good choice for the A43 radio. Li-ion is also the preferred choice for laptops and handheld devices. However, a Li-ion battery system will require more maintenance which involves chargers and a battery analyser.

During tests on a prototype Li-ion battery the following were noted. The Li-ion pack has the ability to provide larger currents than the alkaline battery pack. The Li-ion battery pack is bit smaller and 26% lower in weight compared to the alkaline battery pack. The Li-ion battery pack lasted up to five times longer in discharge tests using the currents drawn by the A43 radio. The battery performs well in the expected operational temperature range of –10 °C to 60 °C. Crushing the cells did not lead to an explosion, but this could depend on how much they are crushed. As expected, the battery starts to burn when the cells are penetrated. To summarise, the Li-ion battery pack built with commercial cells functionally outperformed the alkaline battery pack by far.

The design of a New Generation Battery System will consist of three main components, namely an intelligent battery, a field charger and a base charger with a built-in analyser. The battery consists of a fuel gauge, an SmBus, the required protection of the Li-ion cells and an enclosure which can meet the environmental requirements. The fuel gauge gives the soldier an indication of the capacity left in the battery. The SmBus keeps track of the state of health of the battery as part of the maintenance process and can provide the charger with the required parameters for optimum charging. The field charger will be connected to a vehicle to charge the batteries. The base charger works from 220 V and has an LCD to display the state of health of the battery.

The recommended battery consists of three Li-ion cells in parallel and four cells in series. The capacity of the battery should be between 6 Ah and 6.6 Ah which is still within the transport regulations. It is important to build the battery with good quality cells. This will not only improve the performance of the battery but is essential to meet safety requirements.

The Military Standard document on environmental testing (MIL-STD-81OF) describes the tests needed to qualify the battery system before it can be used in the field. The batteries must be tested in such a way that the soldier can be assured that it will work in all expected environments.

Some of the environmental tests were done on different Li-ion batteries to ensure that the electronic circuits in the battery functioned as specified. The important points to note from this test were that the battery enclosure is an important factor in protecting the battery cells. It is also important to have protection circuits that can reset after the fault condition is removed, as this will improve the reliability of the system.

It is not expected that the typical military environment will be trouble-free for the batteries. A New Generation Battery System will be quite complex and involve more user effort across the ranks. The most significant issue concerning the New Generation Battery System is the loss of capacity over time. This loss must be detected and managed, which in a sense might be seen as a disadvantage for a New Generation Battery System.

Calculations based on typical scenarios for using the A43 radio showed in all cases that a New Generation Battery System will be more effective in terms of mass and volume compared to the alkaline battery system. The New Generation Battery System is more cost effective than the alkaline battery system, but it becomes less and less cost effective with an increasing replenishment interval. Scenarios in which the battery can be charged every day will be both cost effective and ideal for the Li-ion technology requirement. Training scenarios and the border patrol scenario could fall in this category.

The New Generation Battery System includes an SmBus specifically to assist the soldier to maintain the system. It could also be deduced from the models that at some stage the battery will loose some capacity due to aging and therefore it has to be charged more often. This will require additional batteries and additional chargers and at some point the system becomes non-cost-effective. It is therefore important to have a maintenance set-up which can weed out the batteries which have lost too much of their capacity.

To summarise, the suggested solution for the A43 radio is as follows. Build batteries based on Li-ion technology. Use the standard cylindrical cells (1865L200, for example) since these cells are mature and commercially available. A 6 Ah capacity battery should fulfil the user talk time requirements and is not restricted by transportation regulations. Use batteries and analysers with an SmBus since this technology will assist the user to maintain the batteries. SmBus chargers could be designed to be intelligent enough to be used on other batteries as well, thereby catering for future products with similar batteries. Develop a battery enclosure which can protect the cells without adding unnecessary weight. To make the system cost effective, use the batteries as often as possible. Train the user to insure that he understands the technology and can use it optimally.

The SANDF is the main stakeholder and should benefit from this study regarding the following factors. The solution is based on mature and stable Li-ion battery cells. A new generation battery will require a new logistic and maintenance concept from the SANDF, but they could save millions of rand in the long term.

A New Generation Battery System should relieve the operational cost of military units in general, but units responsible for training will benefit the most. When a New Generation Battery System is in place, the cost of maintaining it will be a great deal less. The more these types of batteries are used the better the financial return will be.

The infantry soldier cannot throw away spent batteries as he is now used to doing. However, new generation batteries will save him weight and will allow him to carry out longer missions. What is learned from using new generation batteries on the old tactical radios can be used as important inputs to new projects regarding the design of new tactical radios.

6.2 RECOMMENDATIONS FOR FUTURE WORK

By monitoring the battery system over time, it should be possible to develop supporting software models which use the data from the battery's SmBus. These models should be able to predict battery life and should be able to spot usage trends or problems. Operation planners could use software models which assist them to determine the required number of batteries and chargers for a specific mission.

Sufficient power for the future soldier is a vital requirement which will not be easy to fulfil. New electronics and technologies are constantly being developed and there are numerous possible power technologies which could be used for the future soldier. It is important to continuously research new technologies as a solution to soldier power problems.

The military must define future mission scenarios which could be used to validate appropriate power systems. All this will require a modelling effort that predicts power demand by using mission scenarios, estimating duty cycles, and using power sink specification data for all components of the soldier system.

Improving the energy efficiency of the soldier will require a system-level approach. The design should consider both the energy consumers (sinks) and the power sources. The soldier should be a system and not just a lot of added-on equipment. Everything concerning the soldier should be taken in consideration, such as the environment, disposal, transport, availability, logistics, etc.

There is a need for a detailed understanding of the dynamic characteristics of the power supply system and the duty cycle. Without such details and a good analytical model to evaluate options, it is not possible to create an optimised system. Modelling has the potential to save time and money in the development of efficient portable electronic systems if accurate system inputs can be supplied. Ideally, the military should develop and acquire new equipment based on recommendations and considerations gained from power sources modelling.

In addition, the power demand of specific components during actual or simulated missions should be measured. The information will be used to validate the models and provide realistic boundary conditions for total energy, average power, peak power and duty cycles for various missions. Field testing should use embedded data-logging to track energy and power demand.

Soldier power requirements are changing as fast as new electronics are being developed. In the future, the soldier will also require portable energy for laser-designators, chemical-biological sensors, uniform ventilators, and exoskeleton enhancements.

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Appendix A First battery workshop

1. INTRODUCTION

To gain more knowledge of battery technologies, the following companies were visited:

- Institute for Chemical Technology of Inorganic Materials, Graz University of Technology. This university is doing research work on Li-ion technologies as well as RAM technologies.
- Accupower in Graz, Austria. This company specialises in battery chargers, especially chargers for Ni-MH and RAM batteries.
- Varta Microbattery in Ellwangen, Germany. This company manufactures various deferent types of batteries and they are currently setting up a Li-polymer battery production line.

This section gives some feedback on this visit and concentrates on interesting facts that could influence the A43 battery research.

2. INTEREST GROUP

The people involved during the visit and meetings were:

- Mr Heinz Fellinger, Managing Director of Grand Battery Technologies SA for portable and renewable energy.
- Mr Albertus van Niekerk, Managing Director of Trilogy Technology Systems, which is the operational arm of GBT for Defence Force technologies.
- Mr Dawie Viljoen, Armscor Programme Manager who is involved in selection and procurement for the SANDF.
- Mr Danie de Villiers from Defencetek, which is the technology partner of the SANDF and independent technology advisor for Armscor and the SANDF.
- Mr Hakan Linström, Director of Gripen Industrial Cooperation SAAB Aerospace and responsible for the funding of the 16.5 V RAM battery project done by Trilogy.
- Mr Lars Austrin of Electrical Power Systems (SAAB).
- Mr Issam Al-abassy, Managing Director of Accupower charging systems.
- Professor Martin Winter of Graz University who specialises in Li-ion technologies.

- Dr Waltraud Taucher-Mautner of Graz University who specialises in RAM technologies.
- Mr Siegfried Weitbrecht, General Manager: Marketing at Varta Microbattery.
- Mr Markus Jäger, Product Manager of Varta Microbattery.

3. GRAZ UNIVERSITY OF TECHNOLOGY

A day was spent at the Institute for Chemical Technology of Inorganic Materials at Graz University. This institute does research work on battery technologies namely:

- Li-ion
- RAM
- Fuel cells, etc.

3.1 Materials for Lithium Ion Batteries

This presentation was made by Professor Martin Winter.

Some interesting facts from his presentation were:

- In 1992, the cost of a 1 Ah Li-ion battery was $10. In 2000, the cost of 2 Ah Li-ion batteries was $3.
- The main penetration of Li-ion batteries is high-performance electronic devices, portable equipment and the re-chargeable battery market.
- However, the market is saturated because these batteries last longer, and in general consumers have already bought their electronic equipment. This leads to strong competition on market as well as lower prices.
- It is important for the manufacturers to maintain their safety record.
- Scientists at the University do research in the areas of:
    - Improving materials used in the cells.
    - Lowering the cost of the cells.
    - Higher capacity cells
    - Understanding the reactions in the batteries.
- Protection via an electronic circuit for a Li-ion battery could constitute 50% of the battery's price.
- Some of the research concentrates on metals used to store the Li. These metals could be used in batteries for more energy and increased safety. Li metal batteries have very high energy densities and are not available to the general public.

- No battery is safe, but higher-energy batteries could lead to a higher runaway reaction.
- A Li-ion cell is designed for specific temperature windows. As a result, it cannot cater for both extreme high and extreme low temperatures. The type of electrolyte that is used plays the biggest roll in the battery's performance at extreme temperatures.
- Li-polymer is not a safer technology compared to Li-ion, except for the fact that the electrolytes cannot leak out. Professor Winter does not consider Li-polymer to be an exceptional battery.
- Problems with Li-ion batteries are usually found in prolonged storage and heat generation by electronic equipment.
- Li-ion is cheaper now, but it is still limited to about 1 000 cycles depending on the electrolyte used by the manufacturer.

3.2 Alkaline Methanol Air System

This presentation was made by Gerold Koscher, a postgraduate student at the University.

His presentation covered the current work they are doing on a methanol fuel cell, and some interesting points mentioned were:

- Methanol fuel cells could generate about 4 000 Ah/litre which translates to 5 025 Ah/kg.
- Methanol as a liquid is easier to handle compared to other fuels.
- Methanol is produced world-wide.
- It is cost effective.
- The cell voltage is about 0.9 V. (Low cell voltage and low operating voltage).
- Current research at the University:
  - Developing new electrolytes.
  - Improving the cathode.
  - Lower cost catalyst.
- Methanol fuel cells have the following advantages:
  - Cheaper system.
  - Easier to build.
  - Use in smaller applications, for instance laptops.
  - Instant charging.

- Methanol fuel cells have the following disadvantages:
    - At present it has a lifetime of 1 500 hours (research work to get a lifetime of 5 000 hours)
    - Wide commercial use seems to be still in the future.

3.3 Acidic Direct Methanol Fuel Cells

This presentation was made by Peter Enzinger from the University of Graz.

He is employed in a laboratory called the CD laboratory and is responsible for:

- Fuel cell research.
- Hydrogen production.
- Development of low-temperature fuel cells.
- Modelling fuel cells.
- Testing of fuel cell electrodes and other components.
- The biggest disadvantage of these fuel cells is the storage of the hydrogen.

3.4 Applied Electrochemistry

This presentation was made by Professor Leo Binder.

Some of the work he is involved in:

- Printing thin layers of MnO_2/Zn batteries (very small batteries).
- Working on serial arrays of batteries. Investigating the effects of combining weak cells with stronger cells.
- They have a battery cycle tester with 24 channels up to 5 V with a current drain of 100 mA. Both discharge and charge cycles.

3.5 Rectangular Flat Plate RAM cells

This presentation was made by Andreas Stani, a post-graduate student at the University.

His project is sponsored by a company called BTI. He is busy developing a flat RAM cell with the following advantages compared to the cylindrical battery:

- Low-cost rechargeable battery.
- Could be used at higher temperatures.
- Good capacity retention.
- Different applications, for instance a 14 mm thick credit card size.
- Higher drain currents is possible
- Improved rechargeability.
- The largest component of his work is in the development of the flat pack cathode.

The status of his project so far is:

- Improved cycle life was achieved.
- Less capacity than expected.
- Good flexible form factor achieved.

3.6 RAM Cells 16.5 V Battery Pack Testing

This presentation was made by Dr Waltraud Taucher-Mautner.

GBT South Africa via Trilogy have approached SAAB to sponsor a project to develop a 16.5 V 6 Ah battery pack. From previous experience gained in the SANDF, they are aware of the requirement to replace the battery pack of the A43 radio. GBT mostly sells RAM batteries, and therefore have decided to build a battery pack using AA RAM cells. They have approached Graz University to test these battery packs and their test specification has been drawn up to demonstrate that their RAM battery pack can achieve the same performance as the current alkaline battery pack, but because of the rechargeability this battery pack should be more cost effective.

Some advantages of the RAM technology are:

- Optimum temperature range of 21 °C – 65 °C.
- Less than 1% capacity loss per month.
- Retains at least 80% of rated Ah in a five-year storage period.
- Good for periodic use or use in hot climates.
- AA cell has a capacity of 1 800 mAh.

With the help of Accupower a 16.5 V battery pack was designed. This battery pack consists of 33 AA cells with groups of 3 in parallel and 11 in series. Accupower has provided a battery tester called the AP83000H. This battery tester has 6 channels and can both charge and discharge the batteries. The battery tester is controlled via a PC, which also logs the voltage and current during the charge and discharge cycles. A couple of discharge cycles are specified for the test. These cycles simulate transmitting and receiving modes of the A43 radio. Two battery packs will be used for each cycle test.

The intention of the test is to determine the minimum specification of the battery pack. Battery packs will only be cycled for 10 cycles as the intention of the manufacturer is to guarantee 10 cycles. Looking at the cost of the RAM battery pack, the user should break even at 7 cycles when the price is compared to that of the current alkaline battery pack. The tests are scheduled to be completed by mid-September 2003.

4. MORE ELECTRIC AIRCRAFT (MEA)

Mr Lars Austrin from SAAB Electrical Power Systems gave a presentation on their future work on the Gripen aircraft with Li-ion batteries.

They are currently running a power system project for their new Gripen fighter. The concept is called "Power by wire" and the intention is to fly the Gripen on batteries.

No more:

- Hydraulics
- Pneumatics
- Other mechanical systems.

Rather:

- Electric brakes
- Electric landing gear, etc.

This will have the advantages of:

- Increased efficiency
- Reduced weight

- Increased reliability
- Power for direct-energy weapons, for instance electromagnetic pulse weapons.

This concept was based on the research of their Electric Tank programme, which is a tank with 8 wheels and an electric motor on each wheel.

At present, they will concentrate on a fuel cell combined with a diesel generator and a Li-ion battery. They are working on methods of storing energy, for instance super caps and flywheels.

They expect to reduce the weight of the Gripen by 3 - 8%, which translates to 500 kg. Expected advantages include:

- Reduced maintenance
- Simplified production
- Lower life cycle cost by 2 - 3%.

Eventually the aircraft will fly on fuel cell energy, but this is tricky and still in the future.

5. ACCUPOWER CHARGING SYSTEMS

Mr Issam Al-Abassy gave us a presentation on their charging systems and some battery applications they were involved in.

Some interesting facts from his presentation were:

- Accupower has developed their own charger integrated circuits and their own built-in algorithms for both RAM and Ni-MH. Their chargers use a special pulse at the end of the charging cycle, which translates to charging a battery to its full capacity. The chargers use charging pulses and then a measurement phase followed by a decision phase to determine the status of the battery.
- They can provide advice on charger designs as well as battery pack designs.
- The sale of batteries constitutes 30 % of the company's income.
- They provide back-up service and support.
- They test the quality of the batteries from manufacturers before selling them.
- The next generation AA Ni-MH cell will be 2 300m Ah.

- As an example, he discussed the requirements of a digital camera. In digital cameras, a low internal resistance translates to the ability to take more pictures, even if the capacity of the battery is less. With a high internal resistance, the voltage drop when taking a picture could trigger the flat battery cut-off circuit prematurely.
- They also sell LED flashlights.
- Current commercial grand cell chargers can only charge up to 80% of the cell capacity.
- Their Accumanager charger (designed by Accupower) guarantees 100% capacity. Quality of the charger is an important part of the system.
- At 0.1 C charging current, Ni-MH will not overcharge. This does not work on RAM batteries.
- In cold weather, detecting plus delta V (Ni-MH battery full voltage [1]) is a problem.
- Detecting zero delta V [1] is unreliable if the charger cannot supply enough current for charging.
- In warm weather, detecting negative delta V [1] is a problem due to a very flat charging curve.
- A multi-cell battery has a bigger problem when it comes to detecting the end of charge.
- Cells for a battery pack are selected by their short circuit current and internal resistance.
- Regarding Li-ion batteries the following were discussed:
  - With Li-ion, battery voltage can be used as a capacity indicator.
  - Renata in Switzerland is a company specialising in Li-ion research.
  - Charging changes the volume of the flat Li-ion battery. Equipment design must take this into consideration.
  - Li-ion can be charged at 50 °C with the correct charger. The charger must change the maximum charge voltage depending on the temperature. A charger with a fixed 4.1 V charging voltage will cause problems at higher temperatures. Remember the temperature could be 50 – 60 °C in car. It is possible not to impair the battery cycle life at high temperatures if lower charge voltages are used. However, this will give a lower capacity battery.
  - At high temperatures batteries could lose some of their electrolytes (less capacity).

  - Good electronic control circuits could also discharge batteries for safety reasons.
  - Li-ion manufacturers must concentrate on safety and protection to sell their batteries.
  - Accupower developed 8 cells in series for the UK but this was a very expensive battery.
  - All batteries at low temperatures have problems because of the type of electrolytes used. The charger cannot charge the battery to its full capacity.
  - In general, quick charging will require a bigger charger which is a problem for field charging since a lot of extra weight is undesirable.

6. VARTA MICROBATTERY

A day was spent at Varta Microbattery and our host was Mr Markus Jäger, who is the Product and Key Account Manager.

6.1 Li-ion and Li-polymer batteries

Varta is currently finalising their Li-polymer battery production line. The battery is called Varta Polyflex. Some interesting facts emerged from this discussion:

- Li-polymer is a flat cell, which, during production, could be stacked to give more capacity.
- This type of battery has a very flexible form factor.
- Generally, the battery consists of an anode, a cathode, an electrolyte, a current collector and a protection circuit.
- The Varta Polyflex battery can be drained at 2C. This battery has a capacity of 600 mAh.
- The current form factors are dictated by cellphone manufacturers.
- The biggest advantage of Li-polymer batteries is their low weight and reduced thickness.
- Li-polymer has an energy density from 250 – 350 Wh/litre.
- The protection circuit adds an extra resistance of 30 milli-ohms to the battery.
- The battery's internal resistance is between 80 – 90 milli-ohms.

- For the design of new Li-polymer battery packs, balancing of the cells is now still an unknown but important factor.
- In serial configurations, the charging voltage is very important.
- Protection circuits are designed to limit at discharge and charge currents.
- Varta do their own safety test (UL-approved) on cells bought from other manufacturers.
- For the future, Varta plans to develop intrinsically safe polymer batteries.
- Li-polymer is not safer compared to Li-ion, except that the electrolyte is not a fluid.
- Cells must be optimised for either high or low temperatures.
- The advantage of the lamination process used in the Li-polymer battery is solid contact, higher reliability and good vibration specifications.
- Typical commercially available Li-ion cells are 18650 with configurations such as 4S3P (4 in serial and 3 in parallel).
- Varta prefers the Li-ion cells manufactured by Samsung. These are cells with good low-temperature specifications.
- Cells which are optimised for the intended temperature at which they will mostly be used should be chosen.
- Protection circuits for Li-ion batteries cut off at about 2.35 V.
- The expected remaining capacity of Li-ion at 500 cycles should be at least 70% of original capacity.
- The market price of the Li-polymer cells should be close to the price of Li-ion cells.
- When buying batteries, look for reputable suppliers who have reliable batteries.
- Reliability could be tested as follows:
  - Good cycle life (no problems with the internal resistance).
  - Safety tests according to UL (Underwriter's Lab).
  - The Performance test should measure internal resistance after 500 cycles at 1C.
  - Carry out heat chamber tests.
  - Determine the self-discharge rate.
  - Measure the rate capability (Peak currents).
  - A compromise could be made between the number of cycles compared to cost, but safety should never be compromised.
  - Carry out drop and vibration tests.

- Life cycle cost will depend on the battery price, the charger, how it will be stored and the required logistics infrastructure.

6.2 Factory tour

We had an opportunity to go through the factory. Some facts emerged regarding the tour:

- Some production lines produce 450 small Ni-MH cells per minute.
- Their zinc-air production line produces 500 cells per minute.
- Their aim for the Li-polymer is 40 cells per minute.
- Varta has a product line of 132 types of cells and 11 battery systems.
- They have developed a Ni-MH memory back up cell, which survives on trickle charge and has a lifespan of 6 years in a laptop.
- They have a battery application laboratory where they could assist a client with battery pack designs.

7. CONCLUSIONS

This visit was worthwhile and was set up in such a way that we could address current questions and uncertainties. This was a better method of gaining information compared to a conference where presentations are made, which may or may not be directly related to one's requirements.

Considering the information received and the current battery requirements of the A43 radio, it still makes sense to concentrate on the Li-ion technology. Li-polymer could be the better choice if a lightweight battery is important, but the technology must still prove itself. The advantages of Li-ion are as follows:

- Commercial battery packs are available in configurations which supply 14.5 V 6 Ah.
- These batteries are relatively inexpensive at about R650.
- A battery built up from smaller cells (2 Ah) should be safer than a battery built up with 6 Ah cells.
- It is possible to use the same chargers for Li-ion and Li-polymer.
- Charging requirements of Li-ion are less complicated than for Ni-MH.

Regarding the RAM cells which are undergoing tests at the University of Graz:

- These battery packs are expected to give at least the same performance as the current alkaline battery packs.
- If it were not for their charger requirement, they could have been proposed as an intermediate solution which could have saved the SANDF considerable expense, but it would be too expensive to buy chargers for temporary use.
- It will be of interest to see how the RAM batteries perform, but as mentioned, these batteries will only be guaranteed for 10 charging cycles.
- The ideal use of this type of battery pack is in an application where for instance equipment is permanently connected to a solar panel and the solar panel can provide enough energy to drive the equipment. The RAM battery is then actually on standby and is only used when the solar panel cannot provide enough energy due to the weather.

Appendix B Laboratory tests

As part of this study, tests were done to evaluate the suitability of Li-ion battery technology compared to the currently used alkaline primary batteries. Also included in the investigation was the performance of the universal charger as currently used by the SANDF. The investigation was carried out in a laboratory using primarily the current A43 alkaline batteries, a custom-made Li-ion battery and an electronic load system. It covered the following aspects:

- The physical dimensions of the different batteries.
- Charge and discharge cycles at predetermined loadings.
- Battery performance at various temperatures.
- Safety tests.
- Disposal and transportation.

1. EXPERIMENTAL PROCEDURES

INTERFACE TEST

The battery must interface mechanically and electrically with the A43 radio. This will be a visual inspection.

SIZE AND WEIGHT TEST

The battery size specification is fixed, as the battery must fit into existing enclosures. The weight is specified as 900 g maximum. This will be a visual inspection.

BATTERY PACK CONFIGURATION

The configuration of the cells used in the battery pack should have a maximum voltage of not more than 18 V and a capacity of about 6 Ah. The battery pack should be able to supply a continuous current of minimum 2 A. In the case of Li-ion, the battery pack should be fitted with a protection circuit. This specification shall be confirmed with the specification sheets from the manufacturer.

INTERNAL RESISTANCE TEST

To get an indication of the internal resistance the following procedure was followed:

- The formula as described in Figure 1 was used.
- The calculation was done at every major voltage drop.
- The average of all the calculations was logged.

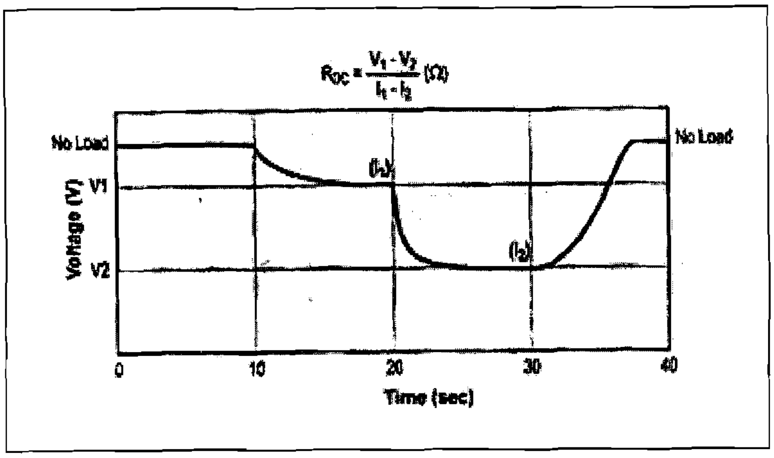


Figure 1: Internal resistance

INITIAL CAPACITY TEST

The minimum required capacity is 6 Ah at 20 °C. The IEEE standard capacity test is specified at 0.2C.

For this test, the electronic load with the following steps were used:

- Ensure that the battery is charged up to 4.0 V / cell (16V).
- The load is set to a constant current of 1.2 A.
- Room temperature is between 15 °C – 30 °C.
- The PC should log both voltage and time up to Cut-off voltage of 9 V.
- The capacity of the battery is calculated by using the product of the discharged current and the discharged duration.

DISCHARGE TIME TEST

This test was designed to simulate the variable load of the A43 radio. For this test the electronic load was used with the following steps:

- Ensure that the battery is charged up to 4.0 V/cell (16 V).
- Constant current mode with current and timing settings as described below:
    - Room temperature of between 15 °C and 30 °C.
    - The PC should log both the voltage and the current.
    - Log the time duration to get to 9 V.

CYCLE A

- Discharge at 950 mA for 1 minute then 250 mA for 29 minutes.
- Cut-off voltage 9 V.

CYCLE B

- Discharge at 1 500 mA for 1 minute then 250mA for 29 minutes.
- Cut-off voltage 9 V.

CYCLE C

- Discharge at 2 000 mA for 1 minute then 250 mA for 29 minutes.
- Cut-off voltage 9 V.

CYCLE D

- Discharge at 250 mA.
- Cut-off voltage 9 V.

VOLTAGE VERSUS CAPACITY TEST

The Li-ion battery packs are designed to be charged to 4.2 V/cell maximum. In a military environment, operational temperatures could be quite high. For safety reasons, the battery packs should not be fully charged. This test determined what the capacity difference was between charging to 4.1 V/cell and 4.0 V/cell. The electronic load was used with the following steps:

- The battery was charged to 4.1V/cell (16.4 V).

- The discharge time test was repeated using cycle C.
- The results were compared with the 4.0 V charge results.

HEAT CHAMBER TESTS

Since temperature reduces the capacity of the batteries, the capacity left must be more than 60%. The radio has a functional temperature range of –10 °C to 55 °C and a storage temperature range of –20 °C to +73 °C.

HIGH-TEMPERATURE OPERATIONAL TEST

Tests were done as described in MILL-STD-810F method 501,4 procedure II with maximum temperature set at 55 °C. The electronic load was utilised as follows:

- The discharge time test was repeated (Cycle B) at 55 °C (battery fully charged).
- The battery was charged at the same temperature up to 4.0 V/cell (16 V).
- The discharge time test was repeated at that temperature.
- The battery's internal temperature was monitored and the test was stopped if the battery temperature exceeded 75 °C.
- When the battery returned to room temperature the internal resistance test was repeated.

LOW-TEMPERATURE OPERATIONAL TEST

Tests were done as described in MILL-STD-810F method 501,4 procedure I with minimum temperature set at –10 °C. The electronic load was utilised as follows:

- The Discharge time test (Cycle B) was repeated at –10 °C (battery fully charged).
- The battery was charged at the same temperature up to 4.0 V/cell (16 V).
- The discharge time test was repeated at that temperature.
- The battery's internal temperature was continuously monitored and the test was stopped if the battery temperature exceeded 75 °C.
- When the battery returned to room temperature, the internal resistance test was repeated.

HIGH-TEMPERATURE STORAGE TEST

Tests were done as described in MILL-STD-810F method 501,4 procedure I with maximum temperature set at 73 °C. The electronic load was utilised as follows:

- The discharge time test (Cycle B) was repeated at 73 °C (battery fully charged).
- The battery was not charged at this temperature.
- The battery's internal temperature was continuously monitored and the test was stopped if the battery temperature exceeded 80 °C.
- When the battery returned to room temperature the internal resistance test was repeated.

LOW-TEMPERATURE STORAGE TEST

Tests was done as described in MILL-STD-810F method 501,4 procedure II with minimum temperature set at –20 °C. The electronic load was utilised as follows:

- The discharge time test (Cycle B) was repeated at –20 °C (battery fully charged).
- The battery was not charged at this temperature.
- The battery's internal temperature was monitored and the test stopped if the battery temperature exceeded 75 °C.
- When the battery returned to room temperature the internal resistance test was repeated.

SELF-DISCHARGE RATE TEST

A battery pack should have more than 60% charge after one month.
The electronic load was utilised as follows:

- The battery was stored fully charged for 30 days at a temperature of 30 °C.
- The discharge time test (Cycle B) was repeated.

CYCLE LIFE TEST

The *cycle life* is the number of times that the rechargeable battery can be charged and discharged before it is no longer able to hold or deliver any useful amount of energy. The retained percentage of the cell's nominal capacity, considered as an acceptable minimum, is

70%. The minimum number of cycles specified is 800. For this test the electronic load was used with the following steps:

- The average internal resistance of each cycle was determined.
- The load was set to a constant current mode with a discharge current set at 5 A continuously.
- Room temperature was between 15°C and 30 °C.
- Cut-off voltage 9 V.
- The PC logged both the voltage and time.
- For safety reasons, the temperature of the battery was monitored and the test was stopped if the temperature exceeded 75 °C.
- When the battery reached the cut-off voltage, the charge mode switched to and a voltage of 4 V/cell and a current of 1C (6A) were used.
- Tests were repeated until 70% of the original capacity was reached.

SAFETY TESTS

High energy density batteries are dangerous. Exercise caution when handling and testing them. The following test must be done in a controlled environment:

SHORT CIRCUIT TEST

Short the circuit by connecting the (+) and (-) terminals of the battery with an 18-gauge wire.

- Connect a thermometer to the battery for temperature reading.
- Short the battery for 10 minutes while compiling the temperature variation.
- Remove the short and wait until it is safe to approach the test area.

OVERCHARGING TEST

Connect the battery pack to a 24 V supply with current limit at 10 A for 30 minutes.

- Monitor the temperature and battery voltage.
- Disconnect after 30 minutes.
- Wait 10 minutes before approaching the test area.
- Test the battery to confirm its operational state.

REVERSE POLARITY TEST

Reverse the polarity by wrongly connecting the battery to the charger. The charger should be set at 16 V with current limit at 6 A.

- Connect thermometer to the battery for temperature reading.
- Apply the reverse polarity for 10 minutes while compiling the temperature variation.
- Disconnect the connection and wait until it is safe to approach the test area.
- Test the battery to confirm its operational state.

OVERHEATING TEST

Use a special oven to heat the battery to 130 °C.

- Heat the battery for one hour.
- This test should destroy the battery.

CRUSH TEST

Crush down 30% of outer diameter, and take measurement. Then apply about 13 kN force, crushing all the plates.

NAIL PENETRATION TEST

Penetrate a 2.5 ~5 mm nail into the cell body. If the battery does not explode, discharge the battery and re-charge with 100% capacity target charge. The battery should give 60% of normal capacity. On the subsequent charge/discharge cycle, the same battery should give 90% of capacity.

BULLET PENETRATION TEST

- Place battery pack in an aluminium M57 box, and shoot it with a 5.56 x 45 NATO calibre round. The aluminium box will show the effects and the reaction of the battery debris.
- Wait half an hour before approaching the target area.

EXTERNAL CAPACITY INDICATION TEST

By analysing the results of the discharge time test, determine if the voltage monitor circuit in the A43 can be used to give an indication of the capacity.

Secondly, discharge a battery fitted with an SmBus and monitor the capacity indication.

ENVIRONMENTAL TESTS

These tests should be done according to MILL-STD-810F specifications. Since the battery packs were only prototypes and not designed to withstand this tests, the tests was not done.

Possible tests to be planned for the future are:

- Low pressure
- Humidity
- Salt fog
- Sand, dust
- Vibration
- Shock
- Electromagnetic radiation.

EXISTING CHARGER TEST

The current Cadex charger must be tested to ascertain if it can be used with this battery technology. This will be done by obtaining the relevant specifications from the manufacturers and charging the prototype batteries.

COST OF OWNERSHIP

The *initial cost* is the cost of purchasing the battery. The cost per *cycle* is derived from the initial cost divided by the number of cycles. For this test, a budget price of R1 000 for the prototype batteries could be used.

DISPOSAL

The disposal of Li-ion batteries is not regulated. These products do not contain heavy/toxic metals such as lead, mercury or cadmium. For this test, a literature search should be done to find out what is the best practice.

2. RESULTS

The graphs of the results are given at the end of this Appendix.

Table 1: Alkaline battery results

Test	Result	Note
Interface	Fits on the A43 radio	
Size and weight	155 L x 62 W x 59 H 980 g	
Battery pack configuration	11 C cells in series.	
Initial capacity	Initial capacity = 3.06 Ah	Tested at 0.2C
Discharge time Cycle A	Discharge time = 9 hours Internal resistance = 4.3 ohm	Internal resistance increases as battery discharges.
Discharge time Cycle B	Discharge time = 4 hours Internal resistance = 4.1 ohm	
Discharge time Cycle C	Discharge time = 1 minute	The battery is not suitable for this current value.
High --temperature operational test	Discharge time = not tested Internal resistance = not tested	This battery started to leak.
Cost of battery	+-R90	
Disposal	Not regulated	

Table 2: 6 Ah Li-ion results

Test	**Result**	**Note**
Interface	Fits on the A43 radio	
Size and weight	156 L x 64 W x 55 H 774 g	
Battery pack configuration	12 x 18650 cells 4 in series, 3 in parallel	
Initial capacity	Initial capacity = 4.6 Ah	Only charged up to 15.4 V
Discharge time Cycle A	Discharge time = 20 hours Internal resistance = 0.5 ohm	Internal resistance constant until about 12.5 V
Discharge time Cycle B	Discharge time = 20 hours Internal resistance = 0.5 ohm	
Discharge time Cycle C	Discharge time = 18.8 hours Internal resistance = 0.5 ohm	
Discharge time Cycle D	Discharge time = 25.9 hours	
Voltage versus capacity test	Discharge time (4.1 V)= 23.2 hours. Discharge time (4.0 V)= 18.8 hours	
High-temperature operational test	Discharge time = 21.9 hours Discharge time after high-temp charge = 22.53 hours Internal resistance = 0.5 ohm	
Low-temperature operational test	Discharge time = 22 hours Discharge time after low temp charge = 20 hours Internal resistance = 0.8 ohm	
High-temperature storage test	Discharge time = 22.5 hours Internal resistance = 0.5 ohm	The battery was taken out of the oven and immediately tested
Low-temperature storage	Discharge time = 17 hours	The battery was taken out

test	Internal resistance = 0.6 ohm	of the oven and immediately tested
Self-discharge rate	Discharge time = 18 hours	Difficult to do this test and assure controlled conditions
Cycle life	37 cycles were completed. Internal resistance varied from 0.4 – 0.8 ohm	No pattern could be found in the internal resistance
External capacity indication	Voltage of the battery does give a fairly good indication of the battery capacity up to about 12 V then the voltage suddenly drops and the protection circuit switches off.	
Cost of this battery	+- R1 000 Cost per cycle so far: +-R1 000 / 37 = R27	This cost does not include any charging cost
Disposal	Not regulated	

Table 3: 8 Ah Li-ion results

Test	**Result**	**Note**
Battery pack configuration	16 x 18650 cells 4 in series, 4 in parallel	
Discharge time Cycle B	Discharge time = 29 hours Internal resistance = 0.47 ohm	
Discharge time Cycle C	Discharge time = 27 hours Internal resistance = 0.47 ohm	

Table 4: Safety test results

Test	Result	Note
Short circuit	No explosion or fire, normal temperature throughout the test	Experienced small spark but subsequent shorts; minimal spark was experienced
Overcharging with 24 V at 10 A	No explosion or fire, normal temperature throughout the test	
Reverse polarity test	No explosion or fire, normal temperature throughout the test	No reading from the power supply. The charging circuit was isolated by a diode
Overheating by external heating up to 130 °C	No explosion or fire	The battery could not hold charge any longer
Crush test	No explosion or fire, normal temperature throughout the test	The battery could not hold charge any longer
Nail penetration	Started to burn and the cell was destroyed	
Bullet penetration test	Started to burn and the cell was destroyed	

SHORT CIRCUIT TEST RESULT

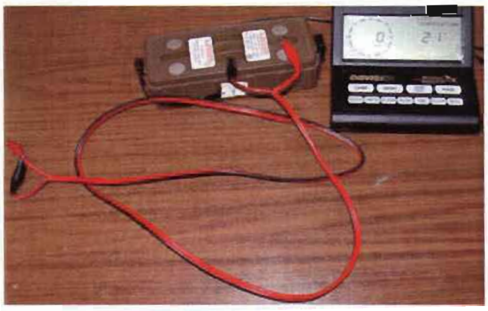


Figure 2: Battery short circuit at room temperate

The battery was shorted (Figure 2) at room temperature for ten minutes. The temperature stayed constant right throughout the test. There were no signs of danger and the wire did not warm –up, meaning that the protection circuitry isolated the problem. After the short the battery was tested and no damage to the battery was found.

CRUSH TEST RESULT

Figure 3: These batteries were run over with a fork lift truck

The pressure on the cells was about 13 kN. The cells did not explode or heat up. There was a chemical reaction, like a boiling solution dripping out of the battery. The voltage capacity dropped from 4.2 V to 120 mV when tested after the crush.

NAIL PENETRATION TEST RESULT

Figure 4: Nail penetration resulting in fire

On two occasions (Figure 4) when a 2.5 mm nail was penetrated into the cell body, the cell immediately reacted with a mini-explosion followed by much smoke. The cell was destroyed. A subsequent charge/discharge cycle could not be done after the penetration.

BULLET PENETRATION TEST RESULT

Figure 5: 5.56 x 45 Nato calibre round fired at the battery

A 5.56 x 45 Nato calibre bullet (Figure 5) was fired into the battery enclosed in a M57 aluminium box to show the effects and the reaction of the battery debris. There was smoke and two small explosions occurred.

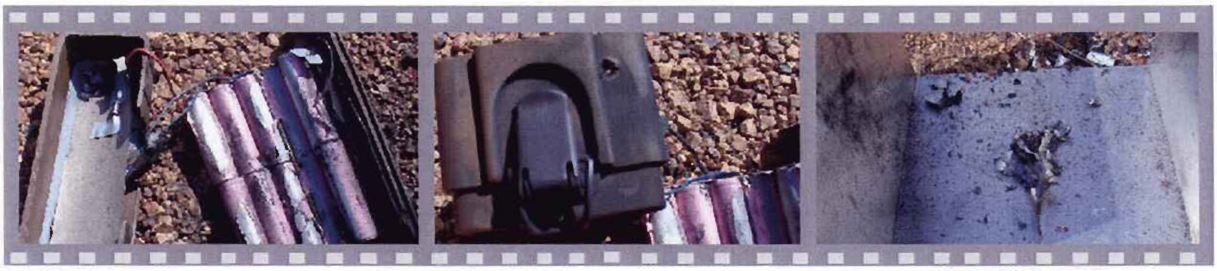


Figure 6: The end results of bullet penetration test

The bullet hit two cells, which were connected axially. It destroyed the first cell and the remnants can be seen on the last slide in Figure 6. The second cell's head plate ruptured, leading to the second explosion seen on the last slide in Figure 5. There were burned-out pieces on the aluminium plate of the battery cover, and the battery contents were dry and could not lead to corrosion.

CHARGERS TESTS RESULT

The Cadex C7000ER Battery Analyzer Extended Ranger was tested. It passed all possible normal charging capability tests when charging nickel-cadmium and sealed acid batteries but worked differently on the Li-ion batteries.

Figure 7 shows a charger state diagram. The Cadex C7000ER Battery Analyzer had a very similar flow diagram.

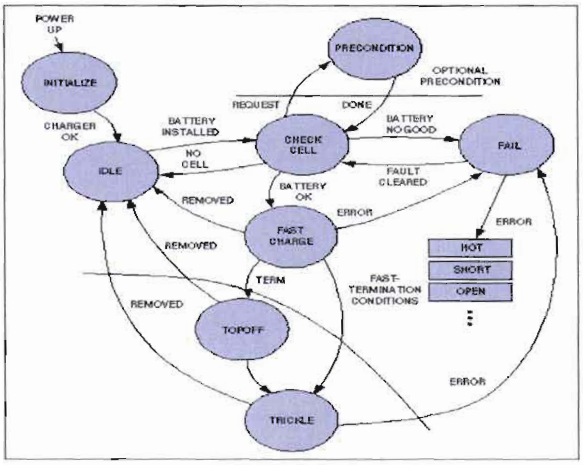


Figure 7: Charger state diagram

INITIALISATION TEST RESULT

Although not part of the actual charging procedure, initialisation with a LED status indicator is an important stage in charging the battery. The charger initialises itself and performs its own self-test. Once the charger determines that a cell has been installed, it determines if the cell is good or bad. It also checks for basic functioning: open, shorts, hot or cold. To test whether or not a cell is chargeable, it uses a special technique to avoid the problem of false rejects for deeply cycled batteries.

A disadvantage of the Cadex C7000ER Battery Analyzer is that when it is interrupted by a power failure it will re-initialise and start from the beginning. No fixed-time charger should be used since it could overcharge if there were a power failure. It is important to monitor the temperature of the Li-ion battery while charging.

CELL DETECTION RESULT

This phase of the charging procedure detects when a battery is installed and whether it can be charged. Cell detection is usually accomplished by looking for voltage on the charger terminals while the charger source is off. It is suggested that the A43 Smart batteries should conduct some kind of exchange of serial data with the battery pack providing all the necessary charging parameters.

The ambient and cell temperatures are also part of a qualification phase. When a charger detects high or low temperature, it should wait for a predetermined interval for the temperature to return to nominal. If this doesn't happen within the allotted time, the charger should reduce the charging current. This action reduces battery temperatures, which increases efficiency. Finally, the cells should be checked for open and short circuits.

The Cadex C7000ER Battery Analyzer is difficult to set up. It will keep on charging and discharging the battery, creating an endless loop if not properly set up. This is not a good feature for use on the battlefield. A good charger should look at voltage, resistance, temperature and current to get the battery into the best possible state. See Figure 8 below for a typical block diagram for charging batteries.

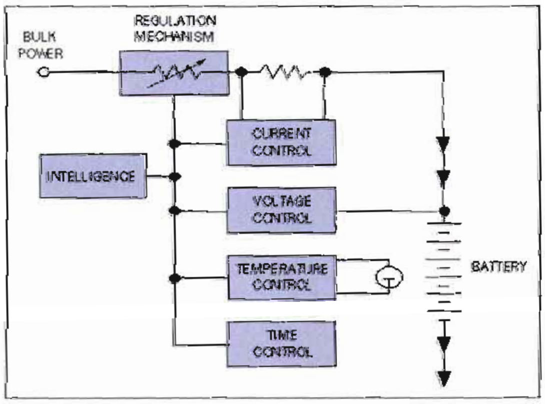


Figure 8: Charging-system block diagram

EXTERNAL CAPACITY INDICATION

A Li-ion battery was fitted with a prototype SmBus controller designed by Freeplay. The controller handles both the SmBus function and the protection circuits. For this test the battery was continuously discharged at 1.5 A for one minute then 250 mA for one minute. Three measurements from the SmBus were plotted (see Figure 9.

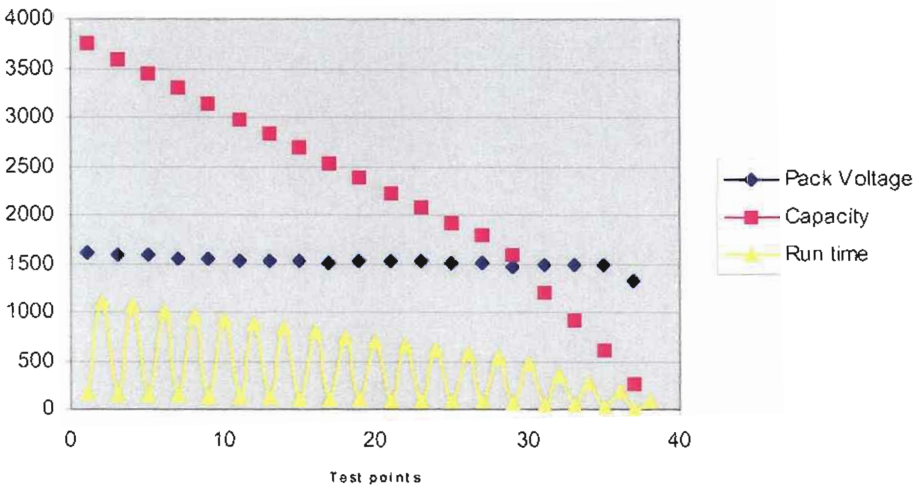


Figure 9: Smartbus data

The blue line shows the voltage of the battery pack and the pink line shows the calculated remaining capacity of the battery pack. The yellow line shows the estimated run time of the battery. The estimated run time changed depending n whether the discharge was 1.5 A or 250 mA. The first calculation predicted a run time of 1 099 minutes if discharge current stays at 250 mA and 154 minutes if discharged at 1.5 A. As mentioned above, the discharge current changed continuously between 1.5 A and 250 mA. The battery lasted for 285 minutes. The calculated capacity gave a good indication of the state of the battery.

The SmBus also use five LEDs to give a rough indication of the remaining capacity.
DISPOSAL

Some information was found in the literature search regarding recycling and disposal:

- Battery recycling is encouraged.
- Li-ion batteries are safe for disposal in the normal municipal waste stream since they are not defined as hazardous waste. They contain no toxic waste, only naturally

occurring trace elements.

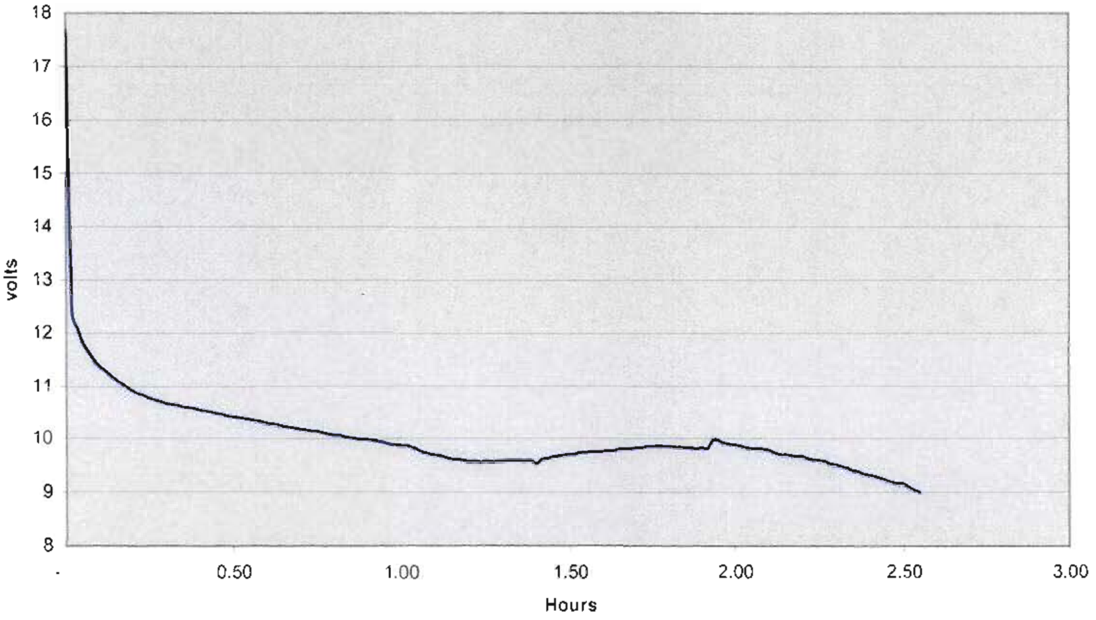
- Even though Li-ion batteries are exempted from hazardous waste disposal standards under the Universal Waste Regulations in the USA, it is advisable to consult with local authorities before disposal because disposal regulations may vary depending on the location.

TRANSPORTATION

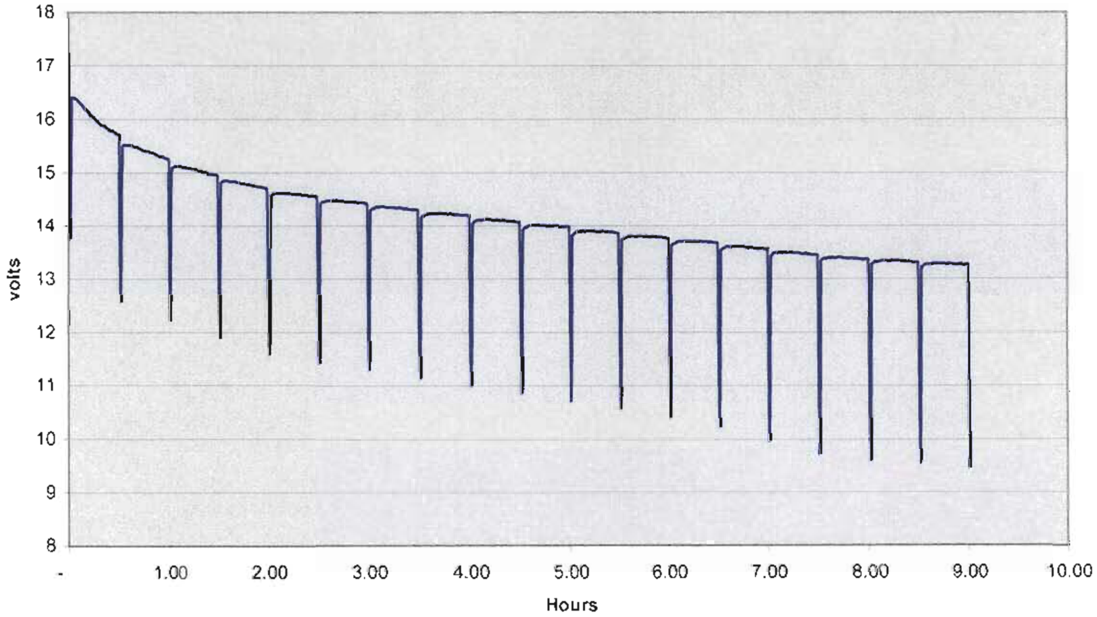
Regarding transportation, the following information was found: Li-ion batteries comply with all applicable shipping regulations as prescribed by industry and legal standards which includes compliance with the UN Recommendations on Transportation of Dangerous Goods; IATA Dangerous Goods Regulations, 44th Edition, 2003.

3. GRAPHS

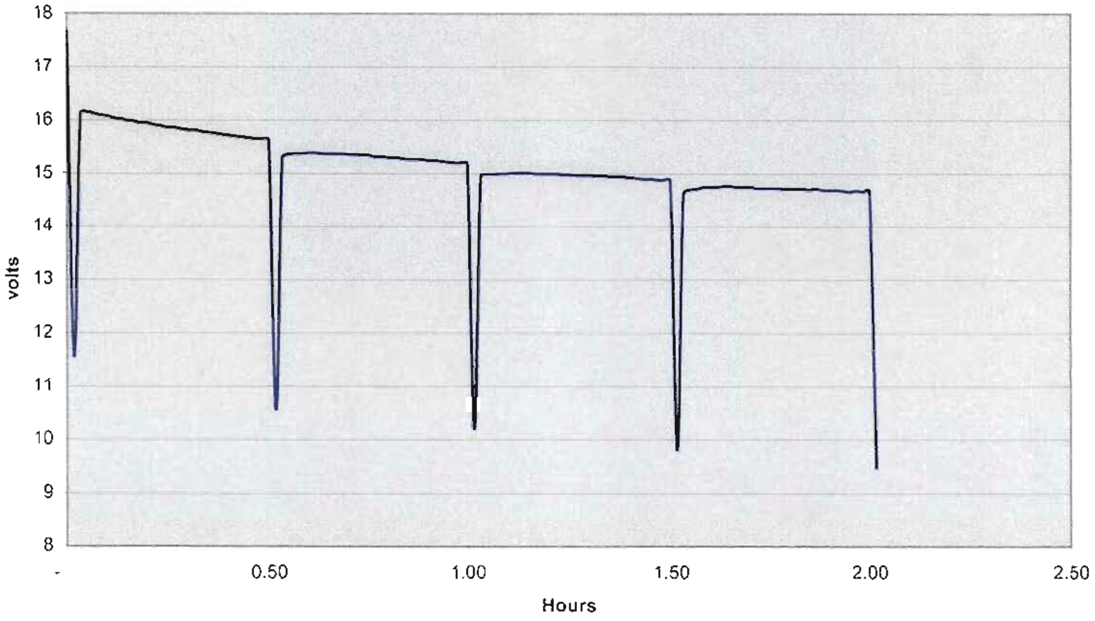
Alkaline discharge @ 1.2A



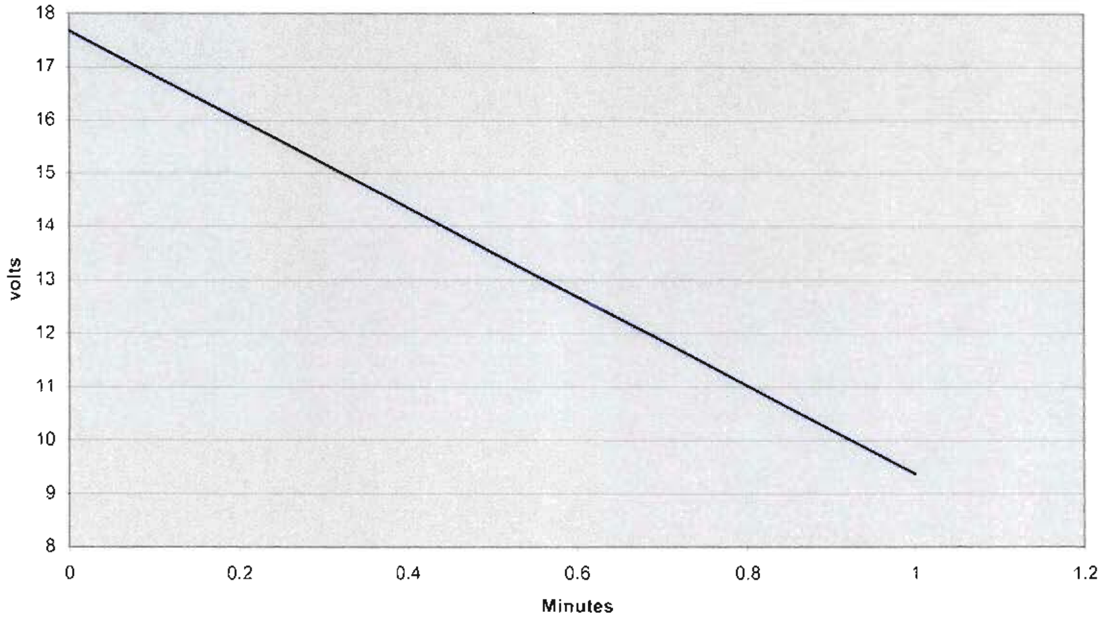
Alkaline discharge @ 0.95A for 1 minute and 0.25A for 29 minutes

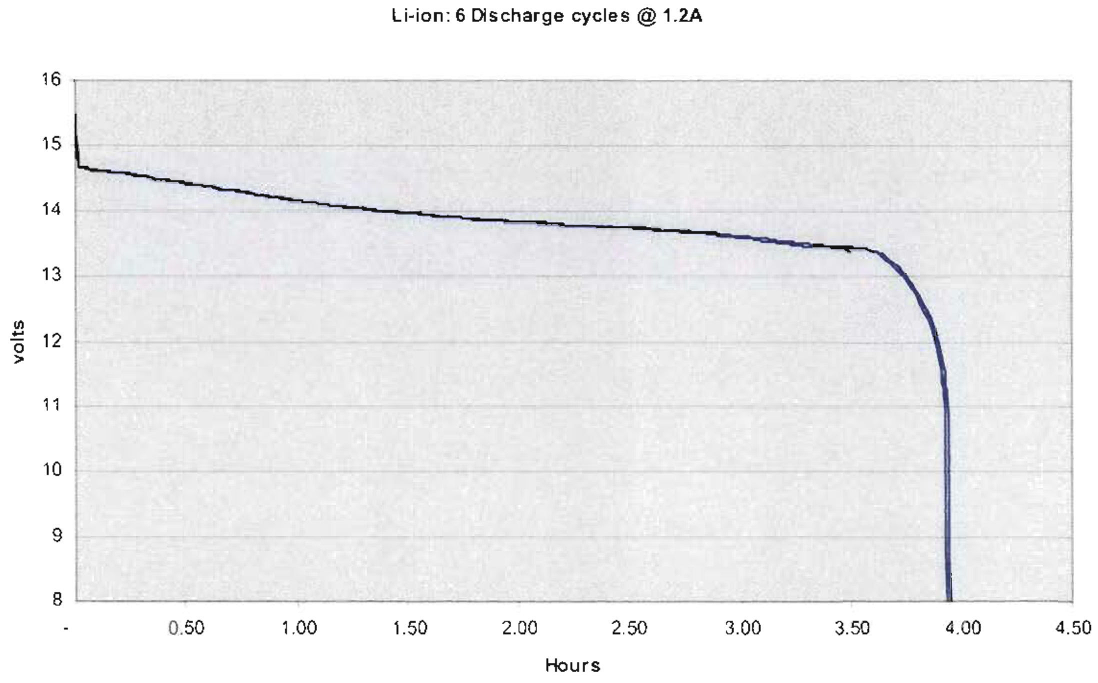


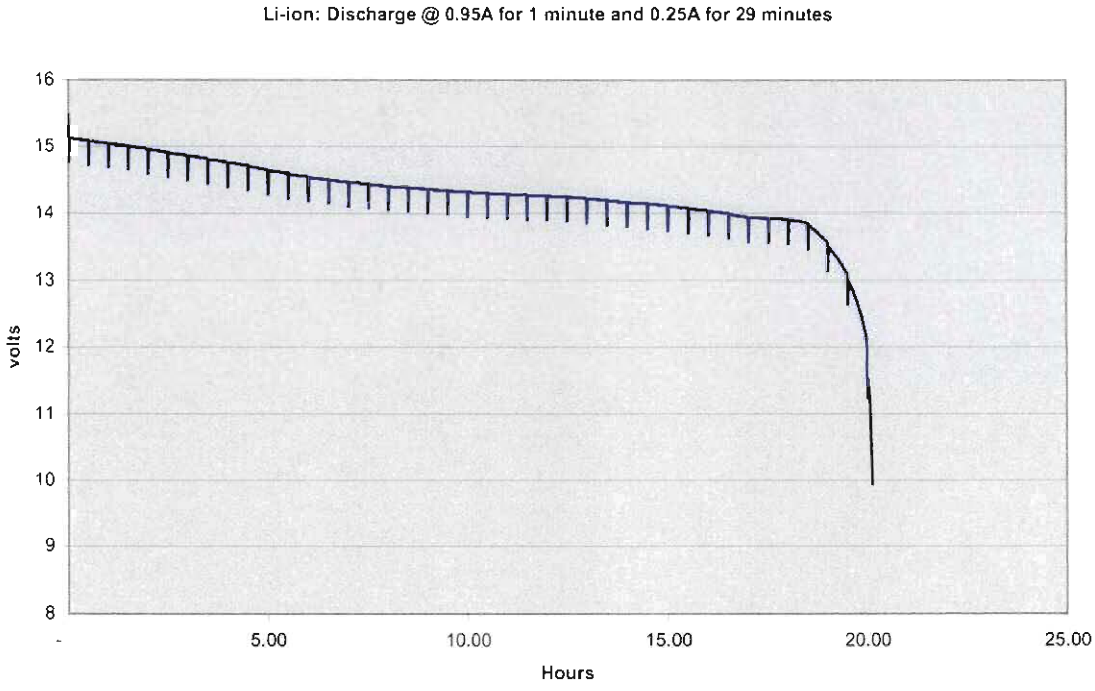
Alkaline discharge @ 1.5A for 1 minute and 0.25A for 29 minutes



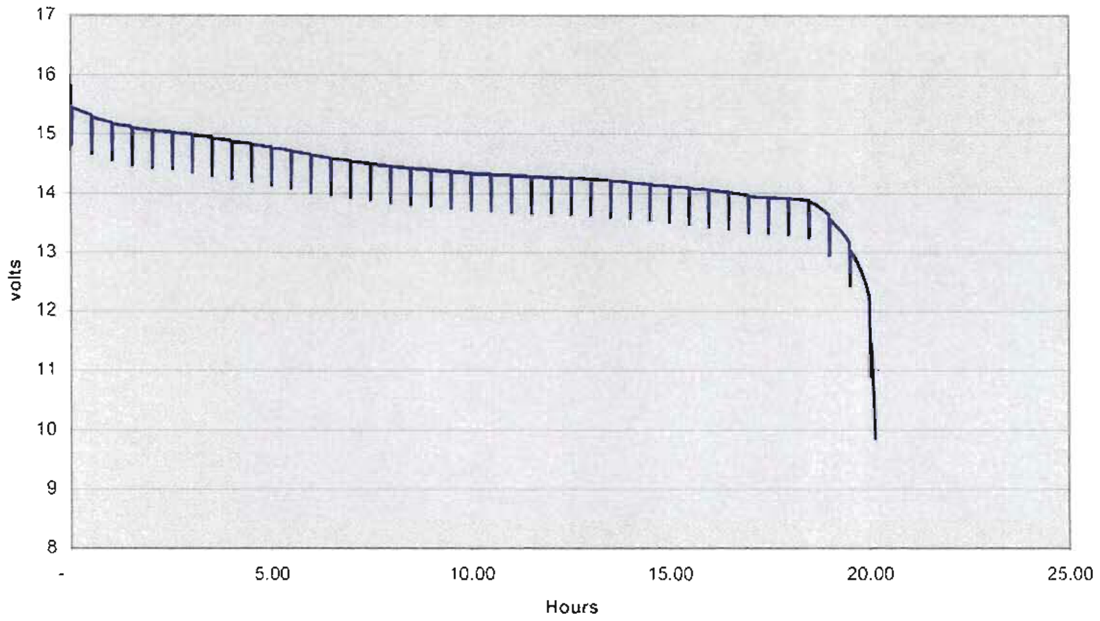
Alkaline discharge @ 2A for 1 minute



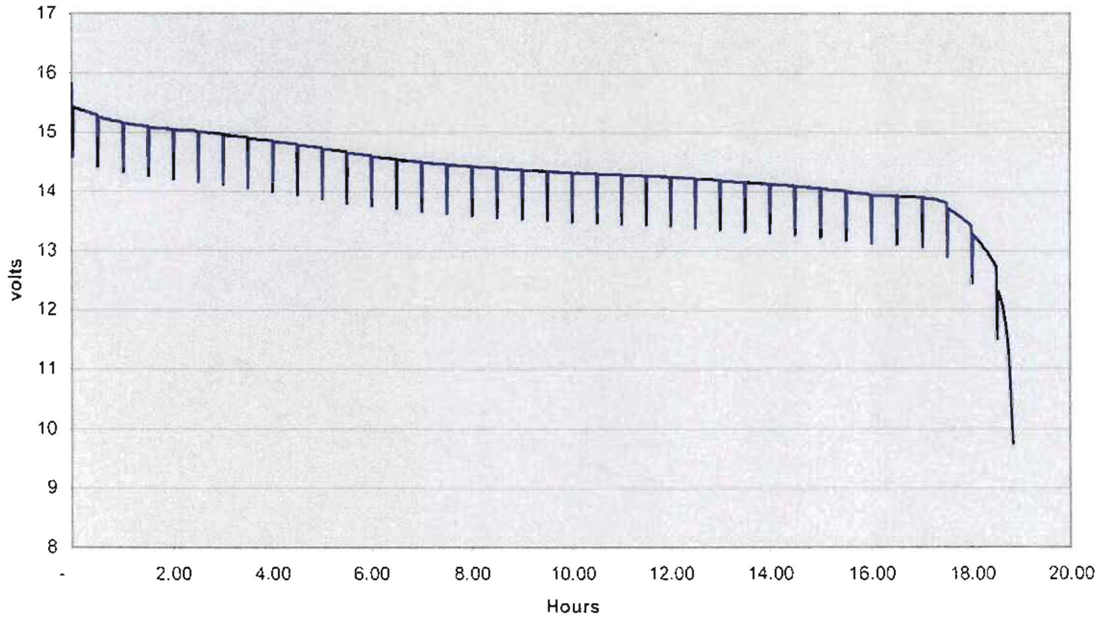

Li-ion: 6 Discharge cycles @ 1.2A
volts
16
15
14
13
12
11
10
9
8
-
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
Hours


Li-ion: Discharge @ 0.95A for 1 minute and 0.25A for 29 minutes
volts
16
15
14
13
12
11
10
9
8
-
5.00
10.00
15.00
20.00
25.00
Hours

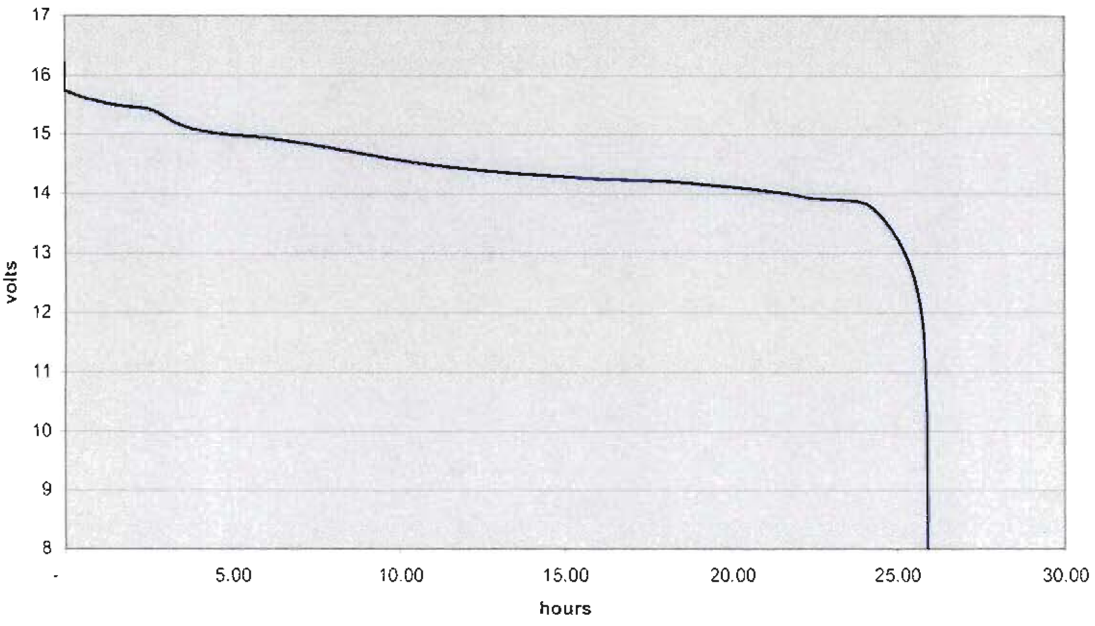
Li-ion: 2 discharge cycles @ 1.5A for 1 minute and 0.25A for 29 minutes



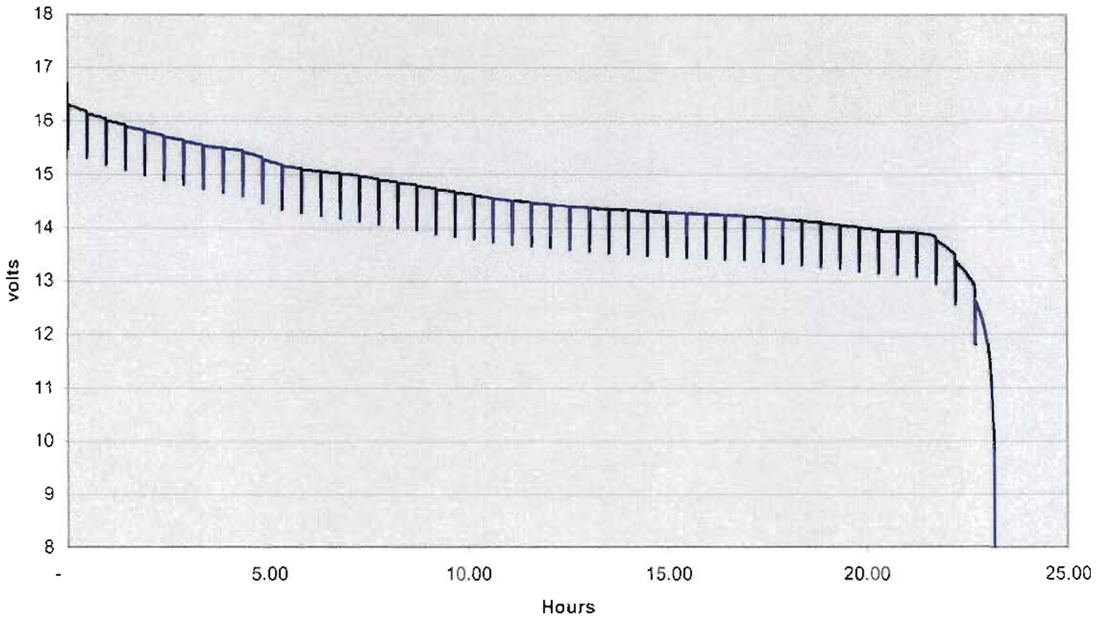
Li-ion: Discharge @ 2A for 1 minute and 0.25A for 29 minutes



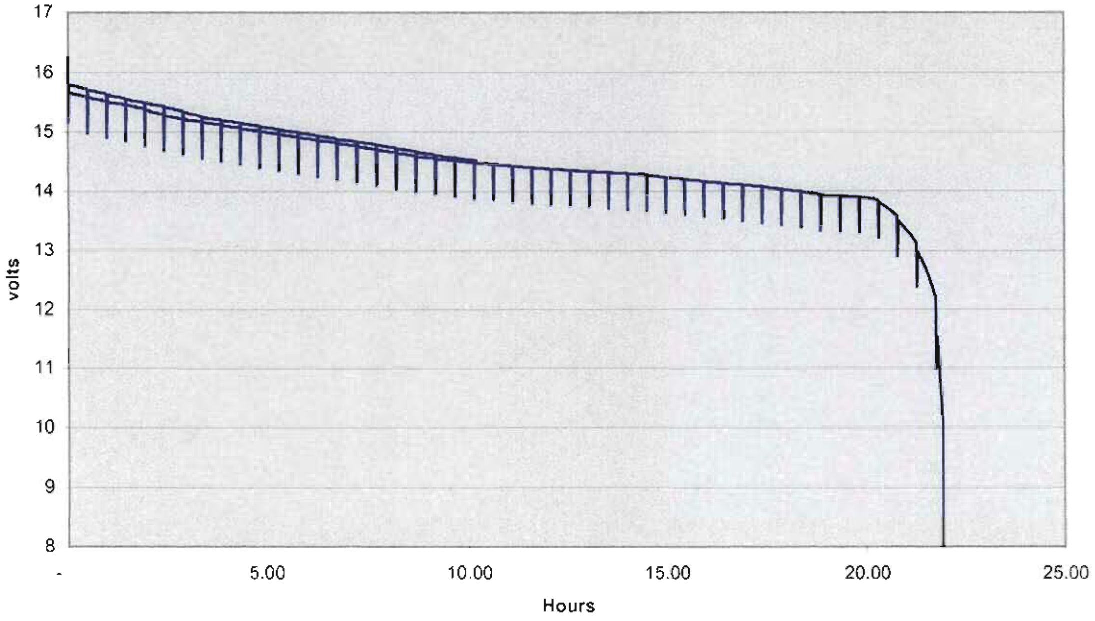
Li-ion: Discharge @ 0.25A



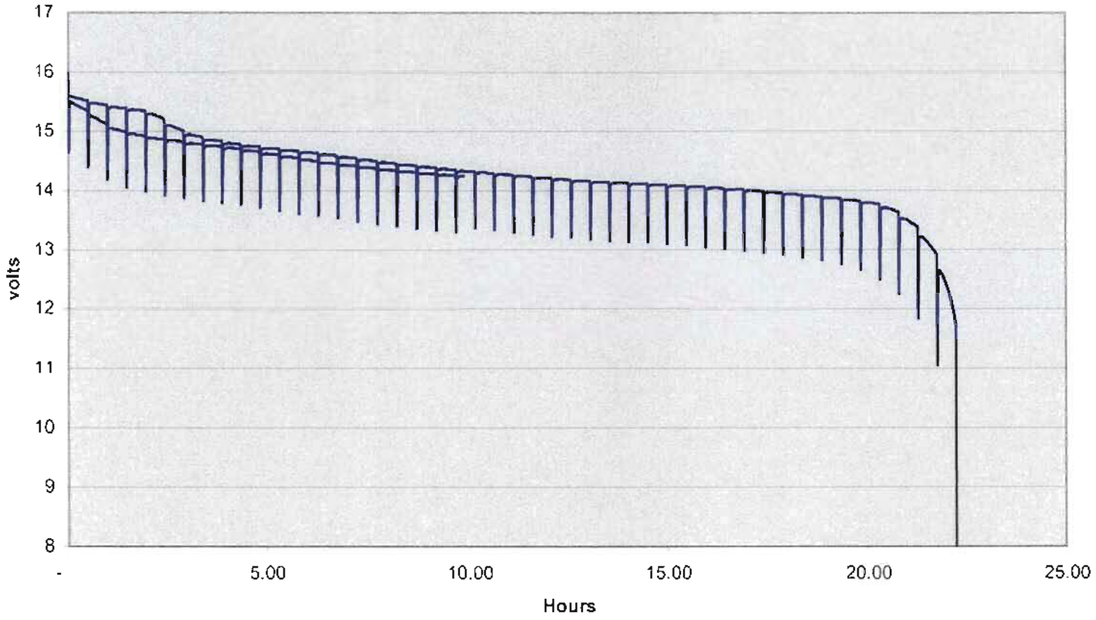
Li-ion: Discharge @ 2A for 1 minute and 0.25A for 29 minutes (Charge to 16.4V)



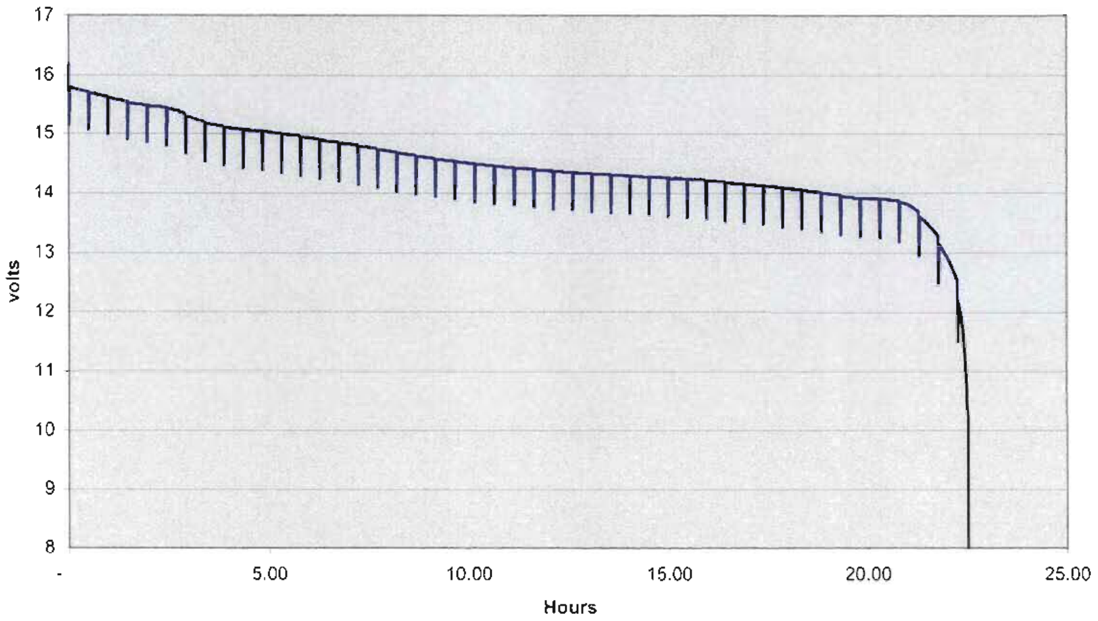
Li-ion: Discharge @ 1.5A for 1 minute (Temperature 55 degrees Celsius)



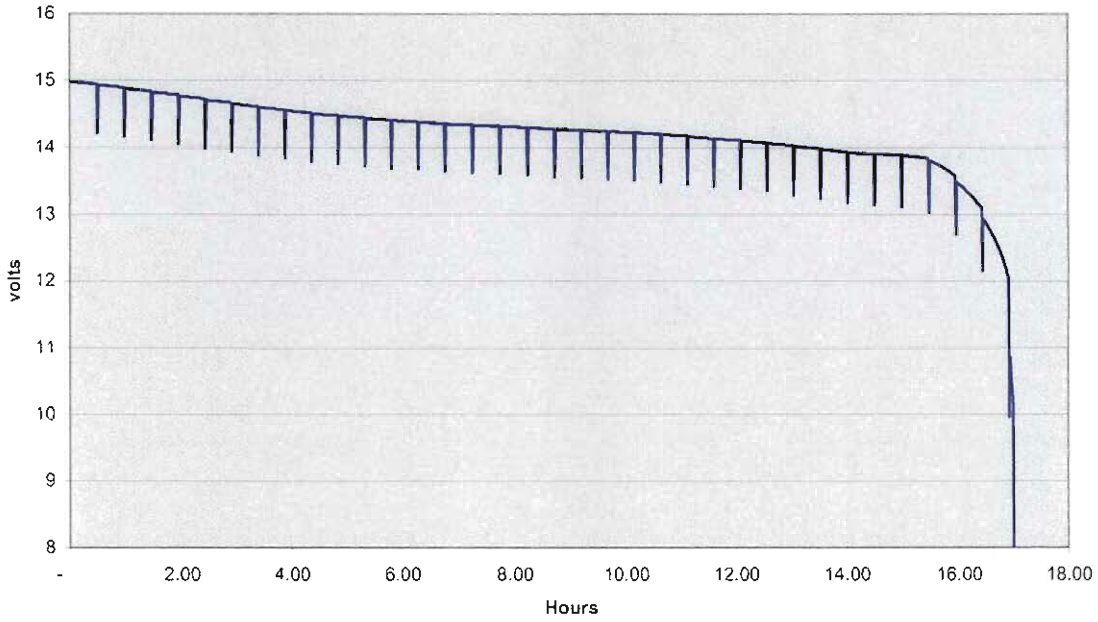
Li-ion: Discharge @ 1.5A (temperature of - 10 degrees Celsius)

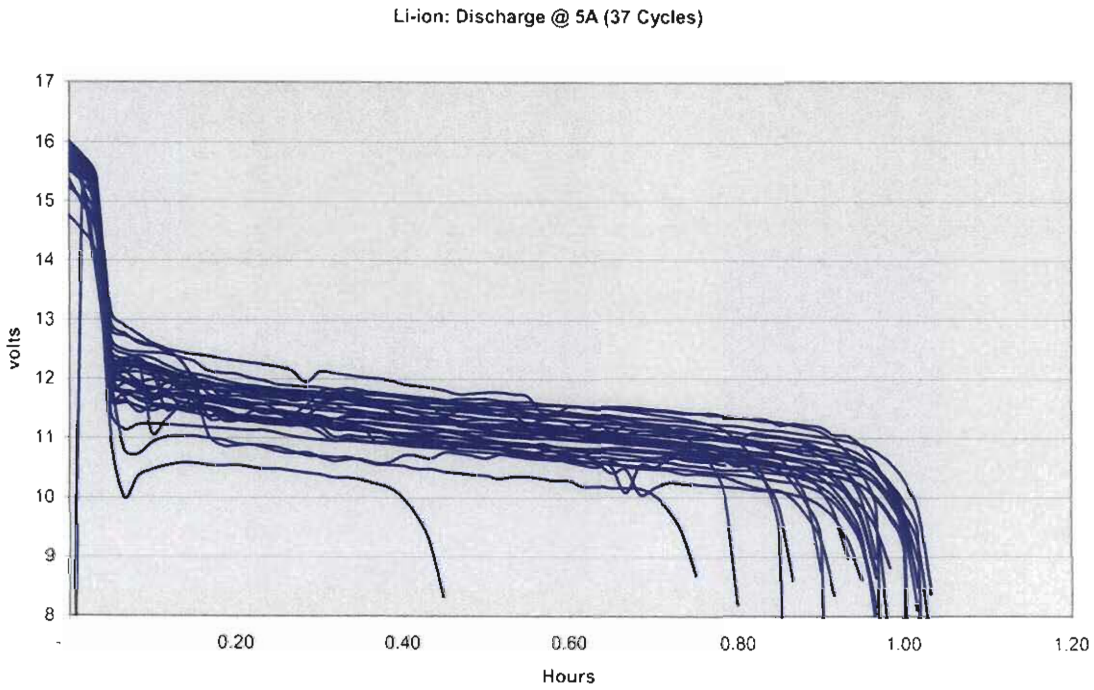


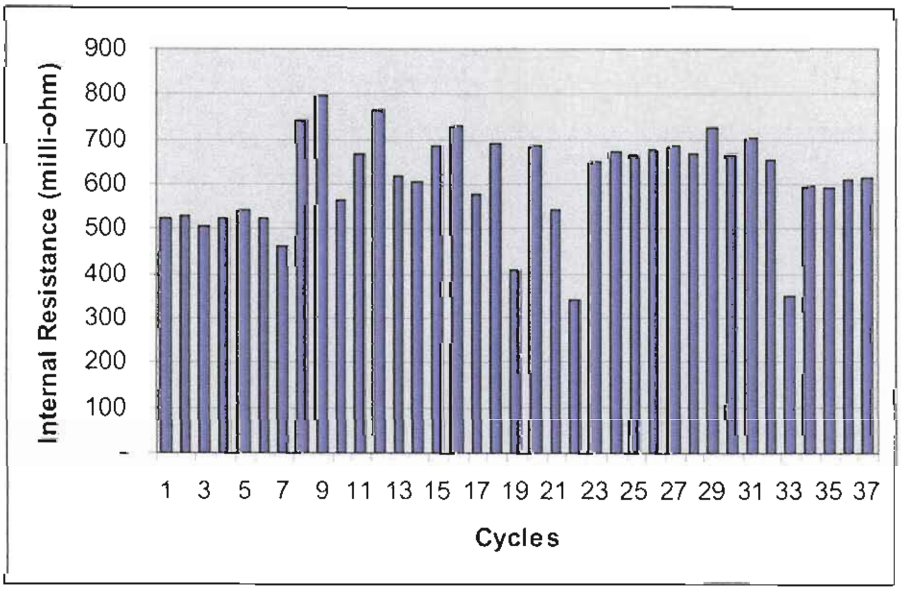
Li-ion: Discharge 1.5A (Stored at 73 degrees Celsius)

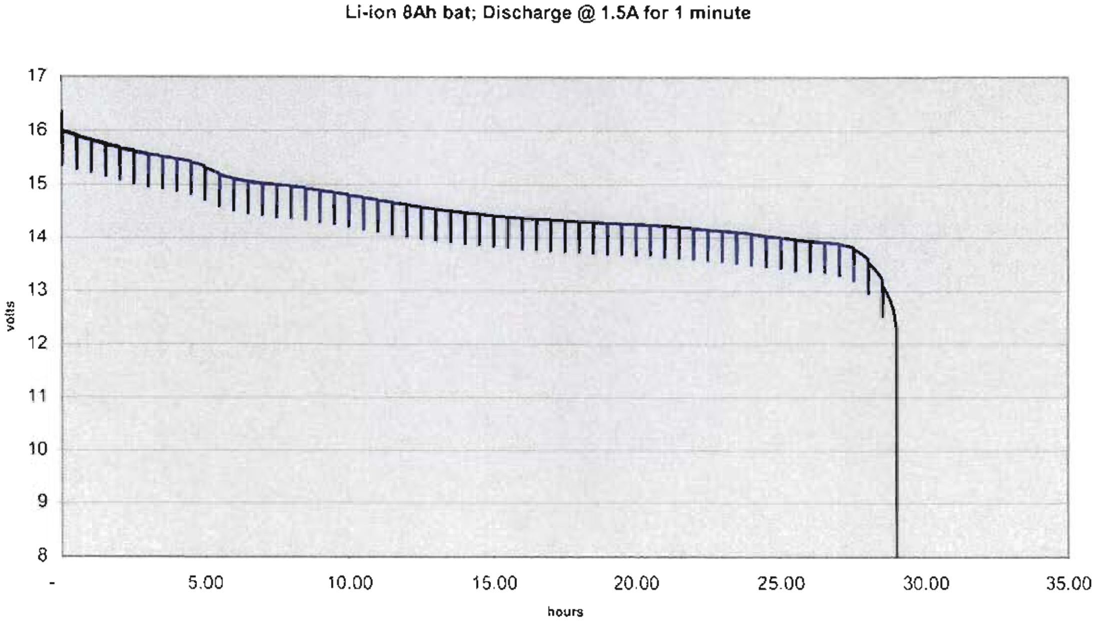


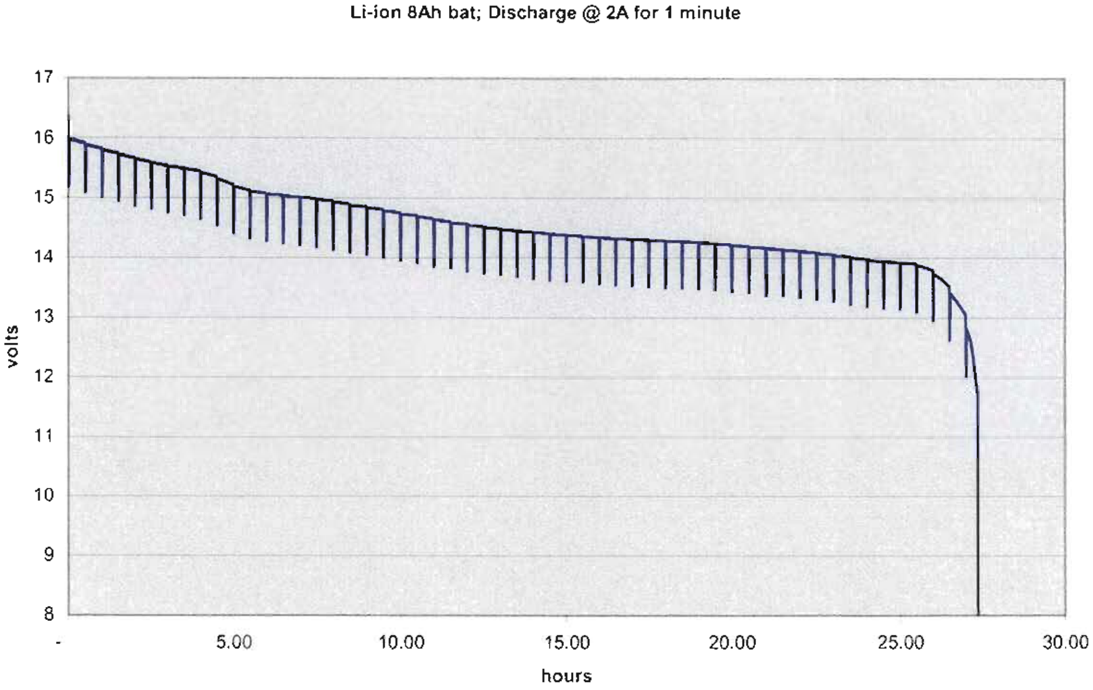
Li-ion; Discharge @ 1.5A (Stored at -20 degree Celsius)




Li-ion: Discharge @ 5A (37 Cycles)
volts
17
16
15
14
13
12
11
10
9
8
-
0.20
0.40
0.60
0.80
1.00
1.20
Hours


Internal Resistance (milli-ohm)
900
800
700
600
500
400
300
200
100
-
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
Cycles


Li-ion 8Ah bat; Discharge @ 1.5A for 1 minute
17
16
15
14
13
12
11
10
9
8
volts
-
5.00
10.00
15.00
20.00
25.00
30.00
35.00
hours


Li-ion 8Ah bat; Discharge @ 2A for 1 minute
17
16
15
14
13
12
11
10
9
8
volts
-
5.00
10.00
15.00
20.00
25.00
30.00
hours

4. CONCLUSIONS

The configurations of the Li-ion and alkaline battery packs are very similar. The Li-ion pack use three smaller batteries in parallel instead of the C-cell used in the alkaline pack. The advantage of the cells in parallel is a lower internal resistance. Due to the voltage of the Li-ion cell the pack only requires four cells in series instead of the 11 cells in series required by the alkaline battery pack. The Li-ion battery pack is a bit smaller and 26% lower in weight than the alkaline battery pack.

It is important to realise that the initial capacity depends a lot on the load current. In the case of the alkaline batteries, the capacity usually relates to a low current drain, typical of the low currents required for commercial equipment. When measuring the alkaline battery pack at 0.2C (IEEE standard) the capacity was only 3 Ah. The Li-ion battery pack's capacity depends on the charge. The capacity specified (6 Ah) is with a full charge. In a military environment where extreme conditions exist, it would be safer not to fully charge the battery. Tests have shown that a charge of 15.4 V instead of 16.4 V still gives a capacity of 4.6 Ah.

The alkaline battery pack was close to the original specification except in the case where the radio required 2 A for data transmission. The latest alkaline batteries are unsuitable for powering the A43 radio. For most of the tests where the A43 load was simulated and the discharge time was measured, the Li-ion battery pack lasted up to 16 hours longer. For instance on the 1.5 A load the alkaline battery lasted four hours compared to the Li-ion battery pack which lasted 19 hours on a load of 2 A.

The Li-ion battery pack lasted 19 hours with a charge of 4 V per cell and 23 hours with a charge of 4.1 V per cell. A discharge time of 19 hours on the A43 radio should be more than enough.

Regarding the temperature tests on the alkaline battery pack, the battery started leaking at very high temperatures (55 °C) and could not be tested. The Li-ion battery was successfully charged and discharged at 55 °C. The discharge time at this temperature was actually a little bit better. Even when the Li-ion battery was stored at 73 °C and tested at room temperature, there was still no reduction in discharge time. At –10 °C there was still no indication of a reduction in discharge time. When the battery was stored at –20 °C and then tested at room temperature there was only a 10% reduction in discharge time. Self-discharge rate was too difficult to test accurately and this test should be repeated in more controlled conditions.

It would take too long to do the 800 expected charge-discharge cycles. The battery was discharged 37 times at a load of 5 A, which should be quite tough on the battery. No noticeable difference could be detected at the 37th cycle. As a rough estimate, and not taking charging cost into consideration, the Li-ion battery has a cost of R27 per cycle. This could be compared to the R90 of the alkaline battery pack. This equates roughly to a 70% saving in cost.

The radio has a built-in voltage indication of the battery pack which could give an indication of the capacity left in the battery. The problem is that the user must have a good knowledge of the voltage-capacity relationship. A Li-ion battery pack fitted with a SmBus and fuel gauge seems to be the best solution for indicating the remaining capacity.

According to the literature, there are no restrictions on disposal of Li-ion batteries. But since Li-ion is a high-energy battery, it would be safer to ensure that batteries are fully discharged before disposal. Safety will always be a factor when high-energy cells are used. Since the Li-ion battery is fitted with a protection circuit, it had no problems handling a short circuit, overcharging with 24 V and a reverse polarity charge. Overheating by heating it to 130 °C destroyed the battery, but there was no explosion. Crushing the cells also did not lead to an explosion, but this could depend on how much they are crushed. As expected, the battery starts to burn when the cells are penetrated.

The Cadex C7000ER Battery Analyzer and Charger was tested. This charger belongs to the SANDF and can charge Li-ion, Ni-Cd and Ni-MH batteries. This charger is very intelligent but requires a skilled operator to set it up. The functions of this charger should be noted and a new charger must be designed with a friendly user interface dedicated to Li-ion batteries.

To summarise, the Li-ion battery pack was built with commercial cells, which are a lot less expensive compared to the military-specification cells. However, functionally they outperformed the alkaline battery pack by far.

Appendix C Qualification tests

1. INTRODUCTION

The aim of this section is to define a qualification / acceptance test for the Li-ion battery, the battery charger and the analyser for the A43 radio. The test is designed to prove the safety of the battery and to qualify the battery and charger as suitable for use in the A43 tactical radio under military conditions.

2. MATERIALS AND METHODS

General laboratory test method guidelines can be found in MIL-STD-810F, Chapter 5.

3. ELECTRICAL TESTS

ELECTRICAL CHARACTERISTICS OF THE BATTERY

The following test is done to verify the electrical characteristics of the battery. 'Complete charge' means charging the battery at 1 C (±4 A) and 16.2 V constant voltage until end of charge is detected (200 mA).

Charge at 15 °C to 25 °C.

VOLTAGE TEST

A fully charged battery should not have a voltage higher than 16.4 V.

INITIAL CAPACITY TEST

The capacity is measured with a discharge current of C/5 (1.6 A in the case of an 8 Ah battery) to 10 V cut-off within 1 hour of complete charge.

The battery voltage should remain above 10 V for more than 5 hours. This should calculate to a capacity better than 6 Ah.

CAPACITY INDICATION

To indicate the remaining capacity of the battery, the battery should be fitted with five LEDs and a push button.

Perform the capacity tests. Record the time when each LED switches off. All five LEDs on indicates 100% capacity and the battery should last for at least 5 hours.

Table 1: Capacity status

LED no.	Time from start of test until LED switches off	Capacity status
5	≤ 1.5 h	80%
4	≤ 2 h	60%
3	≤ 3 h	40%
2	≤ 4 h	20%

CYCLE LIFE TEST

The battery specification should state that the battery can perform 500 cycles of complete charge and discharge. After 500 cycles, the capacity should be equal to or better than 80% of the initial capacity.

For this test, the specifications from the manufacturer should be consulted.

INTERNAL IMPEDANCE TESTS

Measure the internal resistance at 1 KHz after a complete charge.
Initial internal impedance should be equal to or smaller than 50 mΩ.
Internal impedance after 400 cycles should be equal to or smaller than 80 mΩ.

TEMPERATURE TEST

Measure the capacity at each temperature. The battery should be kept for a period of 16 hours at the specified temperature before testing.

At –10 °C, the capacity should be equal to or greater than 60% of the initial capacity.
At 0 °C, the capacity should be equal to or greater than 70% of the initial capacity.
At 70 °C, the capacity should be equal to or greater than 90% of the initial capacity.

STORAGE TESTS

Perform a complete charge. Store the battery for 28 days at 10 to 25 °C. Measure the capacity.

The retention capacity should be equal to or greater than 80% of the initial capacity.

Perform a complete charge. Store the battery for 7 days at 60 °C. Perform a complete charge again. Measure the capacity.

The retention capacity should be equal to or greater than 85% of the initial capacity.

4. MECHANICAL CHARACTERISTICS OF THE BATTERY

The following tests are done to verify the mechanical characteristics of the battery.

WEIGHT

The complete battery pack must weigh less than 1 000 g.

DIMENSIONS

The outer dimensions of the case must be smaller than 155 mm (L) x 59 mm (W).

INTERFACE TESTS

Charger interface

Connect the charger to the battery and verify that the charger is able to charge the battery.

Radio interface

The power contacts should be on top of the battery, 27 mm in length, 10 mm wide and 0,15 mm thick. Connect the battery to the radio and verify that there is a proper connection.

Analyser interface

Connect the analyser to the battery and verify that it is able to interrogate the battery via the SmBus connections.

SAFETY CHARACTERISTICS OF THE BATTERY

The following tests are done to verify the safety characteristics of the battery.

CRUSH TEST

The charged battery is crushed between two flat surfaces. Crushing is continued until a pressure reading of 17.2 MPa is reached (applied force = 13 kN). Once the maximum pressure has been obtained, the battery is released.

The battery should not rupture, smoke or catch fire.

HOT OVEN

The temperature of the oven is raised at a rate of 5 ± 2 °C per minute to a temperature of 130 ± 2 °C. This temperature must be maintained for 60 minutes.

The battery should not rupture, smoke or catch fire.

TEMPERATURE WARNING TESTS

When the temperature exceeds the safety temperature of the Li-ion cells, the system should warn the soldier.

The specifications of the battery cells should indicate that the cells are protected by thermal fuses and resettable fuses.
Check the manufacturer's specifications regarding temperature protection.

SHORT CIRCUIT

The battery is short-circuited by connecting the positive and negative terminals with copper wire with a resistance of not more than 50 mΩ.

The battery should not rupture, smoke or catch fire.

OVERCHARGE

The battery is charged at 1 C (±8 A) current with a voltage limit of 24 V.

The battery should not rupture, smoke or catch fire.

REVERSE CHARGE

The battery is reverse charged at 24 V.

The battery should not rupture, smoke or catch fire.

SAFETY VENT

The battery enclosure should be fitted with a pressure-release vent to ensure the safety of the user.

PENETRATION TEST

The battery is penetrated from the side with a nail having a diameter of 6 – 10 mm. The battery should not rupture, smoke or catch fire.

5. ENVIRONMENTAL TESTS

HIGH-TEMPERATURE OPERATIONAL REQUIREMENTS

The equipment should function according to specifications when subjected to a high-temperature environment as specified in MIL-STD-810F, method 501,4, procedure II, temperature limit +55 °C. Note: See MIL-STD-810F, method 501,4, paragraph 2.4.

HIGH-TEMPERATURE STORAGE REQUIREMENTS

The equipment should survive when subjected to a high-temperature environment as specified in MIL-STD-810F, method 501,4, procedure I, temperature limit +73 °C.

LOW-TEMPERATURE OPERATIONAL REQUIREMENTS

The equipment should function according to specification when subjected to a low-temperature environment as specified in MIL-STD-810F, method 502,4, procedure II, temperature limit –10 °C.

LOW-TEMPERATURE STORAGE

The equipment should survive when subjected to a low-temperature environment as specified in MIL-STD-810F, method 502,4, procedure I, temperature limit –20 °C.

TEMPERATURE SHOCK REQUIREMENTS

The equipment should survive when subjected to a temperature shock environment as specified in MIL-STD-810F, method 503,4.

HUMIDITY REQUIREMENTS

The equipment should survive when subjected to a humidity test as specified in MIL-STD-810F. The limit is as per Figure 507.4-1 for a maximum temperature of 55 °C.

FUNGUS REQUIREMENTS

No testing is required, but proof of design to prevent fungal contamination is required.

SALT FOG REQUIREMENTS

The equipment should survive when subjected to a salt fog environment test as specified in MIL-STD-810F, method 509,4.

SAND AND DUST REQUIREMENTS

The equipment should survive when subjected to a sand and dust test as specified in MIL-STD-810F, method 510,4.

VIBRATION REQUIREMENTS

The equipment should survive when subjected to a vibration test as specified in MIL-STD-810F, method 514,5 procedure I.

SHOCK REQUIREMENTS

The equipment should survive when subjected to a shock test as specified in MIL-STD-810F, method 516,5 procedure I, with test conditions as set out in Figure 516,5-1 for ground equipment.

DROP TEST REQUIREMENTS

The equipment should survive when subjected to a transit drop test as specified in MIL-STD-810F, method 516,5 procedure IV.

LOW-PRESSURE REQUIREMENTS

The equipment should operate/survive when subjected to a low-pressure environment as specified in MIL-STD-810F method 500,4, procedure I.

EMI EMISSIONS AND SUSCEPTIBILITY REQUIREMENTS

The equipment should meet the EMI emissions and susceptibility requirements of MIL-STD-461C for Class B equipment

6. CHARACTERISTICS OF THE CHARGER

The following tests are done on all chargers to verify the characteristics of the chargers.

CHARGE VOLTAGE TESTS

Measure the charging voltage.

The charge voltage should be between 16.2 V and 16.4 V.

CURRENT LIMIT TEST

The maximum current supplied by the charger should not exceed 1 C typically 8 A.

CHARGE TERMINATION TEST

The charger should terminate (no trickle charge) the charge under the following conditions:

- When the charging current is less than 200 mA
- Time-out after 6 hours
- Faulty battery
- Over a temperature of 70 °C.

Monitor the charging after charge termination.
The charger should not allow any floating voltages.

TEMPERATURE MONITORING TEST

Charge the battery at the different temperatures and test the charger function as well as the charger display.

Table 2: Temperature monitoring

Temperature	Function	Display
Below 0 °C	Don't charge	Outside charging temperature
0 °C – 45 °C	Charge	
45 °C – 69 °C	Slow charge	
70 °C	Don't charge	Outside charging temperature

RECONDITIONING TEST

Put an over-discharged battery in the charger.

The charger should use a wake-up pulse and slow charging to recondition the battery.

PROTECTION TEST

The charger should be protected against:

- vehicle spikes
- reverse polarity

as defined in MIL-STD-461.

POWER SUPPLY TEST

- The power supply should run off 220 V AC.
- The power supply should be able to handle at least three chargers simultaneously (six batteries).

Test to see if charging time is within the expected limits.

SELF-TEST

The charger should do a self-test at switch-on. An indication should be given to the user if the charger cannot operate properly.

DISPLAY TESTS

Charger display test

The charger should indicate the following charge status:

- Fully charged
- Charge error
- Charge time-out
- An indication to the user when fast charging has stopped and the topping-off phase has started
- Warning LED
- Cell defective (open circuit or shorted).

Power supply display test

The power supply will be used at a base to convert the 220 V to the correct voltage for the chargers:

- The power supply should run off 220 V ac.
- The input voltage to the charger should be 12 – 32 V dc.
- The power supply should be able to handle at least three chargers simultaneously (six batteries).

7. INTERFACE TESTS

DC INPUT VOLTAGE TEST

The input voltage to the charger should be 12V – 32V DC.

AC INPUT TEST

The power supply should work from an AC input of 220 V.

CHARGER INTERFACE TEST

The charger should connect to the 5-pin connector for charging.

- Pin 1 – Charger gnd
- Pin 2 – Charger positive
- Pin 3 – SmBus thermistor
- Pin 4 – SmBus data
- Pin 5 – SmBus clock.

TEMPERATURE INTERFACE TEST

The charger should be able to sense the temperature of the battery while charging.

ANALYSER INTERFACE TEST

This interface allows the analyser to interrogate the battery.

- Pin 1 – Charger gnd
- Pin 2 – Charger positive
- Pin 3 – SmBus thermistor
- Pin 4 – SmBus data
- Pin 5 – SmBus clock.

8. CHARACTERISTICS OF THE BATTERY ANALYSER

The following tests are done to verify the characteristics of the battery analyser.

SMBUS INTERFACE TEST

Supports the 2-wire SmBus v1.1 interface. For this test connect the analyser to a battery and ensure that there is proper communication.

REMAINING CAPACITY TEST

The user should be warned if the battery has less than 80% of its original capacity left.

BATTERY AGE TEST

The user should be warned if the battery is older than 2 years. The battery SmBus could be used to emulate an old battery.

DEFECTIVE CELLS TEST

The user should be warned if the battery has defective cells.

DISCHARGE BATTERY TEST

The analyser should discharge a battery when:

- The SmBus functions must be recalibrated.
- The battery must be stored.
- The battery must be disposed of.

CYCLE COUNT TEST

The user should be warned if the battery has a cycle count of more than 500.

OVER TEMPERATURE TEST

The user should be warned if the battery has been exposed to high temperatures.

ANALYSER SELF-TEST

The analyser should have the ability to do a self-test.

9. INSPECTION

The following requirements and specifications should be validated.

Each battery should have the following clearly readable markings:

- National stock number

- Part number
- Serial number
- Battery name/type
- Voltage and capacity rating
- Rechargeable battery
- "Do not throw away" in bold red letters
- Date of manufacture
- Batch number.

The following warnings should be indicated on the battery packs:

- Use a specified charger by .... (the manufacturer).
- Do not place the battery in a fire or subject it to heat.
- Do not short-circuit the battery terminals.
- Do not disassemble, alter or solder the battery.

Appendix D Gerotek test report

GEROTEK
TEST FACILITIES

r Defencetech 4383

SANAS
ACCREDITED
LABORATORY

LABORATORY NO. T0005
TEST REPORT:
TESTING OF A43 RADIO BATTERIES
72MN4383-04

Test equipment utilised

Type of Instrument	Lab / Serial No.	Calibration Certificate No.
500mm Vernier	OTF 2229	7232XD1171-1
Altitude chamber	13000023	GC/059/05
Battery test bench	OTF 119	N/A
Climatic chamber	OTF 2636	GC/057/05
Data taker	13000024	202510
Digital scale	13000066	BVVI/05/04
Vibrator system	OTF 896	2005-002

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1. SUMMARY OF REPORT

The failures recorded are listed below.

Test	Brown Battery	Black battery
Temperature test	Open circuit at 70°C	No abnormalities
Overcharge test	Open circuit after ±10 sec	No abnormalities
Reversed charge test	Open circuit after ±10 sec	Open circuit after ±10 sec
High temperature operation	Tripped after 1 hour at 55°C	No abnormalities

The brown battery was operationally tested at 55°C but tripped after ±1 hour. The test was repeated but the battery fail to accept loading, therefore the test at 55°C and -10°C could not be performed.

2. TEST RESULTS

2.1 Electrical characteristic test

2.1.1 Voltage test

The batteries were charged at 16.2V DC to full capacity and the voltages recorded are indicated below.

Charging at 16.2V DC to full capacity	
Brown battery	**Black battery**
16.2V	16.2V

2.1.2 Initial capacity test

The batteries were charged to full capacity before they were subjected to a discharge test with a cut-off voltage at 10V. The discharge current and time before cut-off at 10V are indicated below.

Initial capacity test		
Discharge test	**Brown battery**	**Black battery**
Discharge current	1600mA	1200mA
Time to cut off @ 10V	4 hours 33 minutes	4 hours 50 minutes

2.1.3 Capacity indication test (Brown battery only)

The battery was charged to full capacity and then subjected to a discharge test with a discharge current of 1600mA. The duration for the LED indicator to switch off was recorded.

Capacity indication test		
LED no.	**Time until LED switches off**	**Capacity status**
5	≤1.5 hours	16.2V
4	≤2 hours	14.5V
3	≤3 hours	13.6V
2	≤4 hours	13.2V

2.1.4 Temperature test

Both batteries were fully charged and stabilised at the following temperatures for a period of 16 hours. The voltages were recorded prior to and after stabilisation for 16 hours. The recorded voltages were as follows:

Discharge test at -10°C, 0°C and 70°C				
Temperature	**Brown battery**		**Black battery**	
	Prior to	After	Prior to	After
0°C	16.17V	16.13V	16.19V	16.20V
+70°C	16.13V	0.0V	16.20V	16.15V
-10°C	16.13V	16.13V	16.20V	16.21V

The brown battery went open circuit during the test at 70°C but recovered when it was stabilised at room temperature. Although the battery was open circuit all the LED's (indicating a full battery) lit up when the button was pressed.

2.2 *Mechanical characteristic test*

2.2.1 Dimensions and weight

	Brown battery	**Black battery**
Dimensions	66.8mm (w) x 52.8mm (H) x 173.3mm (long)	52mm (w) x 52.8mm (h) x 147.5mm (long)
Weight	1323.29g	652.30g

2.3 *Safety test*

2.3.1 Short circuit test

The output of the battery was short circuited using a 4mm copper wire. After ±10 minutes the voltages were recorded and were as follows:

Brown battery	**Black battery**
16.2V	16.13V

2.3.2 Overcharge test at 8Amp

The batteries were charged at a rate of 8Amp with a voltage limit of 24VDC.

Results

The brown battery went open circuit after ±10 seconds. No damage or any other abnormalities were recorded. The black battery was not tested due to the unavailability of the units.

2.3.3 Reversed charge test

The polarities of the input voltage were changed around (reverse charge) with the voltage limit set to 24V.

Results

Both the brown and black batteries went open circuit during the test. No other abnormalities were recorded.

2.4 *Environmental Tests*

2.4.1 High temperature test (operational)

The batteries were fully charged before they were stabilised at +55°C for 16 hours. They were discharged while being at +55°C and the results were recorded. See Appendix A for discharge graphs.

Results

Discharge test at +55°C		
Discharge test	**Brown battery**	**Black battery**
Discharge current	1600mA	1200mA
Time to cut off	1 hour 14 minutes	4 hours 43 minutes

It is suspected that the brown battery tripped at ±13V possibly due to a temperature related problem.

2.4.2 High temperature test (storage

Both batteries were stored at a temperature of +73°C for 24 hours. After this period they were allowed to stabilise at room temperature before a functional test was performed.

Results

Although the brown battery went open circuit at +73°C, it recovered whilst cooling down to room temperature. Both batteries were satifactory when tested at room temperature.

2.4.3 Low temperature test (operational)

The batteries were fully charged before they were stabilised at -10°C for 16 hours. They were discharged while being at -10°C and the results were recorded. See Appendix A for discharge graphs.

Results

Discharge test at -10°C		
Discharge test	**Brown battery**	**Black battery**
Discharge current	x	1200mA
Time to cut off	x	4 hour 40 minutes

Although 16.2V was measured on the output terminals, the brown battery went into a current limit mode when connected to the discharge circuit at ±30mA. The brown battery was thus not functionally tested at -10°C.

2.4.4 Temperature shock test

Both batteries were subjected to a temperature shock test with extreme temperatures of -10°C and +70°C. The batteries were stabilised at each temperature for a period of 30 minutes with a change-over period of ±10 seconds. Ten cycles were performed.

Results

No abnormalities were recorded.

2.4.5 Random vibration test

Both batteries were randomly vibrated at frequencies between 10Hz and 500Hz with an acceleration level of 1.04grms. They were vibrated for a period of 1 hour in each axis and were functionally tested after each test.

Results

No abnormalities were recorded.

2.4.6 Low Pressure test

The batteries were subjected to a low pressure test with a simulated altitude of 15000ft. The test was performed at a temperature of +25°C. The voltage was recorded prior to and after the test.

Results

No abnormalities were recorded.

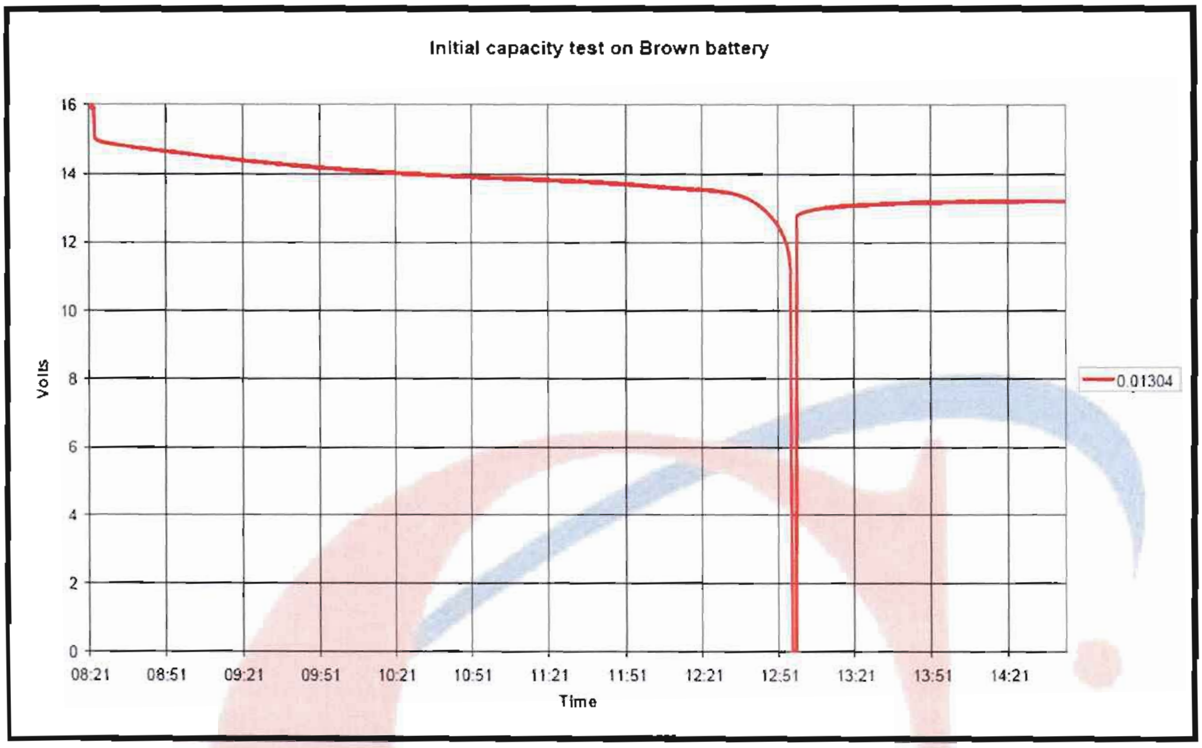
3. UNCERTAINTY OF MEASUREMENT

The reported expanded uncertainty of measurements stated as the standard uncertainty of measurements multiplied by the coverage factor k = 2, which for normal distribution corresponds to a coverage factor probability of approximately 95%.

4. REPORTED UNCERTAINTY OF MEASUREMENT

Not applicable.

APPENDIX A
DISCHARGE TEST GRAPHS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14
12
10
8
6
4
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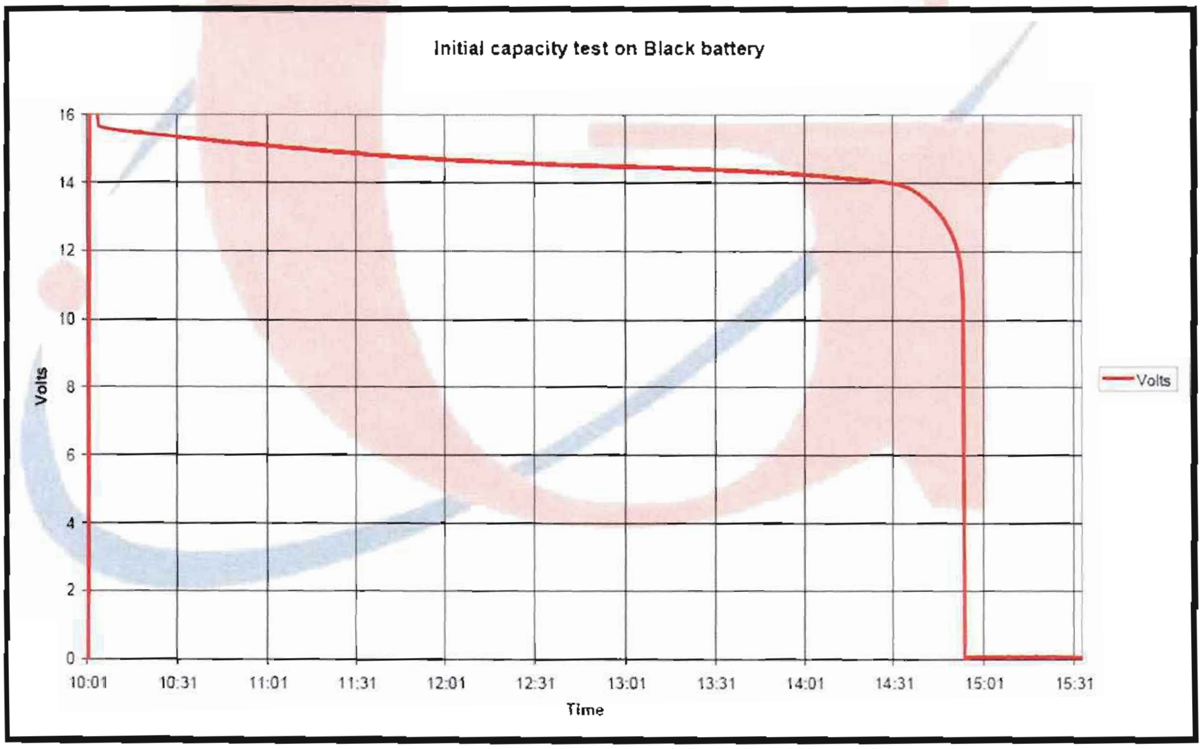
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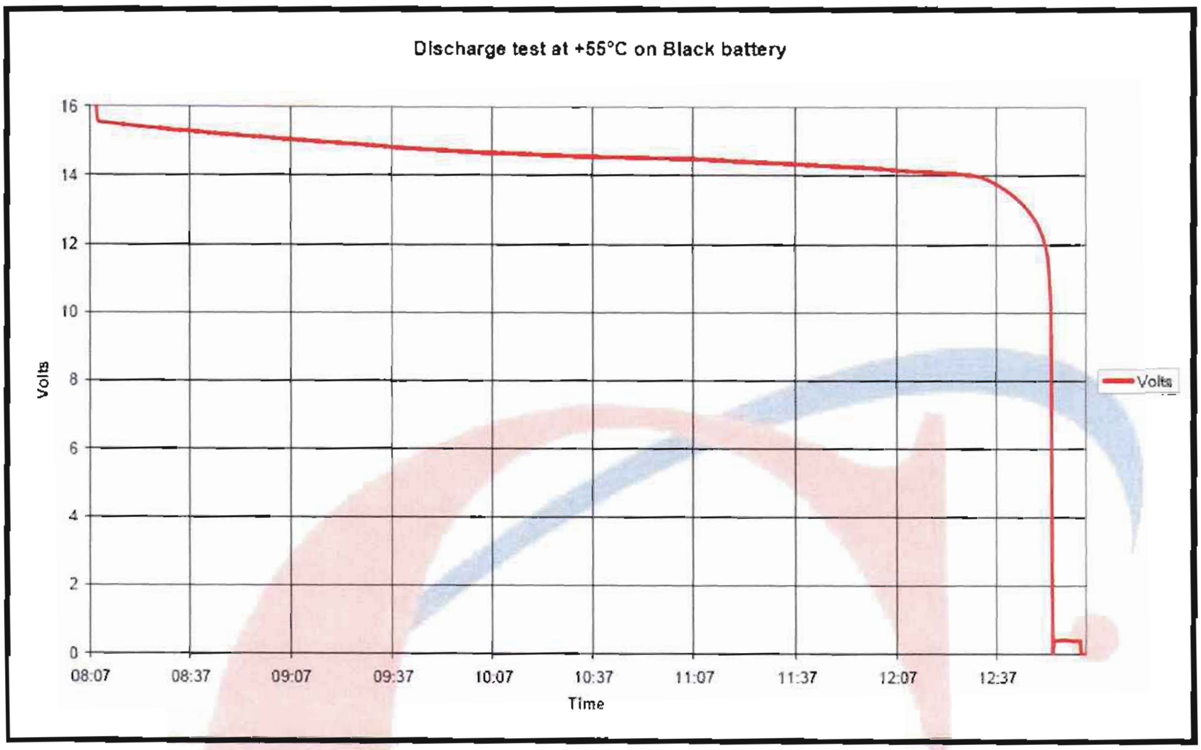
Time
Volts


Discharge test at +55°C on Black battery
Volts
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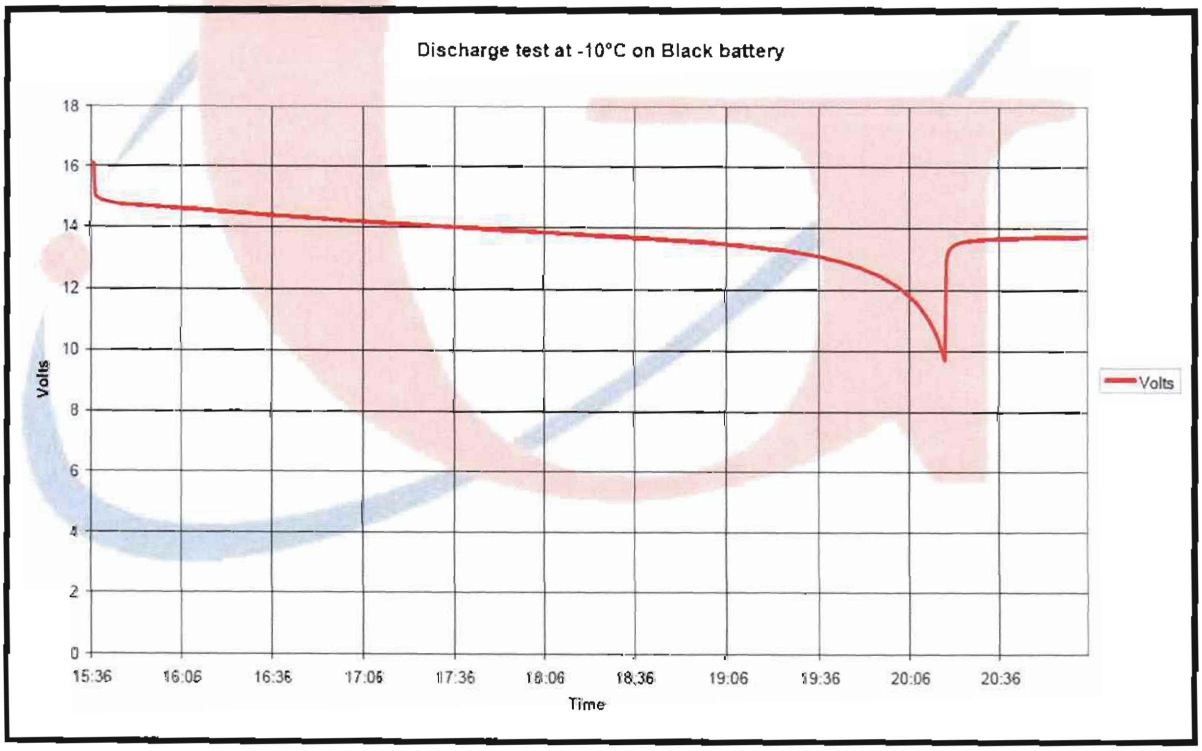
12:07
12:37
Time
Volts


Discharge test at -10°C on Black battery
Volts
18
16
14
12
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4
2
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17:36
18:06
18:36
19:06
19:36
20:06
20:36
Time
Volts

Appendix E Second battery workshop

1. INTRODUCTION

The battery workshop attended is related to the project for new batteries on the A43 radio. We have tested batteries in our laboratory and a specification for a secondary battery system has been drafted. We are currently in the process of testing the secondary battery system, as developed by the industry. To finalise the specification, it was necessary to visit the relevant Li-ion experts, as well as the companies that provided the initial prototypes.

The objective of the workshop was also to:

- Get an up-to-date overview of the latest battery technologies for application in defence communication systems.
- Assess the viability of these technologies from an academic and industrial perspective.
- Discuss the implementation of the lithium-ion programme for the A43 radio with potential suppliers and qualification authorities.

The following places were visited for the workshop:

- Technical University in Graz – Austria.
- VARTA Microbattery – Germany.
- Gaia, Advanced Lithium Systems – Germany.

2. NEW DEVELOPMENTS

SAPHION

Saphion is a phosphate-based lithium-ion battery technology. Lithium-ion batteries are beginning to show up in concepts such as General Motors' Sequel fuel cell crossover, replacing nickel-metal-hydride batteries (Ni-MH). Phosphate-based lithium-ion technology solves one of the biggest concerns with today's oxide-based lithium-ion batteries, i.e. safety. In the event of an accident or failure, oxide-based lithium-ion batteries release oxygen, which can cause a fire, or worse still, an explosion. Phosphates are extremely stable in overcharge or short-circuit conditions and have the ability to withstand high temperatures without decomposing, so the threat of fire or explosion is eliminated. Unlike traditional lithium-ion materials such as cobalt or magnesium oxide, and the nickel in Ni-MH batteries for that matter, phosphate batteries are ecologically safe. In fact, Saphion batteries are landfill-approved in the state of Nevada, USA, where Valence's R&D centre is located. Saphion batteries have a run-time three to four times longer than that of lead acid or Ni-MH batteries.

TOSHIBA

Figure 1: Super Charge Battery

Toshiba Corporation has announced a breakthrough in lithium-ion batteries (Figure 1) that makes long recharge times a thing of the past. The company's new battery can recharge 80% of a battery's energy capacity in only one minute, approximately 60 times faster than the typical lithium-ion batteries in wide use today, and combines this fast recharge time with performance-boosting improvements in energy density.

The new battery fuses Toshiba's latest advances in nano-material technology for the electric devices sector with cumulative know-how in manufacturing lithium-ion battery cells. A breakthrough technology applied to the negative electrode uses new nano-particles to prevent organic liquid electrolytes from reducing during battery recharging. The nano-particles quickly absorb and store vast amounts of lithium ions, without causing any deterioration in the electrode.

The excellent recharging characteristics of a new battery are not its only performance advantages. The battery has a long life cycle, losing only 1% of capacity after 1 000 cycles of discharging and recharging, and can operate at very low temperatures. At minus 40 °C, the battery can discharge 80% of its capacity.

Toshiba will bring the new rechargeable battery to commercial products in 2006. Initial applications will be in the automotive and industrial sectors, where the slim, small-sized battery will deliver large amounts of energy while requiring only a minute to recharge. For example, the battery's advantages in size, weight and safety make it highly suitable as an alternative power source for hybrid electric vehicles.

Major specifications of the new battery:

- *Excellent recharge performance* (The thin battery recharges to 80% of full capacity in only a minute).
- *High energy density* (The prototype battery is only 3.8 mm thick, 62 mm high and 35 mm deep and has a capacity of 600 mAh).
- *Long life cycle* (A prototype of the new battery was discharged and fully recharged 1 000 times at a temperature of 25 °C and lost only 1% of capacity during the test).
- *Temperature* (It discharges 80% of its capacity at minus 40 °C).
- *Eco-friendly* (This speedy and highly effective recharge characteristic of the battery will support CO_2 reduction as the battery can save and reuse energy that was simply wasted before).

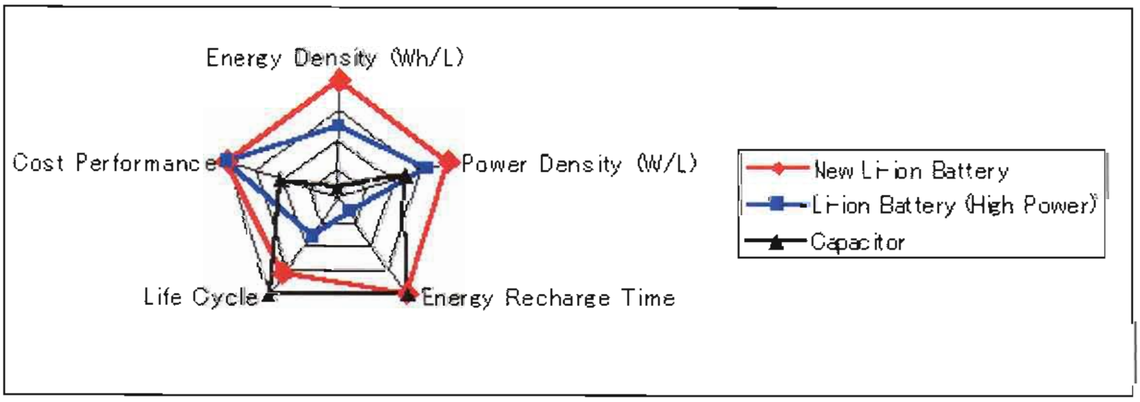

Figure 2: Graph comparing the new battery with other batteries

NEW ELECTRODE MATERIALS

Since they were introduced into the marketplace in 1992, Li-ion batteries have made big gains in energy density. The standard 18650 cylindrical cell, which is commonly used in notebook battery packs, provides a measuring stick. The original cells produced 13 years ago had a capacity of around 960 mAh. Today, 18650 cells with as much as 2 600 mAh of capacity are in production. In the near future, these cells may reach 3 000 mAh, but achieving that performance is likely to require significant changes in anode and cathode materials.

The latest cells are built using lithium cobalt oxide ($LiCoO_2$) cathodes and graphite anodes. The choice of cathode material has remained largely unchanged since the first Li-ion cells were introduced. Improvements to date have been achieved mainly by increasing the packing density and amount of active materials in the cell. And, although some cells employ other cathode materials, lithium cobalt oxide dominates the industry and has set the "standard for capacity, safety and rate," even though its cost is regarded as a limiting factor. The cathode is the most expensive element in the cell.

Two categories of new cathode materials are viewed as likely alternatives to lithium cobalt oxide. For higher energy density, nickel-based oxides, which may also may include cobalt and manganese in the mix, are expected to be applied in new cell designs. "These new cathode materials will make it possible to build higher-capacity cells at lower cost," according to Onnerud. However, he noted that there are still "important safety issues to resolve." In addition, nickel-based cathodes may require a higher voltage range (4.4 V to 4.6 V versus the standard 4.2 V end-of-charge voltage) to achieve higher capacity. The latter characteristic would complicate a changeover from existing cells.

Meanwhile, phosphate-based cathodes such as $LiFePO_4$ represent another alternative to lithium cobalt oxide. The phosphate materials offer greater safety and stability, a more environmentally friendly design and lower cost. However, phosphate-based cathodes present concerns in terms of high power capability.

New anode developments also are on the horizon. Currently, three types of graphite material are in use in Li-ion manufacturing: artificial graphite, mesophase carbon microbeads (MCMB) and natural graphite. Current research into these carbon materials focuses on reducing cost and improving safety.

Sony's Nexelion battery, introduced last February, is an example of a new anode type. The use of a tin-based amorphous material for the anode was partially responsible for Nexelion's 30% increase in capacity versus conventional Li-ion batteries. (The cell also incorporated a cathode that combined Li-Ni-Co-Mn-based oxide with $LiCoO_2$.)

ALTAIR NANOTECHNOLOGIES

Altair's development of the electrode materials has produced several batches of lithium titanate spinel electrode material. This material was used by Rutgers University Energy Research Group to construct several prototype batteries. They then conducted tests on these prototype batteries. The results indicated that batteries constructed using Altair's nano-lithium titanate electrode materials could have the following characteristics:

- *Very fast charge rates* – currently measured at six minutes to a full charge. In the power tools market this is a major breakthrough compared with the current two to four hours. And in the electric vehicle (EV) market this would allow a recharge in the same amount of time as it currently takes to fill a car with gasoline. Rapid charge rates would provide a significant improvement in performance for current EV designs, which at present take several hours to charge, making them practical only for short-haul trips.
- *Fast discharge potential* – required when high amounts of power are needed by power tools and electric or hybrid vehicles. An Altair scientist commented that an EV powered by batteries using Altair's electrode materials would have a speed of 0-60 mph speed, which would leave other EVs in the dust!
- *Extremely long cycle life* – reported by Rutgers at 9 000 cycles and estimated at 20 000 plus charge/discharge cycles. This compares with less than 1 000 for all other types of rechargeable batteries. Using Altair's electrode materials, this would allow lifetime rechargeable batteries. In power tool applications, as well as providing a cost benefit, it also has a substantial environmental impact because it would significantly reduce the toxic hazards from discarded batteries. In EVs, it significantly improves the cost of ownership because the batteries would not need to be replaced during the typical life of the vehicle and in fact could be transferred to a replacement vehicle.

- *Safe design* – Because of the electrical characteristics of the Altair electrode materials, they operate at a level that avoids the explosive potential inherent in current Li-ion batteries. This will allow the construction of the large-configuration batteries required in EVs or telecom switching centres. As well as solving a major safety problem, it will also reduce the cost of battery manufacture because the safety mechanisms included in current Li-ion batteries to mitigate explosions are likely to be minimised.

3. TECHNICAL UNIVERSITY OF GRAZ

As part of the A43 Battery project, the project team visit the Technical University of Graz. We spoke to Professor J. O. Besenhard and Dr Waltraud Taucher-Mautner, both from the Institute for Chemistry and Technology of Inorganic Materials. This opportunity was used to discuss outstanding questions regarding Li-ion batteries, as well as the current trends. The following points were discussed:

BATTERIES

In general, prismatic cells have higher capacity compared with cylindrical cells, but cylindrical cells are stronger and can handle a higher internal pressure.

Ni-Cd cells have to be phased out, except that they can still be used as part of an electronic device if the cell is soldered onto the pc board.

There is no such a thing as a high-energy and safe battery: if you need a lot of energy, it should be expected that the battery will be more dangerous.

In applications where the need is for a long operating time (several days), fuel cells will be ideal, but in the case where the operating time is short (a day or two), batteries will still be the best choice.

At this stage the lifetime of fuel cells is still short (limited cycle life) and they may possibly be used to charge high-capacity batteries.

In the near future the mostly likely energy solutions will be battery/fuel cell hybrids. Fuel cells will probably never replace Li-ion batteries, but will be used mostly for kilowatt requirements.

If you keep your Li-ion battery at the correct temperature and do not deep discharge it, a battery could last more than two years.

When comparing fuel cells, the methanol fuel cell has the advantage that it is easier, but at this stage the USA has opted to develop the hydrogen fuel cell. To store hydrogen safely will always be very difficult.

Zinc-air type fuel cells have the disadvantage that replacing the zinc is complicated and dangerous. Zinc air also does not have good duty cycles.

Li-polymer is only slightly safer than Li-ion, mostly due to the fact that the Li-polymer cells are smaller (less capacity).

Nowadays, the commercial cylindrical cells have added safety factors, namely:

- An internal shutdown separator at 100 °C
- PTC elements to cut the current
- Carbon-filled polymers that shut down the battery at high voltages
- Over-pressure contacts that open at high pressures
- External protection circuits.

The new Li-ion cells with the phosphate-based cathodes are safer, but this is due to a lower cell voltage. It is also not possible to overcharge these cells, which makes them safer in the case where the external electronics have failed.

The new so-called 'nano-technology' Li-ion cells use extremely small (nano) particles which increase the surface areas and allow a faster charge. This type of cell has a lower voltage and less energy density. The cell's characteristics can be compared with those of super-capacitors.

When the particle size of the electrolytes is decreased, the cells can provide higher current rates.

The problem with fast charging is that you might need a 50 A charger.

When doing penetration tests, it is important to do enough of this type of test to ensure that the data collected are statistically relevant.

It is important to look at the credentials of the cell manufacturers when choosing cells for your application. For instance, in Japan most cells are hand-made.

Phosphate-based cells could be cheaper, but they are not in full mass production yet. There is no need, at this stage, to consider these types of technology for the A43 project.

When determining the state of health of a battery, its internal impedance can be used, but a lot of external factors come into play as well, for example the temperature when measuring or the charge state, etc.

The capacity of the battery depends on the current rate, especially in applications that draw pulse currents. Capacity problems usually occur at low temperatures.

At low temperatures, the charging voltage is critical and a voltage-level error will decrease the lifetime of the cells.

At high temperatures, the electrolytes can decompose and this will also decrease the lifetime of the cells.

It is very difficult to build a software model for a Li-ion cell since a combination of too many factors plays a role.

The lifespan of Li-ion batteries depends not only on the chemicals, but also on many external factors, for instance temperature and charge voltage levels. So far, there are not enough practical data available to predict the lifespan of a battery.

Electrolytes decompose over time due to the cell temperature and storage time. A Li-ion cell has only a small quantity of electrolytes which can easily decompose.

It is important when storing a Li-ion battery to ensure that it is not fully charged or deep discharged.

When connecting cells in series, the battery pack becomes more dangerous. A bad cell could drive the good cells into a dangerous state. For this type of configuration, the external electronics are very important.

A lot of development work has been done on making the cells safer, so now it is important to ensure that the external electronics are well designed.

A battery system using phosphate ion can use what is called a 'shuttle' (chemical component) which ensures charging equilibrium in all cells when charging.

FUEL CELLS

Dr Victor Hacker from the Institute for Chemistry and Technology of Inorganic Materials gave a presentation on the current state of fuel cells. The following points were also discussed.

The company Smart Fuel Cell provides a fuel cell that is used in camping mobiles. The company has received a licence to allow them to manufacture and sell methanol. It is allowed to take 200 ml of methanol onto an aeroplane.

Fuel cells need a fixed load and not a variable load.

A fuel cell car is technically possible, but not economically viable.

The current aim for fuel cell development is to get at least 40 000 life cycles.

The fuel cell must have the ability to start a car in cold weather. Fuel cells must be better than a Li-ion battery to ensure penetration of the market.

Developing fuel cells for soldiers should provide an easier entry into the market. This is due to the fact that car engines are relatively cheap and therefore the requirement of this market is a cheaper fuel cell.

Car manufacturers are investing a lot of money in the development of fuel cells.

4. ACCUPOWER

The project team also visited a company called Accupower, which specialises in charging systems. We discussed the A43 battery charging requirements with Mr Issam Al-Abassy, the Managing Director. The following points were discussed.

Accupower's charging technology aims to achieve the shortest possible charging time by means of a long life and charging stability of the batteries. A key competitive advantage is the optimal saturation of the batteries during the recharging process, meaning higher and more stable capacity over the cycles.

The micro-controller, developed by Accupower's R&D subsidiary, adjusts the charging process, charging duration and intensity to the quality, state of health and capacity of every single battery. A continuous data exchange between the batteries and the chargers takes place so that optimal charging is achieved.

Accupower has designed its own quality test plan which it provides to the cell manufacturers before buying cells from them.

When batteries are charged at different temperatures, charging voltage becomes a very important consideration.

The manufacturer of the cells should provide the specification on charging the cells and the charger should be designed according to these specifications.

5. VARTA MICROBATTERY

Varta has provided a prototype battery for the A43 radio. This battery was tested and the results were discussed. Present at the meeting were Mr Will Wells, Product Manager of Varta UK, Dr Manfred Leimkukler, General Manager QA, and Mario Feile, external battery circuit designer. The following points were discussed.

For Varta, safety is one of the very important issues for all battery types. With Li-ion and Li-polymer batteries, many safety measures can be taken to make the battery safe and reliable. Especially for these batteries, additional electronics can be used to keep the batteries within a certain range within which they can be used safely.

The safety of Li-ion and Li-polymer batteries starts with the cell itself. All these cells are tested according to UL1642 and should be approved by performing the following tests:

- abnormal overcharge
- forced discharge
- short circuit
- heating
- crush
- impact
- drop
- humidity
- vibration.

Some tests can be passed with some maximum voltage limitation or the use of safety elements such as a 'Poly-switch' which is documented on the UL website under the file for the special cell.

In lithium round cells a Poly-switch is integrated into the cell. In addition, a CID (current interruption device) cuts the circuit acting on internal pressure.

For prismatic cells additional passive elements improve the safety of the overall system. Most commonly used are the Poly-switches or Thermo-fuses. These passive elements limit or interrupt the current in a failure mode, which is detected as high current or as high temperature.

Using 2.4 Ah cells in a 4s3p connection will produce a battery that falls under the category 'dangerous goods' when transported.

Accelerated testing is not possible since this will change the cell chemicals. High-temperature accelerated tests can be used to compare cells.

New Li-ion technology trends must still find a market for their type of cells. Cobalt-type cells have still the major share of the market.

2.2Ah 18650 is a good robust cell and still, for a battery pack, a safer solution than the polymer cells.

When low- capacity cells are used, fewer safety devices are required.

Charging voltages at high temperatures must be controlled, especially when using vehicle chargers.

When battery manufacturers pot the cells, they must still guarantee that the battery will pass the UL safety tests.

High charging currents do not make a big difference to the charging time. Slower charging will increase the battery lifetime.

No pressure relief is required for the battery enclosure.

When Li-ion cells are discharged to 3 V and then left for 12 months, the cells cannot be recovered.

The external circuit suggested for the A43 battery will be based on the bq20Z80.

The bq20Z80 'gas gauge' technology calculates the remaining capacity in lithium-based battery packs with up to 99% accuracy throughout the entire life of a battery. The new Impedance Track technology allows the user to prolong battery use and always know the exact amount of potential energy left inside the battery.

Because current battery measurement solutions do not calculate impedance as a battery ages, the resulting error rate may be over 50% after a few months of use.

The bq20Z80 precisely gauges changes in impedance, or resistance, caused by battery age, temperature and cycle patterns, to accurately predict the run-time of two-, three- and four-cell battery packs. The technology, which sits inside the flash-based bq20z80 gas gauge chipset, analyses the precise state of charge when a battery pack is in a relaxed state by correlating between a battery pack's open-circuit voltage and its current state of charge and temperature.

Impedance Track relies on a dynamic modelling algorithm to 'learn' how much a battery has degraded through age, temperature or usage, and then correlates typical chemical properties of the anode/cathode system in the battery's cell – no matter what brand of battery cell is used. In fact, Impedance Track allows for the mixing of different manufacturers' cells in a single pack, providing flexibility and continuity of supply.

In operation, the system needs to monitor about 500 s (just over eight minutes) of discharge cycle to be able to recognise the battery's position on the discharge curve. TI claims an accuracy of better than 1% over the life of the battery.

The IC provides an output to drive an LED display (three, four or five segments) and can be used with 7.2-V, 10.8-V and 14.4-V battery packs using the bq29312 as front-end battery protection. Capacity information is passed to the system host processor over an SmBus.

The accuracy and dependability of this system make it a must-have in products that are safety or mission critical.

6. CHARGING SYSTEMS – RRC

The A43 charger specification was discussed with Mr Jorg Christmann, an electronic design engineer, and Mr Christian Trattnig, the Product Manager from RRC power solutions.

The following points will be added to the A43 charger specification:

- AC input voltage range: 110 V – 220 V.
- DC input range: 10 V – 32 V, with a cut-off if the input voltage is below 10 V.
- The charging specification of the cells must be provided by the cell supplier.
- The minimum temperature specification for the LCD is -10 °C.
- The charger must be intelligent enough to handle the SmBus, addressing requirements when six batteries are connected to the power supply/analyser.
- The interface to a PC will be via a USB port.
- The charger should provide an over-temperature warning but still charge the battery if it is not dangerous.
- The charger should not trickle charge but rather switch off completely.
- The charger will obtain the voltage level requirement from the battery.

7. GAIA

To investigate very high-energy Li-ion technologies, GAIA was visited. Dr Markus Schweizer-Berberich and Mr Hans-Joachim Steinwachs discussed the company and their technology.

LTC are the manufacturers of the GAIA® product line of hermetically sealed Li-ion and Li-polymer rechargeable cells and batteries. Products include large-format, high-power cells from 5 Ah to 30 Ah with discharge capabilities to 30C designed for HEV applications, fast-charge batteries for the military and high-energy cells to 100 Ah for stationary applications.

Cells are manufactured in both cylindrical and flat-form factors and employ proprietary extrusion, design and assembly technology. The company assembles custom large batteries complete with electronics (BMS) and communication for the national security, transportation and stationary power markets.

Product line:

- Cylindrical lithium-ion cells from 5 Ah to 60 Ah (including D and CC-cells)
- Prismatic (flat) cells from 6.5 Ah to 27 Ah
- Batteries up to 600 V composed of the above cells (cylindrical or prismatic).

Their Li-ion and Li-polymer batteries encompass both thin and flat prismatic cells, as well as large wound cylindrical (Figure 3) and prismatic cells. They have the ability to handle large footprint cells and assemble cells into large battery stacks.

Figure 3: 45Ah Li-ion cell

Advantages of GAIA Li-ion cells:

- Large and modular cells for design flexibility – common building blocks (cylindrical, prismatic and flexible flat cells) allow for various sizes, shapes and performance demands
- Very low and high operating temperatures from –40 °C to +55 °C
- Proprietary chemistry and technical design for superior performance, safety and long operating life
- Low internal resistance allows for high power output and rapid charging with limited heat generation
- Chemistry and design meet stringent safety demands
- Many thousands of charge/discharge cycles (between 30% and 80% depth of discharge)
- Hermetically sealed, rugged stainless steel containers.

The normal charging method for individual cells is CC-CV, but in a series string of cells the charger cannot handle the individual cells. In addition, unlike lead acid batteries, lithium-ion batteries do not allow higher voltage for equilibration of the cells. To account for this, LTC produces Battery Management Systems (BMS).

The BMS ensures safety during charging and discharging by providing over-voltage and deep-discharge protection. During battery operation, the BMS shuts off the cells in the event of over-temperature, over-current or failure of the cells. In addition, the BMS measures voltage, current and temperature, calculates SOC and SOH and communicates with application-specific electronics. The BMS also provides equilibration of the cells for better life cycle and performance.

Battery charge to 80% capacity takes place in 1 hour.

LTC aims to supply batteries for electrical vehicles in 2008. It is believed that Li-ion will win the future battery race.

When high-voltage Li-ion batteries are stored, the problem is that at high voltages it is difficult to ensure that the material used will always be stable.

Tests have shown that when the Li-ion cells are charged only to 3.9 V, the cell lifetime could be doubled. This also extends the calendar year (i.e. lifetime) of the cells.

The safety test for the transportation certificate can be found in UL1642.

Overcharging is the biggest problem with Li-ion cells. Therefore there is a requirement for an external battery management system. The overcharging test is not required for the transportation certificate.

GAIA do not supply cells close to the size of the 18650 cells because they do not want to compete with the mass production market.

Under a contract, LTC will develop a high-power 14.4-V lithium-ion battery system that will be used to rapidly charge smaller battery packs in the field and that will itself be capable of recharging quickly from another power supply, such as a vehicle-mounted gas-fuelled generator. LTC's high-rate lithium-ion technology is ideal for this application as it reduces charge times to 30 minutes or less from the typical 2+ hours required to charge standard lithium-ion batteries.

Recent military combat experiences have reinforced the critical need for batteries in the field, yet the logistics of maintaining a sufficient supply of primary batteries has been very difficult. Thus, the military is moving to replace primary batteries with rechargeable ones for certain field applications.

8. CONCLUSIONS

It was decided to base the battery on the commercial cylindrical cells which are stronger, can handle a higher internal pressure and have a lot of built-in safety devices. The 2.2 Ah 18650 is a good, robust cell and is still, for a battery pack, a safer solution than the polymer cells.

It is expected that in the near future the mostly likely energy solutions will be battery/fuel cell hybrids. Fuel cells will probably never replace Li-ion batteries, but will be used mostly for kilowatt requirements.

Li-polymer is only slightly safer than Li-ion, mostly due to the fact that the Li-polymer cells are smaller (have less capacity).

The new Li-ion cells with the phosphate-based cathodes are safer, but this is due to a lower cell voltage. It is also not possible to overcharge these cells which makes them safer in the case where the external electronics have failed. These cells are not yet in full mass production and must still penetrate the market.

At this stage the lifetime of fuel cells is still short (limited cycle life) and they will possibly be used to charge high-capacity batteries.

High charging currents do not make a big difference to charging time. Slower charging will increase the battery lifetime.

The external circuit suggested for the A43 battery will be based on the bq20Z80. The bq20Z80 'gas gauge' technology calculates remaining capacity in lithium-based battery packs with up to 99% accuracy throughout the entire life of a battery. The accuracy and dependability of this system make it a must-have in products that are safety or mission critical.

GAIA manufacture sealed Li-ion cells and batteries. Products include large-format, high-power cells from 5 Ah to 30 Ah, with discharge capabilities to 30C. They develop a high-power 14.4-V lithium-ion battery system that will be used for rapid charging of smaller battery packs in the field and that will itself be capable of recharging quickly from another power supply, such as a vehicle-mounted gas-fuelled generator.

Appendix F Tactical cost models

REPORT: DEF 2004/241 ISSUE NO. 1
"TACTICAL COST - A43 BATTERY SYSTEM "
By DUARTE GONÇALVES NOVEMBER 2004

1. INTRODUCTION

The ultimate objective of this study is to determine the life cycle cost (LCC) of a rechargeable battery system (RBS) for the A43 radio. The LCC of the current PBS (primary battery system) is the baseline. This information is intended to support a decision to move to a RBS. Although LCC is important, effectiveness and risk must also be considered. LCC is determined by both tactical and strategic considerations. In this first phase the tactical considerations are investigated.

2. RECHARGEABLE BATTERY SYSTEM MODELS (RBS)

The RBS models deal with two main aspects: effectiveness and LCC. The measures of effectiveness (MOE) for both the PBS and the RBS are:

- Operational availability of the RBS
- Mass of the batteries carried at section level
- Volume of the batteries carried at section level
- Total mass of the batteries
- Total volume of the batteries carried at section level.

MOEs at section level are important when the soldier is dismounted. Total mass and volume are important for transportation.

The RBS effectiveness model is intended to determine when an operational availability of 100% has been achieved given the number of radios and the operational and logistics scenarios. The problem is complicated by the distributed nature of the system. Operational availability is defined here as being able to provide an operational battery for each radio at given geographic locations for a predetermined period of time. Once the system has been shown to offer the required availability, the LCC can then be calculated. The RBS life cycle is defined using ISO 15288 *System Engineering – System Life Cycle Processes*, as (Figure 6):

- Acquisition/transition: new batteries and battery chargers are acquired and new personnel are trained
- Operate: use the batteries in the radio
- Maintain: charge and repair batteries, repair battery chargers
- Dispose: discard failed batteries.

For the moment the development processes have been excluded from the LCC. The main reason for this is that it would be unfair to include the development costs of the RBS when compared against the PBS which is a mature product system. The four processes identified are the ones that will be carried out by the SANDF. Some additional processes are also required for managing the system.

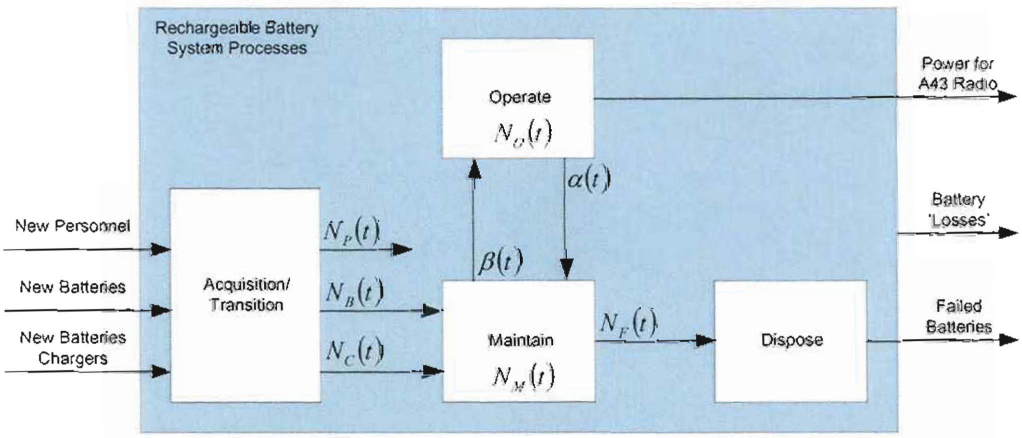

Figure 6: Rechargeable battery system process model

In Figure 6, new personnel enter the system via the transition process in which they are trained. New batteries also enter the system via the transition process for inspection and placement in the maintenance store. The maintenance process interacts with the operate process - flat batteries are charged to render them operational. Flat or partially flat batteries are returned to the maintain process. Occasionally, a battery may fail during operation or maintenance and is sent to the disposal process.

The first step is to relate the battery usage and maintenance rates to the number of operational batteries and the number of batteries to be maintained. This model will be referred to as the RBS rate model. This is followed by the development of usage models which are based on the operational scenarios. Maintenance models support the system level design of the maintenance system. Finally, control and battery acquisition models are considered.

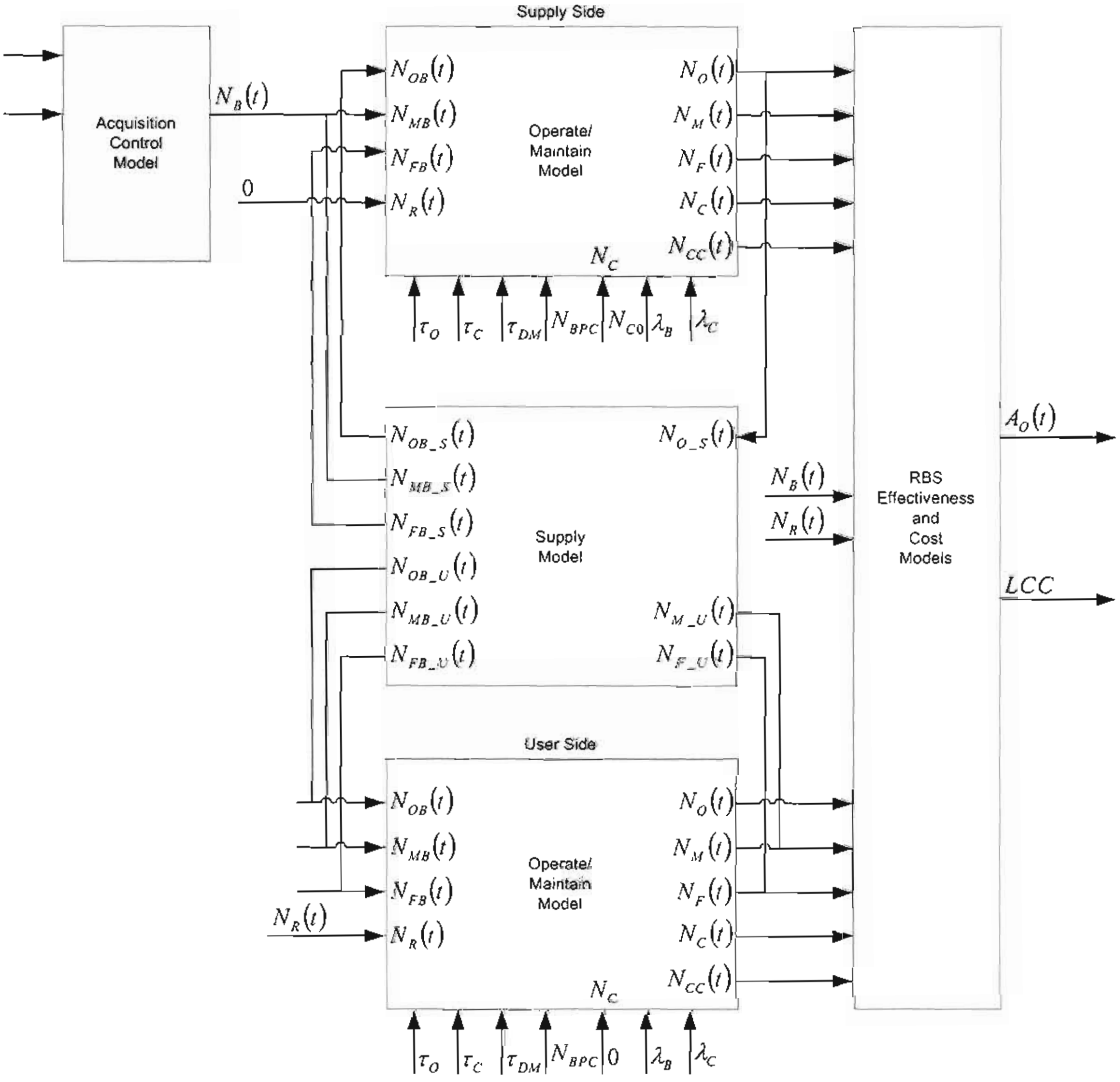

Figure 7: RBS system models

The usage rate and number of radios are external to the RBS. The number of batteries to be acquired and the maintenance rates are the system design parameters.

3. LIST OF SYMBOLS

Table 3: Definition of effectiveness model variables

τ_O	Average operational or usage time per battery for a 1-minute transmit and 29-minute receive cycle on an A43 radio. The battery is assumed to be fully charged initially (h)
τ_C	Average charging time per battery (h)
τ_{DL}	Average logistics delay (h)
τ_{DM}	Average maintenance delay (h)
τ_S	Average replenishment interval (h)
τ_{DL}	Average logistics delay (h)
τ_M	Mission time (h)
τ_{LM}	Average maintenance (labour) time per battery (h)
τ_{LT}	Average training (labour) time per person (h)
τ_R	Average time to repair a battery charger (h)
$N_{OR}(t)$	Number of radios required that are in operation, i.e. have an operating battery
$N_O(t)$	Number of operational batteries
N_{BPC}	The number of batteries that can be charged simultaneously by a battery charger
$N_C(t)$	Instantaneous number of installed battery chargers entering the operate/maintain processes
$N_{CR}(t)$	Number of chargers in for repair
$N_B(t)$	Instantaneous number of new batteries entering the system
$N_C(t)$	Instantaneous number of installed battery chargers entering the operate/maintain processes
$N_P(t)$	Instantaneous number of trained personnel entering the operate/maintain processes
$N_{OB}(t)$	Number of operational batteries entering or leaving the operate process
$N_{MB}(t)$	Number of batteries to be maintained entering or leaving the maintain

	process
$N_{FB}(t)$	Number of failed batteries entering or leaving the maintain process
$N_O(t)$	Number of operational batteries
$N_M(t)$	Number of batteries waiting for maintenance or undergoing maintenance
$N_F(t)$	Instantaneous number of failed batteries
$N_{CCB}(t)$	Number of charge cycles per battery
$N_{CC}(t)$	Total number of charge cycles
$\varepsilon(t)$	The reduction in usage time of a battery
c_{OTL}	The loss in usage time of a battery (per hour)
T_S	Storage time of a primary battery before first use (h)
$\alpha(t)$	Usage rate (batteries/h)
$\beta(t)$	Battery maintenance rate (batteries/h)
$\mu(t)$	Battery charger repair rate (battery chargers/h)
λ_B	Battery instantaneous failure rate (batteries/h)
λ_C	Battery charger instantaneous failure rate (/h)
k	Time in years
C_B	Present cost per rechargeable battery (R)
C_C	Present cost per battery charger (R)
C_T	Present cost of transportation (R)
C_{TV}	Present variable cost of training personnel, not including labour, per person (R)
C_{TF}	Present fixed cost of training personnel (R)
C_{EAC}	Present cost of energy AC (R/(Wh))
C_{EDC}	Present cost of energy DC (R/(Wh))
C_L	Present cost of labour per person per hour (R/h)
C_{PCH}	Present cost of hardware bought over the life cycle (R)
C_{PCE}	Present cost of energy used over the life cycle (R)
C_{PCT}	Present cost of training over the life cycle (R)

C_{PCL}	Present cost of labour over the life cycle (R)
C_{FVH}	Future value of hardware at the end of the life cycle (R)
P_B	Average power dissipated during charging per battery (h)
K_{LC}	Expected life of the system (years)
C_{PLCC}	Annual equivalent life cycle cost (R)
C_{PLCC}	Annual equivalent life cycle cost (R)

4. BATTERY TECHNOLOGY MODEL

A battery model is required for predicting the system effectiveness and LCC. Such a model must provide the following:

- Usage time ('talk time')
- Charge time
- Charge power
- Expected life
- Mass and volume
- Cost.

The usage and charge time are measured in a way that reflects the intended operational scenario.

The battery parameters used in the effectiveness and LCC models are tabulated in Table 3, based on [3]. An alkaline primary battery and a Li-ion battery are considered. The primary battery is the one currently in service and thus forms the baseline. The Li-ion choice is based on a battery technology study [5]. The alkaline batteries are assumed to be new and at full capacity. The usage time is based on measured data with currents representative of those of the A43 radio. This time is based on a 1-minute transmit and 29-minute receive cycle for an A43 radio (discharge at 1 500 mA for 1 minute then at 250 mA for 29 minutes) and is typical of an operational scenario. Additional cost data are available Table 4.

Table 4: Battery parameters

Battery Type	Usage Time (τ_O)	Charge Time (τ_C)	Charge Power	Expected Life (τ_{BL})	Mass	Battery Cost (C_B)
Alkaline battery	7 h	N/A	N/A	3 years ?	980 g	R60
6 Ah Li-ion battery	20 h	6 h	13.2 W	2 years ?	800 g	R2 310

N/A - Not applicable

The battery volume is constrained, and must be less than the A43 radio's battery compartment whose dimensions are 155 mm (L) x 59 mm (W) x 59 mm (H).

It is important to note that the usage time is a function of either storage time in the case of primary batteries or age in the case of rechargeable batteries. The models in Table 5 are proposed for estimating the reduction in usage time, subject to further investigation. The loss factor, c_{OTL}, will be specific to each battery type. For Li-ion batteries, the loss is estimated as $c_{OTL} = 0.2/\tau_{BL}$, based on a 20% loss *in usage time* over the expected life, τ_{BL}.

Determination of the expected life of rechargeable batteries will be based on cost considerations. In order to do this, the reduction in usage time function must be modelled. This can be done by measuring the usage time over a period of years in field trials. Battery reliability is also not well quantified. This is a risk area that needs to be investigated.

Table 5: Models for reduction in usage time

Battery Type	Usage Time Reduction
Alkaline battery	$\varepsilon(T_S) = 1 - c_{OTL}T_S$
Li-Ion battery	$\varepsilon(t) = 1 - c_{OTL}t$

5. USAGE MODEL

The usage rate is dependant on the number of radios, the number of operational batteries and the operating time per battery. The number of required radios that are operating is:

$$N_{OR}(t) = \min(N_O(t), N_R(t))$$

where $N_O(t)$ is the number of operational batteries and $N_R(t)$ is the number of required radios. The usage rate is given by:

$$\alpha(t) = \frac{N_{OR}(t)}{\tau_O}.$$

This means that if there are no operational batteries, then the usage rate is zero. If the usage time τ_O decreases with age then the usage rate is:

$$\alpha(t) = \frac{N_{OR}(t)}{\tau_O \varepsilon(t)}.$$

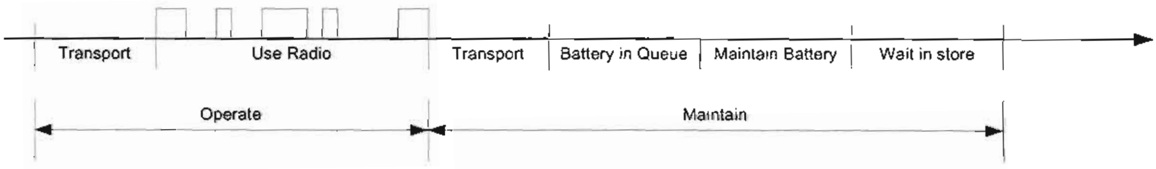

Figure 8: Timeline seen from the point of view of a single battery

6. MAINTENANCE MODEL

Maintenance of the RBS is concerned with three main aspects:

- Supply
- Maintenance of batteries
- Maintenance of battery chargers.

In this section the main concern is the maintenance of batteries. Based on the maintenance concept, battery maintenance is limited to charging and self-test. The reliability requirements of the battery charger are considered briefly here. Two situations are possible at the various maintenance levels:

- no maintenance capability, i.e. the maintenance rate is zero or $\beta(t) = 0$, or

- a charging capability, i.e. the maintenance rate is positive or $\beta(t) > 0$.

The latter case is specifically considered here in more detail.

Each battery charger can charge N_{BPC} batteries simultaneously. Thus, the total number of batteries that can be charged simultaneously is $N_{BPC}N_C(t)$. The time taken for a battery to be charged is τ_C hours. A maintenance delay, which is on average τ_{DM} hours, prevents the start of maintenance or delays batteries becoming available for use. Thus the charging maintenance rate is given by:

$$\beta(t) = \frac{\min(N_{BPC}N_C(t), N_M(t))}{\tau_C + \tau_{DM}}.$$

The first case is where there are more batteries to be maintained than available charging ports. The second is where there are more charging ports than required. If there are no batteries to be charged, then the charging maintenance rate is zero.

Battery chargers will fail at an instantaneous rate of λ_C, assuming a constant failure rate. Since the full maintenance rate requires that all battery chargers be operating, the overall failure rate is $\lambda_C \max(0, N_C(t))$. Thus the rate of change of the number of chargers is:

$$\frac{dN_C(t)}{dt} = \mu(t) - \lambda_C \max(0, N_C(t)),$$

subject to the initial condition $N_C(0) = N_{C0}$. Repair of the battery chargers returns battery chargers to service at a rate of:

$$\mu(t) = \frac{\min(1, N_{CR}(t))}{\tau_R}$$

given that $N_{CR}(t)$ chargers are waiting for repair and this repair takes τ_R hours at a single repair facility. The rate of change of battery chargers waiting for repair is:

$$\frac{dN_{CR}(t)}{dt} = -\frac{dN_C(t)}{dt}.$$

The number of charge cycles per battery for a mission is important for understanding how efficiently each battery is being used. This can be determined from:

$$N_{CCB} = \frac{\tau_M}{2\tau_S}.$$

Energy and labour costs are driven by the number of charge cycles per mission, given by:

$$N_{CC} \approx \frac{N_R \tau_M}{\tau_O \varepsilon(\tau_M)}.$$

These two formulas are average values.

7. SUPPLY MODEL

Batteries are assigned at section, platoon and company level. At the user level, flat or failed batteries are exchanged for operational batteries from the intermediate and supply levels. At the supply level, the number of operational batteries is reduced while the number of flat or failed batteries increases when such an exchange takes place. This is based on the maintenance concept as indicated in Table 1. A tactical model is presented here which is used for mission planning in the simulation. This closed form model must be consistent with the rate model presented in the following section.

Each level of the structure (section, platoon, etc.) has a total number of batteries, N_{BA}, assigned or allocated, for a mission with a replenishment interval of τ_S. This is the maximum number of batteries that can be exchanged. The battery allocation is done at the start of a mission or at any time that certain mission parameters change. If the average replenishment interval is much larger than the average logistics delay, i.e. $\tau_S >> \tau_{DL}$, then the number of allocated batteries can be estimated from:

$$N_{BA} \approx N_R\left(\frac{\tau_S}{\tau_O\varepsilon(\tau_M)} + \tau_S\lambda_B + 1\right).$$

The first term is related to the number of batteries required until the next replenishment. The second term is the expected number of battery failures. If the battery failure rate is low or there is a small number of radios, then this term can be omitted. The last term is required so that every radio has a battery installed while it is being replenished.

Assume the battery life is τ_{BL} hours. For primary batteries this relates to storage time. All batteries are replaced every τ_{BL} hours. Extra batteries must be included for failures, loss of usage time and losses. The mission time is τ_M hours. At this time the mission time must be less than the expected battery life. This is a limitation of the current model but it is easily extended.

Approximately N_{BA} batteries are being maintained. The total number of rechargeable batteries required for a mission is approximately:

$$N_{B0} \approx 2N_R\frac{\tau_S}{\tau_O\varepsilon(\tau_M)} + N_R + N_{BPC}N_C + N_R\lambda_B\tau_M + \text{losses.}$$

Fundamentally, the maximum maintenance rate must be greater than the maximum usage rate or $\beta(t) > \alpha(t)$. Under maximum rate conditions, this can be written as:

$$\frac{N_{BPC}N_C}{\tau_C + \tau_{DM}} > \frac{N_R}{\tau_O\varepsilon(\tau_M)}.$$

Solving for the number of chargers results in:

$$N_C > \frac{N_R(\tau_C + \tau_{DM})}{N_{BPC}\tau_O\varepsilon(\tau_M)}.$$

This relation provides important insight into the problem. Firstly, but not surprisingly, the number of chargers is proportional to the number of radios required. Secondly, the ratio of the charge time and the operating time is the leveraged advantage that translates into a cost saving.

Finally, the more batteries that can be charged per charger, the fewer chargers are required. However, this does not necessarily result in a saving because if one charger fails then N_{BPC} more charging capacity is lost.

8. RBS RATE MODEL

The RBS rate model relates the battery usage and maintenance rates to the number of operational batteries and the number of batteries to be maintained. This model includes the acquisition of new batteries and their failure rate. Quantities required for the LCC analysis, such as the number of charge cycles, are also determined.

In this model the following assumptions or observations have been made:

- the radio operator cannot distinguish between flat batteries and failed batteries
- failed batteries are detected as part of the maintenance process
- the batteries have a constant failure rate
- only operating batteries fail.

One rate model at the user level and one rate model at intermediate/supply level, each with its own states, interacts via the supply model (Figure 7).

The rate at which batteries become operational is equal to the difference between the rate at which batteries are maintained and the rate at which batteries are used. Additionally, $N_{OB}(t)$ batteries can be added or removed from the process. Thus, the 'operate process' differential equation is:

$$\frac{dN_O(t)}{dt} = N_{OB}(t) - \alpha(t) + \beta(t).$$

The 'maintain process' differential equation is

$$\frac{dN_M(t)}{dt} = N_{MB}(t) + \alpha(t) - \beta(t) - \lambda_B N_{OR}(t)$$

where $N_{MB}(t)$ batteries enter the process. The batteries are assumed to have a constant instantaneous failure rate of λ_B. The reliability of the batteries operating in the radios is a series network since the radios form a geographically distributed network. Thus the resulting instantaneous failure rate is $\lambda_B N_{OR}(t)$. The model proposed here is a continuous one and is an approximation since $N_O(t)$ and $N_M(t)$ are positive integers.

The RBS is available if and only if there is an operational battery in every radio or $N_O(t) \geq N_R(t)$ for a given geographical area. Thus, if all $N_R(t)$ radios are operating, 100% availability is achieved. If there are not enough operational batteries for all the radios, then the number of operating radios is $N_O(t)$. A necessary condition for 100% operational availability is that the expected maintenance rate must be greater than the expected usage rate, i.e. $E\{\beta(t)\} > E\{\alpha(t)\}$.

The number of charge cycles during year k, a quantity which will be used in the LCC analysis, is defined as:

$$N_{CCk} = \int_{24\cdot 365(k-1)}^{24\cdot 365k} \beta(t)dt$$

where subscript k is used to indicate the value of a quantity for one specific year. This will include any cycles required for bulk recharging. Similarly, the number of new batteries entering the system during year k is given by:

$$N_{Bk} = \int_{24\cdot 365(k-1)}^{24\cdot 365k} N_B(t)dt\,,$$

and the number of failed batteries during year k is:

$$N_{Fk} = \int_{24\cdot365(k-1)}^{24\cdot365k} \lambda_B N_{OK}(t) + N_{FB}(t)dt \, .$$

Any initial values of a quantity will be defined as $k = 0$, for example, the number of batteries in the system when it starts operating would be N_{B0}. The initial conditions for the state variables are:

$N_M(0) = N_B(0) = N_{B0}$,
$N_{CC}(0) = N_{CC0} = 0$,
$N_O(0) = N_{O0} = 0$, and,
$N_F(0) = N_{F0} = 0$.

9. BATTERY ACQUISITION CONTROL MODEL

All batteries will be replaced after a period of τ_{BL} hours, as determined by effectiveness and cost considerations. This may happen several times over the RBS life cycle. The RBS system must have sufficient batteries to last the battery life cycle without acquiring any new batteries. This means that ideally we should have sufficient batteries to cover battery failures, capacity reduction and other losses.

10. COST MODEL

The LCC is simply all costs associated with either the PBS or the RBS over the life cycle. The cost breakdown structures for the PBS, as a mature product, and the RBS are shown in Figure 9 and Figure 10 respectively. The development process has been excluded from the RBS LCC. The main reason for this is that it would be unfair to include the development costs of the RBS when compared against the PBS which is a mature product. The two cost breakdown structures presented here are not complete, but represent major sources of cost.

Initially, costs are only calculated over the expected life of a rechargeable battery, as opposed to the RBS life cycle. For this reason the model is referred to as a cost model and not a 'life cycle cost' model. This model is more tactical in nature. For a LCC model, a strategic model is also required.

In the previous section, models for system parameters that influence system LCC, such as:

- number of batteries
- number of battery chargers
- number of charge cycles
- number of failures and repairs
- the amount of labour time required to charge and repair batteries

were established subject to the system effectiveness requirement. With these models in place, the LCC can now be considered.

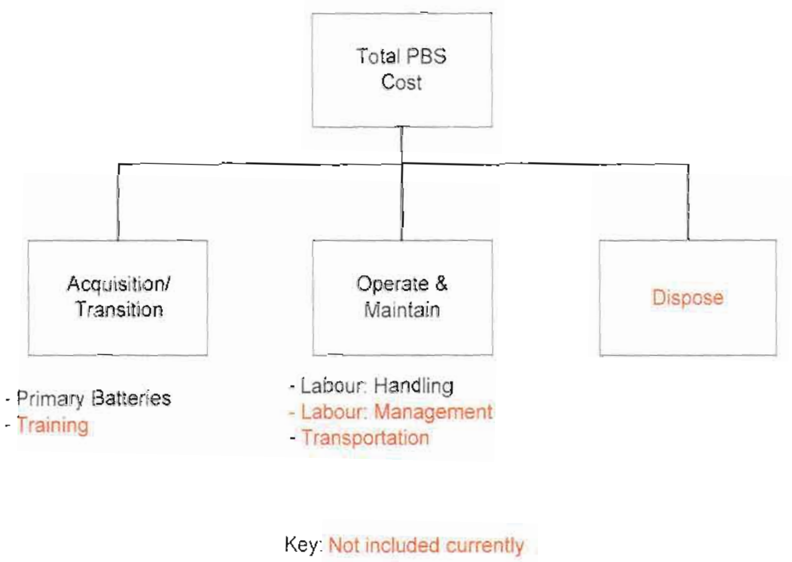

Figure 9: PBS cost breakdown structure

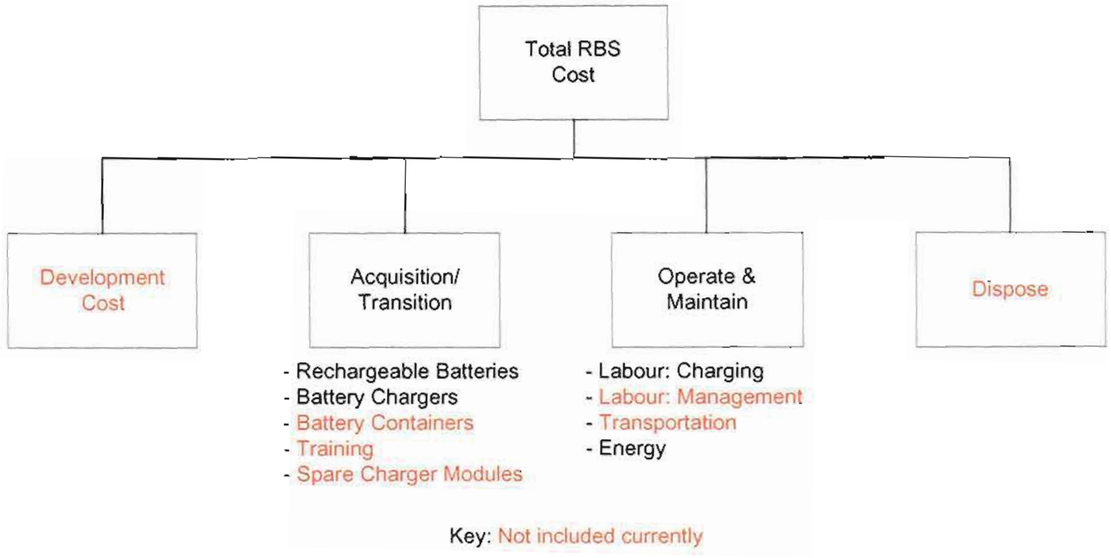

Figure 10: RBS cost breakdown structure

The cost model consists of the following components:

- the present cost of hardware acquired over the life cycle, including batteries:

$$C_{PCH} = \sum_{k=0}^{K_{LC}} \left(C_B N_{Bk} + C_C N_{Ck} \right)$$

- the present cost of labour over the life cycle:

$$C_{PCL} = \sum_{k=0}^{K_{LC}} C_L N_{CCk} \tau_{LM}$$

  The labour time for charging is proportional to the maintenance time and the number of charge cycles. (Additional labour costs to be considered are acquisition, management and store labour costs.)

- the present cost of energy consumed over the life cycle:

$$C_{PCE} = \sum_{k=0}^{K_{LC}} C_E N_{CCk} \tau_C P_B$$

The energy cost is proportional to the charge time, the number of charge cycles and the average power dissipated by the charger for a given charge mode. The actual cost will depend on the proportion of AC or DC power that is used.

- the present cost of training:

$$C_{PCT} = \sum_{k=0}^{K_{LC}} \left(C_{TV} + C_L \right) N_{Pk} + C_{TF}$$

The fixed costs are related to creating training material and facilities and are assumed to occur only once:

- present cost of transportation, C_T
- present cost of disposal, C_D.

The cost of facilities is ignored. These exist and are used for purposes other than just the RBS/PBS. The equipment is not insured.

The transportation distances are obtained from the operational scenarios. The cost of spare battery charger modules and test equipment has not yet been included. This requires an analysis of the failure modes and an estimate of the repairable percentage of failed chargers. This information is not currently available.

The present cost of operating the RBS, taking into account the present costs described above, is:

$$C_{PLCC} = C_{PCH} + C_{PCE} + C_{PCT} + C_{PCL} + C_T + C_D \ .$$

This assumes that the value of the hardware at the end of the life cycle is zero.

11. RESULTS

Results for the PBS and RBS are presented for a two-year mission period which corresponds to the battery life of a rechargeable battery. The number of radios considered is as follows:

- 1 Battalion or 75 A43 radios – graphs and table
- 1 250 deployable A43 radios* – tables only.

In all cases the number of batteries and number of battery chargers was chosen to provide 100% operational availability. It should be remembered that with short replenishment intervals, operational availability is sensitive to logistics delays. Calculations are based on 24-hour operation and maintenance. A 20% loss of usage time was taken into account. Thus these results represent worst case costs, but do not include 'losses'.

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* The SANDF has around 2500 serviceable A43 radios. Of these M.H. believes that 1 250 might be deployed simultaneously.

From Figure 9 it is clear that the number of batteries required for the mission is not a function of replenishment interval for the PBS. Even at a 14-day replenishment interval, the RBS still requires less than a tenth of the batteries. The number of batteries required at section level (Figure 10) for the RBS is about half that required for the PBS. This is in the ratio of usage time of rechargeable batteries (including loss in usage time) to usage time of primary batteries.

Figure 11 is important for understanding why the RBS is more cost effective for shorter replenishment intervals. The number of charge cycles per battery is inversely proportional to the replenishment interval. Thus for the same mission time, fewer batteries are required, but they are charged more frequently. The *total* number of charge cycles is constant over the replenishment interval.

Figures 15, 16, 17 and 18 illustrate graphically the mass and volume both at section level and for the mission. The RBS mass and volume are lower by a factor of over 50. This will result in significant transportation cost savings.

Total cost of the PBS is not a function of the replenishment interval (Figure 19). For the RBS, the cost is proportional to the replenishment interval, but about 75% that of the PBS in the worst case. For short replenishment intervals, the cost savings can be a phenomenal factor of 7!

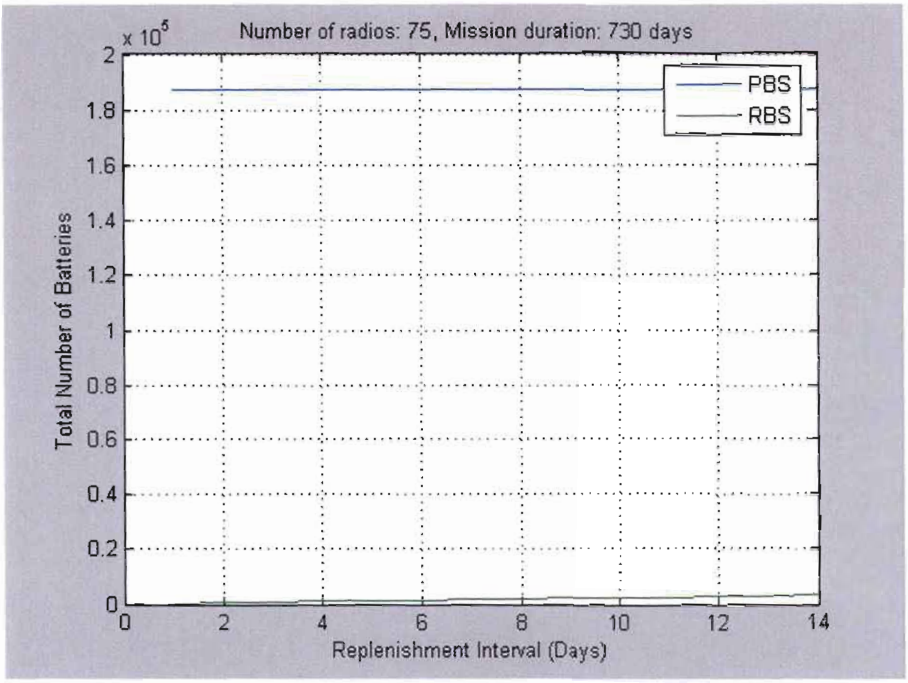

Figure 11: Total number of batteries vs. replenishment interval

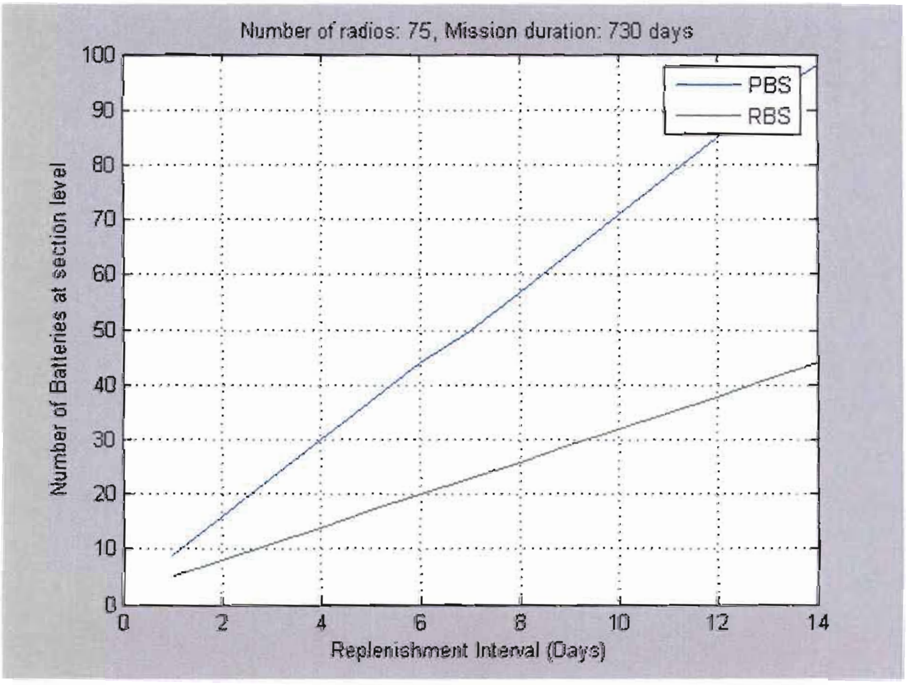

Figure 12: Number of batteries at section level vs. replenishment interval

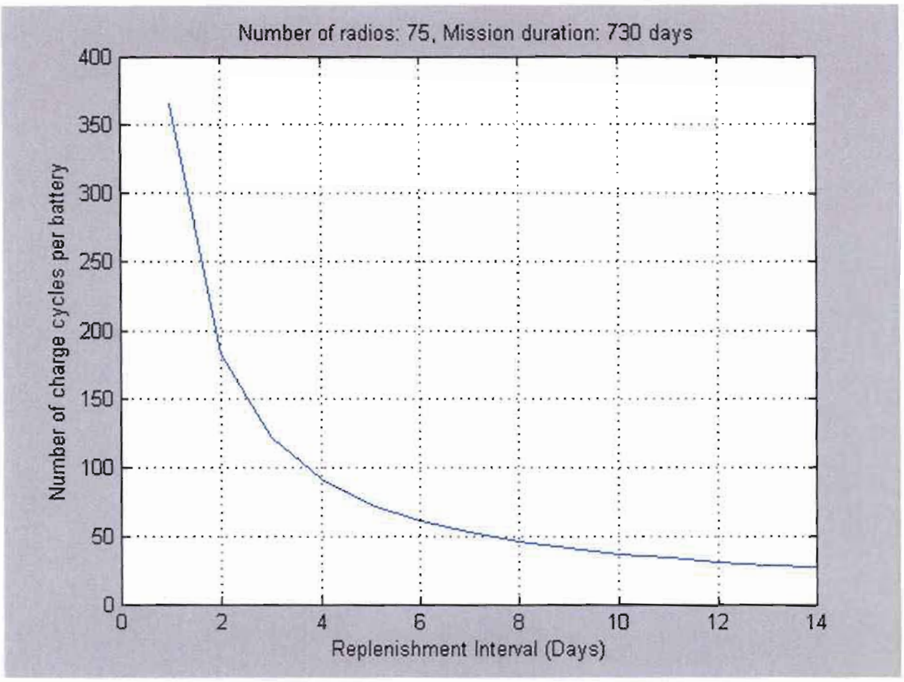

Figure 13: Number of charge cycles vs. replenishment interval

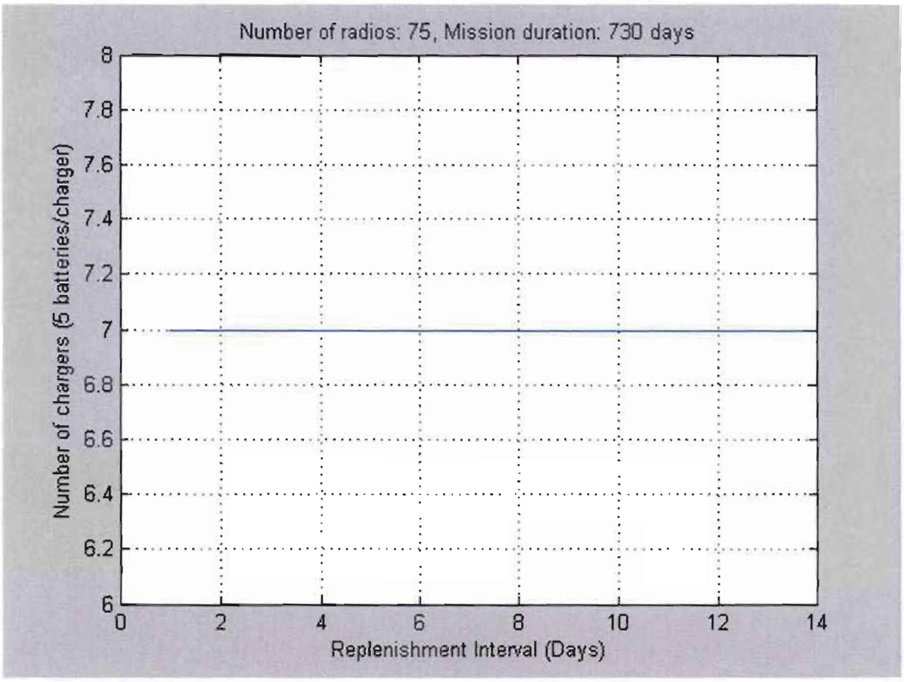

Figure 14: Number of battery chargers vs. replenishment interval

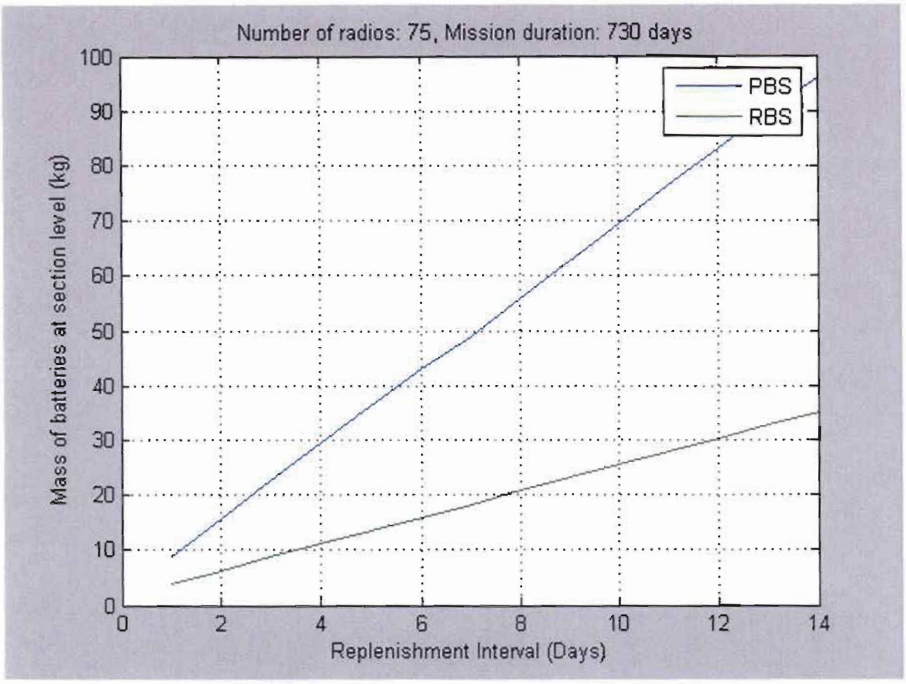

Figure 15: Mass of batteries at section level vs. replenishment interval

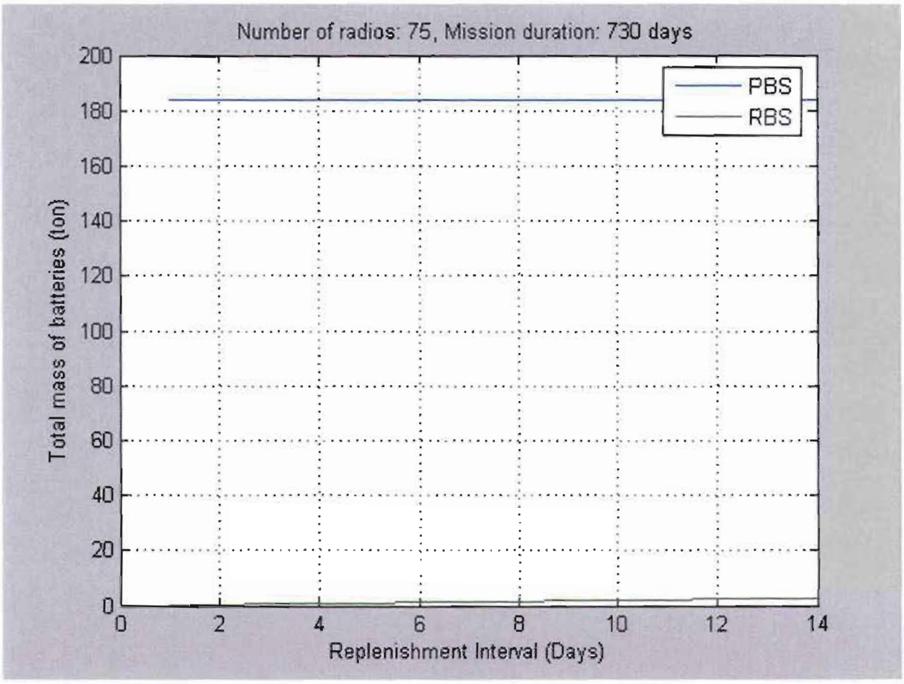

Figure 16: Total mass of batteries vs. replenishment interval

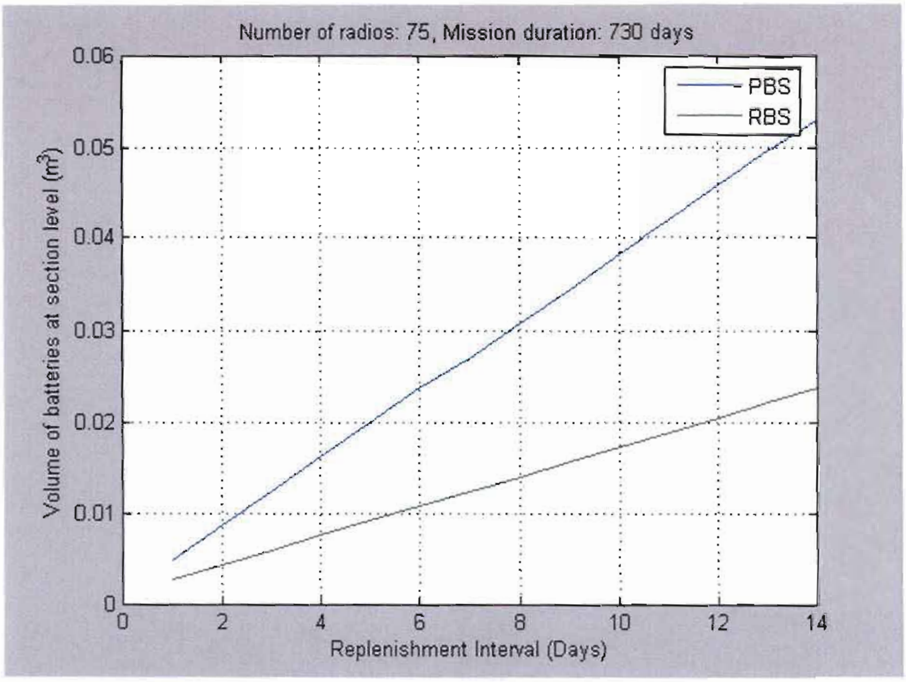

Figure 17: Volume of batteries at section level vs. replenishment interval

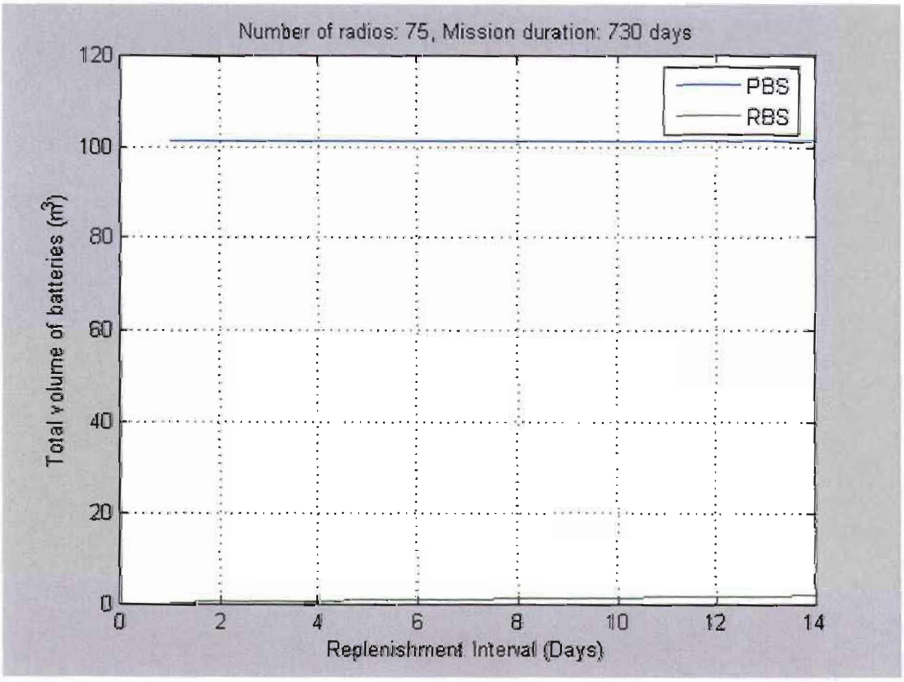

Figure 18: Total volume of batteries vs. replenishment interval

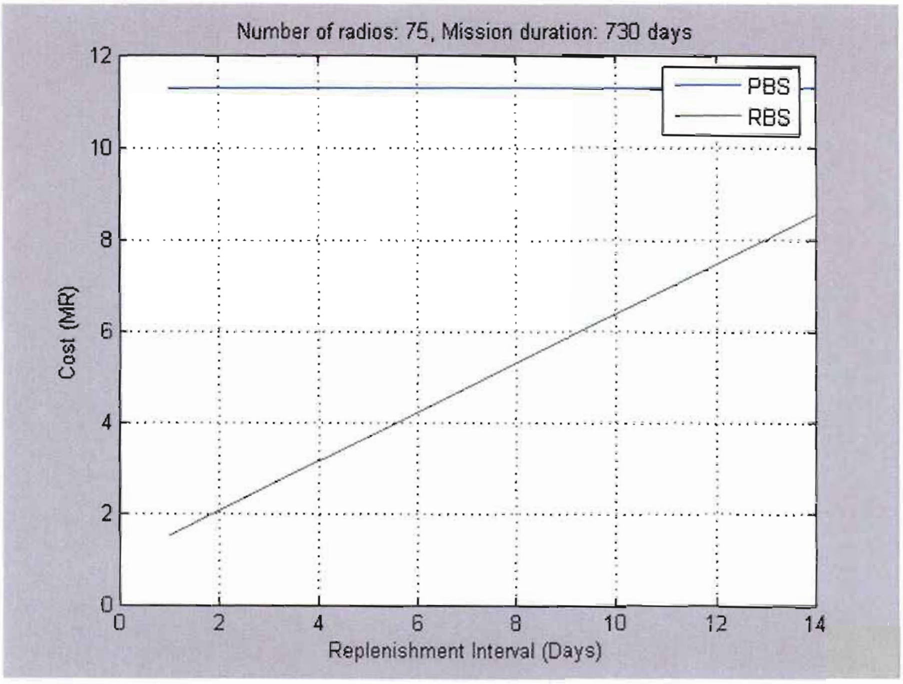

Figure 19: Total cost of batteries vs. replenishment interval

Table 6: PBS and RBS performance for 75 A43 radios over 730 days

Battery Type	Parameter	Replenishment Interval (days)		
		1	**7**	**14**
PBS	Number of batteries	187 715	187 715	187 715
	Mass of batteries - section level (kg)	8.8	49.0	96.0
	Mass of batteries - mission (t)	184	184	184
	Volume of batteries - section level (m^3)	0.005	0.027	0.053
	Volume of batteries - mission (m^3)	101.3	101.3	101.3
	Present labour cost (kR)	10.0	10.0	10.0
	Total present cost (MR)	11.27	11.27	11.27
RBS	Number of batteries	476	1 880	3 518
	Number of chargers	7	7	7
	Number of charge cycles/battery	365	53	27
	Mass of batteries - section level (kg)	4.0	18.4	35.2
	Mass of batteries - mission (kg)	381	1504	2814
	Volume of batteries - section level (m^3)	0.003	0.012	0.024
	Volume of batteries - mission (m^3)	0.3	1.0	1.9
	Present labour cost (kR)	219.0	219.0	219.0
	Present energy cost (kR)	22.5	22.5	22.5
	Total present cost (MR)	1.52	4.76	8.54

Table 7: PBS and RBS performance for 1 250 A43 radios over 730 days

Battery Type	Parameter	Replenishment Interval (days)		
		1	7	14
PBS	Number of batteries	3 128 572	3 128 572	3 128 572
	Mass of batteries - section level (kg)	8.8	49.0	96.0
	Mass of batteries - mission (t)	3066	3066	3066
	Volume of batteries - section level (m^3)	0.005	0.027	0.053
	Volume of batteries - mission (m^3)	1 688.0	1 688.0	1 688.0
	Present labour cost (kR)	166.9	166.9	166.9
	Total present cost (MR)	187.88	187.88	187.88
RBS	Number of batteries	7 825	31 225	58 525
	Number of chargers	97	97	97
	Number of charge cycles/battery	365	53	27
	Mass of batteries - section level (kg)	4.0	18.4	35.2
	Mass of batteries - mission (kg)	6 260	24 980	46 820
	Volume of batteries - section level (m^3)	0.003	0.012	0.024
	Volume of batteries - mission (m^3)	4.2	16.8	31.6
	Present labour cost (kR)	3650.0	3650.0	3650.0
	Present energy cost (kR)	375.8	375.8	375.8
	Total present cost (MR)	24.53	78.58	141.64

12. CONCLUSIONS AND RECOMMENDATIONS

The RBS is *always* more effective in terms of mass and volume than the PBS. The RBS is more cost efficient than the PBS under the conditions considered. The RBS becomes less and less cost efficient with increasing replenishment interval. From the significant reduction in both mass and volume, it is clear that transport cost will be dramatically reduced for the RBS. The energy cost for the RBS is negligible in terms of the total cost.

Indications are that the RBS will be well suited to peace-support type of missions, specifically peace keeping (external scenario). The environmental issues, however, are very challenging.

In this report only one maintenance concept has been evaluated. The maintenance concept presented is not necessarily the best concept. The following alternative or expanded maintenance concepts might be considered:

- **Allow charging at company level** – Charging at company level would reduce the number of batteries required. However, vehicles or generators would have to run continuously which might compromise location unless acoustic or thermal signatures are not suppressed.
- **Phased replenishment** – Since the army structure is grouped in threes, the replenishment interval could be divided into three. Replenishment at a certain level (e.g. company level) would be done in three phases.
- **Hybrid concept** – Use a combination of primary and rechargeable battery technologies since each has certain strengths.
- **Alternative technology** – Alternative technologies could be used with the current option or any of the above alternatives.

Additionally there are new Li-ion batteries appearing on the market (Table 8) which could increase usage time. These present an opportunity to reduce mass and volume even further.

In order to reduce risk it is recommended that the batteries under consideration be evaluated in terms of reliability and expected life (time for the battery to lose, say, 20% of its usage time). Allowing for greater loss in usage time does not necessarily reduce costs.

In fact, trying to prolong the use of batteries beyond a certain point requires not only additional batteries, but also additional chargers. For a given replenishment interval, more batteries are required because of the reduced usage time obtained from each battery. The usage rate goes up. So too must the charging rate go up. It is clear that the maximum permissible usage time loss must be chosen in a way that minimises cost. This requires additional investigation.

The loss in usage or talk time must be addressed in training. Radio operators and planners must be sensitive to the age of the battery.

The tactical models developed here can be used for mission planning. Given the number of radios required for a mission, the replenishment interval and battery-related information, and the minimum number of batteries and battery chargers can be determined. These models can be developed as a stand-alone application with an appropriate user interface.

This report may have answered many questions relating to the tactical use of the RBS (Figure 20). However, there are a number of strategic questions which remain. It is not cost effective to plan for the worst case of a 14-day replenishment interval. In practice, the replenishment interval varies with operating scenario. Also, the system is not always operating 24 hours/day. The acquisition of the batteries must also be considered. This needs to be done in a way that minimises cash flow. A strategic model, of a probabilistic nature, must be developed to determine the expected number of batteries and battery chargers required over the life cycle. This means that fewer batteries and battery chargers than presented here may be required. This will require a change in approach from a consumables-based PBS to a fixed-equipment RBS.

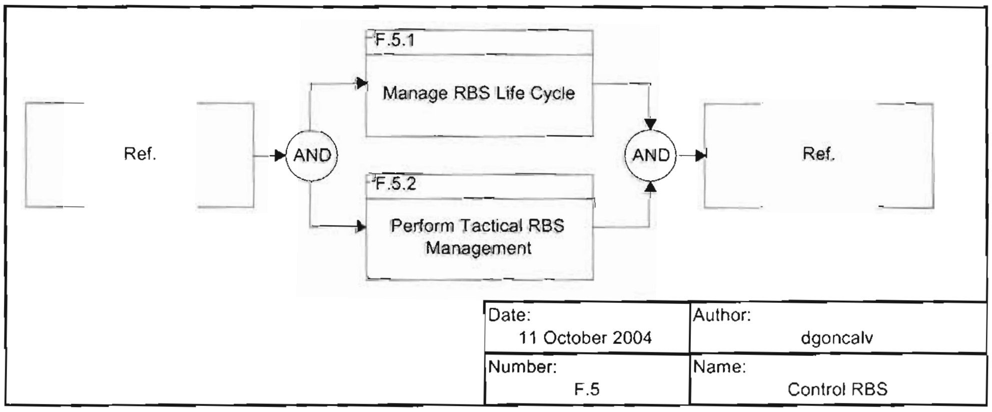

Figure 20: Tactical and life cycle management functions required for RBS

The issue of robustness of the RBS tactical and strategic cost models must be considered. At this stage the cost is not known with certainty. Under certain conditions the system may be very sensitive to variations in certain parameters. Replenishment intervals are never precise in practice.

In fact, there is uncertainty in almost every parameter. The impact of this sensitivity and uncertainty on operational availability and cost must be investigated. For example, it is already apparent that the RBS may be sensitive to battery cost when the replenishment interval is long. Thus even small variations in battery cost could cause a significant variation in total cost.

The stakeholder requirements definition and the system level design ('A' spec) must be captured in individual documents and maintained. Many of the models presented here are relevant to the system level design. Some original requirements, namely functional, physical and interface requirements, have already been captured in CORE, a system engineering tool. It is recommended that this be the sole database for the project. All the required documents can be generated from this database, which will eliminate the problem of inconsistent updating across documents.

13. REFERENCES

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[2] ISO/IEC 15288:2002(E). *Systems engineering – System life cycle processes*, 2002.

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[4] Young, R. M. *Project Warrior: Power Supply and Management Requirements.* ARMSCOR, 05780-100-002, Issue A, 27 May 2003.