Empirical survey of the application of commercial-graded Lithium Polymer batteries in military systems in conjunction with solar panels and fuel cells

A. Roux[a], A. Giesler, D. de Villiers

Council for Scientific and Industrial Research,
John Costas Street, Stellenbosch, South Africa

ABSTRACT

This paper presents the results of an empirical survey into the comparative characteristics of commercial NiCd, Lithium-ion and Lithium Polymer batteries when applied in a range of man portable military radios. The focus is on when the expected load currents varies significantly across the battery's cycle. The study also considers the use of solar panels and fuel cells for in-field battery replenishment. Limited environmental (temperature) stress screening was performed. Several pros and cons will be discussed, but in general the commercial product stood up well in the warmer climates and (being commercial products) with a good cost to performance ratio.

Keywords: Lithium Polymer batteries, Li-ion batteries, NiCd batteries, military application, battery capacity, battery internal resistance, environmental stress tests

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[a] Corresponding author. Tel: +27 21 8876905; Fax: +27 21 886 5055.
E-mail address: aroux@csir.co.za

LEGEND OF ABBREVIATIONS AND ACRONYMS

A	Unit of electrical current = Ampere	mAh	Milli-ampere-hours
A/D	Analogue to Digital conversion	mm	Unit of length = millimetres
A-h	Unit of capacity = Ampere-hours	ms	Unit of time = milliseconds
CSIR	Council for Scientific and Industrial Research	NiCd	Nickel Cadmium
DC	Direct Current	NiMH	Nickel Metal-hydride
FET	Field-effect Transistor	MIL-STD	Military Standard
gm	Unit of mass (gram)	PCB	Printed Circuit Board
GPS	Global Positioning System	RF	Radio Frequency
IC	Integrated Circuit	s	Unit of time = seconds
kg	Unit of mass = kilogram	SM	Surface Mounted (components)
LED	Light Emitting Diode	UUT	Unit Under Test
Li-ion	Lithium Ion		*Greek Letters*
LiPo	Lithium Polymer	°C	Unit of temperature = Degrees C
m	Unit of length = meters	Ω	Unit of resistance = Ohm
mA	Unit of electrical current = Milli-ampere	µs	Unit of time = micro-seconds

1. Introduction

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 [1].

In developing countries it is often required to apply commercial grade components in military systems. This is usually not done as a standard procedure and normally before any such decision is made, extensive tests are performed to qualify the components to be applied in the military systems against military standards, especially with respect to the determination of how well the components stand up against environmental stress.

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]. Figure 1 depicts the typical battery management system of the dismounted soldier (drawing courtesy of Smart Fuel Cells). A soldier would make use of various sources (whichever are available in the operational area – see left hand side of the diagram) to power the equipment (on the right hand side of the diagram). The equipment may directly be powered by the Power Manager, or the equipment batteries may be charged by the power manager using a suitable power source. The boundaries of this study were determined by the search for a battery to serve in position "A" in Figure 1.

Batteries are more often than not a life line for the dismounted soldier, and therefore much attention is given to manage the power of all man-carried equipment, such as GPS, Communications, Situational Awareness Computers, torches, magnified sights, etc. Obviously the soldier would require the portable equipment to be as user-friendly as possible, including its size and weight ("as small as possible and as light as possible"). The most critical new developments are power supply systems. The requirement is to allow the new electronics-based equipment to function effectively for missions up to 72 hours [1], and therefore the military operators want to reduce the weight by a factor of five [4]. Extensive research is therefore being performed world wide to optimise battery and power management systems.

The emerging technologies for batteries seem to be concentrated around the Lithium family, even in the motor car industry as propulsion batteries. In particular, the Lithium Polymer (LiPo) technology is very popular with hobbyists in propulsion systems of model aircraft, cars and boats. The LiPo batteries in conjunction with the new technology brushless DC motors have, in most cases, replaced the ethanol-fuelled or diesel-fuelled main propulsion systems of these models due to its more favourable size and weight for these applications. Buchman [2] stated that the NiMH technology (authors also assume that it included NiCd) was an interim step to Lithium battery technology.

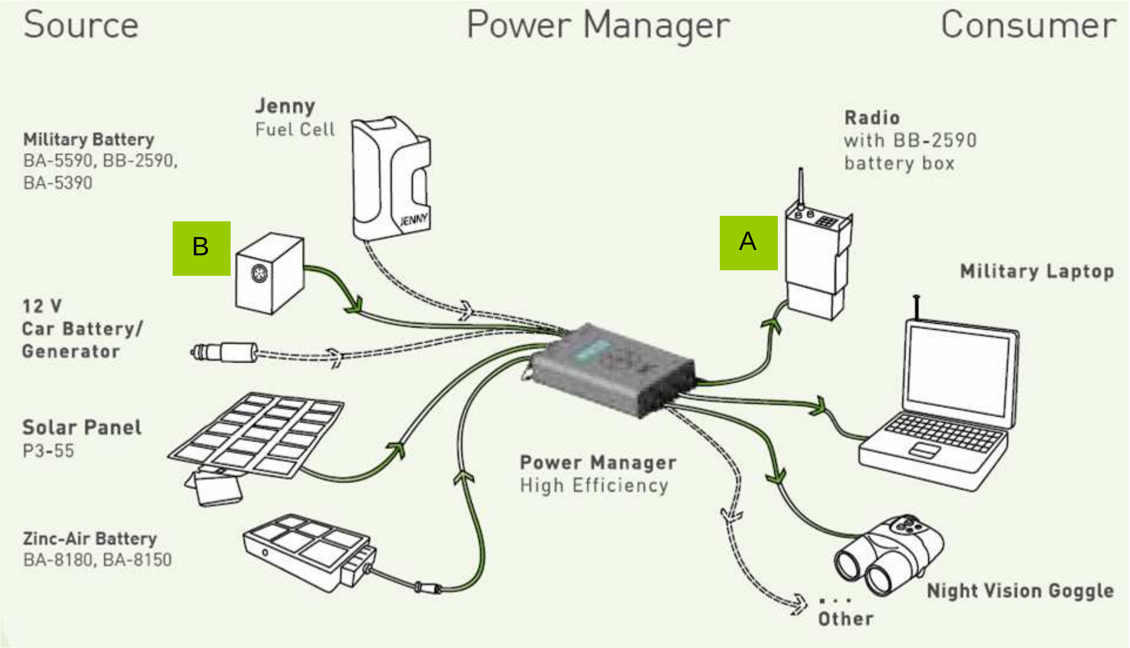

Figure 1: **The Battery Management System of a dismounted soldier, drawing courtesy of SFC**

A LiPo battery employs a thin profile which is a major advantage for Li-polymer cells. The soldier can benefit from Li-polymer mostly when looking at handheld electronic devices and requirements which need very flat form factors. Recent improvements in Li-polymer cells have expanded their reach to military applications. The energy density is rising and may soon exceed that of other Li-ion cells [9].

A LiPo battery was therefore chosen for an experiment to determine its characteristics in a military communications radio[2] (in position “A” in Figure 1) under certain environmental stress conditions. The specific radio has a battery with relatively high capacity, and it is therefore also considered for the battery in position “B” in Figure 1. The one battery would then act as a backup of the other.

The experiment also investigates the success of using solar panels and fuel cells as back-up to its normal charging sources, as shown on the left hand side of Figure 1.

2. Definitions

2.1. Definition of “C”

“C” is an indication of a charge or a discharge current relative to the manufacturer rated[3] Ampere-hour capacity of the battery.

For example, if the manufacturer rated the battery capacity at 2 A-h (or 2000 mAh), then a charge or a discharge current of “1 C”, is 2 A, and “½ C” would be 1 A, etc.

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[2] No specific radio was used, but common characteristics of similar radios were used to determine discharge currents. The physical battery pack of an older generation radio was used to house the battery. The model of this radio is not mentioned and is not relevant to the study.

[3] The manufacturer rates its products according to a specific (usually small) discharge current. It should be understood that this capacity is not valid at all the possible discharge rates, and it is advised to measure the capacity at the usage current if the capacity plays a role in the application.

2.2. Definition of Coulomb-metric Efficiency

Coulomb-metric efficiency is the efficiency with which a battery is charged, by calculation of the ratio of Coulombs stored in the battery to the Coulombs applied via a power source during a charging process.

3. Experimental Procedure

3.1. General

An older generation two-way radio was obtained as a “control” radio. This radio was specifically chosen to determine the dynamics of the load according to which the batteries would be tested. This radio draws a low receiver current of 200 mA, and a high transmitter current of 3.7 A. To complicate the problem, the transmitter output power was dependent upon the battery voltage in a linear relationship described by Equation 1.

$$Power = 0.96x\Big|_{19V}^{25V} - 10.16 \qquad \boxed{\text{Where x is the Battery Voltage}} \tag{1}$$

The radio-battery technology was NiCd using 19 serial cells with (manufacturer specified) capacity of 2800 mAh to produce voltages between 19 V and 25 V. A new pack was assembled specifically for the purposes of this study (see Figure 2) as a “control” battery.

Figure 2: A new NiCd battery pack assembled for this study

This study considered replacing the NiCd battery with a (hobbyist) commercial (manufacturer specified) 4900 mAh 6-cell LiPo battery (see Figure 5). The high-current capability of this battery was manufacturer-rated to be 20 C continuously. A commercial hobbyist intelligent charger and cell balancer was used for charging this battery.

This LiPo battery was empirically compared with a similar standard military Li-ion battery. The latter battery was used in communications equipment of similar function, as well as other applications. The comparative tests were designed to use equivalent programs according to the manufacturer-rated capacity, and voltage. The discharge program was adjusted according to both “C” and voltage to accommodate these differences and to produce a comparative result.

In general, the discharge set-up was constructed according to Figure 3.

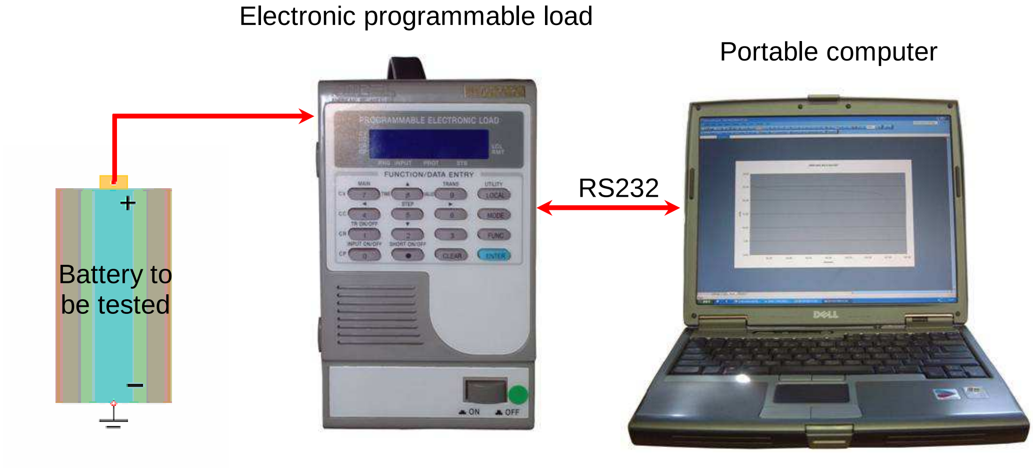

Figure 3: The discharge set-up for all batteries

The amount of energy that can be supplied by a given battery varies significantly, depending on how the energy is drawn [5]. This study examines the battery performance by application of a typical radio load which is pulsed between the low receiver current and the high transmitter current.

The pulsed load model as shown in Figure 4 was used. Both the LiPo and the NiCd were pulsed between 0.2 A and 3.7 A, because the intention was to directly replace the NiCd battery with the LiPo battery. However, to compare the results fairly with the Li-ion technology, the load currents of the Li-ion battery was reduced in accordance with its rated (4 A-h) capacity value, which presents a ratio reduction of 4 : 4.9. The receiver current for the Li-ion battery was therefore set at 0.16 A, whilst the transmit current was set at 3.0 A. The rationale for this reduction was based on the fact that a more suitable Li-ion battery (with capacity upgraded to 4900 mAh) could be obtained on special order. A Li-ion battery of capacity 4900 mAh was not readily available for this study. The results are therefore scaled accordingly to ensure a fair comparison.

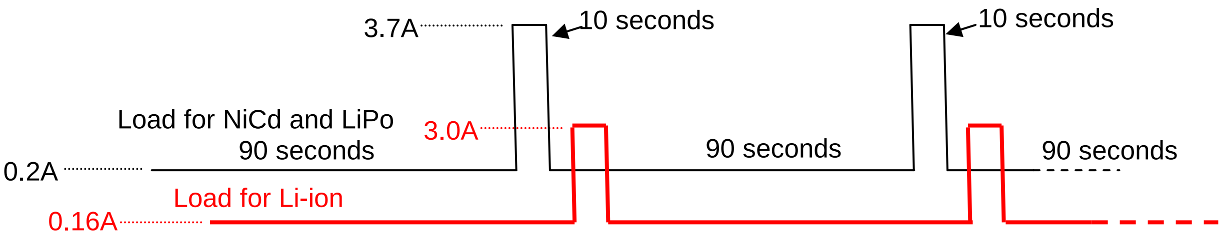

Figure 4: Pulsed load model that was used for the different batteries

It was assumed that for every 10 seconds the radio-operator would transmit, he would be in a receive-mode for 90 seconds. This is a 1 : 9 transmit-receive ratio, according to which the discharge current was programmed.

It is generally known that limitations are placed on the temperature environment when using Lithium batteries. The operational temperature is specified between -20 °C and +60 °C. Charging below 0 °C or above 60°C is not recommended [10]. It was consequently important to characterise the batteries at various temperatures. As a result, the general characteristics of the battery were established first at room temperature, and then at low and high temperatures, making use of the transmitter and receiver discharge currents as depicted in Figure 4.

3.2. Introduction of the technologies that are compared in this study

3.2.1. The LiPo battery

The LiPo battery that was chosen for this study is shown in Figure 5. The six different cells can be seen as they are packed in slices next to each other.

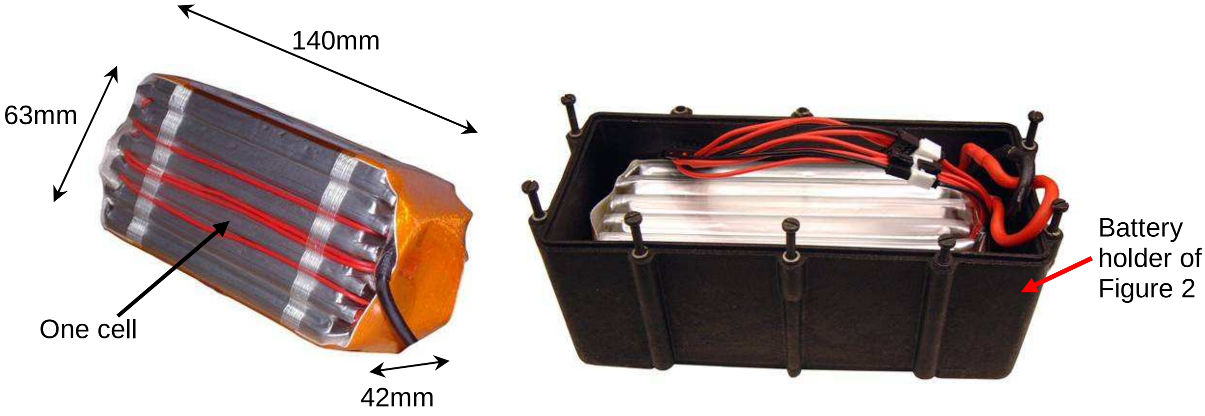

Figure 5: The LiPo battery, showing the reduced size (space in packaging) as compared to the original NiCd battery shown in Figure 2

Hoffart [7] states that Lithium batteries contain no Lithium in a metallic state, but instead use Lithium ions that shuttle back and forth between the cathode and anode of the battery during charge and discharge. The Lithium Cobalt chemistry (relating to the cathode material) has become more popular in laptops, cameras and cell phones mainly because of its greater charge capacity. However, he [7] emphasises that the Li-ion battery technology is not yet mature, and strides are being made towards greater capacities and improved performance. The LiPo battery is a Li-ion battery which uses a solid ion conductive polymer [7] instead of the liquid electrolyte used in standard Li-ion batteries. This change in electrolyte seems to have given the LiPo battery enhanced capabilities, one of which is its lower internal resistance which leads to the capability of delivering higher currents. The lower internal resistance altered both the charge and the discharge characteristics. The charge characteristics show a lower drop in voltage when the load current is increased, and the constant-voltage stage of the charge curve is reduced significantly (see Figure 11).

The mass of this LiPo battery pack is 741 gm, and the volume is 0.00037 m^3. From Figure 8 the capacity after full discharge (by various discharge currents) was measured to be very nearly 4 Ah. To calculate the energy density, the Watt-hours have to be calculated, making use of each corresponding voltage reading. The calculation for this LiPo battery at a load of 1 A, is 89 Wh (not shown). Therefore its Gravimetric Energy Density is 89 Wh/0.741 kg = 120 Wh/kg. Its Volumetric Energy Density is 89 Wh/0.00037 m^3 = 240 540 Wh/m^3. The mass and volume of the battery protection electronic circuitry is not taken into account.

3.2.2. The Li-ion Battery

The commercial Li-ion battery that was compared with LiPo and NiCd during this study was specifically chosen because it is presently being evaluated for use in a military[4] system (see Figure 6). Unfortunately (for the purposes of this study) this battery utilises only four cells in series (two banks in parallel), and a voltage calculation adjustment is made to compare the performance of this battery with the 6-cell LiPo and the 19-cell NiCd batteries.

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[4] For security reasons the specific application and country of service is not mentioned and is not relevant to the study.

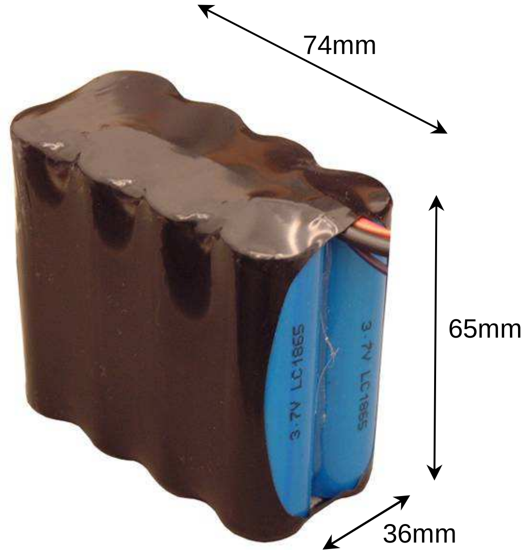

Figure 6: The Li-ion battery pack showing the physical size

The mass of the Li-ion battery is 363 gm, and the assembled pack volume is 0.000173 m^3. From Figure 9 it is shown that the capacity of the Li-ion battery at a 1 A load approximates 3.2 Ah. As for the LiPo battery, calculation of the energy density makes use of each corresponding voltage reading. The calculation for this Li-ion battery at a load of 1 A, is 48 Wh (not shown). Therefore its Gravimetric Energy Density is 48 Wh/0.363 kg = 132.2 Wh/kg. The Volumetric Energy Density is 48 Wh/0.000173 m^3 = 277 200 Wh/m^3. The mass and volume of the battery protection electronic circuitry is not taken into account.

3.2.3. The NiCd Battery

The battery is shown in Figure 2.

The NiCd battery that was chosen for this study emanates from a NiCd pack that was used in similar conditions as for this study. It also powered a radio with approximately the same specifications as described in Paragraph 3.1, and this study therefore presents an ideal comparison with the “older” technologies.

The mass of the NiCd battery pack (cells assembled) is 1.68 kg and the pack volume (not including the battery holder) is 0.000670 m^3. The calculation of the Power Density for the NiCd battery at a discharge rate of 1 A is 53.6 Wh (not shown). The Volumetric Energy Density is 53.6 Wh/0.000670 m^3 = 80 000 Wh/m^3. The Gravimetric Energy Density is 53.6 Wh/1.68 kg = 31.9 Wh/kg.

3.3. Comparison Results

3.3.1. Power Density Comparison

In a value system, the soldier would choose to carry as little mass as possible, and the volume should be as small as possible. A discharge was performed for each of the three batteries at a constant current of 1 A, according to which the Power and Energy Density could be calculated. Both the Volumetric Energy Density as well as the Gravitational Energy Density is shown in Figure 7. It should be noted that the Lithium family outperforms the NiCd battery on both these results (Figure 7 A and B). The Li-ion performs the best in both these sub-results.

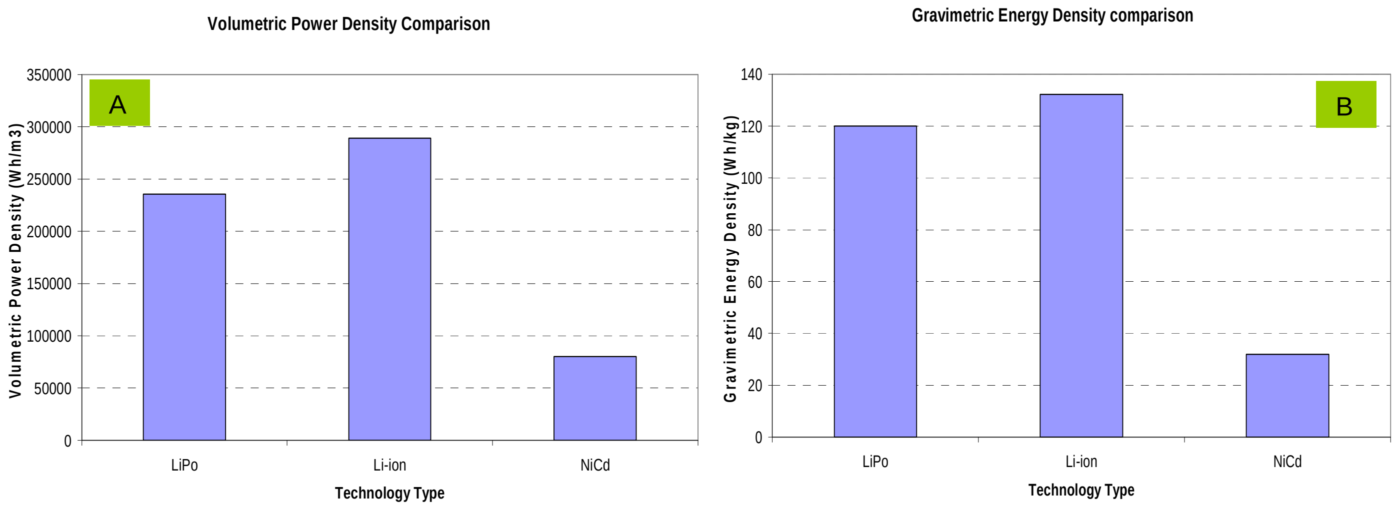

Figure 7: The Volumetric Energy Density (A) and the Gravitational Energy Density (B) of the different technologies

3.3.2. Comparative characteristics of constant current discharge at room temperature

3.3.2.1. LiPo results

Discharges using the LiPo battery were performed at 200 mA, 1 A, 3.7 A, and 5 A at room temperature. The results (shown in Figure 8 A) depict the time-related discharge results, which shows that the higher the discharge current, the shorter the time of discharge becomes, as would be expected. The results in Figure 8 B represent the capacity-calculated discharge curves showing that the capacity remained relatively constant irrespective of the discharge current. This result is a very attractive feature of the LiPo technology in military applications where the exact figures of status are always required, and performance of equipment is required to be predictable.

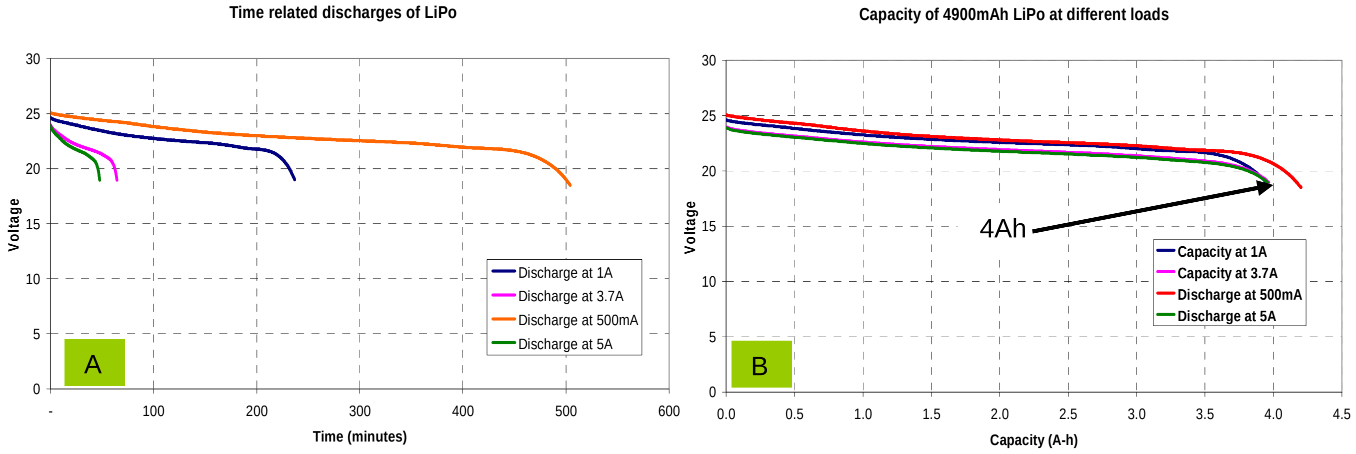

Figure 8: LiPo battery discharged at various load currents at room temperature

It is noted that the measured capacity was around the 4 A-h-mark (Figure 8 B). This is less than the manufacturer-stated capacity of 4.9 A-h. It must also be noted that the capacity was reduced from an initial 4.17 A-h (see Figure 30) probably due to an incorrect storage method. The tests for Figure 8 were performed after the test results of Figure 30.

3.3.2.2. Li-ion results

The discharge curves of the Li-ion battery are shown in Figure 9. It is noted in Figure 9 B that the capacity of the Li-ion also demonstrates a similar characteristic as the LiPo, i.e. that the capacity remains roughly the same at all discharge rates between 0.5 A and 3.7 A.

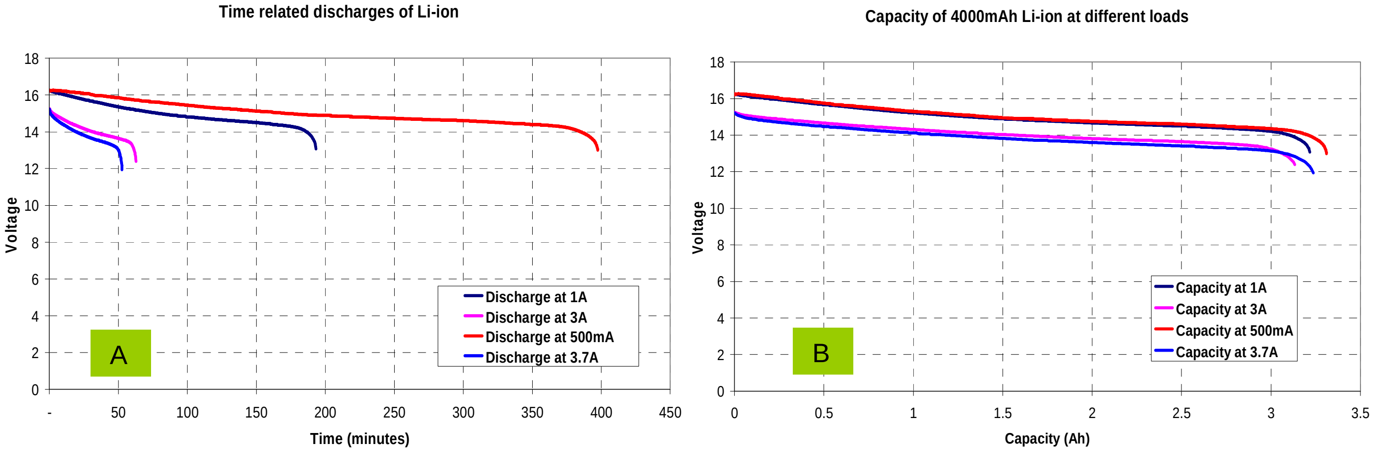

Figure 9: **Li-ion battery discharged at various load currents at room temperature**

The discharge curves of the NiCd battery are shown in Figure 10. The NiCd battery illustrates a characteristic that the capacity increases when the load decreases. This is different to the Lithium family that were tested for this study. This means that the Lithium-family would be more acceptable to a dismounted soldier than NiCd batteries, due to the fact that the capacity is more trustworthy. The remaining capacity (when calculated by internal electronic firmware) for the Lithium family is therefore calculated more accurately.

3.3.2.3. NiCd results

It is also known in general that the self-discharge rate of a NiCd battery is more than the self-discharge rate of the Lithium batteries, and also that the Coulomb-metric efficiency is less. These characteristics are not investigated in this study.

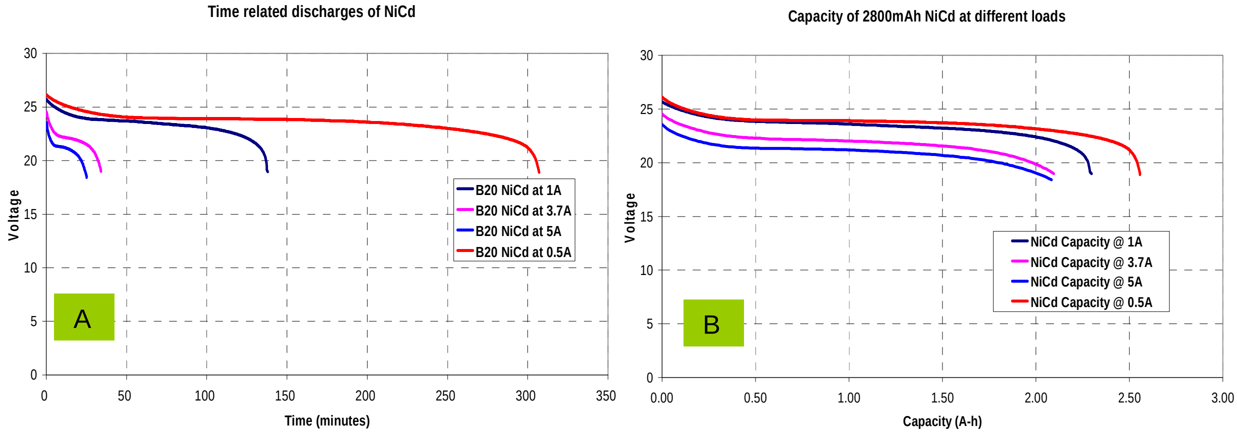

Figure 10: **NiCd battery discharged at various load currents at room temperature**

3.3.3. Importance of Charge characteristics

Park *et al* [8, 892] states that there has been an increase in demand for reducing the charging time of lithium ion batteries for the applications of power tools, electric vehicles, portable electronics and military devices.

The importance of the charge characteristics for the dismounted soldier is quite obvious: a soldier needs to spend as little time as possible in the operational area replenishing, yet ensuring that maximum power is replenished. Soldiers prefer batteries which accept the maximum amount of current that can be supplied from available sources, and prefers to sustain this current until the batteries are fully replenished.

Unfortunately it is not always possible to meet this stringent requirement, due to the charge characteristics of the batteries. Most batteries need to limit the charge current to typically ½C, 1C or 2C to ensure maintenance of maximum life. The Lithium batteries also need to limit the maximum voltage of each cell, thereby reducing the current when this voltage is reached. The current therefore has to be reduced to comply with this characteristic, drawing out the charge time. The NiCd batteries could accept the full 1C or 2C charge, but its voltage then increases to typically 1.5 V (or even 1.6 V) per cell, depending upon charge current, and internal losses are experienced, lowering the Coulomb-metric efficiency. One advantage of the charge-procedure of NiCd batteries, is the fact that a constant current could be applied up to the point where it is detected (by intelligent chargers) that the battery is fully charged.

3.3.4. Comparison of Charge characteristics

The charge procedure for the Lithium family of batteries first starts with a constant-current source (or current-limited source) whilst the battery is still below 4.2 V per cell. As soon as the battery reaches a voltage equal to 4.2 V per cell, then the current is gradually reduced to keep the cell voltage exactly at 4.2 V per cell. The voltage stays constant during this period, and hence the name “constant-voltage” stage. When the current reduces to <0.1C A, then the charge must be removed, or else it is expected that the battery performance would be reduced [7].

Within the Lithium family, the period of the constant-current stage and subsequently the period of the constant-voltage stage differ. The LiPo battery has a typical 13:1 ratio (constant-current to constant-voltage time ratio - see Figure 11 - depending on the charge current limit), whilst the Li-ion battery has a typical 1:1 ratio. In effect this means that, for the same applied current during the constant-current stage, the LiPo battery is charged to a “full” state much quicker than its Li-ion counterpart. Figure 11 shows that the constant current was applied to the LiPo battery for 97 minutes, after which the current was reduced according to the requirement to keep the voltage constant. A “full” status was reached after 110 minutes.

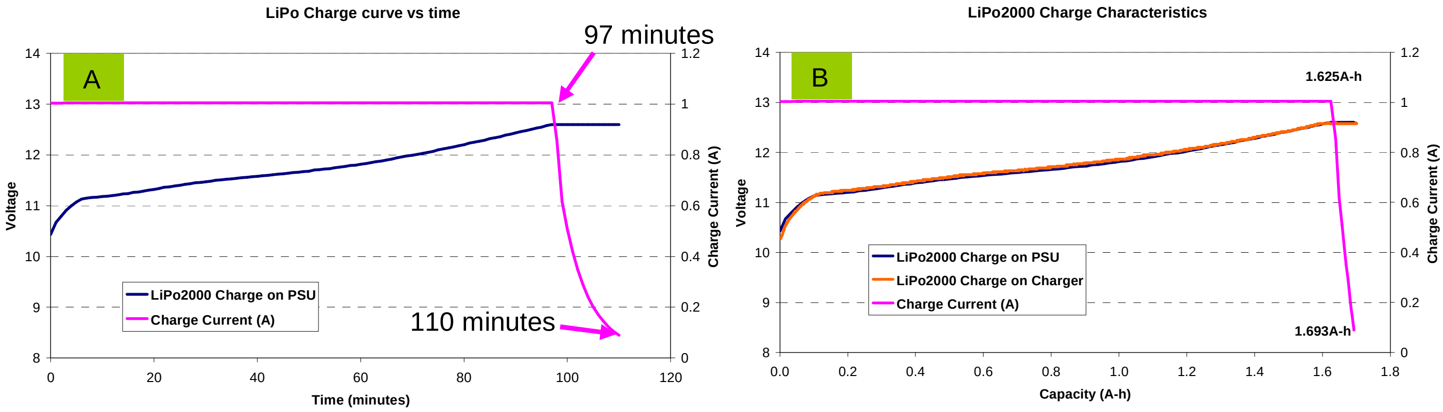

Figure 11: The charge characteristics of a LiPo battery

The results of the experiment shown in Figure 11 mean that the LiPo battery is very nearly at full charge when the constant-current stage is completed (1625mAh/1693mAh=96%). This means that the charge may be stopped at the moment that the charger exits the constant-current stage, and such a charger would be less complex than the usual Lithium chargers. When the battery is not fully charged, the life span of the battery is extended [7], which adds to the reliability that is required from a battery by the soldier in the battle field. By increasing the charge current, the LiPo battery could be charged even quicker.

A similar experiment was performed on a Li-ion battery with measured capacity of 3.6 A-h. The constant-voltage stage results are shown in Figure 12 where it can be seen that 21% (0.76 A-h) of the capacity was added during the constant-voltage stage, which means that 79% (2.84 A-h) was added during the constant-current stage. At 1A charge current, the time taken in the constant-current stage was 2.8 hours, and the time taken in the constant-voltage stage was 3 hours. This ratio approaches 1:1 if the charge current limit is increased slightly, and thus the charge time for Li-ion approaches 6 hours. The constant-current stage could be shortened further if the charge current is increased, but the charge current is again reduced according to Figure 12 after the cell-voltage of 4.2 V had been reached.

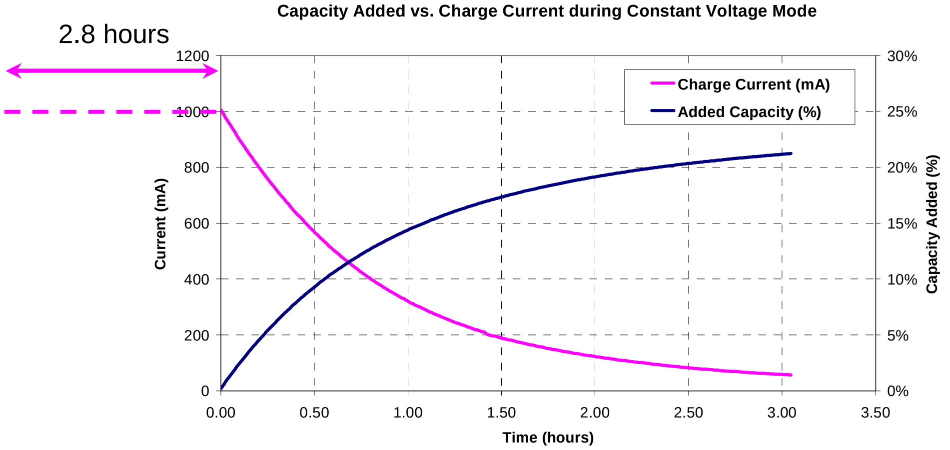

Figure 12: The charge characteristics of a Li-ion battery

The charging characteristics of the NiCd battery differ extensively from the Lithium family, due to its charge-termination method. For many years the users of the NiCd batteries suffered NiCd technology characteristics such as “memory” build-up. This was the result of the application of a small charge current (0.1C) which was sustained for 14 hours (in the early years of charging the NiCd battery). The small current produced dendrites which short-circuited the plates. This meant that less of the plates were available to act as a battery. In those times the batteries were first fully discharged before applying the small charge current for a certain length of time.

One characteristic of the Nickel-family of batteries is that, when it is overcharged, the electrolyte breaks up by electrolysis, rendering the battery unserviceable depending on how much and how often this overcharge occurs.

Since the early years of NiCd development, improved methods have come onto the market to charge the NiCd battery faster, and without the “memory” effects. These new methods also concentrated on terminating the charge process by detecting a negative voltage slope during the charge current application, which signified that the battery was fully charged. The addition of the measurement of a temperature gradient and termination of the charge when this gradient exceeds a threshold, formed part of the modern NiCd charging methods. It was also discovered that some of the Nickel-family of batteries displayed a build-up of internal resistance when left on the shelf for a period of time. The chargers therefore allows for a “warming-up” period during the first minutes of the application of a charge, before the voltage and temperature measurements are taken. This then also implied that the battery did not have to be discharged before the charge process commences, and also that the battery is not overcharged. The “memory” effect has disappeared in both the NiCd as well as the NiMH batteries when the modern chargers are used. Note that if conventional “14-hour” chargers are used, the “memory-effect” will re-appear.

The new methods of charging the NiCd (as well as the NiMH) battery allowed a faster charge to be applied, and it has recently become a standard procedure to charge these batteries within one hour.

This is a very attractive feature to the dismounted soldier in the case where an appropriate current source is available.

This study investigates sources which do not have unlimited current production for the charge process, e.g. solar panels and small fuel cells.

3.3.5. Internal resistance

There are various means to determine the internal resistance of a battery, with various outcomes. The outcome is the important factor for military application, especially how the performance of the tactical equipment is affected by the internal resistance characteristic of the battery. Buchman [2] agrees that the internal resistance is the gatekeeper of a battery and largely determines the performance and run-time. The military application that this study is investigating is the medium power tactical radio, usually carried in a "man-pack" as described in the introduction. The temperatures at which it was expected to get full capability, was between -15ºC and +50ºC, and it was expected to be able to transmit for 10 seconds at full power.

Therefore the tests were designed to determine the internal resistance and overall performance of the batteries between -20ºC and +60ºC to allow for some overlap with respect to the requirements.

The significance of the internal resistance on the transmitted power is demonstrated in this section, taking into account that Equation 1 is valid for all the batteries.

In broad terms, when the transmitter is emitting EM waves into the atmosphere, a current of 3.7A (for this specific radio) is drawn from the battery, whilst the current drawn when not transmitting is 200 mA. It was expected that the time taken for each transmission would be approximately 10 seconds and hence the interest in a 10-second internal impedance. The internal resistance causes the voltage to drop more during the transmit period, and the higher the internal resistance, the lower would be the voltage available to the transmitter.

3.3.5.1. LiPo Internal Resistance

The following tests were performed to determine the 10-second internal resistance of the LiPo battery. At first the environmental chamber was set to 50ºC, and the discharge results at this temperature shown in Figure 13 were obtained. The internal resistance was relatively low, at an average of 0.12Ω.

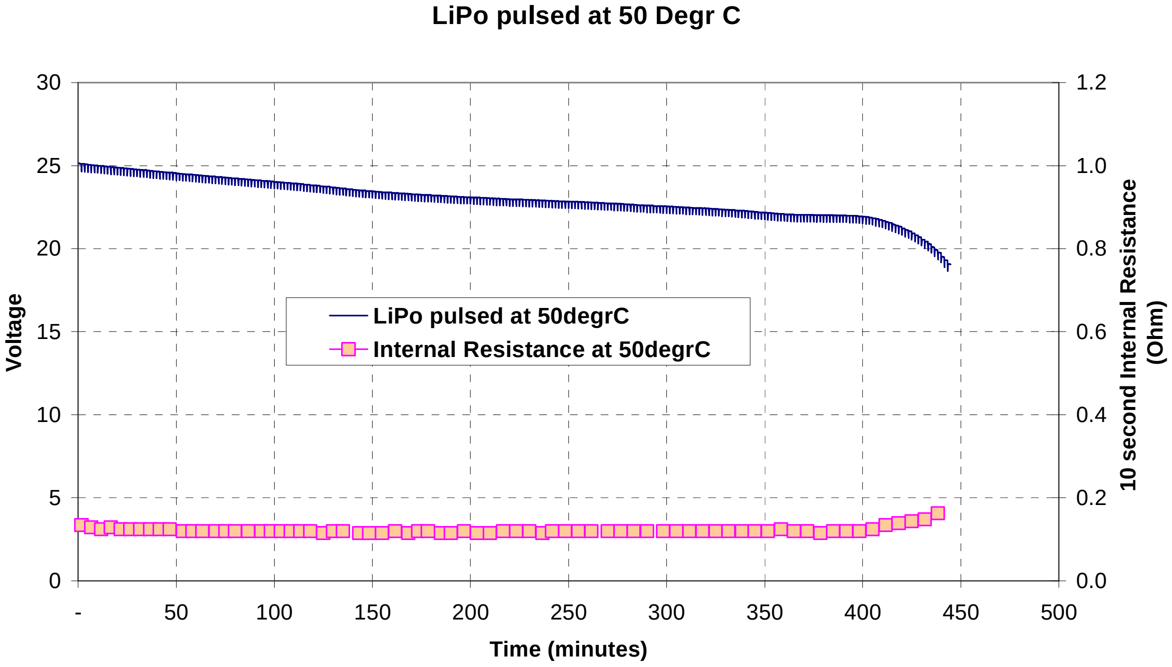

Figure 13: LiPo battery pulsed at 50ºC to determine the 10-second internal resistance

The environmental chamber was then adjusted to 40ºC, and the discharge results at this temperature shown in Figure 14 were obtained. The internal resistance was relatively low, also at an average of 0.12Ω.

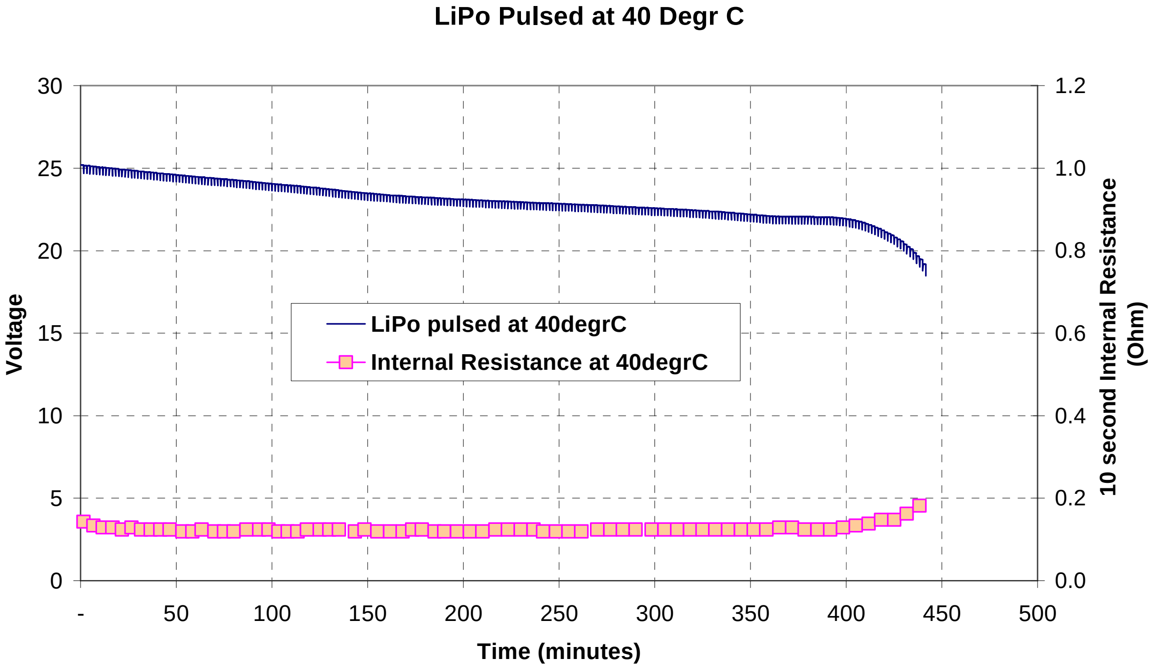

Figure 14: LiPo battery pulsed at 40ºC to determine the 10-second internal resistance

The environmental chamber was then adjusted to 25ºC, and the discharge results at this temperature shown in Figure 15 were obtained. The internal resistance was still relatively low, at an average of 0.27Ω, and climbing towards 0.5Ω towards the end of the discharge process. When Figure 15 is compared with Figure 14, it is noticed that the voltage drop due to the higher current pulses, is larger.

The environmental chamber was then adjusted to -10ºC, but measurements were taken during the process that the temperature dropped. When the battery was completely soaked at -10ºC (point “A” in Figure 16), the chamber temperature was re-adjusted to return to room temperature. The results showing the variation of the 10-second internal resistance with temperature are shown in Figure 16, highlighting the reaction of the internal resistance with changes in temperature, at point A.

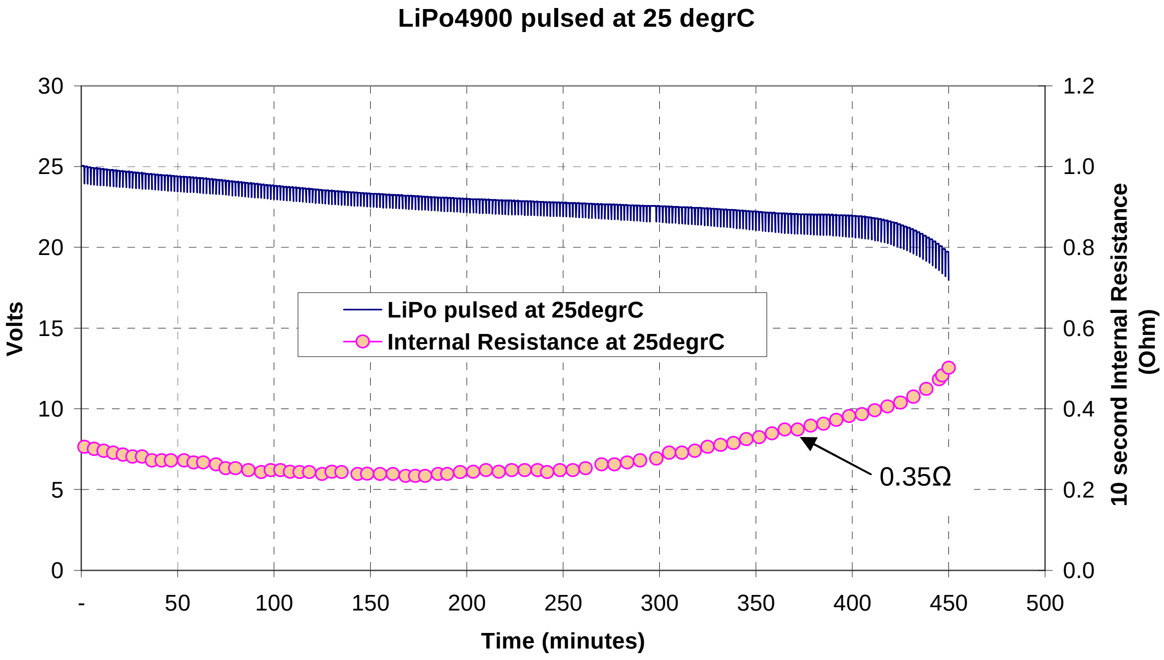

Figure 15: Pulsed discharge of the LiPo battery at room temperature to determine the 10-second internal resistance

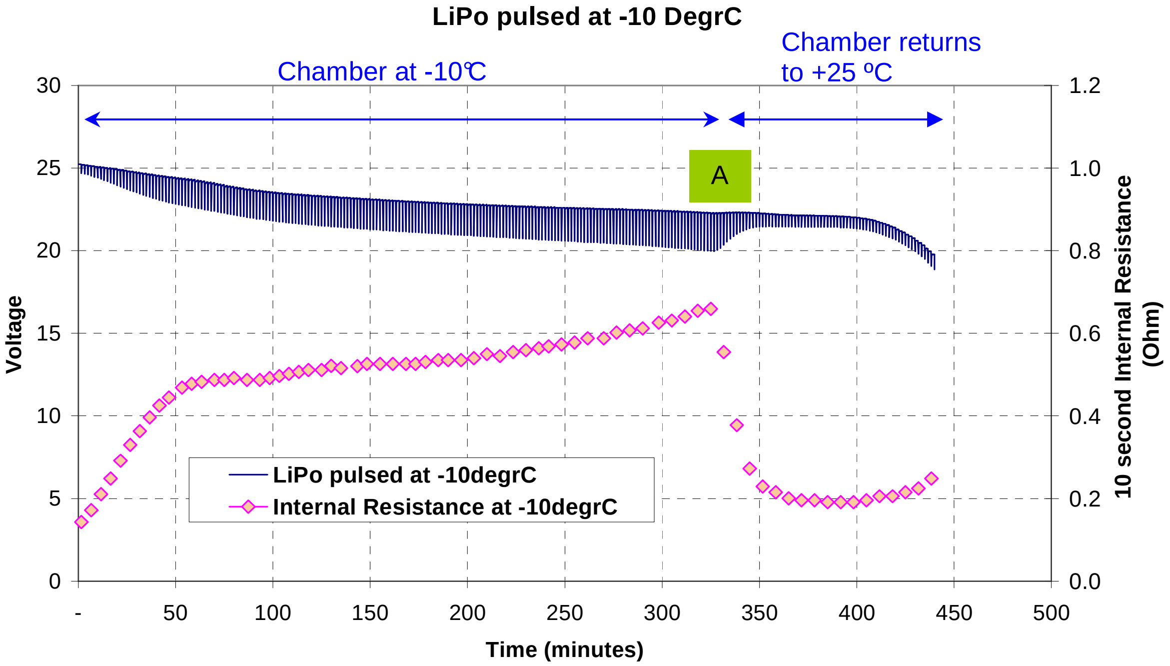

Figure 16: LiPo battery pulsed at -10ºC to determine the 10-second internal resistance

This experiment was performed to show how the internal resistance changes in the colder temperatures. When the colder temperatures are reached, the voltage-drops due to the high current pulses increase. This phenomenon is even more accentuated when the chamber temperature changed from room temperature to -15ºC, as is shown in Figure 17.

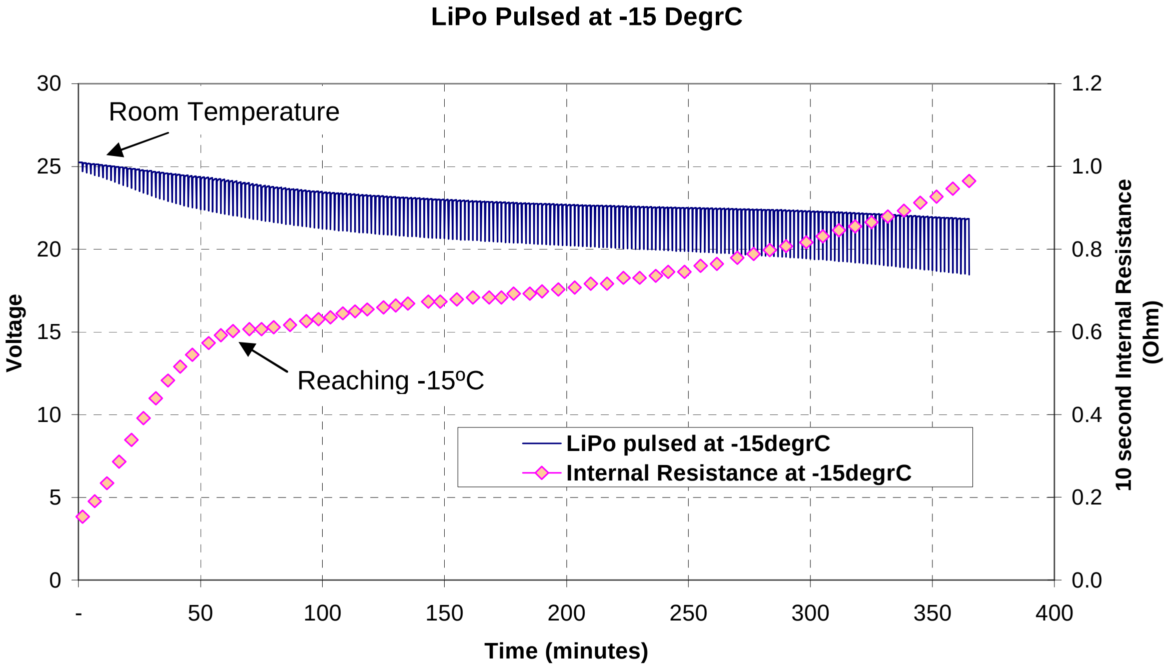

Figure 17: LiPo battery pulsed at -15ºC to determine the 10-second internal resistance

It was also necessary to determine whether the battery characteristics would return to "normal" after the temperature stress. The chamber temperature was programmed to start at +30ºC, then to drop to -20 ºC, and then to return to room temperature. The results are shown in Figure 18, and it is visible that the battery performance returns to "normal" after the temperature stress.

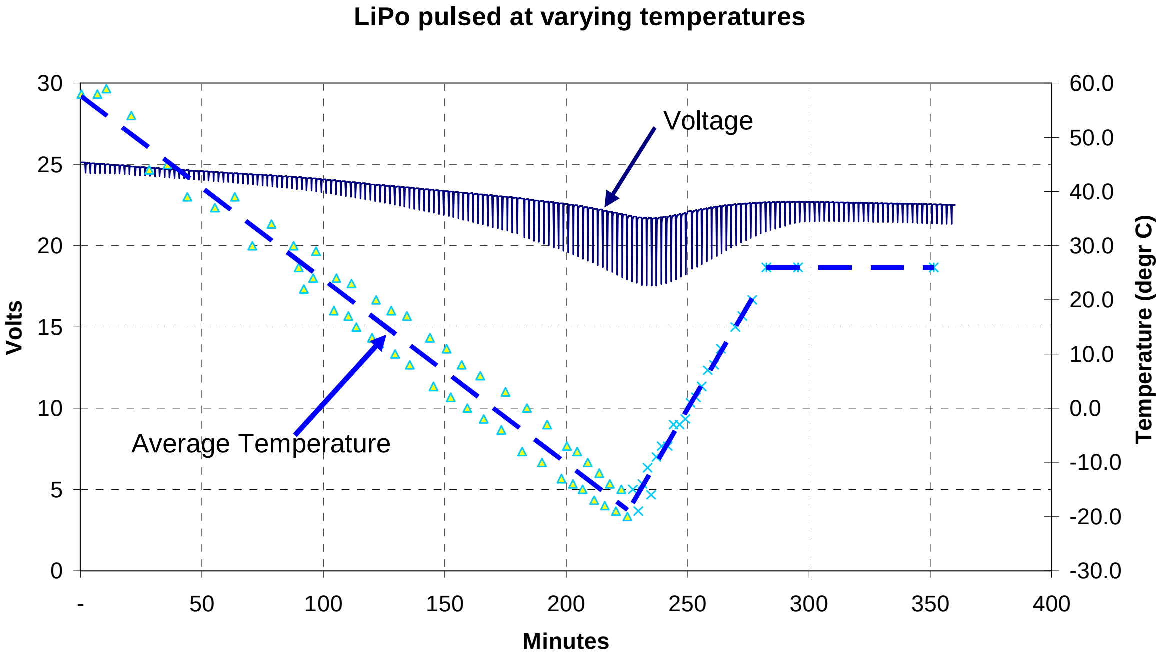

Figure 18: LiPo battery discharge curve using a temperature profile

The internal resistance was calculated from the results of Figure 18, and is shown in Figure 19 relative to the measured chamber temperature. It is noticeable that the internal resistance increases non-linearly as the temperature decreases, and is restored to typically 0.35Ω at room temperature towards the end of its discharge cycle. This corresponds well with the results obtained in Figure 15.

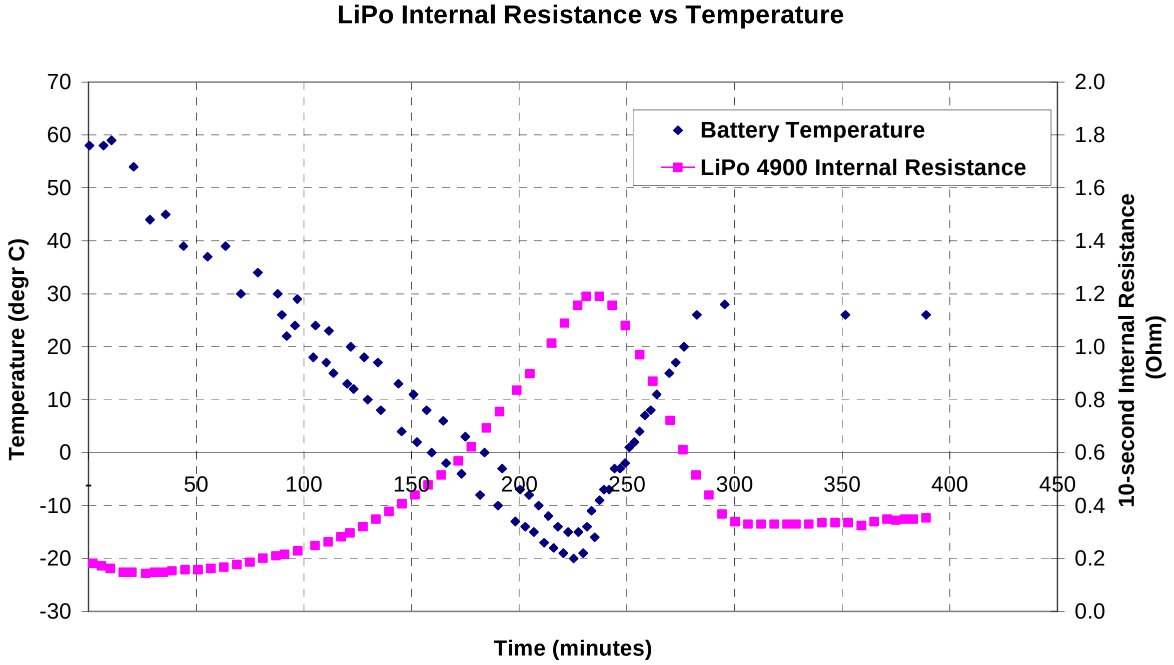

Figure 19: Internal resistance of LiPo battery vs temperature

3.3.5.2. NiCd Internal Resistance

The internal resistance of the 24 V NiCd battery that originally powered the radio, was determined by pulsing the battery between 200 mA and 3.7 A, as shown in Figure 4. The voltage differential was divided by the current differential to obtain the internal resistance. The high current pulse duration was 10 seconds, and thus the result was obtained for the 10-second internal resistance (see Figure 20). The internal resistance was maintained to less than 0.7Ω for most of the discharge process, but increased faster towards the end of the discharge process.

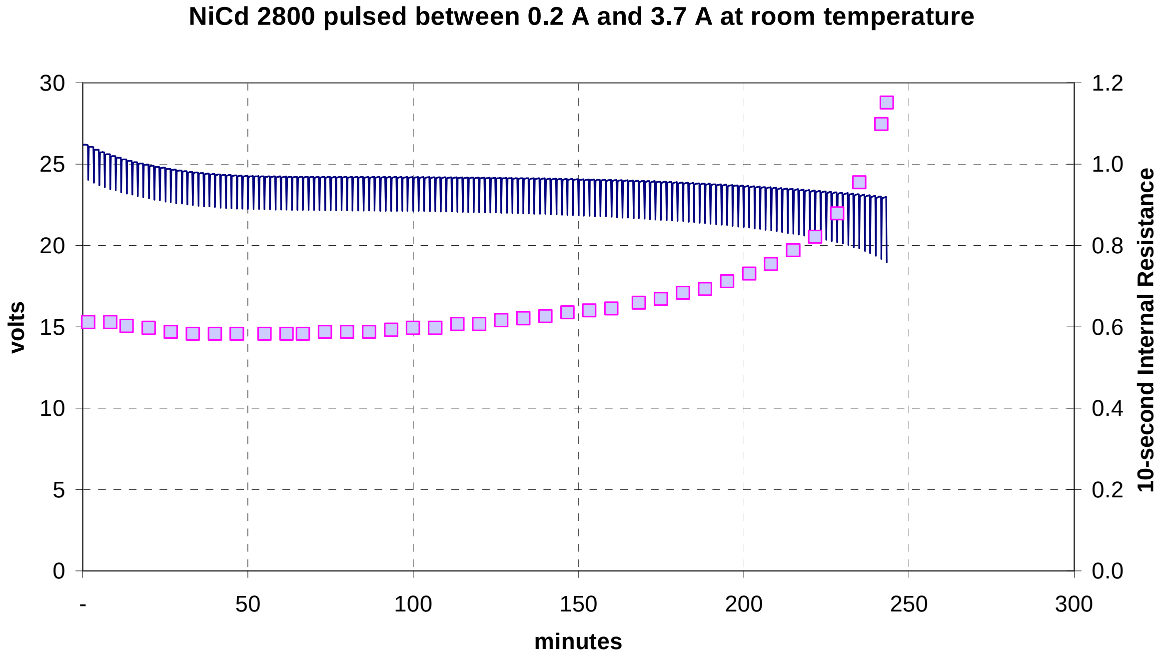

Figure 20: NiCd battery pulsed at room temperature to determine internal resistance

A discharge was performed at varying temperatures to illustrate the effect of temperature on the NiCd battery, and the results are presented in Figure 21. A time-phased temperature result is shown due to the fact that the battery takes time to soak to the environmental temperature.

The NiCd battery voltage, under pulsed load, drops significantly during the high current pulses as the temperature drops (see Figure 21).

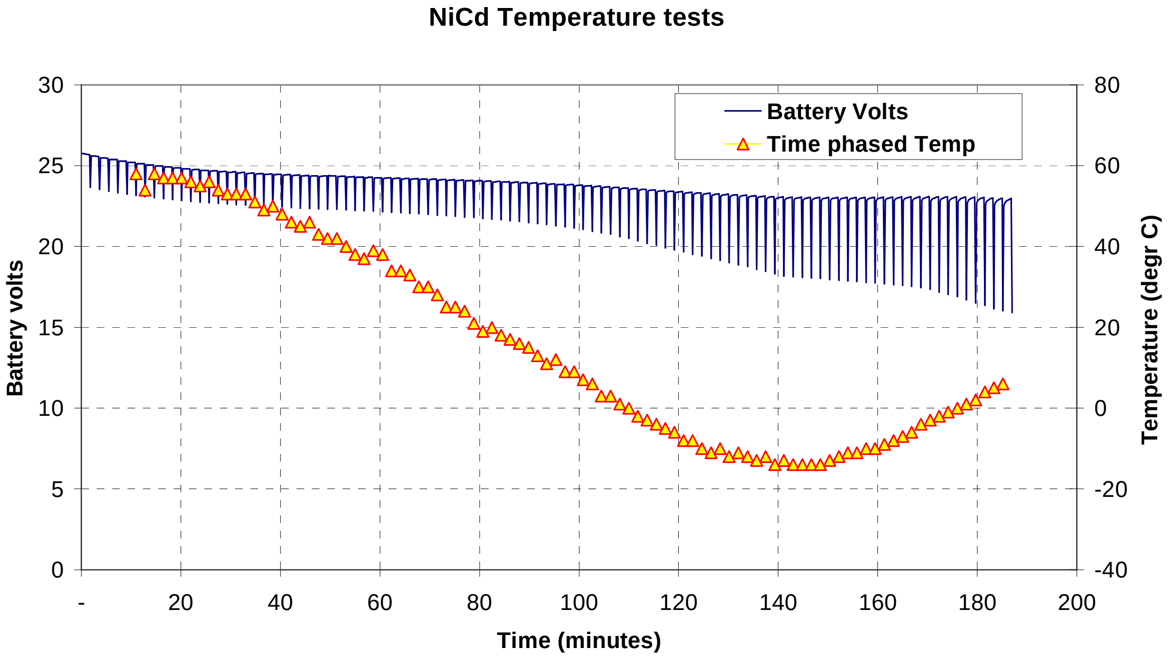

Figure 21: **The effect of temperature on battery voltage for the NiCd battery**

In this instance, the measurements of the internal resistance were taken (see Figure 22) only up to the point where the minimum temperature was obtained, because at that time the battery capacity started to become depleted. It is noticeable that the internal resistance increased significantly after point “A” in Figure 22.

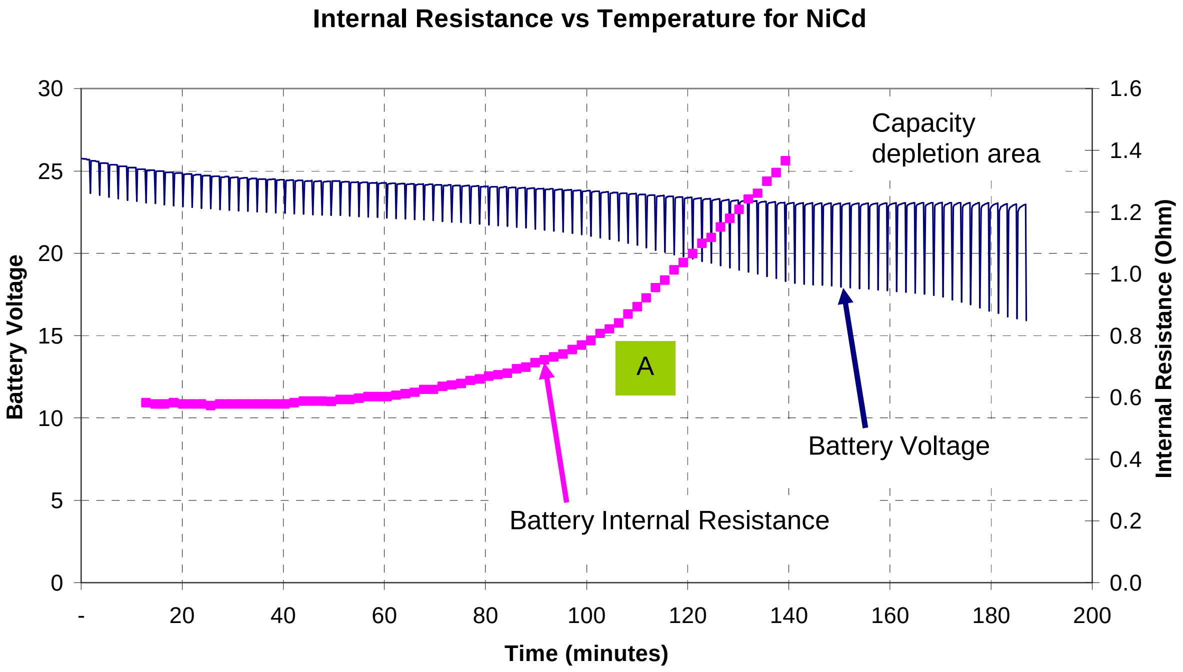

Figure 22: **The effect of temperature on battery internal resistance of the NiCd battery**

3.3.5.3. Li-ion Internal Resistance

The internal resistance of the Li-ion battery pack was determined exactly in the same way as for the other batteries. The result is shown in Figure 23. By visual inspection it can be seen that the internal resistance kept constant at 0.63Ω (within reason, and for the extrapolated 6-cell battery), until the capacity reached its end, when the resistance increased upwards to 0.8Ω. The fact that the internal resistance remained constant is attractive to the military designers, due to the fact that the equipment designs that would utilise these batteries are simplified.

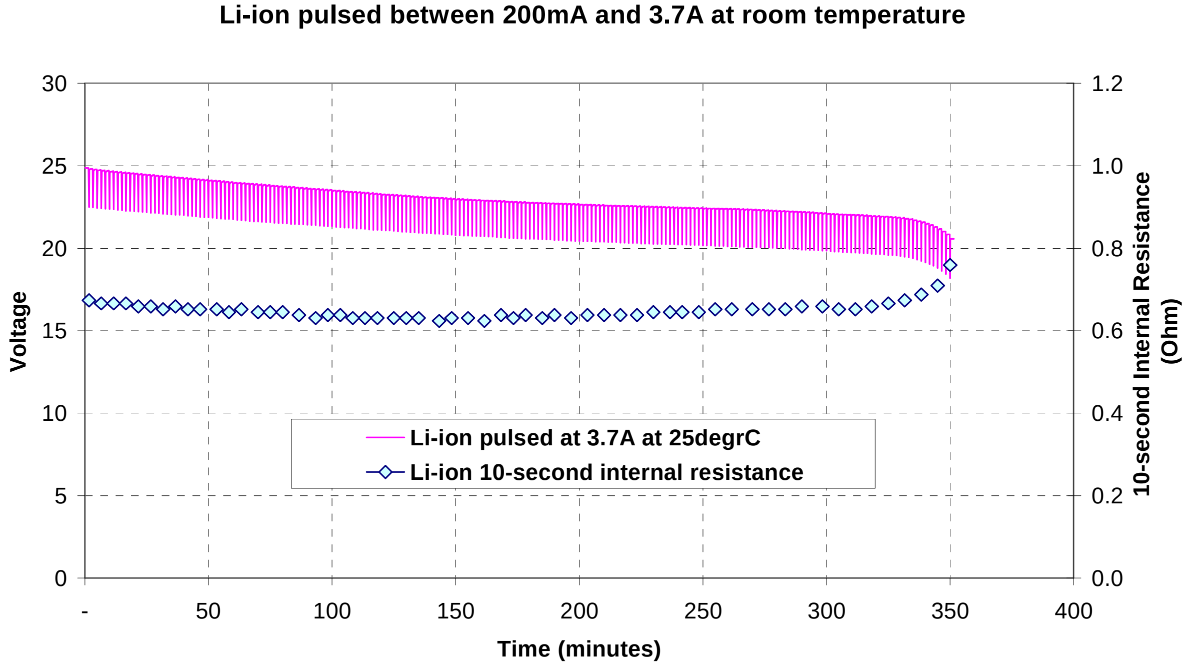

Figure 23: Li-ion battery pulsed at room temperature to determine internal resistance

In this case an experiment was also conducted to determine whether the Li-ion battery would be restored to “normal” after it was subjected to temperature stress. The temperature was set at +60 ºC, after which the temperature was adjusted to -20 ºC. The chamber was kept at -20 ºC for approximately half hour, after which it was returned to room temperature. The results are shown in Figure 24. This battery showed an interesting feature, in that the internal resistance at low currents did not change significantly when the temperature was lowered to -20 ºC, due to the fact that the voltage at the low-current areas (point “B” in Figure 24) did not deviate significantly from a “normal” discharge curve at room temperature. The high current pulses, however, displayed a significant drop in voltage at the lower temperatures (point “A” in Figure 24).

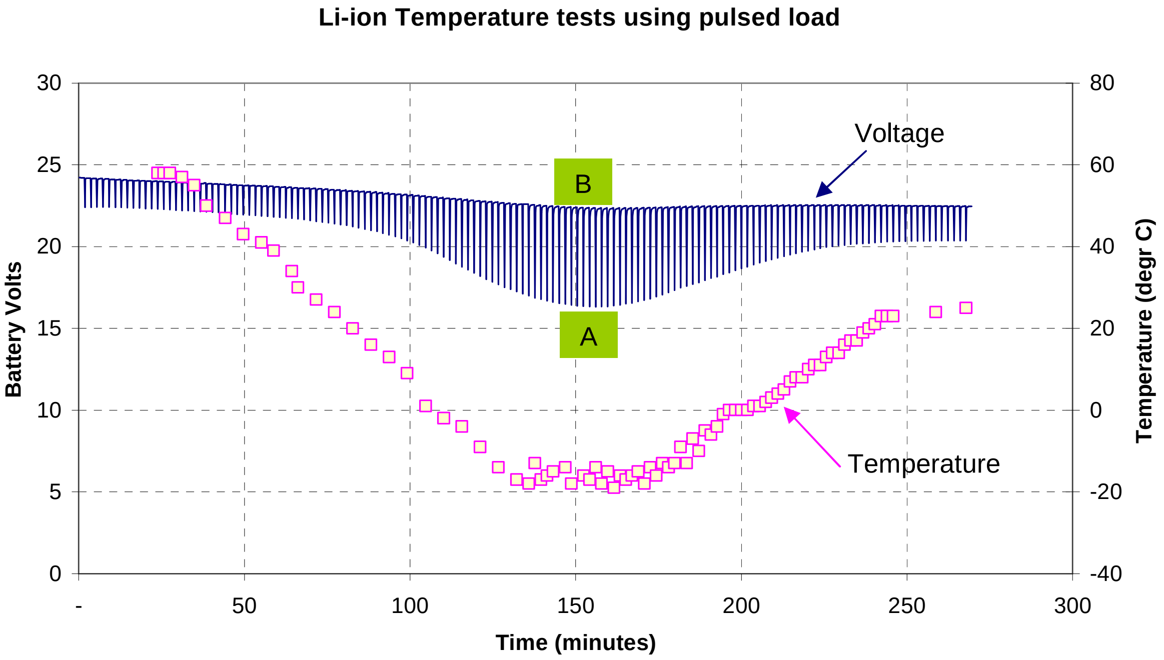

Figure 24: **The effect of temperature on the Li-ion technology**

3.3.5.4. Comparison of Internal Resistance of different technologies

The comparison of internal resistance for the three different technologies of this study at room temperature is shown in Figure 25. This depiction shows that the LiPo technology has the lowest internal resistance at room temperature, and that the internal resistances of Li-ion and NiCd are similar when the battery is fully charged. When the NiCd battery expends its charge through a load, the internal resistance increases significantly towards the end of the discharge process (see point A in Figure 25).

The internal resistance of Li-ion and LiPo show similar characteristics during the discharge curve, although the internal resistance differ in amplitude. With a theoretical compensation included in the comparison between Li-ion and LiPo (Li-ion being extrapolated to equal the capacity of the LiPo), the two batteries finished roughly at the same point in time (“B” in Figure 25).

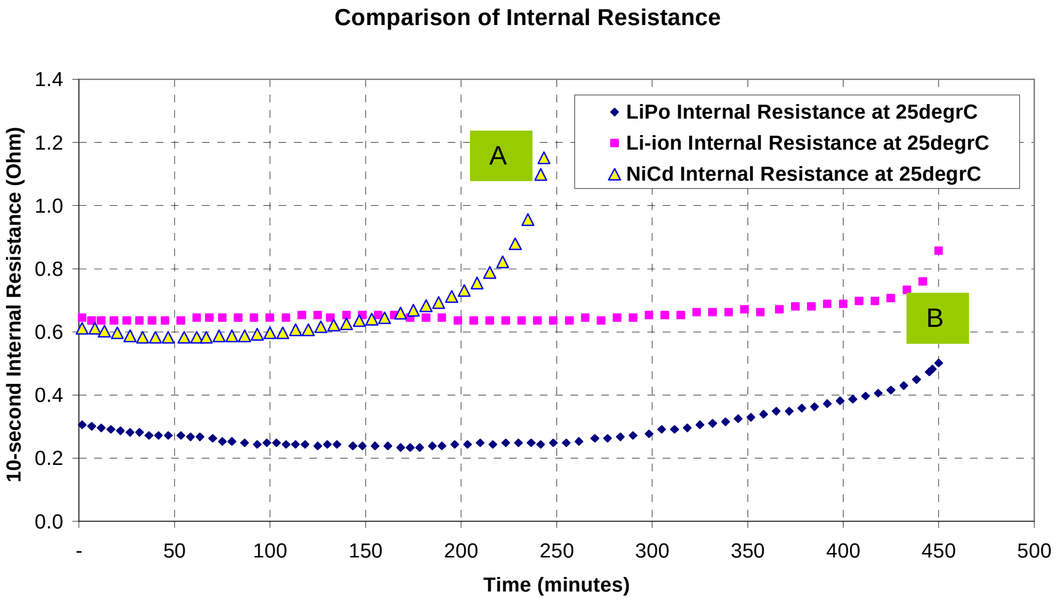

Figure 25: **Comparison of different technology internal resistance at room temperature**

3.3.5.5. Internal resistance at varying temperature

To compare the internal resistance variations as a result of temperature changes, the results of the temperature tests were combined, and the comparison graph is shown in Figure 26. This graph shows that the internal resistance of NiCd and Li-ion are similar at high temperature (60 ºC – point "A" in Figure 26), but also that the Li-ion battery internal resistance diverts to higher levels at cold temperatures (-20 ºC – point "B" in Figure 26). The LiPo battery displays the lowest internal resistance at all temperatures. The graph also shows that the internal resistance of the NiCd battery is the least affected by temperature variations, and this is probably why the military preferred the NiCd technology in the past.

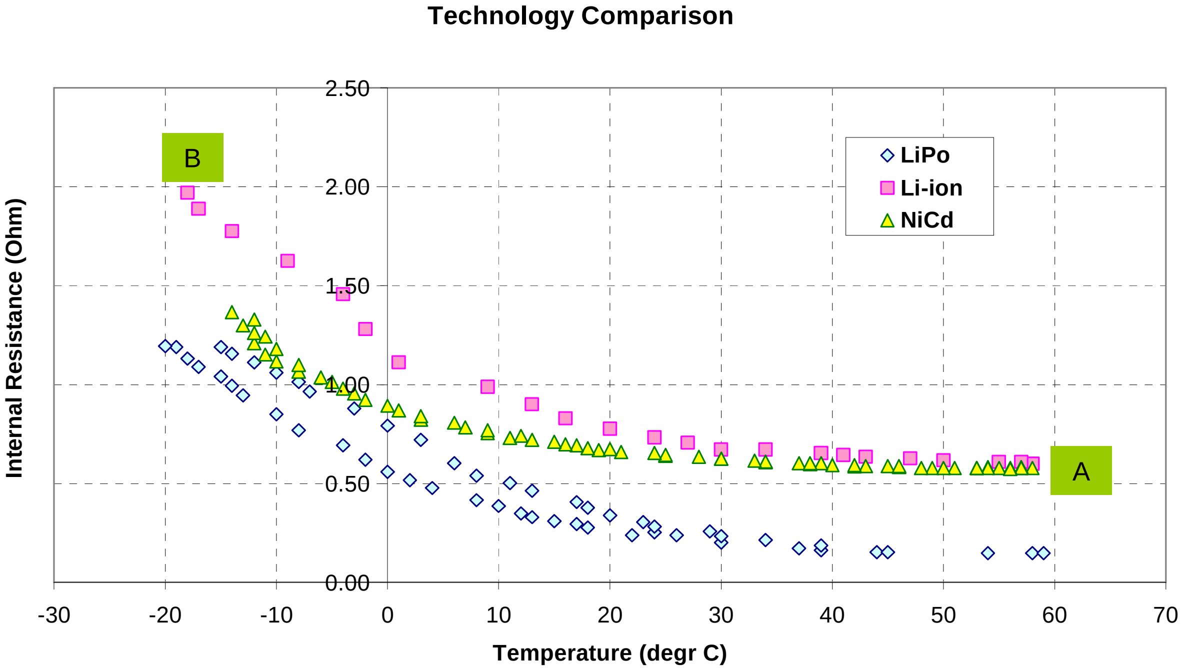

Figure 26: Comparison of internal resistance variations of three battery technologies

3.3.6. Importance of Internal Resistance

The importance of internal resistance is due to the effect that it has on the equipment it powers. For the batteries that were used for these tests, the importance is defined by Equation 1 where the transmitted RF power is reduced as the battery voltage reduces. The results in Figure 27 show that the transmitted RF power reduces as the voltage is reduced as a result of the internal resistance. It should be kept in mind that the voltage also changes as the battery capacity is depleted, and hence the transmitted RF power is a function of both the remaining capacity as well as the internal resistance.

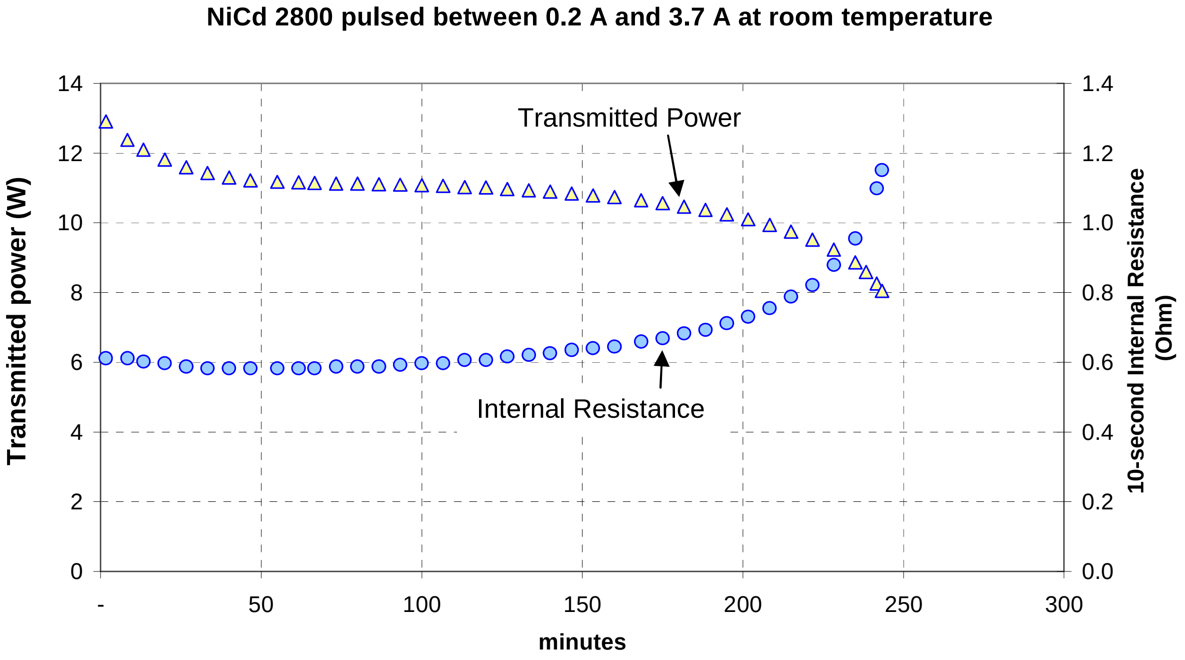

Figure 27: **The transmitted power using the original NiCd battery at room temperature**

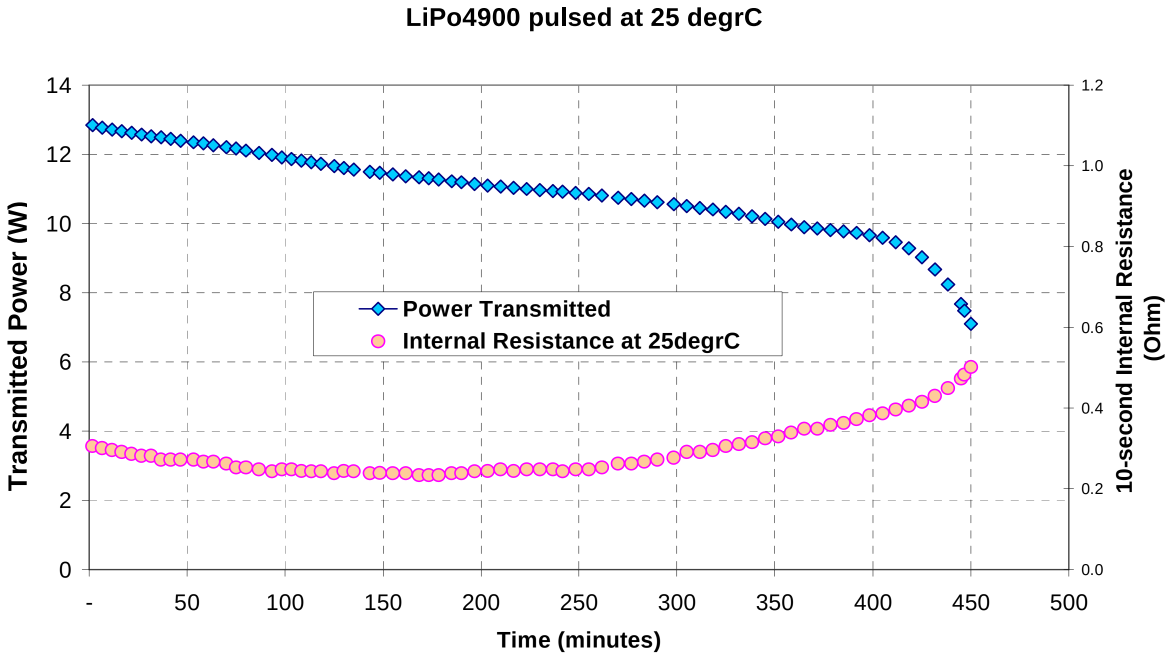

Figure 28: **The transmitted power using the substitute LiPo battery at room temperature**

On face value one may not easily see the advantage of using the LiPo battery over the NiCd battery or the Li-ion battery. Therefore the three results have been combined in Figure 29, extrapolating the Li-ion voltage to equal a 6-cell battery. The current pulses were in accordance with Figure 4 and the temperature was between 20ºC and 25ºC.

Figure 29 clearly shows that both the Lithium family of batteries performed better than (at approximately 190% capacity) the NiCd battery that was originally used in this radio, due to both the capacity characteristics as well as the internal resistance characteristics. The LiPo performed slightly better than the Li-ion battery at room temperature, when the current program of Figure 4 is followed. However, as a matter of interest, for one test only the current for the Li-ion battery was also programmed to pulse between 200 mA and 3.7 A, with the result shown in blue circles in Figure 29. By visual inspection the transmitted power from the NiCd battery was better than the Li-ion battery, until the capacity of the NiCd battery neared exhaustion. The difference between this result and the result indicated by red squares (slightly lower current pulses) is caused by the internal resistance of the battery.

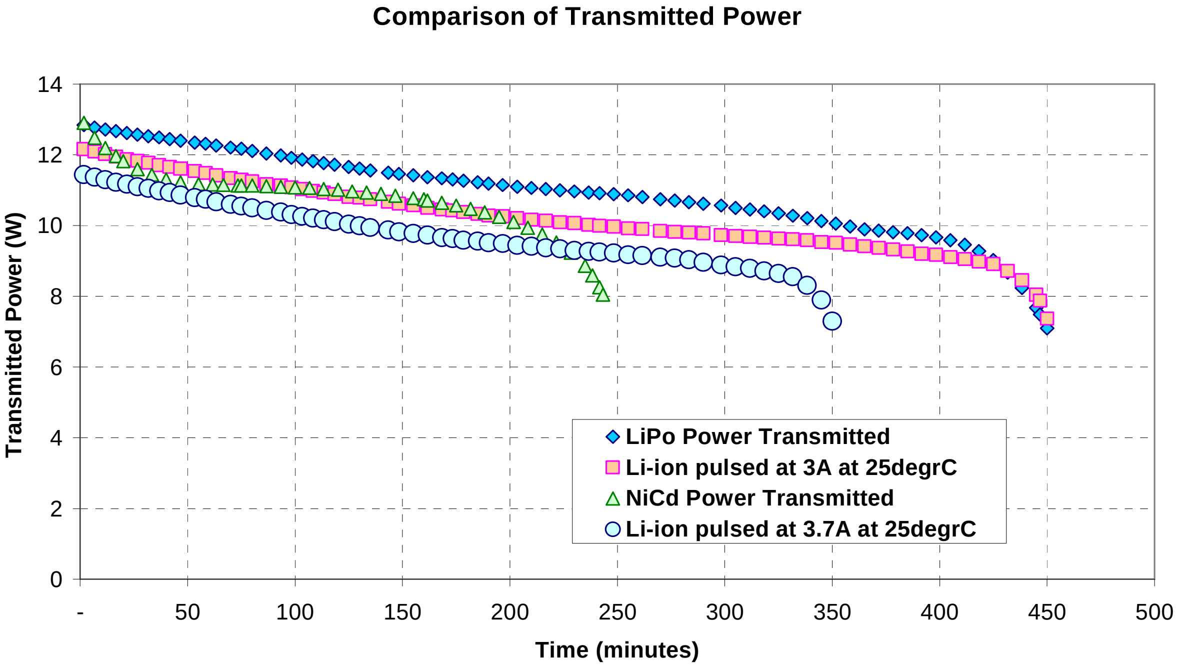

Figure 29: The transmitted power of all three batteries at room temperature

The battery internal resistance therefore plays a large role when the battery powers equipment of which the performance is coupled to battery voltage, and the current supply to the equipment is not constant. Care should be taken by military acquisition organisations to check the battery management of the equipment being acquired in accordance with the results obtained by this study.

3.3.7. Short term shelf life or non-usage store characteristics

The LiPo battery was discharged before storage (see Figure 30, curve indicated by triangles), and then charged to a "full" condition and stored for 30 days. After this 30 day period the battery was discharged (see Figure 30, curve indicated by diamonds). The battery was then charged to a full condition immediately after, and discharged again (see Figure 30, curve indicated by blocks). All discharges were terminated at 19V (3.17 V/cell).

The two curves after the storage period deviated with less than 0.01% from each other, but deviated by approximately 6% from the before-storage discharge. This may indicate a permanent deterioration, and according to Hoffart [7] this may be attributable to the fact that it was stored at full charge. More tests have to be performed to confirm this possible phenomenon.

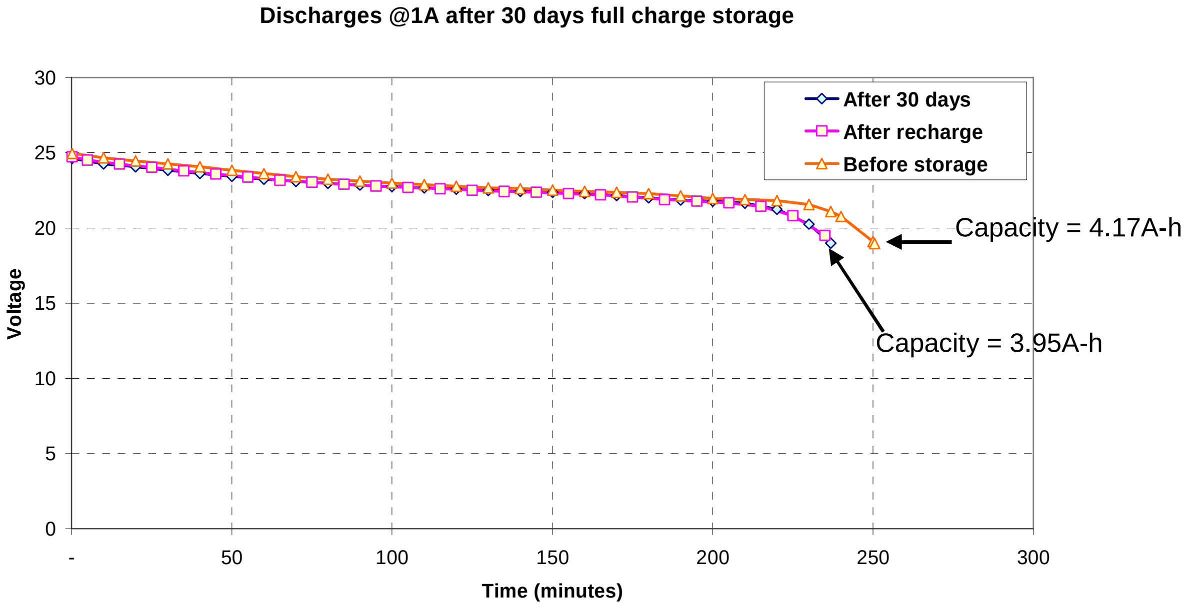

Figure 30: One discharge performed before storage, and two discharges performed after 30 days storage at full charge

3.4. Battery Simulation

In the battery simulation, a generic formulation for system-level models of Li-ion batteries was used. The formulation accounts for nonlinear equilibrium potentials, rate and temperature dependencies, thermal effects and response to transient power demand. To simulate all of this data, the equivalent circuit model (Lijun *et al* [11]) has three components: an equilibrium potential E, an internal resistance having two components R_1 and R_2, and a virtual capacitor C that represents localised storage of chemical energy within the porous electrodes (see Figure 31). During the empirical evaluation of the equivalent diagram, the theoretical results were compared with the practical results. It was found that the model represented in Figure 31 compared well with experimental data at a certain temperature, but deviated from the experimental data particularly at low temperatures. By adjusting component values in the diagram shown in Figure 31, the data obtained at low temperatures could be matched with the simulation data. The schematic diagram does not change.

It is therefore reasonable to assume that some or all of the components shown in Figure 31 are temperature dependant.

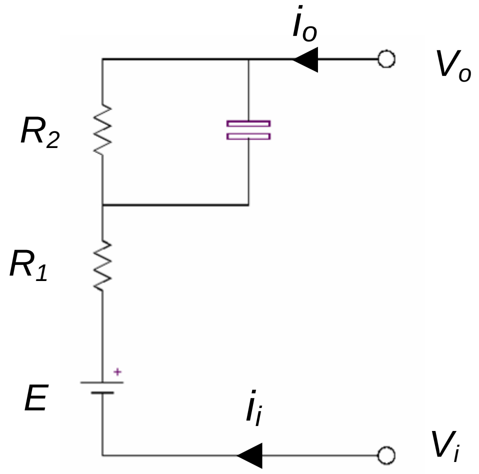

Figure 31: Equivalent circuit diagram of a Li-ion battery

To present an overall picture of the effect that temperature changes have on a battery, the 4-cell Li-ion battery of Figure 6 was pulse-loaded between 200 mA and 3 A, first at a low temperature (-20 °C), then at a high temperature (+30 °C). The results were plotted in graph form to visualise the effect in Figure 32. It can be seen that the pulses have a larger variation at low temperature than at high temperature. The effect is accentuated (enlarged) in Figure 33, for easy cross-correlation with the simulations. The simulation results are superimposed on Figure 33 and shown in Figure 34.

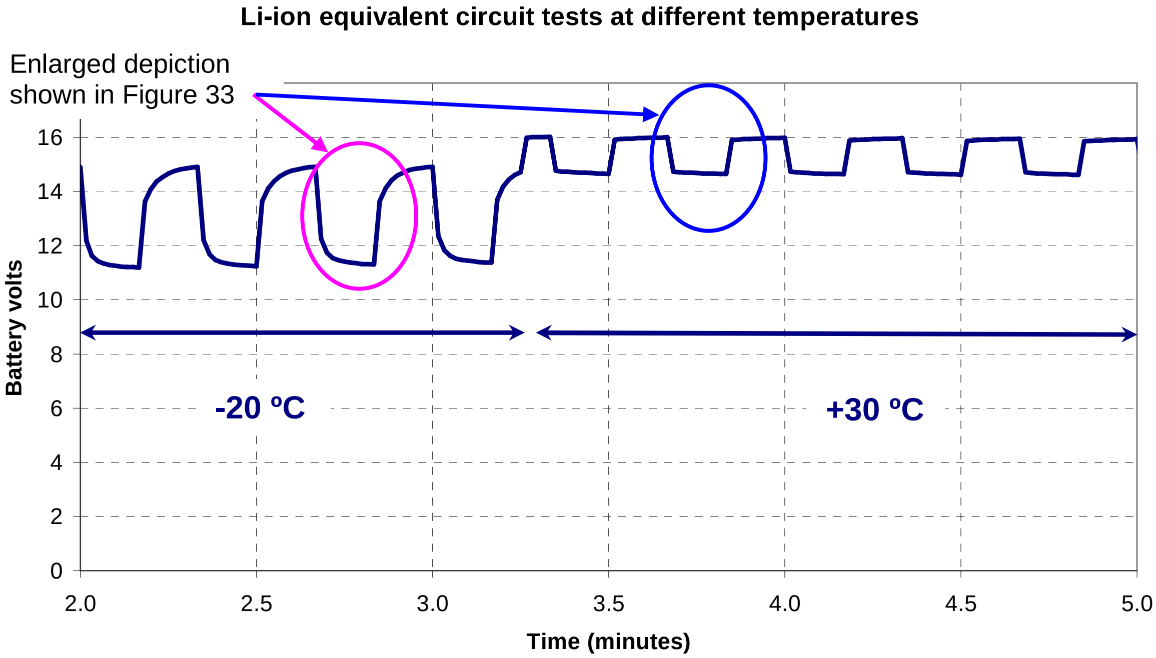

Figure 32: **Measured Li-ion voltage variations as a result of temperature variations during pulsed load**

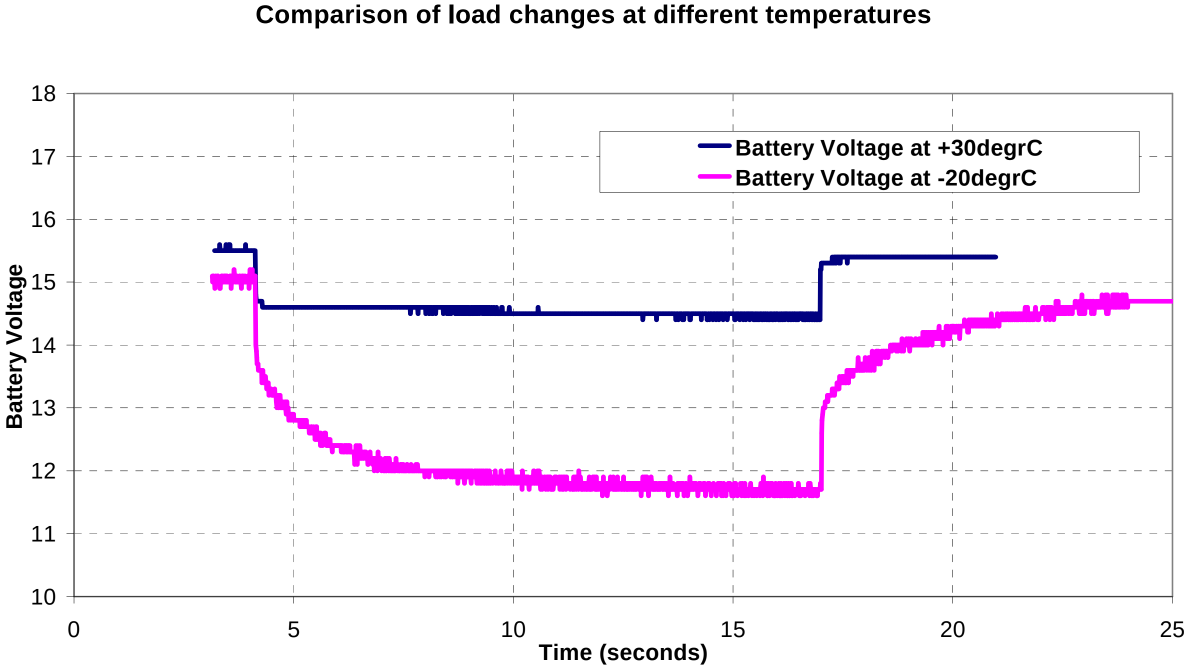

Figure 33: **Measured Li-ion voltage variations as a result of temperature variations during pulsed load, with time axis expanded**

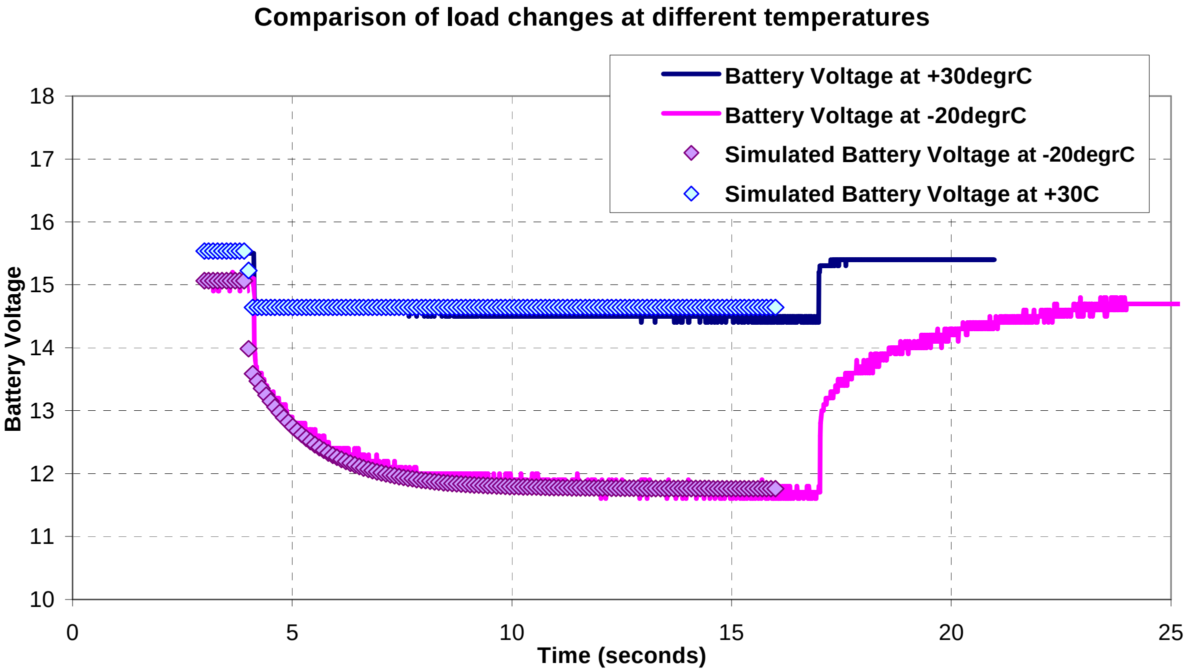

Figure 34: **Simulation results compared with experimental results for a Li-ion battery**

The equivalent circuit (Figure 31) was used in both the high temperature simulations as well as the low temperature simulations to determine which of the components were temperature-dependent. In the high temperature (+30 ºC) simulation the component values were:

R1 = 0.32 Ω
R2 = 0 Ω
C = 0.02 F
Battery Voltage = 15.6 V

In the low temperature (-20 ºC) simulation the component values were:

R1 = 0.7 Ω
R2 = 0.48 Ω
C = 2.1 F
Battery Voltage = 15.3 V

Comparing the battery equivalent circuit values at the two different temperatures, it is reasonable to conclude that all the components are temperature dependent, some more than others, including the ideal battery in the equivalent circuit. An interesting observation is the amount that the equivalent capacitor changes between the two temperatures, which may indicate that the stored energy in the porous plates is larger at low temperatures than at high temperatures, which works in favour of the soldier at low temperatures. However, the total internal resistance increased by an amount which exceeds the advantage gained by increased capacitor value, giving an overall decrease in battery effectiveness.

The changes of the individual components are not linear with changes in temperature, as can be seen by the results shown in Figure 26. The exact equation for the temperature dependency of each component is not calculated for the purposes of this paper.

A noticeable difference between the measured values of voltage in Figure 34, is the fact that the voltage end-value (at the end of the simulation run), is larger than the measured battery voltage. This is attributable to the fact that the equivalent battery was not programmed to drop voltage in the simulation process due to the energy which was expended during the discharge procedure, hence ending with a higher voltage.

3.5. The Fuel Cell

Some programmes are presently investigating fuel cells as a possible alternative to conventional batteries [5]. This study investigates briefly the function of the fuel cell in the role as depicted by Figure 1. In this Figure the attention was drawn to the batteries at points A and B, which formed the main focus of this paper. It would, however, be an incomplete study if other sources were not investigated to augment the battery at point B as a source to charge the battery at point A. It is also reasonable to move the battery at point B to the position at point A, to enable charging the battery (B) with other available sources.

Two such additional sources are Fuel Cells and Solar Panels. This study investigates briefly the role that these two sources would play in the operational and tactical activities of a dismounted soldier.

3.5.1. Fuel Cell general characteristics

Two types of fuel cells which are available on the open market are shown in Figure 35. Commercially available fuel cells are relatively new and therefore it may be expected that the development cycle will continue into the future. The available cells have both advantages as well as disadvantages. The salient advantages are:

One cartridge of methanol fuel will charge a 60 W-h battery approximately 10 times.

The mass of a spare cartridge is much less than one spare battery, making the fuel cell a viable alternative to carrying spare batteries.

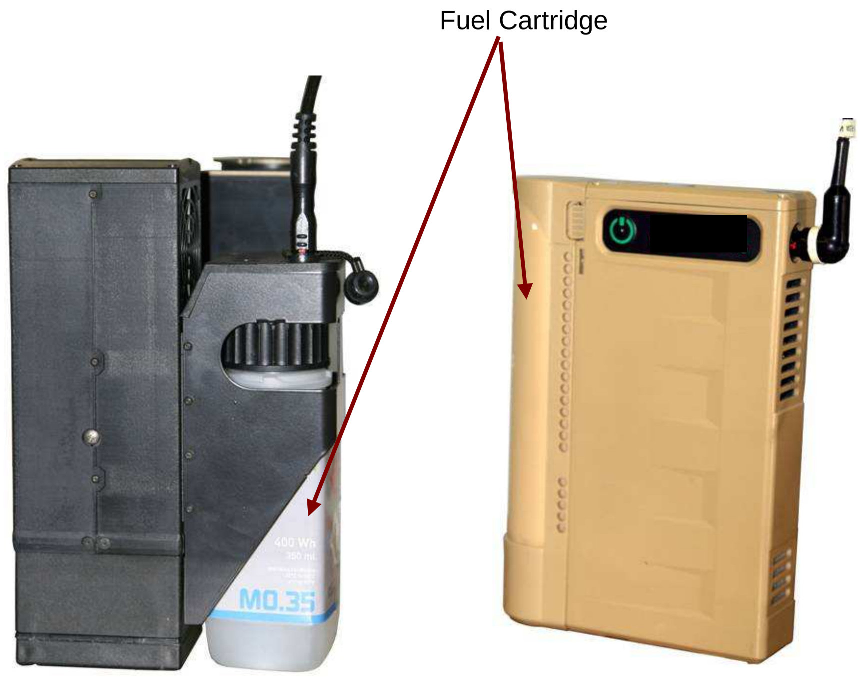

Figure 35: Two of more types of fuel cells available on the open market

The main disadvantages of fuel cells for the dismounted soldier are:

There is a waiting period after fuel cell switch-on before it is ready for use. This waiting period can vary between 5 minutes and 30 minutes, depending on manufacturer.

The fuel cell makes use of a physical pump, driven from its own internal battery, as part of the fuel cell internal mechanics to generate power. This pump makes a certain amount of noise, limiting the available usage area for soldiers who have to keep their position undisclosed in stealth operations.

The general available small fuel cells produce only approximately 25 W of power, and therefore most soldier-carried equipment cannot be driven directly from the fuel cell. It is only used to replenish another battery, i.e. in positions A and/or B in Figure 1, either directly or through the power manager.

In general the voltages available from the fuel cell are programmable between 12 V and 30 V, which limit the number of cells in a battery which are directly charged from the fuel cell. In the cases where the batteries require a larger voltage to be charged (e.g. 8-cell Li-ion or LiPo) one would either have to make use of a power manager (introducing losses) or one would have to charge groups of cells individually (4-cell-groups to be charged individually in the case of a 8-cell battery). This would mean that two fuel cells will have to be carried if charge-time is important, or the charge-time should be doubled in the case of an 8-cell battery.

If, however, the batteries in positions A and B in Figure 1 *are limited by design to a 6-cell LiPo or Li-ion, then the fuel cells which are programmable to 25.2 V would be adequate to charge the battery without intervention of a DC-DC converter, which is the ideal case.*

3.5.2. Source characteristics of the fuel cell

A fuel cell containing internal power management electronics may be programmed to supply the exact voltage which is required for the battery to be charged. Its internal electronics will limit the supply current to the maximum that is available at the programmed voltage.

In the case of a 25 W fuel cell, a 16.8 V (4-cell Li-ion or LiPo) battery could be charged directly at a charge current limited to 1.488 A. This would mean that a 4-cell 4900 mAh LiPo battery would be charged in approximately 3.5 hours to 4 hours, depending on the Coulomb-metric efficiency of the charging system (charger, cell-balancer and battery).

This study found that, on average, the Coulomb-metric efficiency of a commercial charger plus commercial cell-balancer plus a commercial LiPo battery was on average between 80% and 90%, which would mean that the 4900 mAh LiPo battery would be charged to 96% capacity (see Figure 11) in between 3.5 hours (90% Coulomb-metric efficiency) and 4 hours (80% Coulomb-metric efficiency).

To charge a 6-cell LiPo battery using a fuel cell that can produce only 16.8 V, a power manager would have to be used, acting as a DC-DC converter to increase the charge voltage to 25.2 V. This would introduce a further percentage of less than 100% on the system efficiency. E.g. if the power manager is 95% effective, then the charge time would increase to between 3.7 hours and 4.2 hours respectively. Nevertheless, there are fuel cells on the open market which could produce 25.2 V (or more), with which a 6-cell Li-ion or LiPo battery could be charged without the intervention of a power manager and its associated losses.

3.6. The Solar Panel

Solar panels have enjoyed much development attention recently, and soldier-portable panels of 55 W and more are now available on the open market. One such panel was available to investigate its effectiveness of charging the batteries.

A characteristic of most solar panels is their high internal resistance which would be a disadvantage in having to charge the batteries in any fast-charge program. Moreover, the voltage of most man-carried solar panels is only 12 V, which would allow (in most cases) to only charge batteries of typically 9 V or less, if charged directly without a DC-DC converter.

Figure 36: A 55 W solar panel

If the soldier carries more than one solar panel, they could be connected in series, which would allow for the charging of higher voltage batteries.

This paper investigates an interesting application where the soldier only carries one solar panel of 12 V, and a LiPo battery of 25.2 V (6-cell) (Figure 5) has to be charged. This study investigates the possibility of using a DC-DC converter to step the voltage up to the required level with which to charge the battery.

3.6.1. Solar Panel characteristics through a power manager

A 55W solar panel can theoretically supply 4.58 A at 12 V. The incident light, however, would probably change as clouds form, or the daylight starts to fail.

A 55W solar panel was chosen with which to take some measurements. A power manager which was specifically designed with a solar panel port, was used to charge the 4-cell Li-ion battery shown in Figure 6. The battery was pre-charged to 50% using its dedicated charger, before the solar panel was plugged in. The following measurements were taken whilst charging with the solar panel on a cloudy day:

Table 1: Solar panel measurements

Voltage (V)	Current (A)	Power (Watt)
16.12	0.76	12.25
16.36	0.72	11.78

More tests were performed in full sun, using a variable resistor to measure power transfer, and to find a power maximum point. The results are depicted in Figure 37. A curve-fit Equation was applied to both the Current (diamonds) and Power (squares) measurement points. A fit of R^2 = 91% was obtained for a second-order polynomial Equation on the power measurements, and a fit of R^2 = 99% was obtained for a linear Equation on the current measurements, which was expected.

However, the power curve peaked at approximately 14W, which was well below the expected 55W.

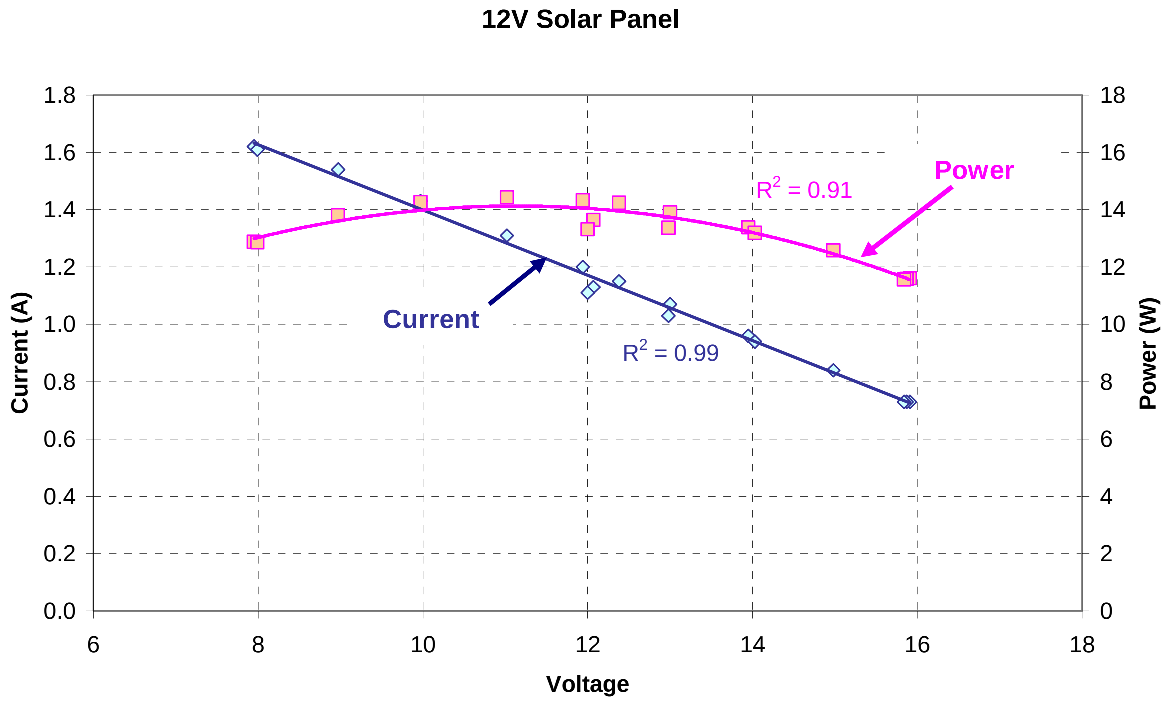

Figure 37: Solar panel power transfer characteristics

A power manager would usually have to form an interface between the 12 V solar-panel and the battery, and would have to be able to manage input voltages from 8 V to the maximum open-circuit voltage of the solar panel. A 25.2 V LiPo battery could therefore supposedly be charged via the power manager at a charge current of theoretically 12V/25.2V*4.58A**Eff*. Table 1 shows that the efficiency on the day of the measurements were only (approximately) 20%. The results shown in Figure 37 suggest that the efficiency would probably stabilise at (approximately) 25% in full sunlight. The total efficiency (if a power manager with efficiency of 95% is utilised) would be lowered to approximately 24% in full sunlight. Using these figures, a battery with voltage of 25.2 V would be charged at 12V/25.2V*4.58A*.24 = 0.52A during its constant current stage.

An effective 0.52 A charge current would charge a 4900 mAh LiPo battery in approximately 9.4 hours to 10 hours, depending on the Coulomb-metric efficiency of the battery. Theoretically a 55 W solar panel is more efficient than a 25 W fuel cell, but the fuel cells usually guarantee their 25 W output, whilst the output of a solar cell is dependent on more factors. As in the case of the tests recorded in Table 1 and Figure 37, the fuel cells would be more efficient than the solar panel which was tested.

Many questions are asked about the internal resistance of a solar panel. One of the methods for the determination of internal resistance is to follow the maximum-power-transfer-law which states that maximum power is transferred at the point where the internal resistance equals the external resistance. Figure 38 shows in graphical form the relationship between external load resistance and transferred power, of which the curve-fitted graph peaks at the point where the external load resistance is approximately 10 Ω, hence it is concluded that the solar panel internal resistance is also 10 Ω.

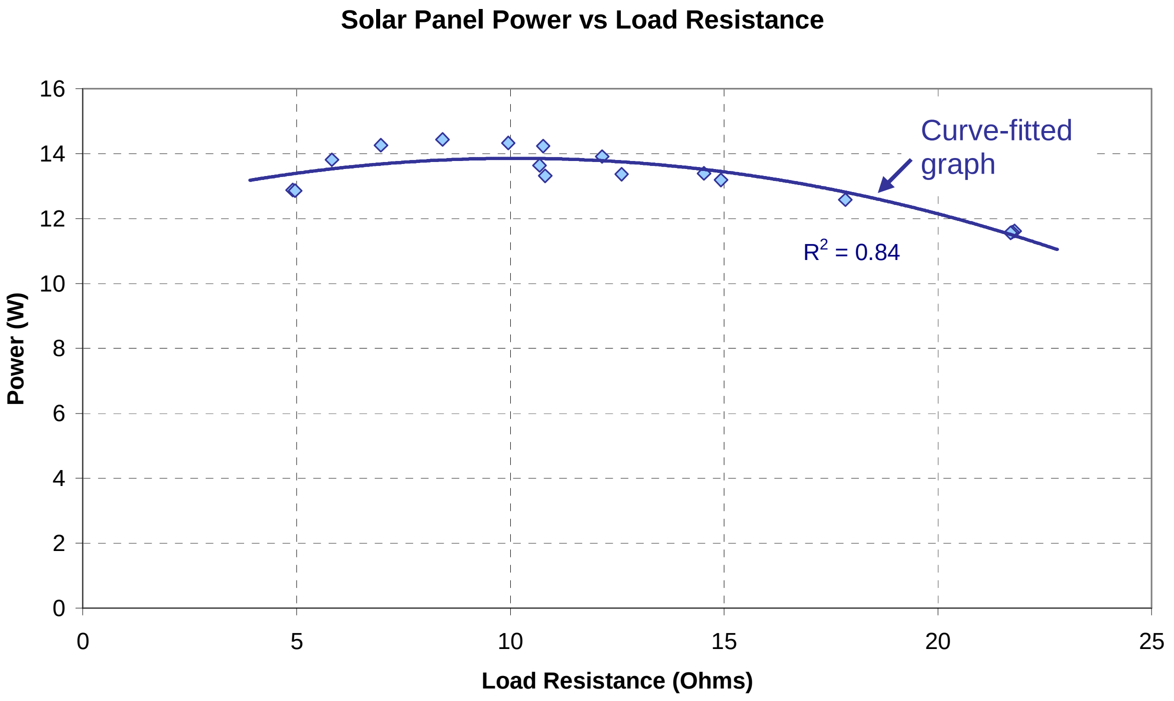

Figure 38: **Determination of internal resistance**

4. Concluding Remarks

In the search for a battery for a tactical radio for the dismounted soldier, the overall characteristics of the Lithium Polymer technology proved in this study to be more applicable than the Li-ion technology as follows:

> The charge characteristics of the LiPo battery are more attractive, because the constant current stage is much longer that the constant voltage stage (see Figure 11), which means that, for the application of the same constant charge current, the LiPo would charge faster than the Li-ion.
>
> The internal resistance of the LiPo battery is less than that of the Li-ion battery over all the tested temperatures (see Figure 26), allowing for the application of a higher voltage during the radio transmission periods.

The LiPo battery (which was tested to be a direct replacement of the NiCd battery) proved to be more applicable than the NiCd battery for the radio application of this study, due to the following:

> The volumetric as well as gravimetric power density of the LiPo battery (see Figure 7) is significantly larger than that of the NiCd battery. More energy is carried in the LiPo battery, which allows for a longer life for the radio before having to replenish the capacity. This also means that the soldier carries less weight for more energy (roughly half the mass and half the volume for twice the energy), when carrying the LiPo battery in stead of the NiCd battery. It must be noted that the battery pack holder should be redesigned to make use of the volumetric advantage.
>
> The charge characteristics have not been compared in this study.
>
> The internal resistance of the LiPo is lower than that of the NiCd at all measured temperatures of this study (see Figure 26), although it is less affected by low temperatures. This means that for the radio application of this study, the transmitted power of the LiPo battery was applied for approximately 180% longer than that of the NiCd battery, and was maintained higher than that of the NiCd battery for 225% longer (see Figure 29).

The LiPo and the NiCd batteries have not been simulated to determine their equivalent circuit characteristics at varying temperatures.

The charge characteristics at the extreme temperatures were not investigated.

The time allowed for this study did not allow for extensive testing of power sources. Only qualitative remarks were recorded, based on little experimentation. It seems, however, that all sources should be tested extensively to determine their applicability in the military milieu. It is advisable for the dismounted soldier to carry both fuel cells as well as solar panels. The logistic burden would be lightened if the sources could be shared among small groups.

The Li-ion battery outperforms both the LiPo as well as the NiCd batteries with respect to the characteristics of volumetric and gravimetric power density. This is an attractive feature for the dismounted soldier in applications such as GPS systems when it is required to supply low currents for long periods of time.

By comparison of the results shown in Figure 18 with the results shown in Figure 24, it is shown that the voltage drop during the low-current cycles (point “A” in both figures) is less for Li-ion than for LiPo at the low-temperature extreme. This means that at low current loads and at all temperatures, it would be more advisable to utilise a Li-ion battery than a LiPo battery due to its better energy density characteristics.

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