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Energy sources for the future dismounted soldier, the total integration of the energy consumption within the soldier system

Jillis W. Raadschelders[a,*], Tiny Jansen[b]

[a]*Department of Energy Technology, TNO-Environment Energy and Process Innovation, P.O. Box 3427300, AH Apeldoorn, The Netherlands*
[b]*Royal Netherlands Army, Army Staff, Directorate of Policy and Planning, Soldier Modernisation Programme,*
Bernhard kazerne Barchman Wuytierslaan, 198 3818 LN Amersfoort, The Netherlands

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Abstract

At present, the energy supply for the electronic equipment of the soldier is problematic. Each component has its own battery pack. These battery packs are not interchangeable and each requires its own charger. Furthermore, because they are all dimensioned to deliver the 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. An energy bus will be integrated within the soldier's system for this. The different components will generate their required voltages from the bus voltage by using high efficiency dc/dc converters. The use of an energy bus with local voltage conversion will facilitate interoperability between different forces. The energy sources can easily be exchanged.

For the near future, batteries are still considered to be the best option for the energy source. Rechargeable batteries are preferred above non-rechargeable ones due to logistic and environmental problems. For the long-term replacement of batteries, the direct methanol fuel cell (DMFC) is considered a viable option.

Several different battery packs were tested for their capability to supply both the required energy and power during a 24 h mission. The tests were carried out with a controlled power method, as maximum power should be deliverable during 10% of the operation time.

Keywords: Applications/portable military equipment; Energy sources/choosing; Fuel cells/direct methanol; Portable batteries

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1. Current operational system

Presently, soldiers of the Royal Netherlands Army (RNLA) as well as many other armies are equipped with an operational package of "separate best systems". The RNLA has always adopted a policy of purchasing the best available option for specific systems.

For the energy supply this has resulted in a situation with the following disadvantages.

- A variety of systems, each with its own energy source.
- The soldier has to carry several different batteries — which battery belongs to which system?
- Infrastructure — various types of batteries must be in storage and distributed in the field.
- Within each component, the current/power management systems are mostly low efficiency variable resistances. These resistances convert the excess voltage of the energy sources into heat.

2. The challenge of an integrated system

This challenge may be defined as "To integrate all the different energy requirements into one, light weight, modular energy source for the future dismounted soldier".

So, one energy source powers all the different components (Fig. 1). The soldier is equipped with an energy bus. This could very well be integrated with the communication network also under development at TNO. The bus is supplied by different energy sources, operating at a set voltage. The different electronic components required by the future soldier are connected to this energy bus. Within each component the current/power management system, is replaced by a highly efficient dc/dc converter.

Representative energy/power requirements in the future for the Dutch dismounted soldier are

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[*] Corresponding author. Tel.: +31-55-549-37-38; fax: +31-55-549-37-40.
E-mail address: j.w.raadschelders@mep.tno.nl (J.W. Raadschelders).

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Operation time	24 h
Energy consumption	400 Wh
Power	0–45 W

The expected duration of maximum power is 10% of total operation time in periods of 1, 2 or 3 min.

3. Advantages of an integrated system

3.1. Inter-operability

Due to the ever increasing participation of the RNLA in international operations (NATO, UN) the RNLA has a need for inter-operability of its soldier system with those of other countries. The concept of the energy bus with local high efficiency dc/dc converters enables easy exchange of energy sources. The only demands laid down on each possible energy source are

- operating voltage within the possible input window of the dc/dc converters;
- connector compatible with the connectors used for the energy bus.

3.2. Operating temperature window of the energy source

The required temperature window has until now been going as low as −40°C. There are virtually no rechargeable batteries which can meet this without losing a significant part of their rated capacity at 20°C.

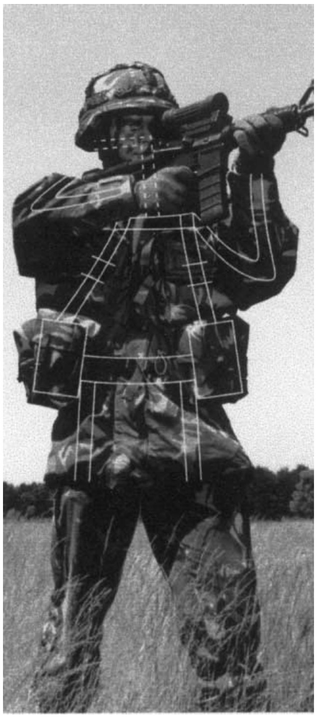

Fig. 1. Integration of power requirements on the future soldier.

The energy grid concept allows the positioning of the energy sources at any place in the soldier's system. If this place is chosen close enough to the body heat might be sufficient to keep the operating temperature of the energy source above 0°C or even above +10°C.

3.3. Energy source changes during missions

With the present system, each component has its own energy source, with its own operating time. This means that at different time intervals the soldier has to change the energy source of a component. During this operation, the soldier is inactive/not using equipment and also the component is inactive. The future soldier system circumvents this problem by utilising a central energy source.

3.4. Gradual implementation of the system

The implementation of an energy network can be done gradually. There is no need to replace all systems which are currently in use. Only the replacement of the power management system is required. This also does not have to be done all at once. The energy network can be used together with all the operational systems.

3.5. Grid/bus voltage

The voltage on the energy grid will vary with energy consumption. The possible operating window depends on the input voltage window of the converters being used, or vice versa!

The efficiency of the converter depends on its input voltage and input voltage window.

General dc/dc converters in high volume production have input windows of between 9 and 18 V or even between 9 and 36 V. This allows the use of four, series connected, Li-ion cells, to give a 16.8–11.0 voltage window (4.2–2.75 V per cell).

4. System electronics

Prior to leaving for a mission, the soldier connects all the energy sources he requires for his mission. The system connects only one energy source directly to the bus, only one being used at a time. After the first one is empty, or fails, the system switches to the next energy source. This will prevent the future soldier from returning with half empty battery packs. Instead, the soldier will have both empty and full battery packs if he returns early from his mission. LED indicators will show which battery packs should be changed and which ones have not been used.

The regulating electronics of the energy network have to fulfil several requirements.

- Uninteruptable power supply to the energy bus.

- Single operating energy source.
- Automatic switching between energy sources.
- Protection of energy sources.
- Minimal energy consumption.

When the energy source that is connected to the bus fails, instantaneously the system electronics have to be able to maintain a minimum voltage on the bus. Switching times of state-of-the-art relays are too long to prevent a reboot of computer systems. For a normal decrease in the output voltage of an energy source, the system can switch to another source before the first reaches its lower operating point.

To avoid having all battery packs half empty, only one may be used at a time. The monitoring of the batteries is made easy since they have comparable duty cycles.

The switching between energy sources must be done automatically. This avoids distracting the soldier at inconvenient moments.

The life cycle of rechargeable batteries decreases when they are discharged too far. The electronics have to disconnect the packs before this happens. A manual override may be introduced for emergencies. The electronics are to be designed to minimise energy consumption of the total system.

4.1. Power management of components

To be able to introduce this soldier systems energy network, several alterations to the existing equipment are required. The power management sections of the different items presently in use have to be replaced. The new power management sections will have to consist of at least a dc/dc converter and an emc filter. The dc/dc converter might have to have multiple output voltages if more than one operating voltage is required within an equipment.

5. Possible energy sources

The "energy sources" project began with the selection of possible energy sources for the dismounted soldier.

The following points of consideration were used to select the possible energy sources:

- weight;
- volume;
- stage of development;
- different signatures on the battlefield (sound, radiation, thermal).

By not meeting these requirements, a thermophotovoltaic system operating at 2000°C, the quasiturbine or a small nuclear power plant are considered not to be realistic options. Also noisy transportable generators, mostly of >100 W output, were not put on the list of realistic options, as well as human power and some other less realistic options.

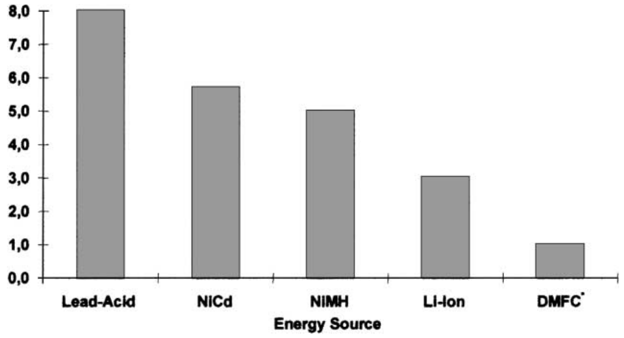

Fig. 2. Weights of rechargeable energy sources for a 24 h mission.

This led to the following short list of possible energy sources (Fig. 2):

- for the near future batteries are still the desired energy sources;
- for the long term future fuel cells are considered to be able to replace most batteries.

Our conclusion from this survey is that the direct methanol fuel cell (DMFC) is the expected long-term solution.

5.1. Batteries

For the near future, batteries are still the energy source of choice. Rechargeable batteries are preferred above non-rechargeable ones due to the logistic problems with non-rechargeable batteries. The recharging is more easily dealt with, and in most cases logistic fuels are used to power the battery chargers. However the specific energy (Wh kg^{-1}) of non-rechargeable batteries is generally higher than that of rechargeable batteries.

5.2. Fuel cells

In the long term, in a number of applications, batteries are expected to be replaced by fuel cells or combinations of both.

The fuel cell for the soldier application can be either a solid polymer fuel cell (SPFC) or a direct methanol fuel cell Fig. 3, using, respectively, hydrogen and methanol as fuel. Other fuel cell types are not suitable due to their high operating temperature.

The fuel cell principle enables a separation between power and energy. The maximum required power determines the size of the fuel cell, the required energy for a mission determines the amount of fuel to be carried. The specific power (W kg^{-1}) of the SPFC is roughly twice that of the DMFC. This means the DMFC will be twice the size and weight than that of the SPFC, for the same power output.

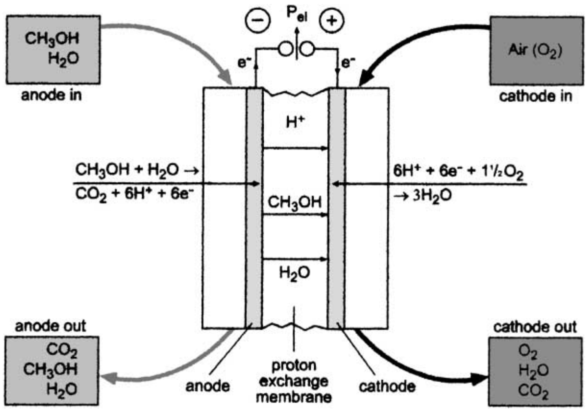

Fig. 3. Schematic representation of the reactions in the direct methanol fuel cell.

Table 1
Properties of fuel

Fuel	Specific energy (Wh kg^{-1})	Density (kg dm^{-3})	Energy density (Wh dm^{-3})
Methanol	5500[a]	0.8	4400
Hydrogen (pure)	32800[a]	8.9×10^{-5}	2.94
Hydrogen (pressurised)	<350		
Metal hydride	<600		

[a] These values do not include auxiliary equipment.

Hydrogen can be packed either as liquid, pressurised or as a metal hydride. Methanol is a liquid and has a very high specific energy (Wh kg^{-1}), see Table 1.

6. Problems with fuel cells

For the long term, a partial replacement of the batteries by fuel cells is expected, but they have some specific challenges, besides the technical ones.

6.1. Air supply to the fuel cell.

When a soldier operates within wet areas, the air supply to the fuel cell may be temporarily blocked. This would stop the energy supply to all of the components of the soldier system. One possible solution would be to utilise small rechargeable battery packs to overcome these periods of air supply blockage.

This introduces the requirement for a sophisticated electronic circuit. The fuel cell voltage window is rather large — compare 4.1–2.75 V for a single Li-ion cell.

6.2. Methanol fuel

Hydrogen, in any of the storage methods, is not considered a viable option for fuel supply. Methanol is a liquid and therefore can be easily stored and transported. In some countries it is used as car fuel (sometimes mixed with gasoline). However, methanol is toxic and must not be consumed.

7. Experimental testing

On the basis of the short list of options, a test programme was developed to obtain insight into the performance and problems to be expected from the use of batteries and, in a later stage, fuel cells. The experiments were carried out with Digatron BTS600 battery test equipment, so enabling us to use fully reproducible test sequences. The computer can control current, potential and power, both for charge and discharge. The test profiles are scaled to the nominal energy content of the tested battery packs.

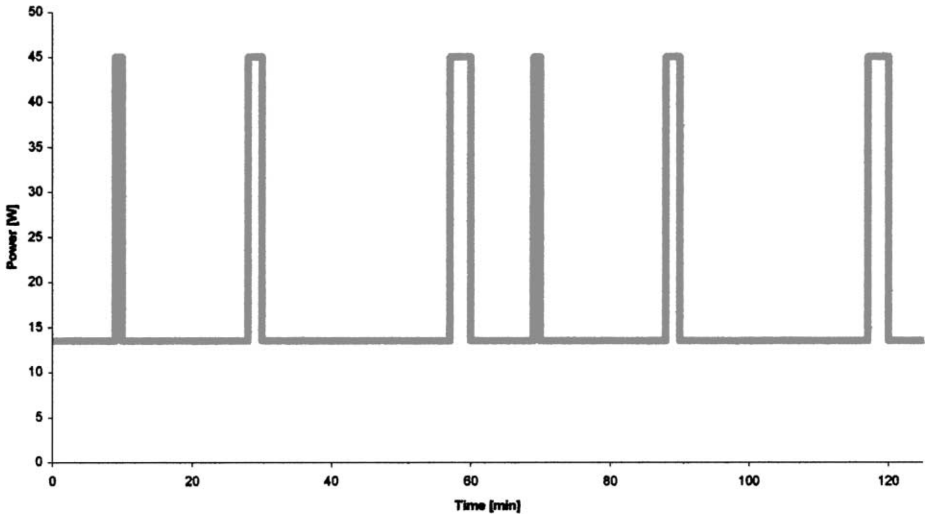

Fig. 4. Load profile for SMP application. 13.5 W continuous, plus three distributed single 21.5 W pulses of 1, 2 and 3 min duration every hour.

Table 2
Battery packs tested[a]

Battery chemistry	Non-rechargeable (NR/R)	Cell capacity (Ah)	Cell voltage (max–min) (V)	Battery capacity (Ah)	Battery voltage (V)	Battery energy (Wh)	Battery weight (kg)	Specific energy (Wh kg^{-1})
Alkaline	NR	10	1.3–0.7	10	8.0–3.5	80	0.70	114
Li–$SOCl_2$	NR	13	3.7–2.0	39	7.4–4.0	280	0.60	465
Li–SO_2	NR	7.5	3.0–2.0	37.5	15.0–10.0	560	2.30	245
Li-ion[b](1)	R	5.5	4.1–2.7	5.5	16.4–11.0	80	0.60	135
Li-ion(2)	R	5.0	4.2–2.7	5.0	16.8–11.0	70	0.50	144

[a] The values in this table are the nominal values, supplied by the manufacturers.

[b] These Li-ion cells showed peculiar behaviour after cycling at −10°C and tests were stopped with these battery packs.

Table 3
Weights of the battery packs[a]

Battery	Weight (kg)
Alkaline	3.50
Li–$SOCl_2$	0.86
Li–SO_2	1.51
Li-ion[b](1)	2.96
Li-ion(2)	2.78

[a] These numbers do not include any packaging, protection or external wiring of the battery packs.

[b] These Li-ion cells showed peculiar behaviour after cycling at −10°C and tests were stopped with these battery packs.

The operational requirements for the future soldier system (SMP), led to the repetitive power versus time test profile shown in Fig. 4 (see Table 2).

The nominal values for the specific energy of the different batteries are used to calculate the required battery weight for an energy content of 400 Wh (see Table 3).

The rechargeable battery packs are full-scale test packs. They have an operating voltage of 16.8–11.0 V, and should be capable of delivering the maximum power requirement of 45 W, required by the SMP system. The energy content of the battery pack determines how many repetitive 1 h discharge cycles (Fig. 3) it can, or should be able to, deliver. Other batteries are being, or will be tested in the near future. Results will be presented when they will be available.

8. Results

8.1. Charging and discharge capacities of the rechargeable battery packs

Capacity tests have only been done with the rechargeable battery packs. The non-rechargeable batteries were only tested with the actual load profile. The following capacities were obtained (see Table 4).

Both charging and discharging was done at the stated temperatures. Future tests of the discharge capacities at different temperatures will include charging at room temperature. Several battery manufacturers do not recommend the charging Li-ion batteries below 0°C. Fig. 5 shows the room-temperature performance of a single Li-ion cell from manufacturer 1, at constant current loads between 1 and 5 A.

8.2. Voltage–time profiles obtained during the SMP test

8.2.1. Room temperature (20–25°C)

The Li-ion battery pack from manufacturer 1 was able to deliver the required power, 13.5 W continuous and 45 W pulsed, for 4 h. A total of 4.5 Ah and 67 Wh were supplied by the pack in that period, 84% of its nominal capacity.

The Li-ion battery pack from manufacturer 2 was able to deliver the required power for a little over 4 h. A total of 4.8 Ah and 69 Wh were supplied by the pack in that period, 96% of its nominal capacity.

Table 4
Performance of Li-ion batteries at different currents and temperatures

Discharge current (A)	−10°C Li-ion(1)		0°C Li-ion(1)		20–25°C Li-ion(1)		20–25°C Li-ion(2)	
	In Ah	In Wh	In Ah	In Wh	In Ah	In Wh	In Ah	In Wh
1	4.16	13.8	5.17	19.0	5.58	21.1	4.79	17.5
2	3.97	13.0	5.03	17.9	5.60	21.0	4.87	17.6
3	3.60	11.7	5.18	18.1	5.60	20.7	4.86	17.2
4	3.36	10.7	5.17	17.8	5.59	20.5	4.85	16.8
5	3.25	10.2	5.15	17.5	5.57	20.2	4.83	16.4

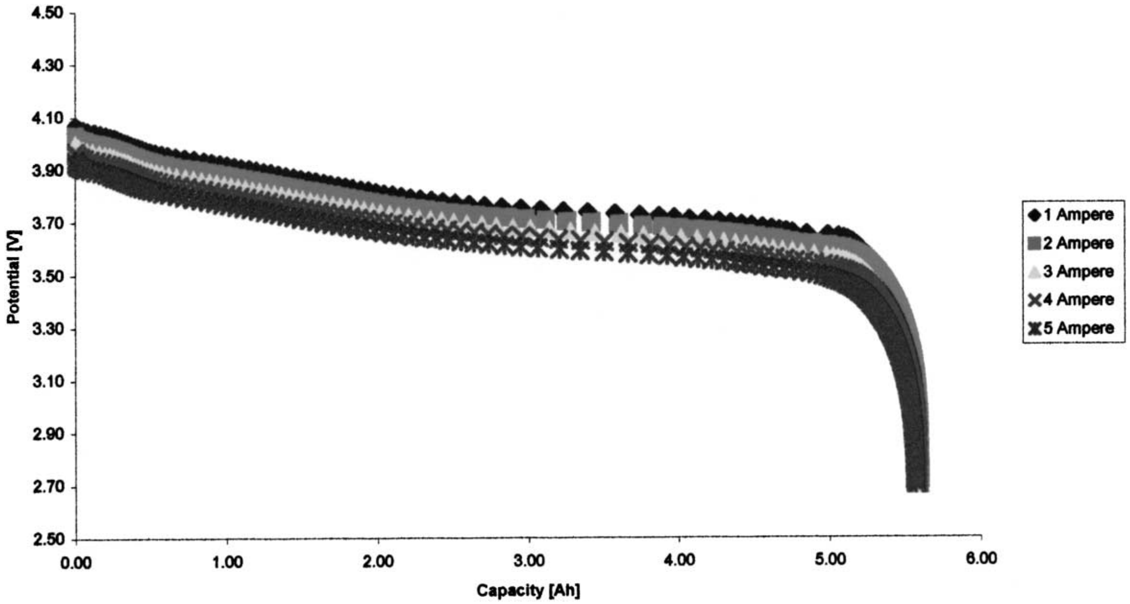

Fig. 5. Voltage vs. withdrawn capacity for different discharge currents from a Li-ion(1) cell.

The alkaline batteries were capable of supplying energy for 10 h under load. The maximum power obtained was 7 W (three-seventh of the continuous load profile). Total delivered energy and capacity was 32 Wh and 5.5 Ah. The nominal values were 75 Wh and 10 Ah. So, only 42% of the theoretical energy was released.

The Li–SOCl$_2$ battery showed very poor rate capability. The power rating of the test profile had to be scaled down to a 7 W continuous/20.5 W pulse profile. The pack was able to supply energy at this rate for 15 h. Total delivered energy and capacity was 125 Wh and 19.7 Ah. The nominal values were 280 Wh and 39 Ah. So only 45% of the theoretical energy was released.

The Li–SO$_2$ battery pack had an extremely flat voltage profile. During the required 24 h of the SMP cycle it showed no significant voltage decrease (Fig. 6). However, the battery pack was over-rated at 560 Wh instead of the required 400 Wh. In consecutive 30 h, it delivered 500 Wh, so 90% of the theoretical energy was released. The Li–SO$_2$ battery also showed good performance at the maximum power level.

8.2.2. Low temperature

The Li-ion battery pack(1) was able to deliver the full-required power, 13.5 and 45 W for 2 h at −10°C. A total of 2.5 Ah and 33 Wh were supplied by the pack in that period,

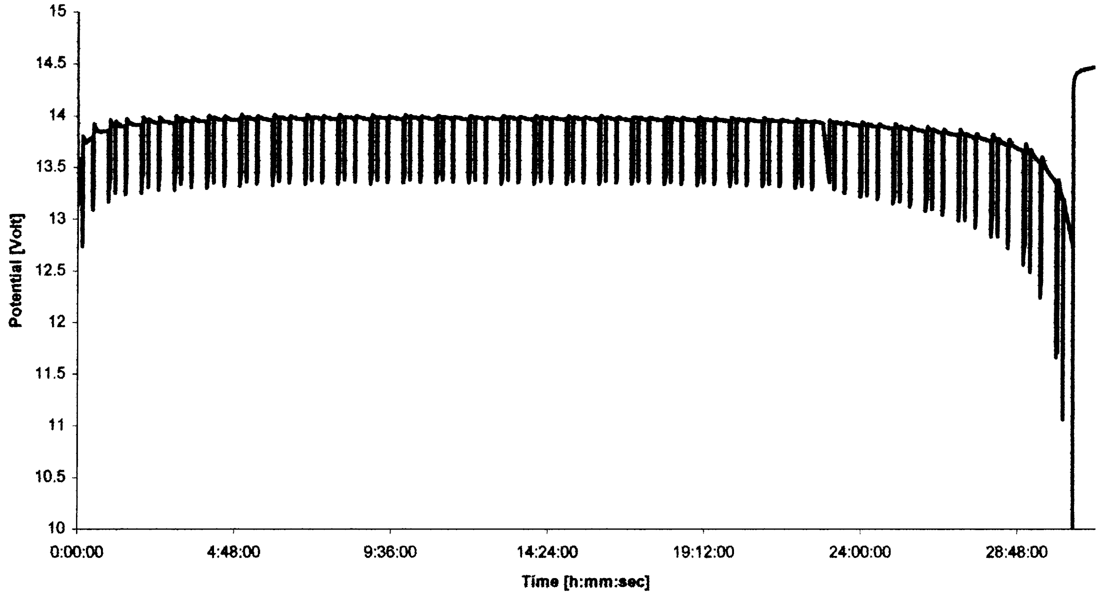

Fig. 6. 12 V, 37.5 Ah Li–SO$_2$battery pack discharged at room temperature to the SMP profile of Fig. 4.

42% of its nominal capacity. That is only 50% of the energy released at room temperature. The pack showed dimensional changes after charging at −10°C and the tests were stopped.

9. Future research

The Li-ion packs will be tested for their performance at low and high temperatures. Charging at low or high temperatures will be investigated and also the effects of charging at room temperature followed by discharge at low or high temperature.

We will be testing the battery packs at different temperatures to determine their cycle lives. Discharge will be carried out to the SMP profile and charging according to the charge regime given by the manufacturer.

Decrease in capacity and rate capability will be monitored by capacity tests at various constant currents. A first version of the electronic power control unit will be tested in 2001. Integration of actual soldier equipment with the energy grid is also scheduled for 2001.

The possible operating conditions of the energy source will be determined in close co-operation with the TNO institutes involved in the development of different soldier system components. Special attention will be given to the operating temperature and the possibilities for influencing its lower limit.

10. Conclusions

The integration of the energy consumption of the soldier system has several advantages.

- Each separate component can become lighter and smaller, the energy source can be placed more comfortably, the soldier has less concern about the changing of batteries for all his systems. The total energy consumption of the system can be reduced by implementing high efficiency power management (dc/dc converters) within the separate components, hence reducing the amount of energy the soldier has to carry.
- National Forces are more and more faced with international operations. The principle of the energy network for the future dismounted soldier would enable more interoperability between European and International forces. The system requires only small stepwise changes towards operational systems, not complete replacement at one time.
- It enables easy modernisation of equipment in the future.
- The specifications for the energy source allows the use of a wide variety of possible energy sources. On the other hand it also enables more and more uniformity in the operational energy sources.
- Batteries are still considered the best option for the near future. Rechargeable ones are preferred. For the long-term future it is believed that the direct methanol fuel cell holds enough promises to become a viable option. The use of liquid methanol on the future battlefield is considered more realistic then using hydrogen, in any form.
- Batteries, or any energy source, for the energy network have to comply with only a few specifications: (a) Their operational voltages must lie within the input voltage window of the dc/dc converters used. (b) They must be able to deliver both the power and energy required by the specifications.

The experiments showed good performance of the two Li-ion battery packs at room temperature. However their capacity dropped significantly at lower temperatures, where charging becomes problematic. Charge time increases highly and one of the Li-ion battery packs showed dimensional changes after being charged at −10°C.

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