EVS24
Stavanger, Norway, May 13-16, 2009

Application of a mechanical methodology for lithium-ion battery life prediction

C. Dudézert[1,2,3], P.Gyan[1],S. Franger[2], Y. Reynier[3], H. Burlet[3]
[1]*Renault, Technocentre, Guyancourt, France, Christophe.dudezert@renault.com*
[2]*Université Paris XI, Orsay, France.*
[3]*CEA/LITEN, Grenoble, France.*

Abstract

Reliability of energy storage devices is one of the foremost concern in hybrid electric vehicles (HEVs) development. Battery ageing, i.e. the time dependent degradation of battery energy and power, depends on the in-use solicitations endured by the storage system. Therefore, the connection between solicitations and battery life must be analysed and modelled to match battery in-service life with the car lifetime. Large variation in cycling duration and amplitude make life prediction an intricate issue.

Mechanical physicists have developed a quick and exhaustive methodology to diagnose reliability of complex structures enduring complex loads. This "fatigue" approach expresses the performance fading due to a complex load based on the responses due to basic loads. A performance fading variable named "damage" combines the load history endured by the system and its state of life.

The battery ageing study described in this article consists in adapting this mechanical approach to complex electrochemical systems. The test protocol has started with the definition and the application of basic electronic loads to commercial batteries. Regular diagnosis called "check-up" has recorded the performance fading from impedance and capacity measurements. The "check-up" analysis has underlined the sensitive parameters particularly impacted by solicitations. Eventually, the influence of the basic loads combination on the sensitive parameters evolution is established.

Keywords: Reliability, Fatigue, Battery life, Loads, Performance fading, Lithium Ion, Test protocol.

1 Introduction

1.1 Industrial context:

To develop electric vehicles (EV or HEV), car manufacturers must meet three main requirements that are the cost, the performance and the safety of their electrical devices. In that view, the knowledge in battery ageing mechanisms and kinetics ensure the performance and the security sustainability of the battery pack during the vehicle use. Moreover, the battery ageing expertise leads to optimize the battery pack sizing and thus to minimize the energy on board and the cost of the storage system. Consequently, battery ageing appears as a major issue in the electric or hybrid vehicle development process.

1.2 Technical context:

Most of current studies [1] focus on detailed description of the mechanisms responsible for electrochemical system performance fadings. This microscopic view does not establish a connection between specific solicitations and performance fading. However, as simplified in Figure 1, information on the impact of the solicitation on battery performance fading seems to be a key data to match the effects of the driving cycle to the electric system life and then define the optimum battery pack:

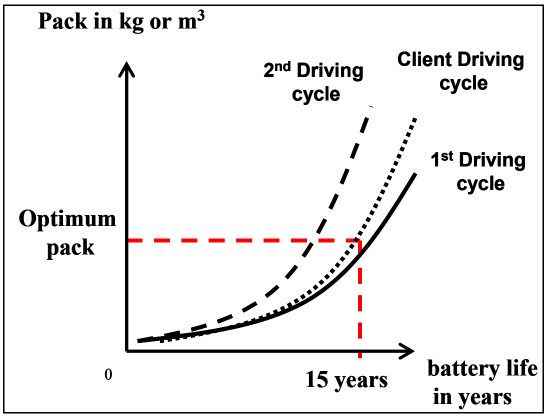

Figure 1: definition of the optimum battery pack as a function of the battery life and the driving cycle

Moreover, an accurate knowledge of the battery sensitivity to solicitations would allow to identify high life consuming solicitations and to generate adapted battery management strategies.

1.3 State of the art:

1.3.1 The Freedomcar consortium:

The main large-scale study dealing with the influence of the cycling phases on battery ageing has been led since 2001 by the Idaho National Laboratory and the Argonne National Laboratory through FREEDOMCAR project [2]. This project has built its cycling phase analysis from some arbitrary automotive specifications which consisted in defining battery cycling life as the battery ability to ensure 300,000 cycles with 240,000 cycles at 60% of rated power, 45,000 cycles at 80% of rated power and 15,000 cycles at 95% of rated power. On the whole the consortium issues can be split in three main tasks.

First of all, the study has consisted in designing an experimental accelerated cycling protocol [3], [4] able to assess any battery technology cycling life. From this protocol, the battery technology ageing performance [5] is quantified through the assessment of several ageing factors measuring the kinetics of the battery performance fading. Actually, these factors also named accelerating factors (AF) characterise the impact of a solicitation on battery life.

The innovative aspect of this method comes from the close connection between the accelerating factors definition and the mechanics reliability theory.

The works described in this article follow this way to adapt accelerated cycling ageing procedure to battery cycling life study.

The second main task developed by FREEDOMCAR partners was the development of a battery life prediction tool. Its structure is mainly based on the evaluation of the accelerating factors introduced above and their arbitrary combinations as a function of the cycle specifications [3].

One of the issues developed in this paper is precisely the characterisation of the solicitation combination as regards to the ageing impact.

The third task was the elaboration of a Monte Carlo simulation tool as a validating statistical tool [3]. This tool attempts to assess the complete battery pack life from the previous battery life tool and some cell to cell variability considerations.

On the contrary our study has been scaled for a single cell view.

The FREEDOMCAR project eventually succeeded in establishing a global study structure to quantify the battery reliability as regards to the cycling impact. It has been chosen to keep the main experimental considerations for building our protocol. However, in our case, the ageing modelling due to a combination of different conditions will be based on experimental observations.

1.3.2 Cycle counting:

Although the Freedomcar works were focused on the application of a set of repeated solicitations, no relation has been established between the number of cycles applied and the battery life. Actually, the cycle counting which characterises a fatigue-like view had begun with studies led by the Ohio State University [6]. These works assert the adaptation of the mechanical theory to electrochemical systems. They particularly recommend defining a basic cycle from its nature in terms of depth of discharge, current profile and temperature. However, little experimentations on Li-ion systems have been realized yet from these theoretical recommendations. This paper describes a first experimental confrontation of this basic cycle based theory.

2 Common issues with mechanics:

Establishing reliable battery life estimation for systems undergoing complex loads presents similarities with studies developed in mechanics to determine structure reliability. In that way, metal fatigue method has been built to estimate empirically failures due to cyclic loads. As described in Figure 2, the fatigue methodology consists in expressing system life as a function of the solicitation level.

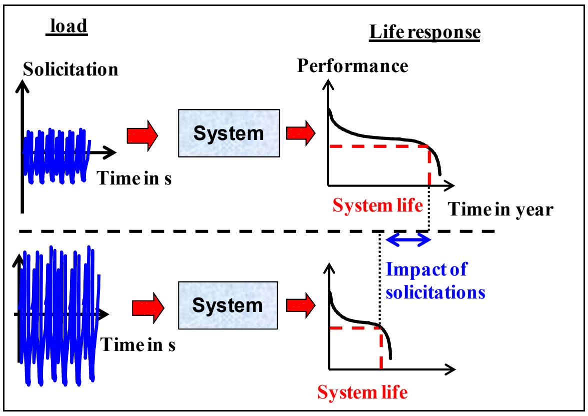

Figure 2: description of the fatigue-like load studies

Battery systems are complex materials which are likely to endure complex loads in case of EV or HEV applications. The fatigue approach which focused its analysis on solicitations seems relevant as regards to our application.
The approach described in this paper attempts to follow the same methodology and adapts it to electrochemical systems.

3 Adaptation of the fatigue methodology:

3.1 Load analogy:

3.1.1 The mechanical damage:

The mechanical theory is mainly based on the repeated application of a basic load on materials. This load is physically transmitted through a force (F) to the system. From the system point of view, this force (F) is endured through its active area (S). In this way, the system is subjected to a stress (σ) which represents the distribution of the force through the active area (σ=F/S). Due to cyclic loading, the mechanical system ages. This ageing is associated to a loss of mechanical properties due to a decreasing of the active area caused by an expansion of damaged zone (cracks nucleation and coalescence). The mechanical fatigue theory eventually gathered the internal irreversible evolutions through the notion of damage closely associated to the active area evolution. Damage refers to the state of life of the system through a physical consideration like active area.
Similarly (Figure 3), the current load might be seen as the solicitation imposed by the operator to a battery system. The application of a repeated current load impacts the internal properties of an electrochemical system. Then, the electrochemical damage can be identified experimentally by measuring the irreversible evolutions and try to bind them to the solicitations imposed.

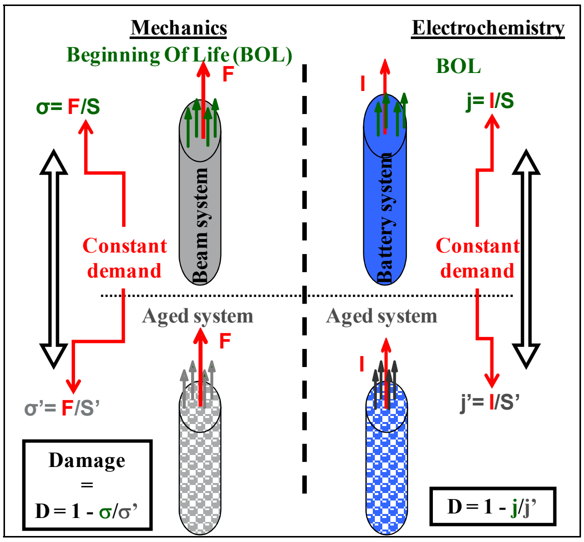

Figure 3: analogy between mechanical load and electrochemical load

3.2 Definition of the basic load:

As explained previously [7], the definition of a basic solicitation is necessary to perform a fatigue-like study. Practically, it implies a current load defined as simple as possible and characterised by a few set of parameters (Figure 4)

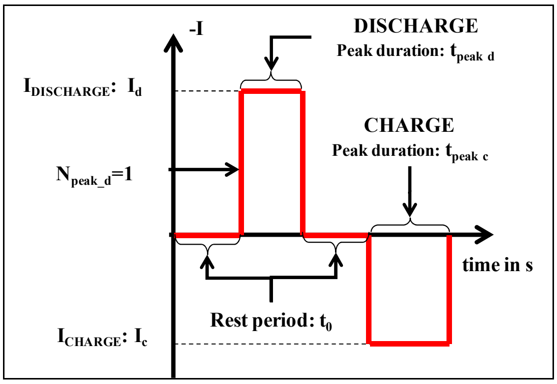

Figure 4: definition of a basic load named "microcycle"

As introduced in a previous publication [7], this basic load also named "microcycle" ensures a reliable control of the battery cycling. Thus, an accurate sensitivity study can be established.

4 Experimental procedure:

4.1 Cell description:

Two sets of commercial cells provided by the same battery-maker have been tested. They are both composed of a lithium titanium oxide anode and a lithium manganese oxide cathode (LTO/LMO) with a capacity of respectively 5Ah and 2Ah. These sets of batteries enable to evaluate whether the battery size have an impact on the ageing kinetics and mechanisms. Afterwards, the battery size consideration is named the "scale effect".

4.2 Factors of solicitation:

4.2.1 Temperature:

The main effect of a temperature rise is a decrease of the activation energy and an increase of any chemical reaction kinetics. [8] This phenomenon generates a double time-scale effect:

- It speeds up electronical exchanges as well as diffusion processes for reactions responsible for current generation. This effect is combined with a global improvement of conductivity. These short-term effects increase battery efficiency.
- It enhances parasitic reaction rate and increases consumption of Lithium by formation of inactive products. This long-time scale effect leads to impedance rise and capacity fading which are both commonly named ageing.

Temperature is the most influent external parameter in terms of ageing. This parameter can be controlled with a climatic or thermal room. In our case only two temperature levels have been tested: 35°C and 45°C.

4.2.2 Current level:

Among a wide range of sensitivity factors, the current level appears as the simplest in terms of test bench control. Three basic cycles have been defined in Figure 5. They are named respectively "I_30C", "I_15C" and "I_10C. They exchange exactly the same charge amount (~3% of the rated capacity) but at three different current level.

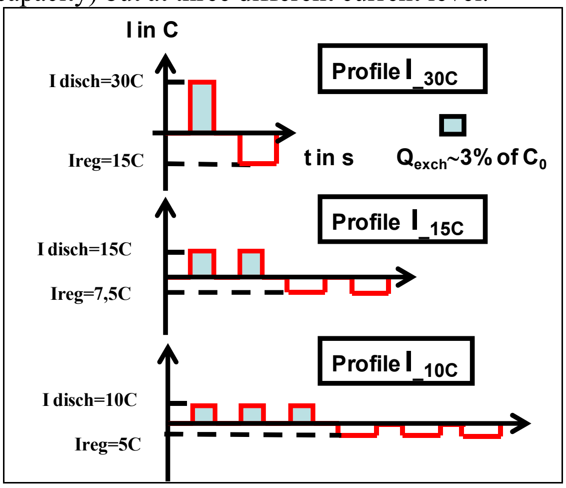

Figure 5: definition of the current profiles

All these profiles keep the charge balancing constant. It means the charge throughput exchanged in discharge mode is the same as the one exchanged in charge mode. Charge balancing is an easy way to stabilize load cycling to a constant average state of charge (SOCm). It seems to be necessary when SOC is considered as a main ageing factor [7]. All the calendar and cycling tests have been realized around a constant state of charge of 50%.

4.3 Load presentation:

4.3.1 Cycling load:

Every test has followed the same global procedure. Each test corresponds to a specific profile detailed just above. All along the cycling procedure, a measure of the battery health named check-up reveals the cell state of life. The number of microcycles applied between two check-up varies as a function of the specific test.

Figure 6: test structures in function of the profile applied

As shown in Figure 6, four types of tests have been performed and have been named as a function of the profile applied. The duration of a test depends on the profile length. Afterwards, except for the calendar, tests the test duration has been counted in terms of the number of microcycles (Ncycle) applied. In this way the test comparisons are directly based on the amount of charge exchanged.

4.3.2 Temperature load:

Two temperature conditions have been tested for the different tests realized. Moreover, in order to quantify the scale effect (see 4.1) a test has been repeated for the same profile and the same temperature. The design of experiment is summed up in the table I:

Table 1: design of experiment for 2 Ah and 5 Ah cells

	temperature	
Test	35°C	45°C
I_30C	5 Ah	
I_15C	5 Ah	
I_10C	2 Ah	2 Ah
I_0C	2 Ah + 5 Ah	2 Ah

4.4 Check-up:

As shown in Figure 6, regular measurements of capacity and impedance brought out the parameters sensitive to solicitations. This paper will focus on the capacity fading as a function of the solicitation.

4.4.1 Capacity measurement:

FreedomCar study [9] has proved that C/1 capacity fading with ageing results from both irreversible lithium consumption in parasitic reactions and impedance rise. On the contrary, C/25 capacity reduction seems independent of impedance rise effects. The impedance rise and the capacity fading are two different ageing effects. Preferably, a measurement that succeeds in decoupling both origins is more relevant. Subsequently, a low rated capacity measurement has been chosen to quantify the capacity fading. However, the duration of a low rate capacity measurement is too long to be repeated regularly. This issue was solved by the works of Marc Doyle and John Newman [10] who introduced a protocol which consists in a series of seven successive discharges from very high rate (10 C) current level to very low rate (0,01 C) interrupted with a 5 minutes relaxation period.

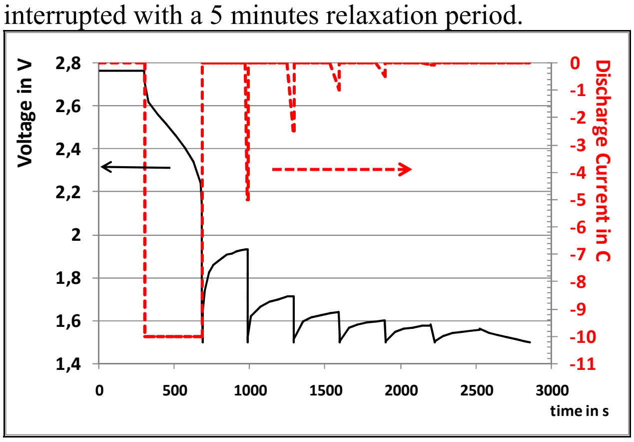

Figure 7: decreasing rate capacity measurement

The capacity measurement described in Figure 7 is a quick way to access a low rated capacity measurement. This measurement was repeated twice per check-up. The capacity value deduced and announced in the following results represents the average of the two 0,01C capacity measurements.

5 Results:

5.1 Cell composition:

The curve of the open circuit voltage vs state of charge corresponds to the chemical signature of the battery. The Figure 8 confirms the perfect similarity between the compositions of the 5 Ah and 2 Ah cells.

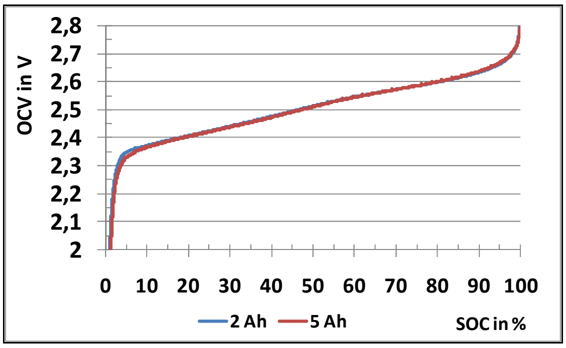

Figure 8: comparison between 2 Ah and 5 Ah OCV curve

In addition to the similarity in terms of composition, next studies will compare the behaviour of these two sets of batteries.

5.2 Calendar evolution:

As said in 4.2.2, the calendar evolution is observed by a regular diagnosis of a battery stored at 50% of SOC.

5.2.1 Capacity losses:

As seen in 4.4.1, the capacity measurement corresponds to a low current rate. The capacity ageing is quantified through the notion of capacity loss (1). In this way, the capacity after loading is directly compared to the initial capacity

$$L = \frac{C_0 - C}{C_0} * 100$$

$$L = \text{capacity loss in } \% \qquad (1)$$

$$C_0 = \text{initial capacity}$$

$$C = \text{capacity of an aged cell}$$

Moreover, the capacity loss notion (1) is a dimensionless parameter that makes possible a comparison between 5Ah and 2Ah cells.

5.2.2 Comparison of the 5Ah and 2Ah cells:

The Figure 9 compares the response of the 5Ah (diamond markers) and the 2Ah (square markers) cells in condition of storage at 35°C. The Figure 9 shows a quite superposed evolution between the two types of cells.
This observation leads to the conclusion that the "scale effect" (see 4.1) has no incidence in terms of ageing behaviour. From now, the conclusions associated to 2Ah cells will be generalized to 5 Ah cells and vice versa.

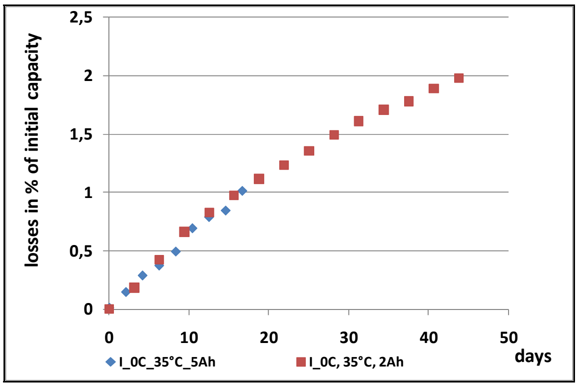

Figure 9: comparison between 2 Ah and 5 Ah cells behaviour

The classical description of the calendar tests is expressed in days of storage. From now, for practical reasons, when comparisons between cycling and calendar tests will be established, each test will be expressed as a function of the number of microcycle applied (Ncycle). Therefore, for the calendar conditions, the number of microcycles will correspond to the storage time divided by the microcycle duration.

5.2.3 Temperature effect:

As seen in 4.2.1, temperature is likely to accelerate degradations led by chemical reactions. The Figure 10 compares the ageing kinetics of two 2Ah cells in storage conditions at respectively 35°C (square markers) and 45°C (diamond markers).

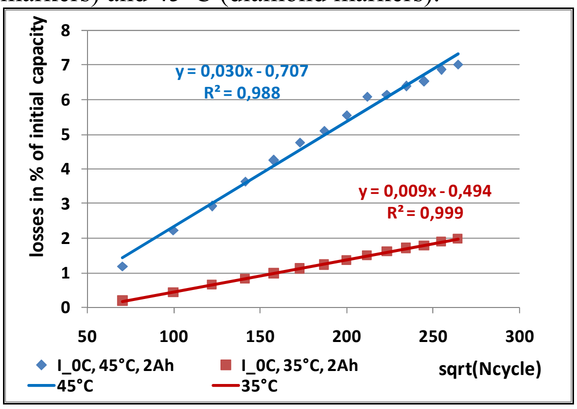

Figure 10: influence of the temperature on calendar ageing

The Figure 10 shows a significant increase of the capacity loss (around 3 times higher) due to the increased temperature level.

5.2.4 Modelling:

As shown in the Figure 10, the capacity losses during storage conditions can be simulated by square root evolutions as follows:

$$L = A_{cal} * \sqrt{Ncycle} + B_{cal}$$
$$L = \text{capacity losses in } \%$$
$$A_{cal} = \text{ageing rate coefficient} \quad (2)$$
$$B_{cal} = \text{constant}$$
$$Ncycle = \text{number of microcycles}$$

Generally, this model is associated to layer growth generated by parasitical chemical degradation reactions on graphite electrode [8]. The Figure 10 leads to the conclusion that this evolution can be generalized for LTO/ LMO batteries. The stability of lithium titanium as regards to the electrolyte lets supposed a main contribution of the manganese-based electrode. The impact of the ambient temperature on the ageing kinetics can be quantified via the ageing rate coefficient (A_{cal}):

Table 2: influence of the temperature on calendar ageing rate coefficient

Acal	T in K
0,009	308
0,03	318

5.3 Low current cycling effect:

The Figure 11 here-below underlines cycling effect on ageing by a direct comparison with the calendar capacity decrease:

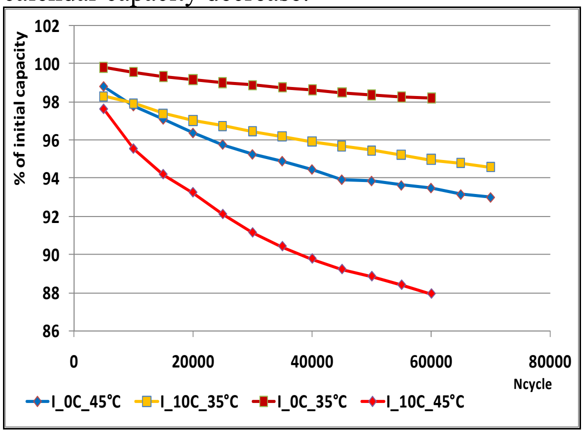

Figure 11: influence of the cycling load on ageing

The differences between the calendar and the cycling curves respectively at 35°C and 45°C show that the impact of the cycle loading on ageing depends on the ambient temperature.

5.3.1 Modelling:

Similarly to the modelling proposed in 5.2.4, the Figure 12 shows that, in a first order approximation, the capacity evolution of a cell enduring cycle loading fits with a square root trend:

$$L = A_{cyc} * \sqrt{Ncycle} + B_{cyc}$$
$$L = \text{capacity losses in } \% \quad (3)$$
$$A_{cyc} = \text{ageing rate coefficient}$$
$$B_{cyc} = \text{constant}$$

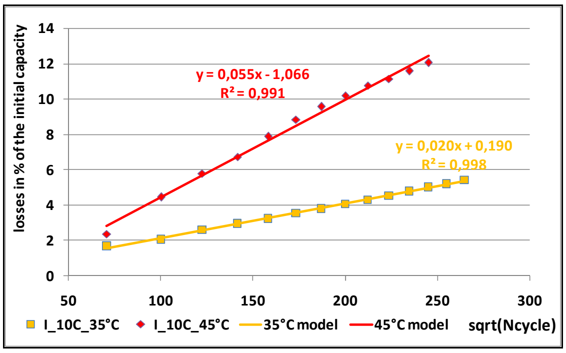

Figure 12: modelling of the cycling ageing evolution

The cumulative impact of the temperature on ageing can be quantified by the cycling ageing rate coefficient:

Table 3: influence of the temperature on cycling ageing rate coefficient (for 10C cycling)

Acyc	I in C
0,068	15
0,083	30

5.4 Combination of the calendar and low current cycling effects on ageing:

Knowing how the calendar and the cycling ageing combine is an essential issue to recognize the part of each effect on the global cell response. From the data previously introduced, the following section discusses this point.

5.4.1 Reconstitution:

The Figure 13 compares the capacity losses measured for the cycling "I_10C" test set at 45°C to the sum of the capacity losses from the "I_10C" test set at 35°C and from the calendar test at 45°C.

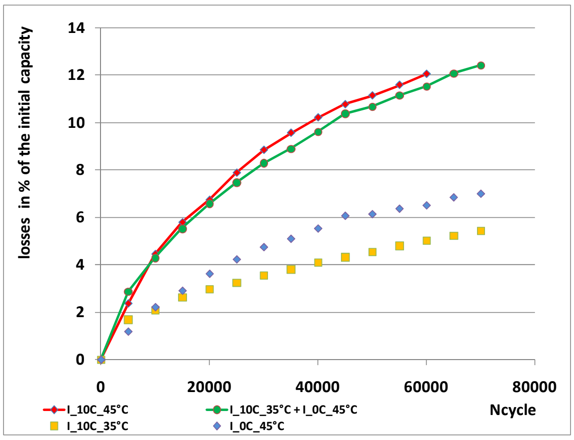

Figure 13: reconstitution of the I_10C_45°C losses from the sum of I_10C_35°C and I_0C_45°C losses

From Figure 13, in a first order approximation, the two curves can be considered as similar allowing adding the calendar ageing to the cycling ageing.

5.4.2 Modelling:

The modelling suggested in 5.4.1 implies that at each ageing time, the contribution of the calendar ageing can be summed to the contribution of the cycling ageing. It means that the kinetics of both phenomena can be summed. From 5.2.4 and 5.3.1 we can conclude that:

$$\mathbf{L}_{\mathbf{cyc+cal}} = \left(\mathbf{A}_{\mathbf{cyc+cal}}\right) * \sqrt{\mathbf{Ncycle}} + \mathbf{B}_{\mathbf{cyc+cal}} \qquad (4)$$
$$\mathbf{A}_{\mathbf{cyc+cal}} = \mathbf{A}_{\mathbf{cyc}} + \mathbf{A}_{\mathbf{cal}}$$

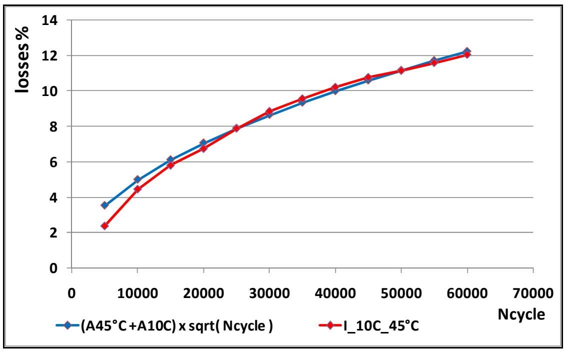

Figure 14: comparison between re-formed ageing model and measurement test

The Figure 14 confirms that this first order model which fits quite well with the data.

5.5 High current loading:

Two complementary tests have been set on 5Ah batteries enduring high current loading. Therefore, the Figure 15 shows the evolution of the capacity loss as function of square root of microcycle number for two cells loaded respectively at 15C and 30C at 35°C.

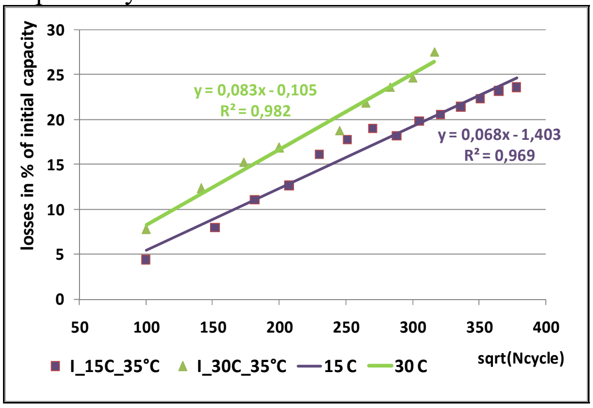

Figure 15: influence of high current cycling on battery ageing

The Figure 15 confirms that the square root model is still reliable for high current loading and shows the influence of the current level loading on ageing. The Table 4 quantifies the ageing coefficients for the both high-current tests.

Table 4: influence of the current level on cycling ageing rate coefficient (at 35°C)

Acyc	I in C
0,068	15
0,083	30

5.6 Conclusions:

These first sets of experiments have shown that the ageing kinetics are influenced very strongly by temperature and current rate. Besides, it has been observed that in a first order approximation the high temperature and low current cycling processes were superposed.

6 Discussions:

Just like in the Freedomcar project [4], the design of experiments detailed in 4.3.2 was inspired by the notion of accelerated tests introduced by the mechanical reliability theory. From now on, it is interesting to transpose the information raised in §5 in terms of reliability notions.

6.1 The capacity damage:

The damage notion contains both physical and practical information. As explained in 3.1.1, the damage evolution is governed by the physical degradation mechanisms. Moreover, the damage must be associated to a practical consideration through the system failure definition. The battery engineering arbitrary defines the capacity loss failure level by a decrease of about 25% of the initial capacity. It leads to the damage definition as follows:

$$D = \frac{C_0 - C}{C_0 - Cf} = L * (\frac{C_0}{100 * (C_0 - Cf)}) \quad (5)$$
$$Cf = capacity\ at\ failure$$
$$C_0 = initial\ capacity$$

From equation (5) the capacity damage (D) grows from zero at the beginning of life to 1 at the end of life. As seen in equation (5), damage is also proportional to the capacity losses (L) and consequently follows exactly the same degradation mechanisms.

Physically, the capacity ageing expresses the fading of the available interstitial sites during ageing. The filling of the whole available interstitial sites corresponds to the Lithium ion exchanges from the electrolyte to the active material through an active area (S).

$$C = \int_O^t I * dt = \int_O^t \iint_S j * dS * dt$$
$$C = S * \int_O^t j * dt \quad (6)$$

j = current flow associated to the constant current rate I

In this way, damage can be physically seen as the evolution of this active area during ageing:

$$D = \frac{C_0 - C}{C_0 - Cf} = \frac{S_0 - S}{S_0 - Sf} \quad (7)$$

6.2 Ageing accelerating factors:

Generally, a statistical model developed from accelerated life tests establishes a relationship between life and stress factors. Although few experiments have been carried out to surely link stress factors to battery life, this section establishes the basic principles related to a statistical model.

6.2.1 Definition:

The accelerating factor (AF) notion refers to the link between the system life in nominal conditions and the system life under specific conditions that shorten the tests while keeping the same degradation mechanisms. As suggested in FreedomCar project, [3] it has been chosen to compare the ageing kinetics obtained with and wihtout accelerating factors namely the temperature and the current level:

$$AF_{1\to2} = \frac{\left(\frac{\partial C}{\partial N}\right)_2}{\left(\frac{\partial C}{\partial N}\right)_1} \quad (8)$$

C = capaciy
N = number of microcycles
1 = first test condition
2 = second test condition

6.2.2 Transitivity property:

The 35°C calendar ageing has been arbitrary chosen as the reference state. Consequently, the accelerating factor is expressed as:

$$AF_{ref\to X} = \frac{\left(\frac{\partial C}{\partial N}\right)_X}{\left(\frac{\partial C}{\partial N}\right)_{ref}} \quad (9)$$

X = experimental condition

The property underlined in 5.4.1 leads to the conclusion that:

$$AF_{ref\to 10C\_45°C} = \frac{\left(\frac{\partial C}{\partial N}\right)_{10C\_45°C}}{\left(\frac{\partial C}{\partial N}\right)_{ref}}$$
$$AF_{ref\to 10C\_45°C} = \frac{\left(\frac{\partial C}{\partial N}\right)_{10C} + \left(\frac{\partial C}{\partial N}\right)_{45°C}}{\left(\frac{\partial C}{\partial N}\right)_{ref}} \quad (10)$$
$$AF_{ref\to 10C\_45°C} = AF_{ref\to 10C} + AF_{ref\to 45°C}$$

The equation (10) shows the transitivity property of the accelerating factor with regards to the calendar and the cycling ageing.

6.2.3 Temperature accelerating factor:

The ageing processes influenced by the temperature are commonly associated with the Arrhenius life –temperature relationship [11]. This relationship refers to the ageing due to parasitical chemical reactions. Therefore, the rate of a simple (first order) chemical reaction follows the Arrhenius law:

$$rate = A * \exp(-E/kT) \quad (11)$$

E : the activation energy in eV
k : the Boltzmann's constant
T : the Kelvin temperature
A : constant

The equation (11) expresses the system failure as the creation of a critical amount of parasitical products:

$$\text{critical amount} = \text{rate} * (\text{time to failure}) \qquad (12)$$

In this way, the comparison between two tests only influenced by the temperature defines the accelerating factor as follows:

$$AF_{1\to2} = \exp(-\frac{E}{k} * (\frac{1}{T_1} - \frac{1}{T_2})) \qquad (13)$$

From the Table 2 the identification of the AF factors implies activation energy of a parasitical reaction around 1eV.

6.2.4 Current level accelerating factor:

In case of a single accelerating stress, the widely used model is the inverse power relationship [11]. It supposes that the stress variable V is positive and then:

$$N_{EOL\ 1} = \frac{B}{V^{\gamma_1}}$$

$N_{EOL\ 1}$ = number of microcycles at end of life in contidion 1 (14)

γ_1 = the power

B = constant

In our case, the inverse power relationship (14) leads to the current level acceleration factor:

$$AF_{1\to2} = \left(\frac{I_1}{I_2}\right)^{\gamma_1} \qquad (15)$$

I = the current level in C

The Table 4 allows to assess γ_1 around of 0,3. The equations (10), (13) and (15) imply that once the accelerating factor is identified for some calibrated cycling and calendar conditions, it is possible to assess any acceleration factor for all the combination of temperature and cycling conditions.

6.2.5 Conclusions:

First, the fatigue approach has been useful to rationalize the cycling notion and to associate a specific current level to a microcycle.

Subsequently a reliability analysis has shown that the mechanical methodology can be adapted and applied to complex systems like batteries. The test protocol has been validated and performed with several ambient temperatures and cyclic loads. The experimental data processing has allowed us to understand and modelled the combination of calendar and cycling effects as regards to the current level.

The influence of both temperature and current level has been quantified practically through accelerating factors.

Although main difficulties are inherent to the reproducibility of the battery response in order to be confident with the accelerating factors assessed, the ageing study procedure is now in service.

7 Further works:

This paper has detailed the basic principles relatives to the reliability theory like the accelerating factor notion and tries to adapt them to electrochemical cells.

From now on, the statistical approach needs a lot of further experiments to confidently evaluate the life system scatter for different stresses. In the future, other tests must be done to confidently quantify the accelerating stress factors and then understand how damage from numerous solicitation sources combine.

Moreover, a similar methodology must be developed to model the impedance rise effect observed for high power battery cells.

Acknowledgments

This work has been largely managed and supported by Renault and CEA/LITEN (Grenoble). A part of the experimental means has been kindly provided by the CEA / INES (Chambery).

Besides, lots of technical notions tackled in this article have been first discussed with the whole French SIMSTOCK project partners.

References

[1] J.Vetter and. Al., *Ageing mechanisms in lithium-ion batteries,* Journal of Power Sources, 147 (2005), 269-281

[2] *PNGV Battery Test Manual*, DOE/ID-10597, Revision 3, February 2001

[3] Advanced Technology Development Program For Lithium-Ion Batteries, *Battery Technology Life Verification Test Manual*, INEEL/EXT-04-01986, February 2005. p5-10, p 9-16, Appendix D

[4] DOE advanced Technology Development Program for Lithium Ion Batteries: *Interim Report for Gen 2 Cycle Life Testing*, INEEL/EXT-02-01055, p4-5

[5] FREEDOMCAR Battery test Manual for Power-Assist Hybrid Electric Vehicles, DOE/ID-11069 October 2003, p15-17

[6] Lorenzo serrao, Zakaria Chehab, Yann Guezennec, Giorgio Rizzoni, "*An ageing*

Model of Ni-MH Batteries for Hybrid Electric Vehicles", Vehicle Power and Propulsion, IEEE Conference, 2005

[7] C. Dudézert, S. Franger, F. Ternay, R. Balmy, H. Burlet, *A fatigue-like methodology study of high-power Lithium-ion batteries*, AEA Congress, 2008

[8] M. Broussely and al, *Aging mechanism in Li ion cells and calendar life predictions*, Journal of Power Source, 97-98, (2001), p 13/21

[9] D.P.Abraham and al, *Performance degradation of high-power lithium-ion cells- Electrochemistry of harvested electrodes*, Journal of Power Sources, 170, (2007), 465-475

[10] Marc Doyle, John Newman, Jan Reimers, *A quick method of measuring the capacity versus discharge rate for a dual lithium-ion insertion cell undergoing cycling*, Journal of Power Source, 52, (1994), p211/216

[11] W. Nelson, *Accelerated testing, Statistical models, Test plans, and data analyses*, Wiley series in probability and mathematical statistics, (1990), p 75/92