# An Aging Model of Ni-MH Batteries for Hybrid Electric Vehicles

Lorenzo Serrao (serrao.4@osu.edu), Zakaria Chehab (chehab.1@osu.edu),
Yann Guezennec (guezennec.1@osu.edu), Giorgio Rizzoni (rizzoni.1@osu.edu)
The Ohio State University, Center for Automotive Research
930 Kinnear Rd
Columbus, OH 43212 USA

*Abstract* - **The extensive use of batteries in hybrid electric vehicles (HEVs) today requires establishing an accurate model of battery aging and life. During a battery's lifetime, its performance slowly deteriorates because of the degradation of its electrochemical constituents. Battery manufacturers usually provide aging data that will show this degradation. However the data they provide result from standard aging tests, in which the battery is discharged and charged thousands of times with identical current profiles (or cycles). Using these data many aging models have been developed that relate the maximum number of battery cycles to the Depth of Discharge (DOD) of the current profile used.**

**In this work, we focus on the development of an aging model suitable for applications in which the battery is used with no pre-defined cycles, as in the case of hybrid-electric vehicles. Laboratory experiments and concepts borrowed from fatigue analysis are applied to the relationship between battery aging and the most important operational conditions that affect its life, i.e. its operating temperature and current history.**

## I. Introduction

*Motivation*

Time produces undesirable effects in batteries that result in the deterioration of their performance, which in turn results in the deterioration of the HEV performance and fuel efficiency. These undesirable effects include the loss of rated capacity, faster temperature rise during operation, less charge acceptance, higher internal resistance, lower voltage, and more frequent self-discharge. The most drastic effect is the loss of rated capacity. Battery manufacturers define a battery's end of its life as the moment it can only deliver up to 80% of its rated amp-hour capacity. After this moment, it can still be used for a long time at reduced capacity. Research shows that the life of a battery is influenced by many factors. The most important factors are extreme temperatures, overcharging, discharging, rate of charge or discharge, and the DOD of battery cycles [1]. Most of the previous work in this topic compared the effect of the aging factors to a battery's cycle life. The cycle life of a battery is defined as the number of discharge cycles a battery is capable of delivering before its nominal capacity falls below 80% of its initial rated capacity [4]. These cycles are identical, which is not the case for HEV applications. Our paper focuses on HEV battery aging in which the current history cycles differ according to the driving cycles the vehicle experiences.

*Extreme Temperature*

Temperature can have a double effect on a battery's performance. Temperature can both increase the efficiency of the battery and can significantly shorten its life. As temperature increases, the effective internal resistance of the battery decreases. This will improve the battery efficiency, however higher temperature causes faster chemical reactions (The Arrhenius equation), and in particular it will increase the rate of unwanted chemical reactions that cause permanent damage to the components of a battery. The Arrhenius equation shows that the rate of chemical reactions is exponentially related to the temperature. So the rate of the unwanted chemical equations will double as the temperature increases by 10°C [4]. Previous work has shown that exposure of a nickel-metal hydride (Ni-MH) battery to a temperature of 45°C will decrease its cycle life by almost 60% [4], [1]. Figure 1 shows the relationship between the percentage of cycle life available and the change in temperature.

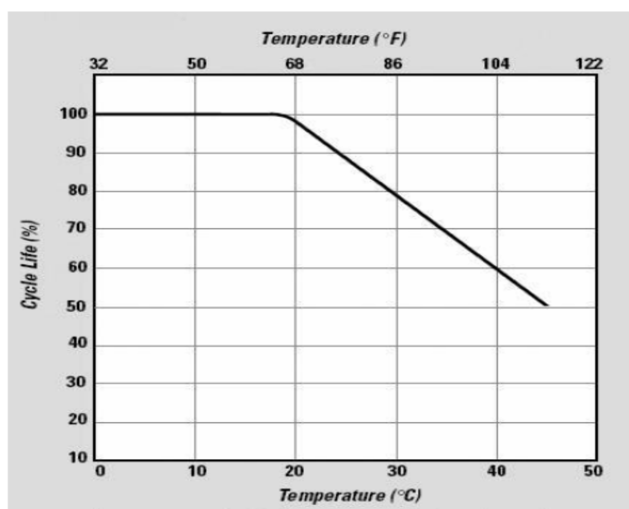



Figure 1: Influence of the temperature on cycle life [1]

*Overcharge and Over-discharge*

Batteries usually have voltage limits that characterize the amount of charge present. These voltage limits change with temperature, however it is important for a battery's region of operation to always be within these safe limits. Overcharging, or exceeding the upper voltage limit will cause irreversible chemical reactions which can damage the battery. The reason behind this is that after all the active chemicals have been transformed, forcing more electrical energy will cause some chemical components to break down into forms that can not be recombined [4]. Overcharging also causes a significant increase in temperature and pressure. This may cause mechanical failures such as swelling of the battery, short circuits between parts, and interruptions in the current path. At that point, if the overcharging is not terminated, it will cause the battery to explode and release dangerous chemicals and gases that may cause fire [5]. Excessive discharge also causes permanent damage to the battery and speeds up the aging process. Figure 2 shows how the electrodes of an Ni-MH battery will reverse if there were a significant over-discharge. Tests have shown that a small amount of overcharging or over-discharging will not cause premature failure of the batteries but will significantly shorten its life. For example, some tests showed that over-charging Ni-MH batteries by 0.2 V will result in a 40% loss of cycle life and a 0.3 V over-discharge of lithium-ion batteries can result in 66% loss of capacity [4]. It is important at this point to note that when looking at cycle-life aging of a battery, it is assumed that the cycles are chosen so that they would not overcharge or over-discharge. That is why we did not focus on the effect of overcharge or over-discharge.

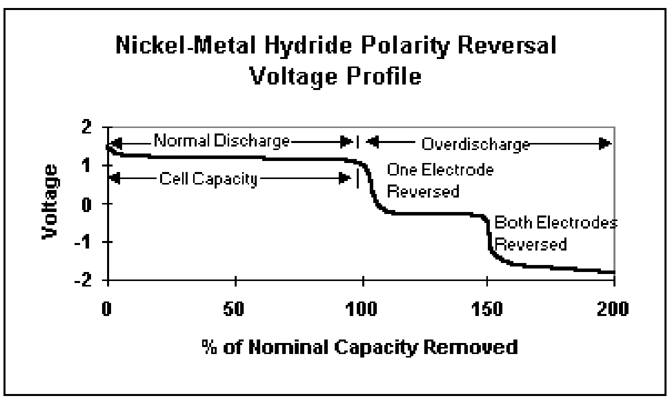



Figure 2: Nickel-Metal Hydride Cell Polarity Reversal Voltage Profile [5]

*Depth of Discharge*
DOD is defined as the amount of Amp-hours (Ahs) removed from a battery cell expressed as a percentage of the rated capacity [6]. DOD is the opposite of State of Charge (SOC). For example, the removal of 25 Ah from a fully charged 100 Ah rated battery results in a 25% depth of discharge [4]. Extensive research has been done in trying to relate the cycle-life of a battery to the DOD the cycle achieves. It has been found that the relationship between the cycle-life and the DOD is an exponential one as can be seen in Figure 3. Figure 3 shows that the cycle life is much greater when the DOD in each cycle is smaller. In this example, the battery can last 5000 cycles if it is discharged by 10 % in each cycle, or 500 cycles if the DOD is 90 %. It is important to understand that these results make sense only if the battery is discharged and charged hundreds or thousands of times with the same "current history", i.e. with subsequent identical cycles such as simple square waves or pulses [4], [7]. The model proposed in this paper, instead, is suitable for predicting the battery aging for applications in which the battery is aged with no pre-defined cycles. However, it takes into account the limitation imposed by typical HEV Control Strategies, which are engineered to keep the DOD of the battery above 50% [4].

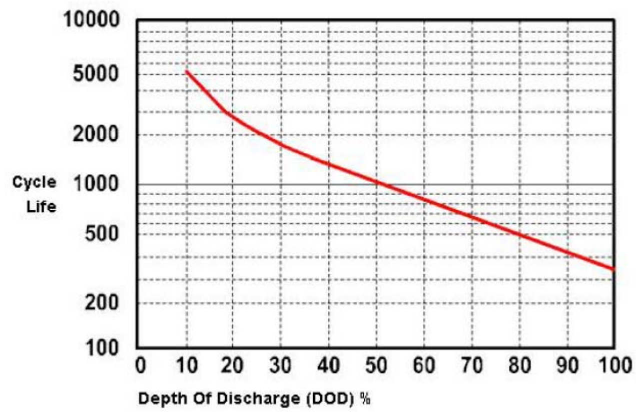



Figure 3: Example of the dependence of the cycle life on the DOD [4]

*Charge and Discharge Rates*
Not much research has covered the relation between higher current rates and battery aging. However, higher current applications have the reputation of being harder on a cell's expected lifetime [1]. The higher the discharge rate the greater the loss in conductivity between plates. Furthermore, drawing a certain amount of charge from a less conductive plate will cause uneven current distributions and higher stress on the battery cells [7]. This idea is similar to mechanical fatigue. Usually battery manufacturers perfrom their life testing with identical current cycles at a single discharge rate. The difference between two cycles that have the same final DOD but different maximum current amplitudes and different durations will be explored more extensively in this paper.

*Objectives*
The main objective of this study was to develop a general methodology for the analysis of HEV current histories on the aging of the battery, and then to implement this methodology so as to be able to describe the decay of the characteristics of the battery, namely the battery capacity, the maximum voltage, and the effective internal resistance. All this will allow us to predict the battery end of life if the current or load history is known. The main difference between this study and previous research is relating real-world load profiles to battery aging instead of relating pulse cycles to HEV battery life. An example of previous work done is the Aging experiments done on the Toyota Prius Ni-MH batteries from Panasonic, in which a cycle is a simple discharge pulse. Figure 4 shows how the capacity of the battery decreases as the number of pulse cycle increases, and how the internal resistance increases as the capacity decreases. Figure 5 shows

a real-life current profile from the Challenge X team at The Ohio State University.

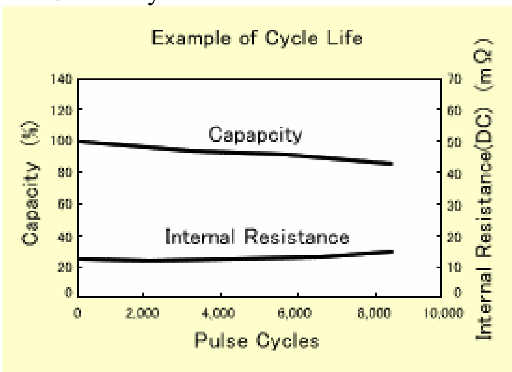



Figure 4: Aging data from the Prius Battery pack [7]

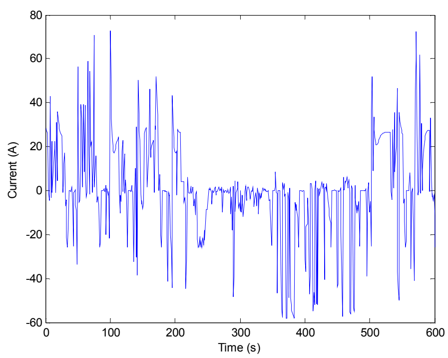



Figure 5: Challenge X Current Profile

## II. Battery Model

There are several ways of tracking of battery age or state of health. One way would be to measure the effective internal resistance after several cycles under the same conditions of SOC and temperature. As a battery ages, its internal resistance will rise, reducing the battery's ability to charge to a certain capacity. However the internal resistance of a battery varies with SOC and temperature, so to determine an accurate representation of the internal resistance, we must first create a model of the battery that will show the variation of the resistance and open circuit voltage with respect to state of charge and temperature. To do this, we conducted a series of experiments on a 7.2V Panasonic battery cell from the Toyota Prius battery pack.

*Experimental Procedure*

The objective of this experiment was to find the open circuit voltage (Voc) and the total effective resistance ($R_e$) of a 7.2V, 6.5Ah Ni-MH Prius battery cell as a function of atate of charge (SOC) and temperature (T). The experimental procedure was as follows:

1. Apply a load profile to the battery at specific starting temperature.
   - The current profile should be such that at each measurement the temperature and the state of charge do not change significantly after each cycle.
   - Current Cycle used:

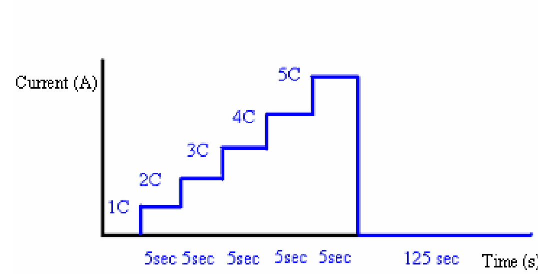



Figure 6: Current Profile Used in the Experiment. Where 1C=6.5A

   - This Cycle will cause a 2% change in the SOC of a battery when applied.

2. Measure voltage, actual current, and temperature inside the battery.
3. Repeat 1-2 until the batteries reach a minimum voltage.
4. Repeat 1- 3 for different starting temperatures.

This will allow us to gather data for slightly different points of temperature and SOC.

*Experimental Analysis*

The current profile used above resulted in the following voltage variation for a given SOC and temperature, in figure 7.

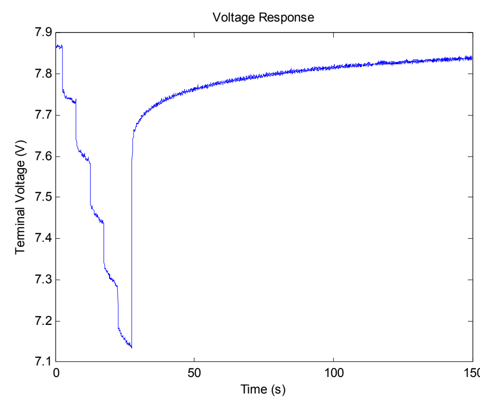



Figure 7: Voltage Response for the Above Current Profile

From the data collected above, we can extract the open circuit voltage and the effective resistance and other parameters using the following Thevenin model, shown in Fig. 8.

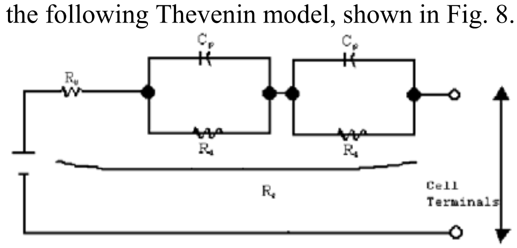



Figure 8: Thevenin Model

Where $R_e$ = ($R_h$ + $R_d$) = total effective internal resistance, $R_h$ = effective instantaneous resistance, $R_d$ = delayed resistance, and $C_p$= parallel capacitance

The open circuit voltage is the voltage at the end of our current profile; i.e. when the current has a value of 0A.

However if we look closely at the voltage response at the instant the current becomes zero we see that it is composed of two parts, an instantaneous jump (from $V_{load}$ to Vi), and then an exponential rise (after Vi).

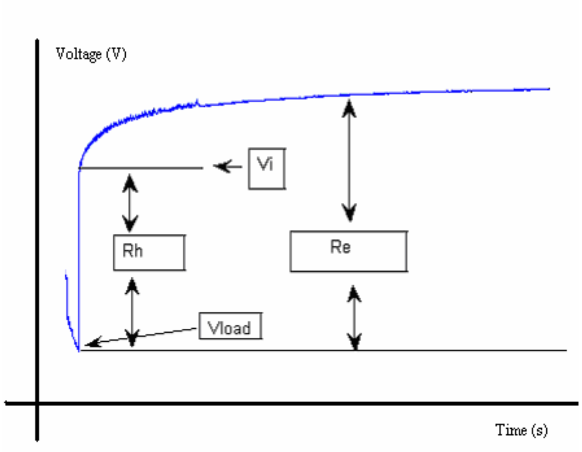



Figure 9: Voltage Rise

Furthermore if we try to fit the exponential rise we get the figure below:

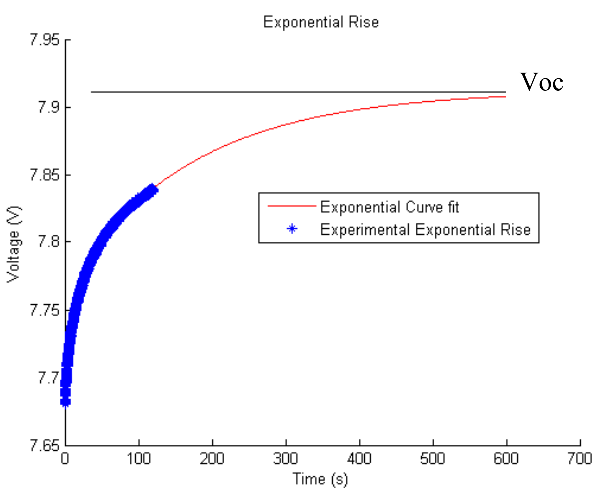



Figure 10: Exponential Rise

The equation of the curve fit was determined to be:

$$V = V_{oc} + A \cdot e^{-\tau_1} + B \cdot e^{-\tau_2} \tag{1}$$

So from the data we acquired we can get the battery model parameters by applying the following equations:

$$R_e = \frac{(V_{oc} - V_{load})}{I_{load}} \tag{2}$$

$$R_h = \frac{(V_i - V_{load})}{I_{load}} \tag{3}$$

The parameter of interest for the aging experiments is the effective internal resistance $R_e$. Note that the parameters from the equations above will serve as only one data point in the SOC-T plane. After that we reapply the current cycle to get the effective resistance at a different (temperature, SOC) point in the SOC-T plane.

*Results*

The open circuit voltage and the effective internal resistance were calculated at each data point in the SOC-T plane using (1) and (2). The figures below show how the effective internal resistance and the open circuit voltage vary with respect to SOC and temperature. Note that for simplicity, in what remains of this paper we will be referring to the effective internal resistance as internal resistance and will be denoting it R instead of $R_e$.

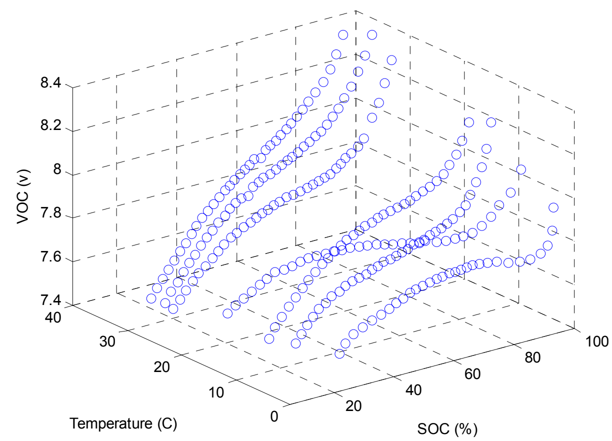



Figure 11: Voc points acquired

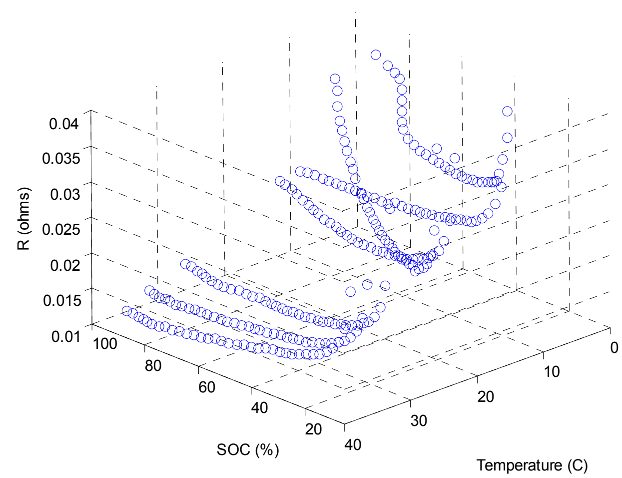



Figure 12: R points acquired for discharge

Clearly the experimental results verify that the internal resistance of the battery decreases as the temperature increases. The figures below show the surface fits of the above figures.

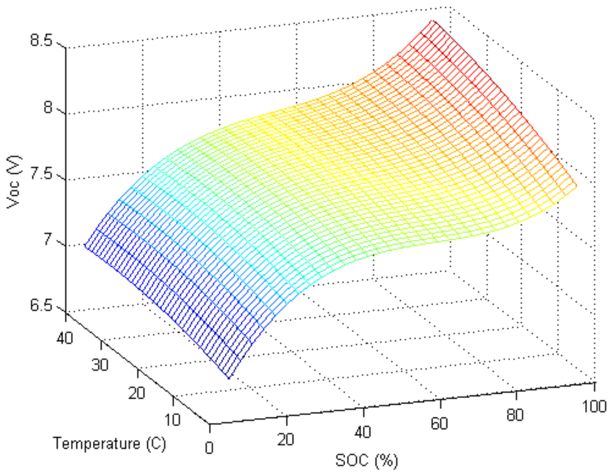



Figure 13: Voc surface plot

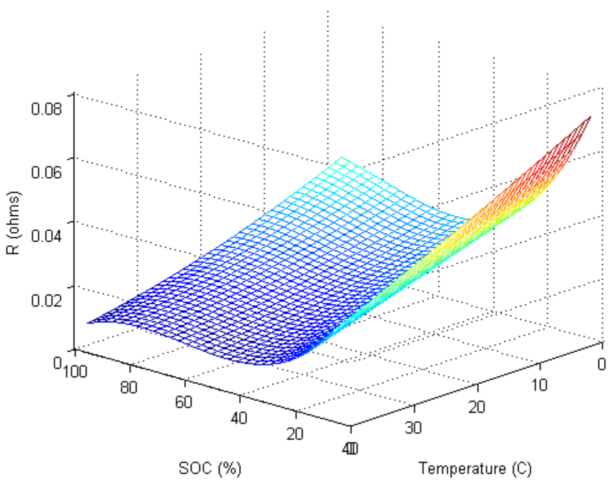



Figure 14: R discharge surface plot

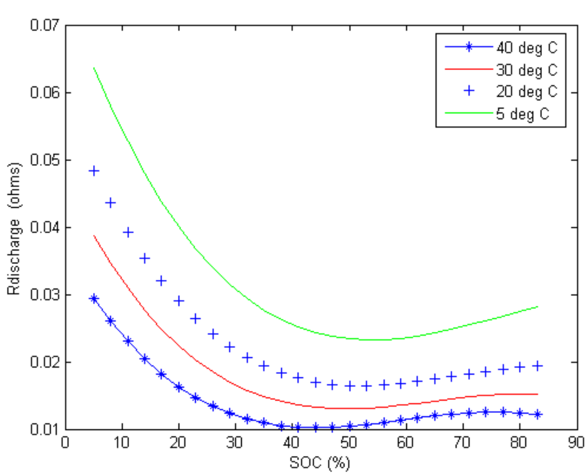



Figure 15: R discharge at different Temperatures

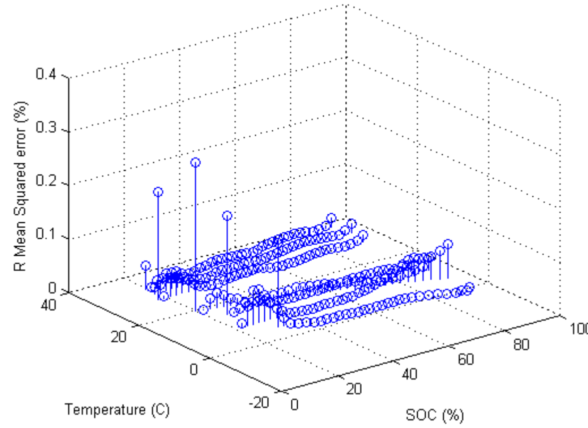



Figure 16: Percentage mean square error for R discharge

In order to find the charge resistance, the same experimental procedure was applied with the same current profile but using charging instead of discharging.

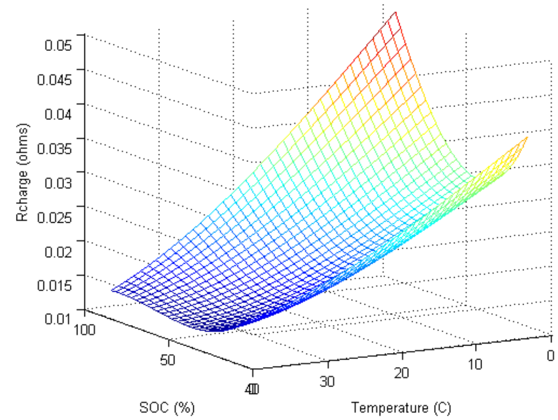



Figure 17: R charge surface plot

To check our results, we simulated the battery model using the surface plots and compared the simulated results to the experimental ones. Figure 18 shows this comparison.

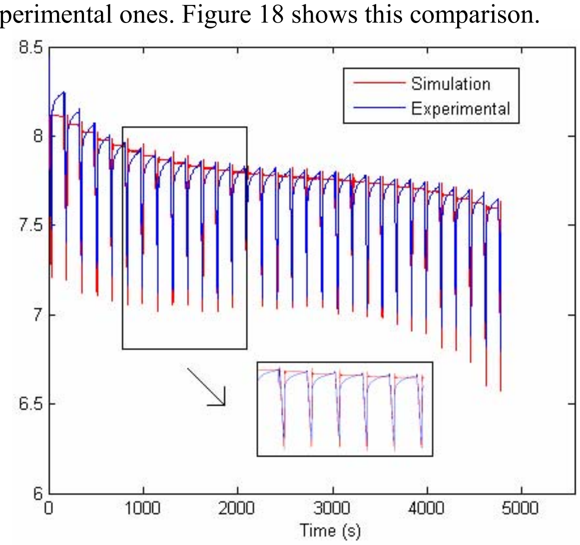



Figure 18: Experimental vs. Simulated results

At this point, we are able to estimate the internal resistance and the open circuit voltage of the battery, given the measured temperature and the state of charge (obtained as integral of the current). This information will be used in the aging model.

## III. Aging Model

*Basic Ideas*

The basic hypothesis we formulate is that each time the battery is discharged, a certain amount of battery life is irreversibly worn out. This is based on the physical damage mechanisms that lead to the battery end of life, related to the electrochemical processes inside the battery as described in the Introduction.

The residual life after $N$ discharge events can be expressed as follows:

$$\Lambda_{res} = 1 - \sum_{i=1}^{N} \frac{L_i}{L_{tot}(i)} \quad (4)$$

Where $\Lambda_{res}$ is the life expressed as a fraction of total life, $L_i$ is the amount of life spent in the *i-th* condition and $L_{tot}(i)$ is the total life in the *i-th* condition. This concept is the same as the damage accumulation in the study of mechanical fatigue.

In this paper, $\Lambda$ is used for fractions of life, while $L$ is used for life expressed with absolute units.

*Definition of the Battery Life L*

The most common definition of battery life is as cycle life. This is easy and meaningful when the load history of the battery is regular, so that a "cycle" is always the same. However, in HEVs, the battery is not cycled on a regular basis, because the current history depends on the driving path. Thus, the definition of life as number of cycles would imply the designation of a "standard" or "equivalent" cycle, which would lead to non-intuitive results. For this reason, in this work the battery life $L_{tot}$ is expressed as a total amount of charge that can be drawn from the battery, i.e., time integral of the current, as proposed by [3]. According to this definition, the battery end of life is reached as soon as the sum of charge drawn from the battery, the total Ah or charge life arrives at a certain level. The two definitions of life are equivalent, and they can be derived from each other, considering that the amount of charge drawn from the battery during each cycle is the product of nominal capacity and DOD. The charge life of a battery can be derived from the cycle life using the following equation:

$$L_{Ah} = L_{cyc} \cdot DOD \cdot Ah_0 , \quad (5)$$

where $L_{Ah}$ is the life expressed in Ah, $L_{cyc}$ is the life expressed as number of cycles at the depth of discharge $DOD$, and $Ah_0$ is the nominal capacity of the battery.

For example, for a 6.5 Ah battery, the $L_{Ah}$ using figure 19 is**:**

$$L_{Ah}(DOD = 10\%) = 5400\,\text{cycles} \cdot \frac{10}{100} \cdot (6.5\,\text{Ah}) = 3510\,\text{Ah}$$

$$L_{Ah}(DOD = 20\%) = 2700\,\text{cycles} \cdot \frac{20}{100} \cdot (6.5\,\text{Ah}) = 3510\,\text{Ah}$$

$$L_{Ah}(DOD = 30\%) = 1500\,\text{cycles} \cdot \frac{30}{100} \cdot (6.5\,\text{Ah}) = 2925\,\text{Ah}$$

...

We can see that the charge life at 10% and 20% DOD is the same. This is because although we are using less cycles, the amount of charge drawn is more. Hence we find that the curve that gives the Ah life as a function of DOD is not exponential, but of a quadratic shape.

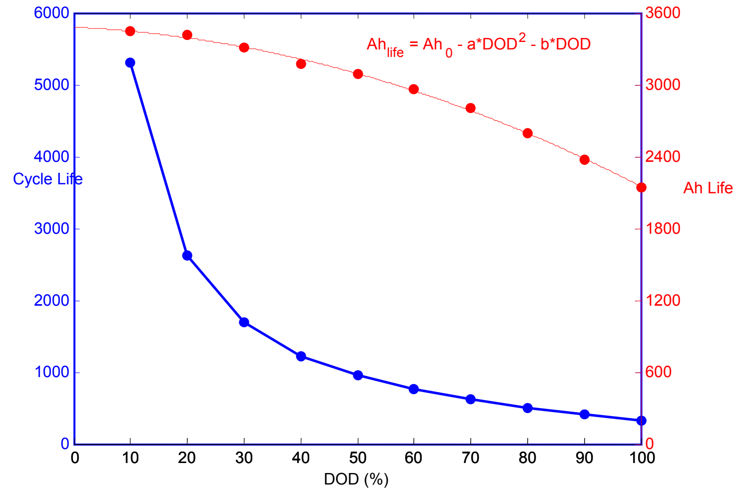



Figure 19: Comparison of cycle life and Ah life (the scale of Ah life is not accurate because it is based on an arbitrary value of nominal capacity. However the shape of the curve is independent from that value).

*Effect of Current History*

As mentioned earlier the depth of discharge of a profile, its peak current, and its shape all affect a battery's life. Simply integrating the current over time will not be sufficient to find the amount of life removed from the battery, so the DOD and the shape of the cycle should also be taken into account. Figure 20 below shows two different current cycles having the same Ah discharge, but having different effects on a battery's life. The triangular profile has a higher peak and produces a higher reduction of life. In general, sharper shapes produce higher reduction of life.

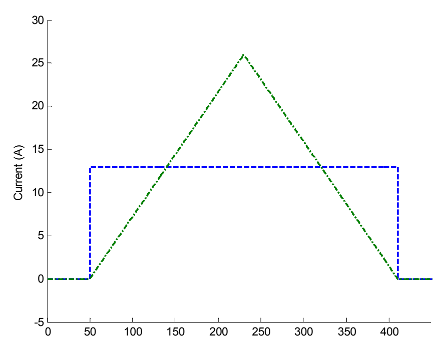



Figure 20: Two current Profiles having same integral but different effects.

*Evaluating the life reduction after a series of cycles*

In general, to evaluate the effect of a cycle on the battery life, the effective DOD must be reduced or extended, depending on the actual current profile. A good method to compare the effects of two cycles seems to be the comparison of their root mean square (RMS). In this work, a "cycle" is defined as any period between two points in which the current becomes zero. The current history will be composed by a succession of cycles, each different from the other. For each of the cycles, the effective DOD is the product of two factors:

- the "measured" DOD, defined as:

$$DOD_{meas} = SOC_{start} - \frac{\int_{cycle} I \, \mathrm{d}t}{C_{nom}} \qquad (6)$$

($I$ being the current, $C_{nom}$ the nominal capacity and $SOC_{start}$ the state of charge at the beginning of the cycle). In this work, we will consider positive a current which discharges the battery, and negative a current which charges the battery.

- the correction factor $c = \mathrm{f}\left(\frac{RMS}{RMS_{nom}}, \frac{T}{T_{nom}}\right)$, where $\frac{T}{T_{nom}}$ is the ratio between the actual temperature and the nominal temperature, $\frac{RMS}{RMS_{nom}}$ is the ratio between the RMS of the considered cycle and that of the nominal aging cycle, i.e. the cycle from which the curves of Figure 19 are obtained; $f$ is a generic function, it will be described later.

In order to evaluate the effect of a generic current profile, curves like the example shown in Figure 19 must be provided by the manufacturer, and information about the kind of cycle that has been used is necessary to evaluate $T_{nom}$ and $RMS_{nom}$.

The effective depth of discharge over a given cycle is then:

$$DOD_{eff} = \mathrm{f}\left(\frac{RMS}{RMS_{nom}}, \frac{T}{T_{nom}}\right) \cdot DOD_{meas} . \qquad (7)$$

$DOD_{eff}$ can be used as an input to the Ah life curve of Figure 19 to determine the total life (in terms of charge) corresponding to that cycle. Then eq. (4) will give the residual life.

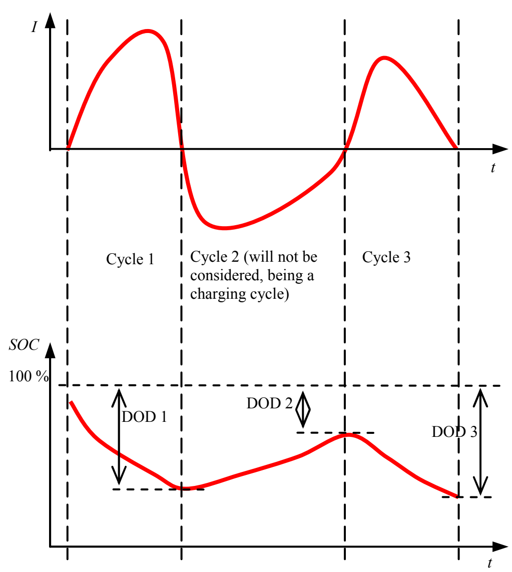



Figure 21: An example to explain the definition of cycles, depth of discharge and state of charge.

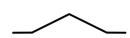
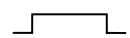
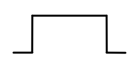
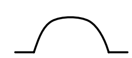
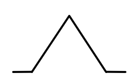
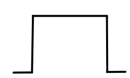
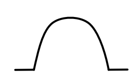
*Experimental activity*

In order to explicitly define the function $f$ that appears in (7), a series of experiments must be performed. A set of current histories different for DOD and RMS (shape) are created, and are presented in Table I. The objective is to compare the effects of different "basic" cycles, in order to estimate an expression for the function $f$, which will then be validated by applying (7) to an arbitrary, realistic current history taken from a HEV. To estimate the aging effect the internal resistance is used. The capacity is best suited for being used as an aging metric, but since measuring the capacity is a lengthy procedure, the internal resistance is used. This can be easily estimated from the basic measurement of voltage and current.

The experimental procedure is composed of the following steps.

1. Find a curve relating the battery capacity and resistance to the total amount of charge drawn, at rated thermal and DOD conditions (25°C ambient - 10 %). This is the same curve shown in Figure 4.

TABLE I
SCHEMATICS OF THE TEST PROFILES

| shape: / DOD: | *triangular* | *square* | *sine* |
|---|---|---|---|
| 10 % |  |  |  |
| 30 % |  |  |  |
| 50 % |  |  |  |

2. Apply one of the basic current profiles given in Table I, repeating it until a significant variation of battery resistance can be seen.

3. From the variation of resistance, evaluate the percent of life that has been used (see Figure 22).

4. From the measured discharge and the percent of life, it is possible to find the total life of the battery, $L_{tot}$ (Ah).

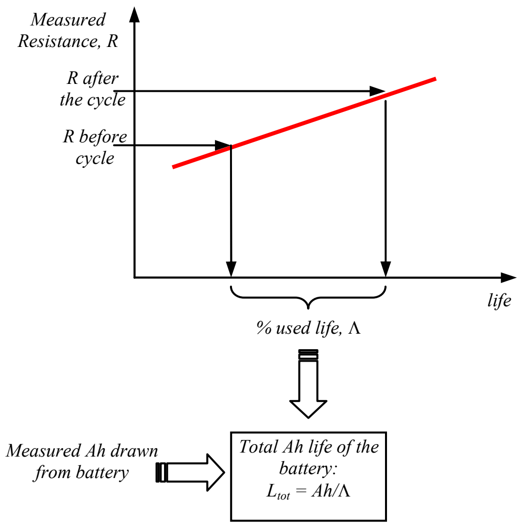



Figure 22: Assessing the total life of the battery. The internal resistance R is measured before and after the cycle, in the same conditions of SOC and temperature.

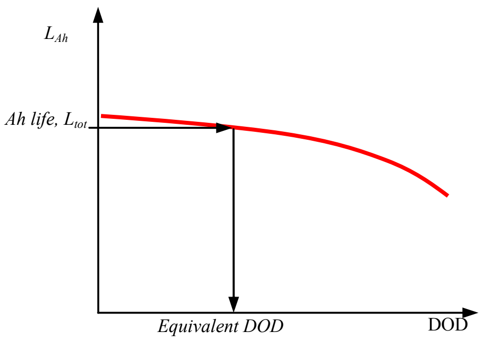



Figure 23: Meaning of the "equivalent DOD".

5. Introducing the total life of the battery in the Ah life curve of Figure 19, the equivalent DOD of the cycle can be found (see Figure 23).
6. The ratio between the equivalent DOD and the measured DOD gives the value of the correction factor $c = \mathrm{f}\left(\frac{RMS}{RMS_{nom}}, \frac{T}{T_{nom}}\right)$ for the considered conditions.
7. Repeating the experiments for different conditions (current history and temperature) will generate a set of points for the function *f*, which will be used to explicitly express *c*.

Once the value of *c* has been determined, the model can be used on real world conditions.

*Application of the model*

Given a current history, or measuring it on the vehicle, the application of equations (4) and (5) to the identified cycles (see Figure 21) will give the reduction of battery life. The prediction of the end of life is then possible if one assumes that all the future current cycles of the battery have the same characteristics as the recorded ones.

For example, let us suppose that a real world driving path with duration of 1 km has the current history shown in Figure 21. From the current history, many current cycles (according to our definition) are identified. For each of them, applying eq. 7, one gets:

$$DOD_{eff}(i) = c(i) \cdot DOD_{meas}(i),$$

which, introduced in the Ah life curve of Figure 19, gives $L_{tot}(i)$, i.e. the Ah life corresponding to each cycle.

Then, the residual life after the driving test is given by eq. 4:

$$\Lambda_{res} = \Lambda_{start} - \sum_{i=1}^{N} \frac{L_i}{L_{tot}(i)}$$

where $L_i$ is the integral of current during the i-th discharge cycle, and $\Lambda_{start}$ is the residual life at the beginning of the test ($\Lambda_{start}$ = 1 if the battery is new).

## IV. Conclusions and Future Work

An aging model that can be used to find the reduction of life after a generic discharge cycle has been described. The next part of the work will be to perform a series of experiments in order to explicitly describe the relationship that gives the equivalent DOD.

## V. Bibliography


[1] R. Somogye, *An Aging Model Of Ni-MH Batteries For Use In Hybrid-Electric Vehicles*, Master Thesis, The Ohio State University, Columbus, 2004

[2] B.Y. Liann, A. Urbina, T.L. Paez, *Life Prediction of Lead-Acid Batteries in Stationary Backup Power Applications*, Sandia National Laboratories.

[3] S. Drouilhet, B.L. Johnson, "A Battery Life Prediction Method for Hybrid Power Applications", in *Proceedings of 35th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, 1997.

[4] MPower Solutions Ltd, "Custom Power Solutions" http://www.mpoweruk.com/

[5] Moltech Corporation, NiMH Application Manual http://www.moltech.com/techdata/appmanuals/NiMH_Application_Manual.asp

[6] Batmax Glossary, http://www.batmax.com/glossary.php

[7] Panasonic EV Energy Co., Ni-MH battery for EV http://www.peve.panasonic.co.jp/catalog/e_kaku.html

[8] H. Kim, *Dynamic Battery Modeling In Hybrid Electric Vehicles*, Master Thesis, The Ohio State University, Columbus, 2002.