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# Results and comparison of seven accelerated cycling test procedures for the photovoltaic application

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**Abstract**

Choosing the right battery for a given photovoltaic (PV) system is a key question, because it strongly influences the cost and reliability of the system. This paper presents results of seven test procedures experienced at the GENEC battery test facility. A set of four complementary tests is selected, covering the various types of photovoltaic systems. Moreover, the analysis of these results gives an estimation of the ageing rate for the different types of batteries used in photovoltaic systems.


*Keywords:* Lead–acid battery; Photovoltaic; Degradations; Cycling test; Ageing

## 1. Introduction

In most stand-alone photovoltaic (PV) systems, an energy storage system is required to ensure the continuity of energy supply, while solar irradiation, and thus energy supply from the PV module, is intermittent. In most of the systems, the storage system selected is lead–acid battery (LAB), mainly because of its low cost and local availability. In the investment cost of a PV system, the main part is the PV array. Anyway, in the overall cost over 20 years, the storage is half of the cost, because of the battery replacement. This is why the battery is often considered as being the ‘‘weak point’’ of a PV system, in terms of cost, lifetime and reliability.

In this application, the battery has specific constraints, which can be very severe for LAB. The battery is cycled daily, sometimes with high depth of discharge (DOD). The recharge is done with the current from the PV array, and thus depends on the available solar irradiation. In case of bad weather conditions, the battery can remain for a long period in the discharged state, which is very penalizing, and different from the other applications of LAB. In addition to this, the maintenance is not always optimal. This can lead to a strongly reduced lifetime compared to what could be expected. Since several years, we have analysed the degradations of LAB back from field installations. The degradations can be very different: ‘‘hard’’ sulphation, stratification, shedding/softening of the active mass, and corrosion.

There are different types of PV systems, for which different LAB technologies are used. In solar home systems (SHS) (typically 50 Wp module, 70 Ah battery), one finds mostly SLI or ‘‘solar’’ flat plate batteries. In domestic stand-alone systems, and in professional systems (PV-Telecom, PV-UPS), tubular batteries will be used. In navigation systems (such as lighthouses), VRLA batteries are also used.

In this context, the choice of a LAB model for a given installation is always a difficult issue. One has to estimate its possible lifetime and to optimise the overall system cost. To answer these questions, accelerated test procedures are used. Conventional battery tests are not directly usable because of the specific operating constraints related to the PV use, and therefore specific tests have been designed for the PV application. There are two possible approaches: the first one is to design specific tests accelerating specifically each degradation [1], the other one is to design cycling procedures close to field conditions. This paper deals with the second approach.

Our laboratory GENEC has been working in the field of development of such test procedures for more than 10 years, and this paper is an analysis of the results of these 10 years of testing. Several cycling test procedures are available, and the major question is which one to choose depending on the application for which the battery is intended.

This comparison allows to:

- give indications for the selection of the procedure to be used for a given application;
- compare the performances of various battery technologies;

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- estimate the degradation rates of various battery technologies.

It gives a general overview of the battery behaviours for various technologies and also provides the background necessary to battery simulation and modelling (short-term and long-term behaviour).

## 2. Description of the tests

### *2.1. Battery cycling*

All cycling tests were performed on commercially available lead–acid batteries of different technologies, from a large number of manufacturers.

Since this paper compiles experiments done over 10 years, experiments were done using different cycling equipments. However, all cycling test benches are composed of a power supply for charging the battery, an electronic load for discharging it with controlled current, and an acquisition system from HP (Agilent). Each test bench is computer-controlled, and the battery voltage and current are monitored. The batteries are placed in a temperature-controlled water bath.

### *2.2. Physico-chemical analysis of the cycled batteries*

After reaching the end-of-life criteria, which are specific to each procedure, the batteries are analysed using different physico-chemical methods, in order to characterise the ageing effects and to link them with the cycling procedure the batteries have been submitted to.

After opening the battery tank, a first analysis allows identifying qualitatively some of the degradation modes: brittle grids (indicating corrosion), white marks (indicating hard sulphation), active mass softening and shedding. The electrodes are then rinsed and dried, under neutral atmosphere for the negative plates to avoid oxidation of the active mass. Samples are taken in the top, middle and bottom of each electrode, in order to assess for the potential electrolyte stratification and its consequences.

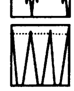
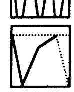
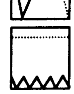
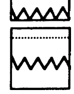
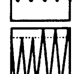
The chemical titration of the active mass components indicates the Pb, PbO, and $PbSO_4$ content for the negative electrodes, and $PbO_2$, PbO, and $PbSO_4$ for the positive electrodes. Before tear-down analysis, the batteries are always fully charged. The $PbSO_4$ content gives thus the hard or ‘‘irreversible’’ sulphation of the battery plates. SEM analysis allows locating the lead sulphate crystals, while chemical titration only gives the overall $PbSO_4$ content. If these crystals are located close to the grid, the conductivity will be decreased. On the other hand, if they are close to the electrolyte side, the electrolyte diffusion will be more difficult. XRD analysis is also performed in some cases.

Cross-sections of the positive grid are observed after encapsulating in transparent epoxy resin and polishing using a PRESI Mecapol P220U automatic polishing machine, on abrasive paper then on cloth with diamond suspension. Samples are examined using an Olympus BX51M optical microscope, under polarized light in order to emphasize the different zones of the sample (grid, corrosion layer, active mass). This observation gives information about the corrosion layer width and morphology [2].

### *2.3. Description of the cycling test procedures*

The seven cycling test methods are described schematically in Table 1. The diagrams show the evolution of the state of charge (SOC) versus time for each test. A more detailed description can be found in [3].

Table 1
Schematic description of the seven cycling test procedures

| Number | Name | SOC evolution | Description |
|---|---|---|---|
| 1 | Cycling test from the IEC 61427 standard [4] |  | 30% DOD with high current, carried out around low SOC then around high SOC |
| 2 | Cycling test from the NFC 58-510 standard [5] |  | Daily cycling (20% DOD) combined with a seasonal cycling with quite low current |
| 3 | Cycling test designed for SHS batteries in Morocco |  | Deep daily cycling (90% DOD) with high current |
| 4 | Cycling test from the Qualibat project [1] |  | Deep cycling (60% DOD) with very high current |
| 5 | Cycling test around 10% SOC |  | 20% DOD with moderate current |
| 6 | Cycling test around 40% SOC |  | 20% DOD with moderate current |
| 7 | Cycling test for rural electrification in France |  | Repetition of major cycles composed of five cycles with low overcharge, followed by five cycles with strong overcharge. |

The experiments were performed on approximately 40 batteries from 18 different manufacturers. Four main technologies were investigated:

- flat plate flooded starter batteries, designed for power;
- flat plate flooded solar batteries, with thicker plates, for a better cycling ability;
- tubular plate flooded batteries;
- flat plate VRLA batteries.

### 2.4. Representation of the results

Cycling test results are usually expressed as capacity loss versus the number of cycles. If this approach is useful to compare different batteries within the same test procedure, it is meaningless for the comparison over different test procedures, because the cycling profiles are different. The significant parameter for comparing different cycling profiles is the total amount of charge (cumulated Ah) discharged by the battery. Anyway, this value has to be normalised to the rated capacity of the battery, to allow the comparison of different batteries. This ratio also represents the number of rated capacities given back by the battery during its life. It thus allows comparing the service rendered by a battery whatever the cycling profile.

An estimation of the average lifetime for each group of battery was done as follows: the lifetime is evaluated as the number of discharged capacities when the battery has lost 30% of its initial capacity. Extrapolation was used when the cycling test was not carried long enough to measure 30% capacity loss.

We also derived from the cycling test results an estimation of the capacity loss per discharged capacity. In that case, a linear regression was performed using only the experimental points with capacity loss below 50%. The slope of this straight line was taken as an estimation of the capacity loss of the battery per discharged capacity, allowing a comparison between several batteries, or between several cycling procedures. Fig. 1 shows an example of this calculation.

## 3. Results

### 3.1. Results of the accelerated cycling tests

Fig. 2 shows the estimation of the mean lifetime for the four battery technologies investigated (starter, solar, VRLA and tubular) and for each cycling test. The calculation was done as explained in Section 2.3. Except for cycling tests 5 and 6, a common ordering is observed: the tubular batteries have by far the longer lifetime, followed by VRLA, solar, and starter batteries. This is not surprising, and in strong relation with the battery cost. In particular, stationary tubular batteries have very long lifetime, and even an accelerated cycling test can last very long, often requiring 1–2 years for a significant capacity loss.

Anyway, cycling test procedures 1 and 2 emphasise more strongly the differences between the technologies. These two procedures have the common characteristic of being standard procedures for the accelerated ageing of PV batteries [4,5]. Procedure 1 [4] intends more to represent the accidental conditions, when the PV system sizing is not very good or the weather very bad and/or very good: the battery is cycled at low SOC for a number of cycles, then at high SOC for another number of cycles. Procedure 2 [5] is designed to represent the cycling conditions of a PV system in temperate countries, with the superposition of daily and seasonal cycling.

The batteries lifetime is similar when using procedures 3, 4 or 7. These three procedures include large-span cycles, representing a PV system with a very low autonomy, as it can be the case for SHS: the user consumption is so high that the full capacity of the battery is discharged every day. The cycles are performed at currents of at least $I_{10}$.

On the contrary, procedures 5 and 6 (20% DOD around 10 and 40% SOC, respectively) do not give a clear classification of the technologies, and the lifetime of the different batteries is quite similar.

When plotting all capacity loss curves on the same graph (Fig. 3), the first observation is that, even if this common

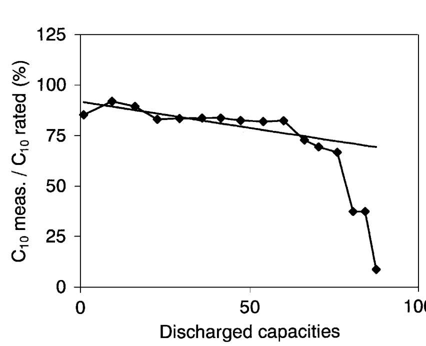



Fig. 1. Example of experimental curve of capacity evolution and its linear regression calculated with the experimental points where the capacity is above 50% of the rated capacity. The slope of this straight line gives an estimation of the degradation rate of the battery.

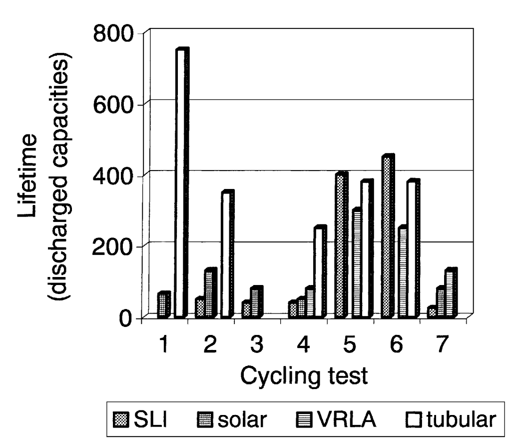



Fig. 2. Estimation of the mean lifetime for the four battery technologies investigated (starter, solar, VRLA and tubular) and for each cycling test.

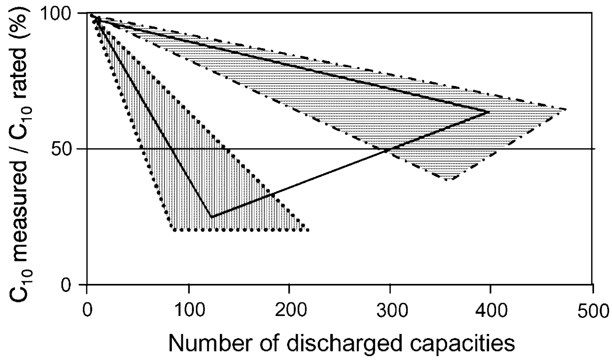



Fig. 3. Compilation of the minimum and maximum capacity loss curves for all investigated procedures and batteries. (⊟) tubular batteries; (▤) solar batteries; (◫) starter batteries.

classification can be maintained, there is a very high dispersion between batteries in the same technological family. This is easily explained by the differences within a same family: the grid alloy, active mass composition, manufacturing process, cell geometry are factors which give the batteries quite different performance. This means that there is no absolute rule: in other words, a ''bad'' solar battery can have lower performances than some starter batteries.

These graphs allow giving high and low limits of capacity loss per discharged capacity (as defined above), for each technology. Moreover, the intermediate curves (not shown in Fig. 3) give a mean capacity loss per restored capacity for each technology. Fig. 4 shows these results. The mean values of capacity loss (Table 2) can then be used as a first approach for taking into account the battery ageing. These values will then be useful for instance for a refining of the technico-economical analysis of PV systems. For the first time, ageing phenomena can be integrated into system sizing simulations, taking into account the battery technological family.

### 3.2. Battery degradations induced by the cycling tests

We have shown that cycling procedures with common characteristics induce common battery technology classification. This observation should then be related to the physico-chemical degradations induced: two procedures causing similar battery degradations should favour the same battery technologies in terms of lifetime.

Table 2
Average value of the capacity loss per discharged capacity for the seven cycling test procedures analysed

| Battery technology | Tubular | VRLA | ''Solar'' flat plate | Starter |
|---|---|---|---|---|
| Mean capacity loss per discharged capacity (%) | 0.07 | 0.21 | 0.36 | 1.52 |

The physico-chemical analysis of the batteries after cycling tests, associated to the analysis of the cycling profiles (currents and DOD in particular), gives the overall types and amount of degradations associated with each of the seven cycling test procedures.

Four types of degradations were observed:

- stratification of the electrolyte, indicated indirectly by the difference in $PbSO_4$ content in the active mass at the top and bottom of the electrodes;
- ''Hard'' sulphation;
- corrosion of the positive grid;
- softening and shedding of the active mass.

The extent of these degradations for each cycling test procedure is given qualitatively on Fig. 5, with four degradation levels: high, medium, low, and no degradation.

Stratification is observed in all cases, but particularly in procedures 2, 5 and 6, since they include long time periods without reaching the full SOC. There is little or no water electrolysis, and the electrolyte is not mixed. The sulphuric acid produced during the charge stays in the bottom of the battery tank, which induces ''hard'' sulphation in the bottom part of the electrodes. Procedure 1 also includes 50 cycles at low SOC, but 100 cycles at high SOC follow, during which the battery can recover from this stratification.

''Hard'' sulphation is observed with all cycling tests: it is the most common degradation mode of batteries in the PV application. Procedure 5 most induces ''hard'' sulphation, since the cycling is done only around 10% SOC, which is very low.

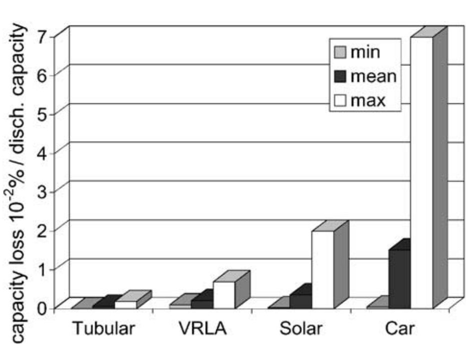



Fig. 4. Diagram of the minimum, mean and maximum capacity loss per discharged capacity, for each battery technology.

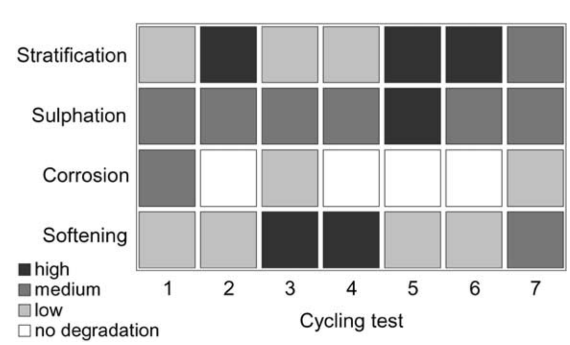



Fig. 5. Degradation level induced by each of the cycling test procedures, estimated by physico-chemical analysis of the batteries and analysis of the cycling profiles (current, DOD).

Corrosion of the positive grid occurs during cycling tests 1, 3 and 7, where the battery reaches full SOC quite often. Anyway, it is never very strong, which is also the case for field batteries. On the other hand, some battery technologies are very sensitive to this degradation, which depends in particular of the positive grid alloy.

Softening and shedding have been joined in this analysis, because shedding is more or less induced by softening: the active mass particles loose contact with the current collector,

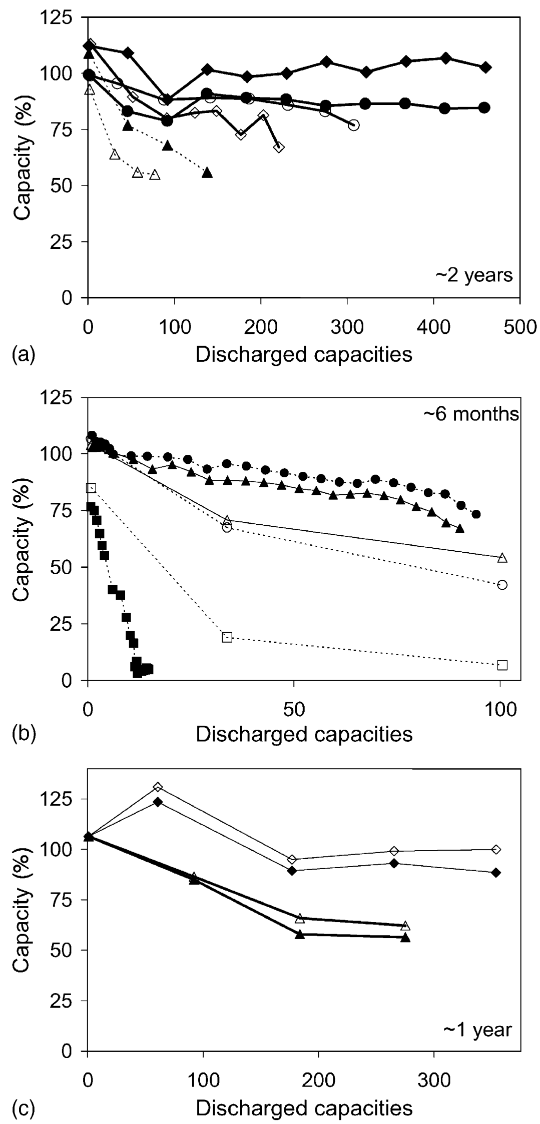



Fig. 6. Comparison by pairs of the cycling test procedures. (– – –): starter, (—): solar, (━): tubular batteries. Full symbols: procedures 1, 3, 5; open symbols: procedures 2, 4, 6, respectively. (a) Procedures 1 (IEC 61427) and 2 (NFC 58-510) (◆) tubular 1, procedure 1/(◇) tubular 1, procedure 2; (●) tubular 2, procedure 1/(○) tubular 2, procedure 2; (▲) starter 1, procedure 1/(△) starter 1, procedure 2. (b) Procedures 3 (SHS) and 4 (Qualibat) (▲) solar 1, procedure 3/(△) solar 1, procedure 4; (●) starter 1, procedure 3/(○) starter 1, procedure 4; (■) starter 2, procedure 3/(□) starter 2, procedure 4. (c) Procedures 5 (10% SOC) and 6 (40% SOC) (▲) tubular 1, procedure 5/(△) tubular 1, procedure 6; (◆) solar 1, procedure 5/(◇) solar 1, procedure 6.

and then fall down in the bottom of the battery tank. All 7 procedures induce softening and shedding, with emphasis on procedures 3, 4 and 7. These procedures have the common characteristic of large cycles, with high current ($I_3$) for procedure 4. During these large cycles, the active mass is charged and discharged fully, and the particles size difference between the charged and discharged state causes their softening.

In conclusion, all seven procedures are quite representative of the field conditions, at least from a degradation point of view. The batteries analysed in GENEC after their use in different types of PV installations have similar degradation modes. Going more into the details, the current profiles used in the seven cycling tests are quite different, but this is also the case on the field: there are several types of installations, in different climates, and the user consumption can also be variable.

### 3.3. Comparison of the different accelerated ageing tests

On the seven analysed tests, six are redundant by pairs: their SOC profiles have common characteristics. These are the pairs that we have compared here. Most of the tests were carried out on different batteries, however the comparison could be made on the basis of common batteries tested (Fig. 6). In each pair, the tests emphasise a similar type of degradation (Fig. 5). Standard tests 1 and 2 aim at simulating constraints close to real operating conditions, by cycling the battery in various states of charge. Tests 3 and 4 tests carry out deep and intensive cycling to induce shedding–softening. The cycling tests around 10% SOC and 40% SOC (tests 5 and 6) induce stratification and significant sulphation.

Examples of batteries presented on these graphs show that the only tests for which a real difference is observed are tests SHS and Qualibat, with a clear advantage for the last one. Average capacity losses per restored capacity are multiplied by a factor 3 or 4. The difference between NFC and IEC tests is less important: the difference in degradation rates is about 0.15% per discharged capacity in favour of NFC standard. The difference between tests around 10 and 40% state of charge is not significant. However, from the experimental point of view, the test around 10% SOC is easier to control than the test around 40% SOC.

## 4. Conclusion

In spite of the behaviour variations within the same technological family of batteries, an average behaviour can be pointed out by analysing the data from multiple tests and batteries. This comparison has been performed by using the number of discharged capacities as measuring unit for the battery sollicitation.

These figures allow the first integration of the ageing phenomena into simulations according to the type of battery considered. They are also useful either to select a technology of battery for a given application, or to select a battery within a technology.

It results from our comparison of seven battery cycling tests that NFC 58-510 standard test, Qualibat, around 10% of SOC and ''rural electrification'' form a set of complementary tests from the degradation point of view. They are then applicable to various categories of PV systems, while minimising the test duration. Depending on the future operating conditions of the batteries to be tested, it is now possible to choose among these four tests.

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