APPLICABILITY OF ACCELERATED TESTING CONDITIONS ON LEAD-ACID BATTERIES FOR PV SYSTEMS – RESULTS FROM CYCLING AND DEEP-DISCHARGE LABORATORY EVALUATION

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ABSTRACT: This paper reports on the applicability of accelerated lifetime procedures on solar type lead-acid batteries. Two different testing procedures were examined, namely “cycling” test and “deep discharge” test. The “cycling” test simulated battery-shedding phenomena, while the “deep discharge” test provoked rapid battery sulphation and examined the recovery capability of a battery. Seven lead-acid battery types were tested from five different manufacturers. The results showed that flooded batteries lasted approximately 500 cycles under the accelerated conditions of the “cycling” test. The equivalent cycling ability was calculated more than 1300 cycles under normal operating conditions taking into account that during its lifetime the battery’s capacity does not fall below 80% of the nominal. With VRLA batteries, the final results indicated that under accelerated conditions, cycling capability was between 265 and 305 cycles for three different battery types. This corresponds to an average of 1100 cycles at room temperature. These results are satisfactory in terms of battery performance and also, in terms of validation of the applicability of the accelerated cycling procedure as a standard test in laboratories for the assessment of the lifetime of lead-acid batteries.
Keywords: Batteries – 1: Experimental Methods – 2: Evaluation – 3

1. INTRODUCTION

The applicability of accelerated lifetime procedures on solar type lead-acid batteries is examined in this paper. The performance evaluation procedures refer to “cycling” and “deep discharge” conditions. The work presented in this paper was co-funded by the EC within the JOULE III Programme. The relevant project was entitled, *“QUALIBAT – Investigations for a QUicker Assessment of LIfetime and other key characteristics of photovoltaic BATteries”*, contract No JOR3-CT97-0161.
The battery tests were carried out at CRES in the period between 1998 and 2000. The Battery Laboratory is equipped with programmable cycling machines, a water bath and an environmental chamber for temperature regulation.

2. GENERAL TESTING CONDITIONS

The test procedures were according to the specified conditions that have been discussed and agreed by all project partners, namely GENEC, CRES, CIEMAT, OLDHAM and CHLORIDE. The varying parameters were current rate, upper and lower cut-off voltage values, charge and discharge time and temperature.

2.1 Definition of a Capacity Test

Depending on the battery type, a procedure for the discharge capacity measurement at any State Of Health was developed. Assuming that before a capacity test a battery is at a high SOC level, the procedure is described step-by-step in Table 1.

Table 1. Lead-acid battery capacity test procedure

Step	Description	
1	**Temperature:** Battery at open circuit until $T = 25^0C$.	
2	**Initial Discharge:** Discharge at a 0.1×C/10 rate until 1.80V per cell end voltage.	
3	**Recharge (flooded)**	**Recharge (VRLA)**
	Constant current method. I_{C1} = 0.25×C/10 for 3h I_{C2} = 0.07×C/10 for 7h Notes: ▪ Recharged Ah ≅120% of the nominal at discharge (C/10 rate). ▪ V_{max} unlimited.	Constant voltage method. I_{C1} = 0.20×C/10 for 20h, V_{max} = 2.35Vdc I_{C2} = 0.01×C/10 for 4h, V_{max} = 2.35Vdc
4	**Rest Period:** Battery under evaluation at open circuit condition for 24h to reach $T = 25^0C$.	
5	**Discharge:** Discharge at a 0.1×C/10 rate until 1.80V per cell end voltage. Measure Ah exchanged.	
6	**Conditioning:** Repeat steps 3 to 5 another two times (three cycles in total).	
7	**Capacity Measurement:** Repeat steps 3 to 5. Battery capacity is the Ah value of the 4th cycle, Step No 5.	

2.2 Selection of Battery Types

Seven lead-acid battery types were evaluated from five different manufacturers, including VRLA and flooded types. All batteries were designed and manufactured for solar stand-alone systems applications. The main characteristics of these batteries are summarised in Table 2.

Table 2. Lead-acid battery types and characteristics

Manufacturer / Series	Type	Capacity Rates, [Ah]
Sonnenschein / Dryfit A512	VRLA gel, flat plate, 12V	104(C/10), 115(C/20), 95(C/5), 73(C/1)
Trojan / 5SH	Flooded, flat plate, 12V	150(C/10), 183(C/100), 165(C/20), 139(C/5)
Trojan / Pegasus GB12-97	VRLA gel, flat plate, 12V	91(C10), 97(C/20), 82(C/5), 65(C/1)
Trojan / T–875	Flooded, flat plate, 8V	139(C/10), 167(C/100), 150(C/20), 126(C/5)
Bären / Solar SGi 170	Flooded, flat plate, 12V	121(C/10), 170(C/100)
GNB / SUNlyte 12-5000X	VRLA, flat plate, 12V	87(C/10), 100(C/100), 93(C/24), 72(C/5)
NWES / Solar–1 SO-6-85-17	Flooded, flat plate, 2V	720(C/10), 879(C/100), 845(C/20), 480(C/1)

3. ACCELERATED CYCLING PROCEDURE

Scope of this test was to investigate a battery's ageing mechanism under accelerated cycling conditions. Fast ageing was achieved by setting the operating temperature at 47^0C, which simulates the shedding phenomenon. Duty cycle was set at 1.5 and 3 cycles per day for the VRLA and the flooded battery types respectively. The "cycling" procedure is presented in Table 3.

Table 3. Accelerated cycling test procedure

Step	Description	
1	**Temperature:** Battery at open circuit until T = 47^0C.	
2	**Discharge (flooded)**	**Discharge (VRLA)**
	$I_D = 0.33 \times C/10$ for 2h Notes: DOD = 66% of the C/10 rate, V_{min} = (1.80÷1.90)V per cell.	$I_D = 0.22 \times C/10$ for 3h Notes: DOD = 66% of the C/10 rate, V_{min} = (1.80÷1.90)V per cell.
3	**Recharge (flooded)**	**Recharge (VRLA)**
	Constant current method. $I_{C1} = 0.25 \times C/10$ for 2h $I_{C2} = 0.071 \times C/10$ for 4h Notes: Recharged Ah ≅ (120÷125)% of the C/10 rate, V_{max} unlimited.	Constant voltage method. $I_{C1} = 0.19 \times C/10$ for 10h, V_{max}=2.28V $I_{C2} = 0.01 \times C/10$ for 3h, V_{max}=2.28V Notes: Recharged Ah ≅ (105÷125)% of the C/10 rate, V_{max}=2.28V at 47^0C is equivalent to 2.35V at 25^0C.
4	**Cycling:** Repeat steps 2 and 3 for approximately 80 cycles. Notes: Duration of daily cycling is, ▪ Flooded: 2h (discharge) + 2h + 4h (recharge) = 8h per cycle, thus 3 cycles per day. ▪ VRLA: 3h (discharge) + 10h + 3h (recharge) = 16h per cycle, thus 1.5 cycles per day.	
5	**Capacity Measurement:** After a cycling period, measure battery capacity (see details in Table 1).	

Every 50 to 70 cycles, a capacity test was carried out at 25^0C in order to measure the battery residual capacity.

3.1 Results from the Accelerated Cycling Test

The laboratory results are presented in Figures 1 to 6.

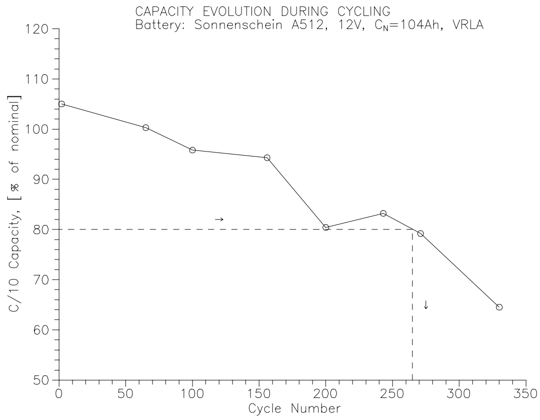

Figure 1. A512 accelerated cycling test

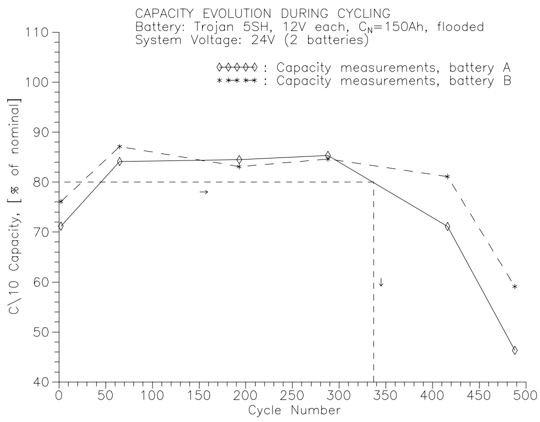

Figure 2. 5SH accelerated cycling test

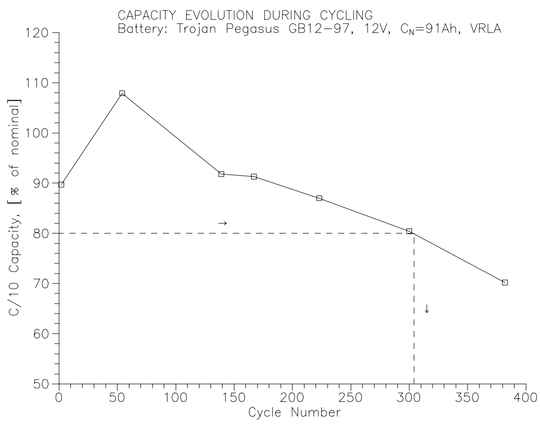

Figure 3. Pegasus GB12-97 accelerated cycling test

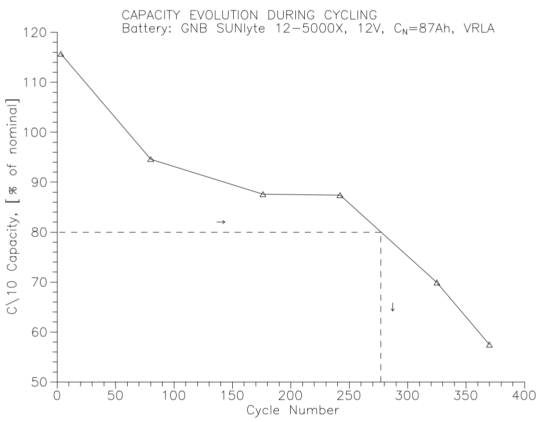

Figure 4. GNB 12-5000X accelerated cycling test

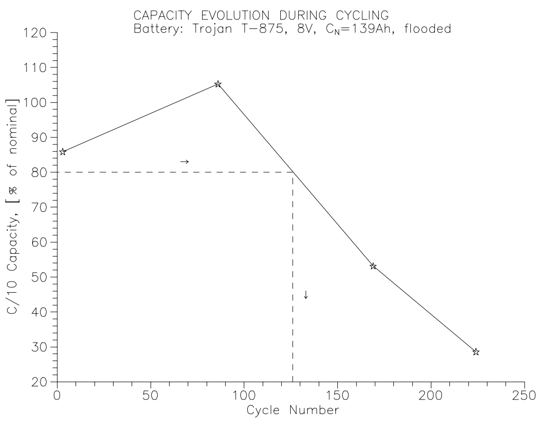

Figure 5. T-875 accelerated cycling test

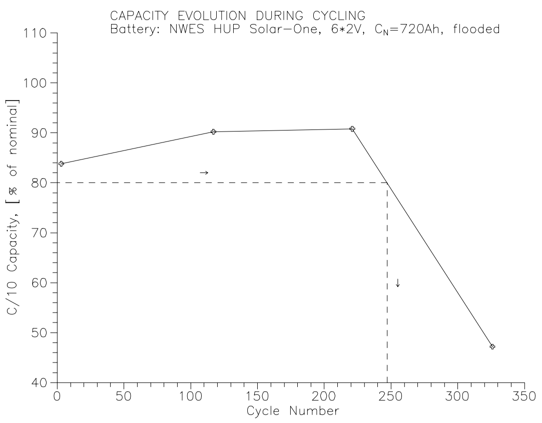

Figure 6. SO-6-85-17 accelerated cycling test

The experimental results indicate that flooded batteries lasted approximately 500 cycles under the accelerated conditions of the "cycling" test. The equivalent cycling ability was calculated more than 1300 cycles under normal operating conditions taking into account that during its lifetime the battery's capacity does not fall below 80% of the nominal. With VRLA batteries, cycling capability was between 265 and 305 cycles for three different battery types under accelerated lifetime conditions. This corresponds to an average of 1100 cycles at room temperature. These results are satisfactory in terms of battery performance and also, in terms of validation of the applicability of the accelerated cycling procedure as a standard test in laboratories for the assessment of the lifetime of lead-acid batteries.

4. ACCELERATED DEEP DISCHARGE TEST

Scope of this test was to examine the effect of deep discharge, and thus sulphation, on lead-acid battery performance. The accelerated "deep discharge" procedure was achieved by setting the batteries at extremely low state of charge for a long period. A detailed description of this procedure is presented in Table 4.

Table 4. Accelerated deep discharge procedure

Step	Description
1	**Battery Conditioning and Initial Capacity Test:** Charge and discharge rates are according to the battery type (flooded or VRLA), see Table 1. Capacity measurement in cycle 4 at 25^0C temperature.
2	**Deep Discharge Period 1:** Each deep discharge period consists of 4 cycles. Test temperature = 25^0C.
2a	**Cycle 1:** Discharge with 0.1×C/10 rate until battery voltage reaches 1.80V per cell.
2b	**Complete Discharge:** Connect a resistive load of 1Ω per cell, i.e. 6Ω for 12V, across the battery poles to reach extremely deep discharge. Step period = 28 days.
2c1	**Re-charge** for 96h with upper voltage limit 2.40V per cell for both flooded and VRLA battery types. The 0.1×C/10 recharge rate is recommended. Note: no limitation in Ah charged is set in this step.
2c2	Instead of 2c1, an alternative procedure is suggested. **Recharge** an amount of 1.5×C/10 Ah of the nominal capacity, with upper voltage limit 2.40V per cell for both flooded and VRLA battery types. Recharge rate may not be set. If not free, the C/10 rate is suggested.
3	**Deep Discharge Cycles 2, 3, 4:** Repeat the procedure of step No 2 three times. Note: each discharge carried out in 2a is an indication of the battery capacity.
4	**Capacity Test: C**apacity test procedure, see Table 1.
5	**Deep Discharge Periods:** Repeat steps 2 and 3.
6	Repeat steps 4 and 5 until the battery end of life.

From the procedure described above it is noticed that, following a full recharge regime, the deep discharge condition was repeated four times before a capacity test.

4.1 Results from the Accelerated Deep Discharge Test

Four batteries were evaluated under "deep discharge" conditions. The laboratory results are presented in Figures 7 to 10.

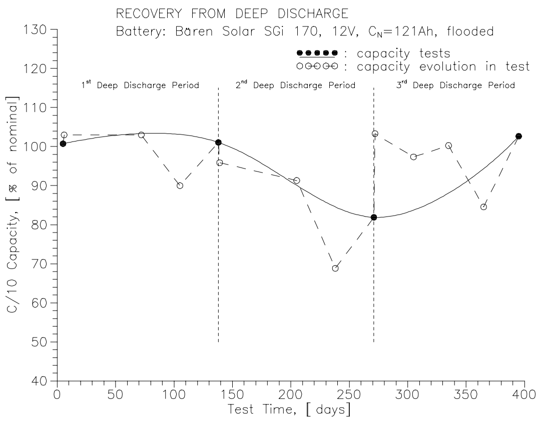

Figure 7. SGi 170 accelerated deep discharge test

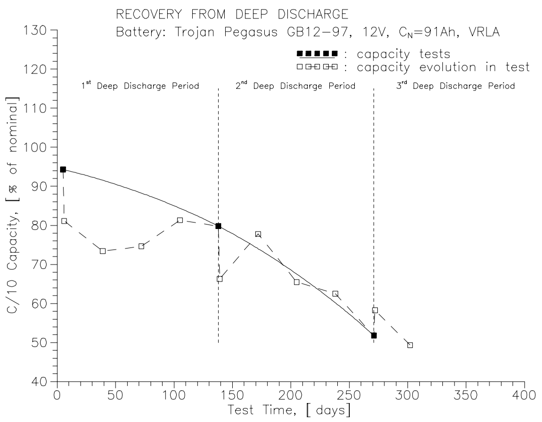

Figure 8. Pegasus GB12-97 accelerated deep discharge test

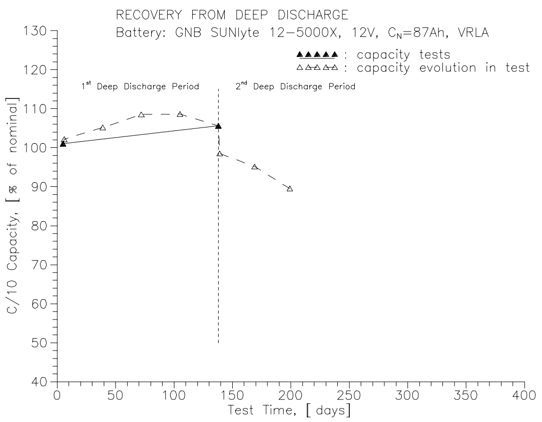

Figure 9. GNB 12-5000X accelerated deep discharge test

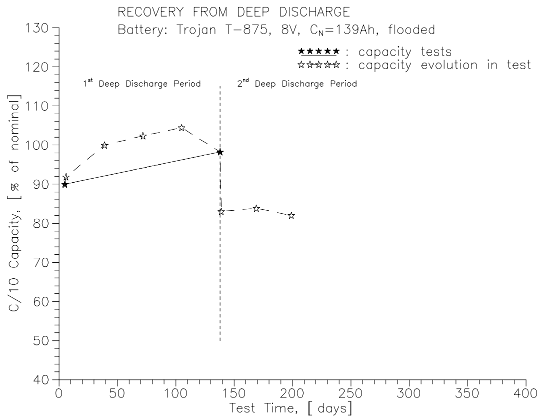

Figure 10. T-875 accelerated deep discharge test

Concerning the recharge methodology, the initial procedure described in step 2c1, Table 4, was modified as it was proven that the expected accelerated battery ageing due to high sulphation was prevented. In fact, with 96h recharge, batteries were de-sulphated during charging as positive energy transfer was in the order of 3 to 6 times more than the nominal C/10 capacity. Although this is a very useful practice for conditioning lead-acid batteries in real PV stand-alone applications, the objective to establish a quick evaluation methodology was not satisfied and excessive recharge was replaced by an energy transfer of exactly 1.5×C/10 Ah, see step 2c2.

The results show that the batteries selected have very good capacity recovery characteristics from long deep discharge conditions.

5. CONCLUSIONS

Two methodologies for quick evaluation of the performance of lead-acid batteries were investigated in this paper. In particular:

- Accelerated "cycling" test, simulating the shedding ageing mechanism.
- "Deep discharge" test, simulating sulphation of the plates.

Each of the two procedures was described in detail for both flooded and VRLA battery types. The experimental activities were undertaken in the Battery Laboratory of CRES and the results indicated that all batteries had satisfactory performance under accelerated cycling conditions. In terms of the applicability of the accelerated cycling procedure, the results were coherent and thus, such conditions were validated and can be used as a standard test in laboratories for quick assessment of the lifetime of lead-acid batteries. The applicability of the "deep discharge" methodology was also investigated and certified for by evaluating 4 batteries in the laboratory.