Test Results from the PV Battery Cycle-Life Test Procedure

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Abstract. Cycle-life testing has been conducted on the Deka ‘Solar’, Dynasty Division of C&D Technologies ‘Dynasty’, and Sonnenschein ‘Dryfit’ gel valve regulated lead-acid batteries to evaluate their performance in small stand-alone photovoltaic (PV) systems. The PV battery test procedure uses regulation voltage, charge rate, charge-amp-hour to load-amp-hour ratio, depth-of-discharge, and low-voltage-disconnect as test variables to measure the available battery capacity to the low-voltage-disconnect and end-of-test battery capacity to 1.75 volts per cell. Each cycle-life test sequence includes 25 shallow cycles, 6 deficit-charge cycles to low-voltage-disconnect, 10 to 20 recovery-charge cycles, and 40 to 50 more shallow cycles, for a total of 91 cycles per test sequence. Test results after 1,001 cycles on the above batteries have indicated that the Deka and Sonnenschein batteries lost capacity at a slow but consistent rate. The Dynasty battery experienced an initial drop in capacity but recovered most of it later in the cycle-life test. The test results also demonstrate that the “PV Battery Cycle-Life Test Procedure” is an effective means to evaluate battery performance using charging parameters similar to a stand-alone PV system.

INTRODUCTION

The “PV Battery Cycle-Life Test Procedure” used at Sandia National Laboratories and at the Florida Solar Energy Center has been in development for over seven years. Initial work by Harrington and Swamy, et al. [1,2] explored the unique operational profiles that PV batteries are exposed to and the testing requirements needed to simulate the PV cycle profile in a laboratory environment. This work made it clear that traditional battery test procedures from the Battery Council International (BCI) [3] were not fulfilling the testing needs of the PV industry. The BCI cycle-life tests were specifically designed for the motive power industry where relatively high charge and discharge rates, with complete recharges every cycle, are the norm. Batteries in PV systems continually suffer from limited power for recharge and extended periods when they are left in a partially charged condition. It is important for any PV battery test procedure to duplicate the shallow cycling, deficit-charge cycling, low charge and discharge rates, and limited recharge or finish-charge as found in PV systems. Over the last few years there has been a significant effort by the PV Global Accreditation Program (PV GAP), the IEEE Standards Coordinating Committee 21 (IEEE SCC21), and the International Electrotechnical Commission (IEC) to develop standardized test procedures for batteries used in stand-alone PV systems. The test procedure and test results in this report represent Sandia’s effort at providing the PV industry with a standardized “PV Battery Cycle-Life Test Procedure.”

*Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

PV Battery Cycle-Life Test Procedure

The PV Battery Test Procedure is designed to cycle the test battery in a way that attempts to simulate the daily charge and discharge cycles of a PV system in high and low solar resource periods. The test procedure shallow cycles the battery to a high state of charge (SOC) every day to simulate high solar resource, and deep discharges the battery to the low-voltage-disconnect (LVD) to simulate low solar resource. It is not intended to, nor can it, measure actual PV battery cycle-life. It is intended to make comparative performance evaluations based on typical stand-alone PV system design parameters.

The input test parameters are adjustable as needed to conform to system design and battery requirements. These design parameters include regulation voltage (Vr), charge and discharge rate (C/X), available charge amp-hour (Ah) to load Ah ratio (C:L), daily depth of discharge (DOD) in percent, battery temperature in °C, and LVD. In addition to the test parameters, the deficit-charge cycle recovery period is also an important variable in this test procedure. As the C:L ratio increases, the number of deficit-charge cycles decreases and the time spent at regulation voltage increases accordingly. It is very important for batteries in stand-alone PV systems to recover from this deficit-charge condition using only the limited charge provided by the PV. Deficit-charge recovery in PV systems is more difficult than in other deep-cycle applications because of the extended time that the battery spends in a discharged condition. In many PV systems the battery may not completely recover from LVD for weeks-to-months at a time. As in all battery testing, the value and quality of the test results are dependent on how well the test parameters duplicate the basic characteristics of the battery application. Every effort has been made to duplicate the PV system cycle profile in this test procedure.

Test Objectives

1) Identify batteries that operate well in the stand-alone PV-cycle environment.
2) Identify the PV battery charging parameters that result in the best cycle-life.
3) Increase PV system reliability and thus reduce life-cycle cost.

Test Procedure

A graphical representation of the “PV Battery Cycle-Life Test Procedure” extracted from test data is plotted in Figure 1. A detailed overview of the test procedure is listed below.

1) ***Initial Battery Charge*** - Returns lost battery capacity from self-discharge during storage after manufacturing. Initial charge procedures should be specified by the battery manufacturer.
2) ***Initial Capacity*** - Measures initial battery capacity at the test discharge rate to LVD and 1.75 vpc (10.5 volts) after the Initial Battery Charge.
3) ***Cycle Test*** - Cycles batteries using charge control specified by the PV system design and in a scenario that resembles the daily discharge and charge cycles of a stand-alone PV system. The cycle test consists of:
   a) 25 sustaining charge cycles at specified test parameters,
   b) six deficit-charge cycles to the predetermined low voltage disconnect,

   c) 10 to 20 recovery-charge cycles calculated based on Ah discharged and total Ah available each cycle, and
   d) 40 to 50 sustaining-charge cycles at specified test parameters.
4) Cycle testing can be terminated as required or when the battery capacity in Ah at the end of discharge to LVD is 20% less than the initial available capacity during the first deficit-charge cycle period.
5) Temperature should be held constant. The standard test temperature is 25°C, but other temperatures can be used. Stabilized temperature baths or room temperature control is required.
6) ***Final Capacity*** - The discharged Ah to 1.75 vpc (10.5 volts) at the end of a test sequence.

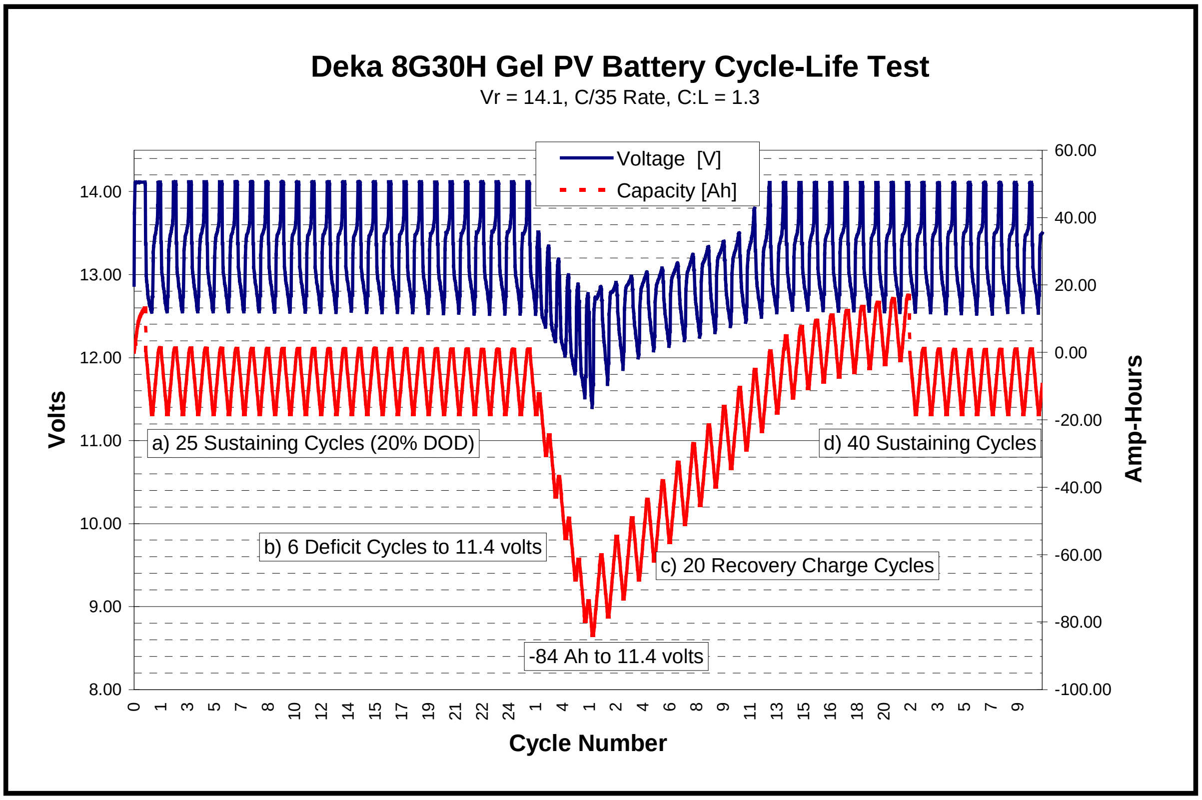

Figure 1. Test Sequence 1.

PV Charge Controllers and Data Acquisition

Counting the Ah charged into a battery when a PV charge controller is employed requires a fairly fast sample rate. Voltage, current, Ah, and temperature data sampling of two samples per second is recommended for PV charge controllers due to the switching nature of these devices. Recording and integration of this data is recommended at a maximum interval of 30 minutes, depending on capabilities. Data points are also recorded at the beginning and end of each discharge and charge cycle. An integrating ampere-hour counting device is an acceptable substitute to computer controls.

Initial Charge

Prior to performing the Initial Capacity rating an Initial Charge needs to be performed.

The battery manufacturer should be consulted for battery charging instructions for an Initial Charge. The investigator should request the charging specifications similar to the data listed in Table 1 (showing default initial charging parameters). This procedure may be referred to as the Initial Charge, boost charge, or freshening charge. In any event, when requesting this information it should be communicated that this will be a charge sequence intended to get the battery to 100% SOC or ready for installation in a PV system. The method of recharge is the current-limited, constant voltage method.

If the battery manufacturer cannot be contacted, Table 1 parameters are included as guidance for this charging sequence. The Initial Capacity rating should be performed no more than 24 hours after this Initial Charge sequence. For informational purposes only, record the amount of recharge in amp-hours. This is intended to identify any unusual battery handling or damaging storage conditions.

Table 1. Default Initial Charging Parameters.

Type	Voltage limit, vpc	Voltage limit, nominal 6/12v	Minimum duration of constant voltage regulation or equalization charge period
Vented (flooded), lead-antimony	2.55	7.65/15.3	3 hours
Vented (flooded), lead-calcium	2.66	7.98/16.0	3 hours
VRLA (AGM & Gel)	2.35 or 2.40	7.05/14.1 7.2/14.4	12 hours

NOTES:
Current should be limited to 3.0 amperes per 100 Ah of manufacturer’s 20-hr, rated capacity.
vpc= volts per cell, AGM= Absorbed Glass Mat, Gel = gelled-electrolyte

Initial Capacity

After Initial Charge, the battery will be discharged to the minimum discharge voltage specified by the battery manufacturer. This voltage is usually 1.75 vpc (10.5 volts) for deep-cycle lead-acid batteries. The capacity test will be conducted at the discharge and charge rate desired in the cycle test. During discharge, the battery voltage and Ah removed should be recorded.

Procedure for Capacity Measurement:

1. Determine the nominal or manufacturer’s battery capacity rating for the discharge rate desired. Use average current from PV system design or see Table 2 for recommended discharge/charge rate if actual PV system rate is unknown.
2. Set the discharge rate (constant current or for a resistive load use rated current at 2.0 vpc) for the current determined in Step 1.
3. Begin discharge, record battery voltage, current, Ah removed to LVD, and Ah removed at termination voltage (1.75 vpc or other specified).
4. Recharge the battery in accordance with Initial Charge procedure.
5. Plot the data showing voltage and Ah at the specified discharge current to end point voltage (Figure 2).
6. Determine the percentage of overcharge for the recharge rate by dividing the charged Ah by the discharged Ah times 100 - i.e., (Ah charged/Ah discharged)*100 = %

overcharge). Percentage of overcharge calculated here is a reasonable estimate of what is required to return the battery to a high state-of-charge after a full discharge has been performed.

Cycle Parameter Determination

Table 2 is provided as a baseline for cycle parameter determination. The values identified in Table 2 are a good starting point for most PV and battery systems. Other Vr set-points, charging rates, C:L ratios, DOD's, and temperatures can be used when based on battery manufacturer's recommendations or PV system design and user requirements.

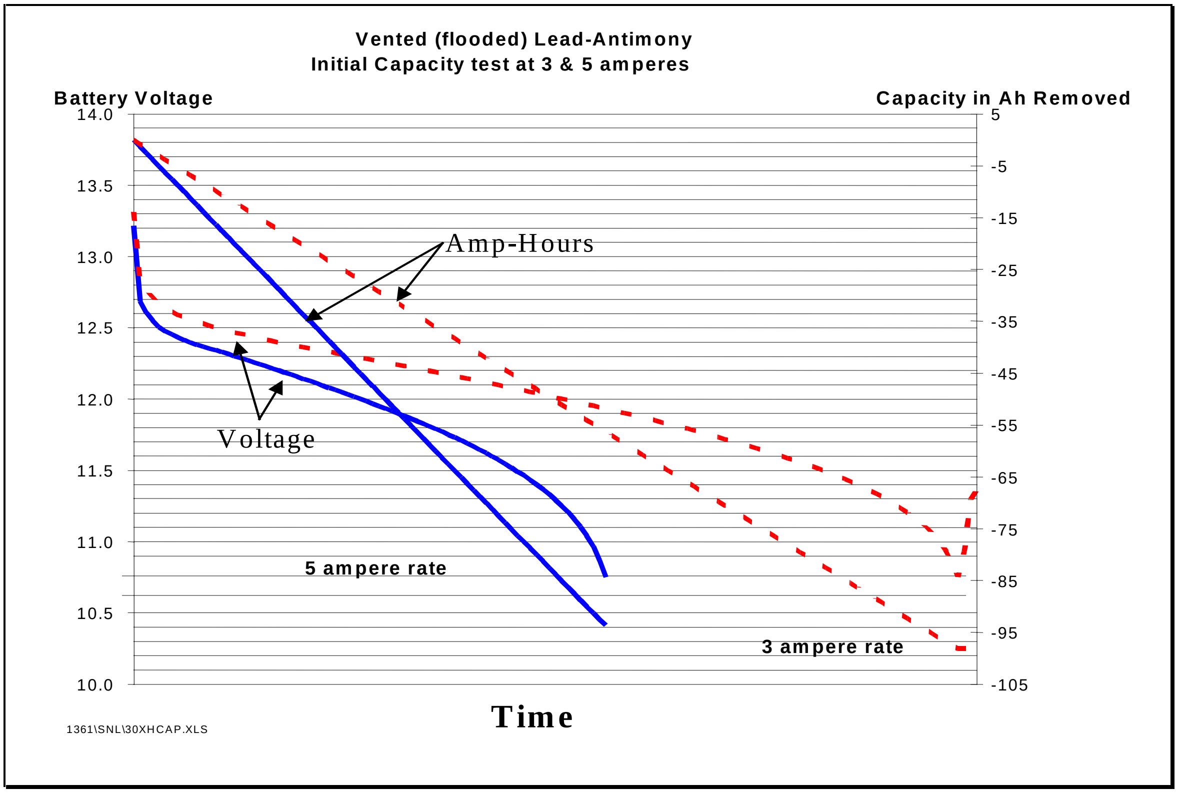

Figure 2. Battery Voltage and Capacity (Ah).

Table 2. Default PV Battery Cycle Test Parameters.

Variable	VRLA AGM/Gel	Vented (Flooded) Lead-Antimony
Vr Set-point (12 volt)	14.1 or 14.4	14.4 to 14.7
Charge Rate	Capacity/35	Capacity/35
Discharge Rate	Capacity/35	Capacity/35
C:L Ratio	1.3	1.3
DOD%	20	20
Temperature °C	25	25

PV Battery Cycle-Life Test Procedure

Steps for 80-Ah 12 volt VRLA Battery:

1) Identify sustaining charge parameters: a) Vr set-point (*2.35 vpc*, *14.1 volts*), b) discharge/charge rate (*C/35*, *2.3-amps*), c) daily DOD (*20%, 16 Ah*) d) LVD (*1.9 vpc, 11.4 volts*), and e) C:L ratio (*1.3*).
2) Conduct Initial Battery Charge and Initial Capacity test at discharge and charge rate. Record available battery capacity to 1.9 vpc (*11.4 volts*) and capacity to 1.75 vpc (*10.5 volts*).
3) Calculate deficit-charge required to discharge battery to LVD in six (6) cycles (70 Ah/6 cycles = 11.7 Ah/cycle).
4) Calculate the number of recovery cycles plus five (5) cycles required for a 70 Ah deficit charge recovery. *70 Ah/((16 Ah discharged x 1.3 C:L) - 16 Ah discharged) + 5 cycles = 20 cycles*
5) Begin twenty-five (25) sustaining discharge and charge cycles at specified Vr, rate, C:L ratio, and DOD.
6) Begin six (6) cycles at deficit C:L ratio (-11.7 Ah/cycle) designed to discharge to LVD.
7) Begin twenty (20) recovery discharge/charge cycles using sustaining charge parameters from Step 1.
8) Begin forty (40) sustaining discharge/charge cycles using sustaining charge parameters from Step 1.. Total number of cycles per test sequence should be ninety-one (91).
9) Terminate test as required or when available battery capacity to LVD is 20% lower than the initial value or when the 91-cycle test sequence is complete after the required number of test cycles. A Final Capacity test is conducted after the last 91-cycle test sequence..

Results

The test results discussed in this report are from three different VRLA gel batteries using the manufacturers' recommended regulation voltages of 2.35 (14.1) or 2.40 vpc (14.4 volts). The C:L ratio, charge and discharge rate, and LVD were based on typical PV system design considerations.

Table 3 shows the PV Battery Cycle-Life Test Data. Table 3 includes the battery manufacturer and model number, regulation voltage (Vr), initial battery capacity, capacity to LVD, total number of cycles, final capacity, capacity loss per cycle in Ah, initial Ah overcharge, final Ah overcharge, and the number of deficit charge cycles.

Initial Battery Capacity

The initial battery capacity measurements were conducted using the indicated regulation voltage and rate for each battery. Each battery was boost charged for 12 hours at the regulation voltage before discharging at the test rate for the capacity measurements at 1.9 vpc and 1.75 vpc (11.4 and 10.5 volts). Recharge included the same 12-hour finish-charge at regulation voltage. The 11.4 and 10.5 volt capacities for the Deka batteries were both 80 and

92 Ah with overcharge values between 107 and 110%. The Dynasty Division of C&D Technologies battery capacities were 71 and 82 Ah and 71 and 83 Ah with overcharge values between 105 and 106%. The Sonnenschein battery capacities were 102 and 114 Ah and 107 and 115 Ah with both overcharge values at 109%. It should be noted that the above overcharge values are for 100% DOD cycles and for battery recharge to about 90% SOC the recharge efficiency is near 99%. For 20% DOD cycles, at least half of the recharge is in the inefficient charging range between 90 and 100% SOC; therefore, the required overcharge to recover the battery back to 100% SOC should be greater than the overcharge measured for 100% DOD cycles. This is an important consideration when evaluating the cause of battery capacity loss.

Test Sequence Battery Capacity to LVD

The available capacity measurements to the 1.9 vpc (11.4 volt) LVD in each test sequence indicates that the Deka and Sonnenschein batteries lost capacity at a slow but consistent rate of –0.021 to –0.042 Ah/cycle based on the initial and final capacity measurements to 1.75 vpc (10.5 volts). The measured available Ah loss was between 19 and 22Ah or 19-26% of the available capacity to LVD. The Dynasty Division of C&D Technologies battery deviated from the capacity loss trend by first losing about 5 Ah of available capacity in sequence numbers 2, 3, and 4 and then gaining it back in sequences 5 through 11. The capacity loss for the Dynasty battery was calculated at -0.001 Ah/cycle. The final available capacity loss was 2 Ah, or just 3%. A plot of available battery capacities to LVD vs. the test sequence number is in Figure 3 and is useful to see the performance trends.

Total Number of Cycles

At least one of each of the batteries tested was cycled for 1,001 cycles before testing was terminated. This represents about 2.74 years of cycling in a PV system. One battery from both Deka and Dynasty was automatically terminated prematurely at cycle number 374 and 182. This was due to a low voltage spike in the battery cycle tester and not the battery itself. Available capacity to LVD on the batteries terminated early did not indicate that any significant capacity differences existed between the two batteries still under test and the terminated battery.

Initial and Final Ah Overcharge

Battery overcharge in this test procedure was defined by:

$$\text{Overcharge} = (\text{charged Ah} / \text{discharged Ah}) \times 100$$

The initial battery overcharge (Ah in/Ah out) was measured at cycle number 1 and the final overcharge was measured at cycle number 1001, or when the test was terminated. The results indicate that overcharge is between 107% and 113% initially and drops quickly to the 103% to 106% values seen at the end of test. Usually battery manufacturers will recommend about 110% overcharge for their VRLA batteries cycled at about 20% DOD. In this test the overcharge values are lower than would be optimum for the battery due to the efficiency losses that occur in shallow cycling.

Table 3. PV Battery Cycle-Life Test Data.

PV Battery Cycle-Life Test Results

		Initial Cap to 10.5 V	Test Sequence Ah Capacity To 11.4 Volts (LVD)												Total # of	Final Cap @ 10.5 V	Cap Loss	Cap Loss	Initial Ah Over-charge	Final Ah Over-charge	Deficit Charge Cycles to Vr	Deficit Charge Cycles to Vr
Battery	**Vr**	**Ah**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Cycles**	**Ah**	**%**	**Ah/Cy**	**%**	**%**	**Seq. #1**	**Final Seq.**
Deka Solar 8G30H #1	14.1	92	80	84	81	79	77	74	71	69	67	65	63	62	1001	61.3	33	-0.031	107	103	18	13
Deka Solar 8G30H #2	14.1	92	80	87	83	81	78	*							374	76.4	17	-0.042	108	103	19	17
Dynasty GC-12100B #1	14.4	82	71	71	66	66	65	69	70	70	70	70	69	69	1001	80.4	2	-0.001	113	105	17	17
Dynasty GC-12100B #2	14.4	83	71	70	66	*									182	73.2	12	-0.054	112	103	17	17
Sonnenschein A212/11A #1	14.1	115	107	111	108	106	104	102	101	99	97	101	95	92	1001	94	18	-0.021	109	106	18	15
Sonnenschein A212/11A #2	14.1	114	102	108	104	102	114	99	97	94	90	90	88	86	1001	84	26	-0.030	111	105	19	12

*Test terminated by false low voltage reading

To increase overcharge would require a larger C:L ratio and/or a higher regulation voltage. The higher regulation voltage would probably increase water loss, but may reduce the capacity loss rate. With a C:L ratio of 1.3, the battery spends about 2.6 hrs at regulation voltage every cycle, which is significantly less than the 12 hours required for the boost charge or complete finish-charge required by the Initial Capacity test. Further testing would be required to quantify the performance enhancing effects of increasing the C:L ratio and/or regulation voltage.

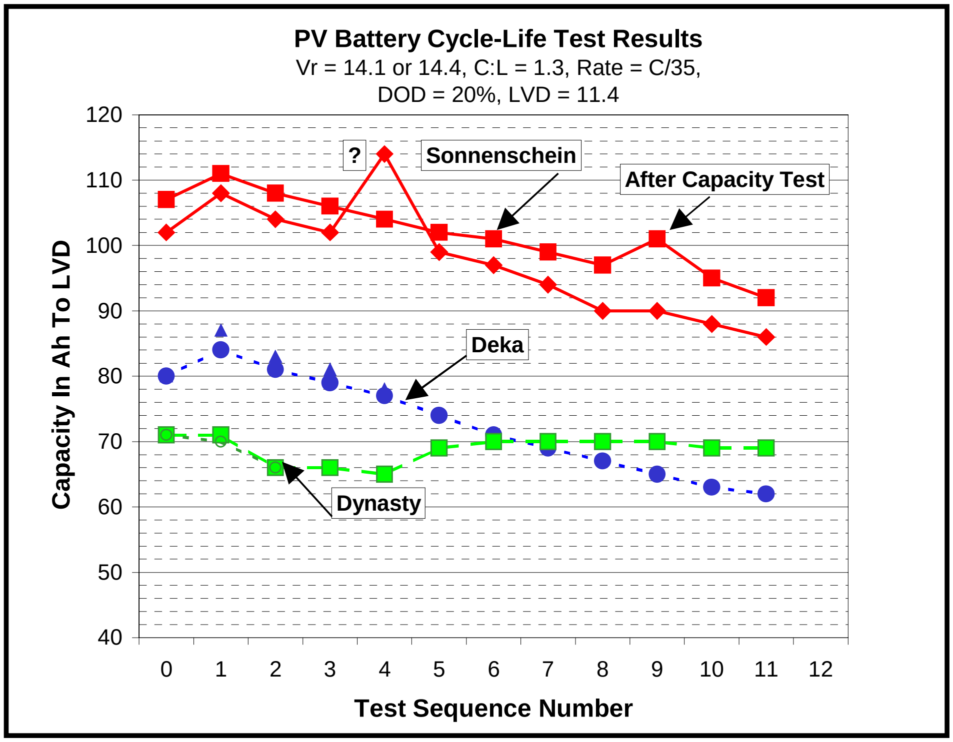

Figure 3. Battery Capacity to 11.4 Volts.

Deficit-Charge Cycles to Regulation Voltage

The deficit-charge cycles to regulation voltage include the first deficit-charge cycle and all cycles thereafter that do not reach regulation voltage during charge. This is a useful number because it is an indicator of how long the battery spends in a discharged condition before reaching regulation voltage. The days spent in a discharged condition can be calculated by adding the charge and discharge times. The cycle time calculations indicate that each day produces 1.4 test cycles. Based on the number of cycles per day, the above batteries spent 9.3 to 13.5 days in a partially charged condition from regulation voltage to LVD back to regulation voltage. If battery performance problems arise after the deficit-charge cycle period, then the deficit-charge cycle period can be reduced by increasing the C:L ratio.

Conclusions

Based on the test results, it is possible to identify some significant conclusions from this work. These include the following:

1) The C:L ratio may be one of the more important test parameters for VRLA batteries achieving rated cycle-life. The C:L ratio determines the number of cycles spent in deficit-charge recovery and the time spent at regulation voltage every day. This is probably the most important PV system battery charging parameter for maintaining VRLA battery health.
2) The batteries used in this test performed well and should last at least 3-years in a PV system using a similar design. These results were obtained using the battery manufacturers recommended cycling regulation voltage, current limited constant voltage charging, and typical PV system design parameters such as a minimum charge to load ratio (C:L) of 1.3 and a C/35 charge and discharge rate at 25°C.
3) Further testing would be required to quantify the performance enhancing effects of increased C:L ratio and/or regulation voltage on the Deka and Sonnenschein batteries.
4) The "PV Battery Cycle-Life Test Procedure" proved to be very useful in verifying and comparing battery performance under controlled laboratory conditions that were similar to stand-alone PV systems.

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