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BATTERY EVALUATION METHODS AND RESULTS FOR STATIONARY APPLICATIONS

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Abstract: Evaluation of flooded lead-acid, Valve Regulated Lead-Acid (VRLA), and advanced batteries is being performed in the power sources testing labs at Sandia National Laboratories (SNL). These independent, objective tests using computer-controlled testers capable of simulating application-specific test regimes provide critical data for the assessment of the status of these technologies. Several different charge/discharge cycling regimes are performed. Constant current and constant power discharge tests are conducted to verify capacity and measure degradation. A utility test is imposed on some units which consists of partial depths of discharge (pulsed constant power) cycles simulating a frequency regulation operating mode, with a periodic complete discharge simulating a spinning reserve test. This test profile was developed and scaled based on operating information from the Puerto Rico Electric Power Authority (PREPA) 20 MW battery energy storage system. Another test conducted at SNL is a photovoltaic battery life cycle test, which is a partial depth of discharge test (constant current) with infrequent complete recharges that simulates the operation of renewable energy systems. This test profile provides renewable system designers with critical battery performance data representative of field conditions. This paper will describe the results of these tests to date, and include analysis and conclusions.

Introduction

The Energy Storage Systems (ESS) Research and Development Program, managed and funded by the U.S. Department of Energy (DOE), develops and evaluates electrical storage technologies for utility, industrial, and renewables applications. Sandia National Laboratories (SNL), as a DOE laboratory, conducts the ESS Program in cooperation with industry partners such as Energetics,

Inc. As part of its technical mission in support of the ESS Program, SNL performs in-house battery evaluation of improved and advanced storage components to characterize prototype and development units. These evaluations are performed by utilizing specialized and unique facilities established at SNL over many years of program activities involving numerous battery technologies.

Evaluation of flooded lead-acid, Valve Regulated Lead-Acid (VRLA), and advanced batteries is being performed in the power sources testing labs at Sandia National Laboratories (SNL). These independent, objective tests using computer-controlled testers capable of simulating application-specific test regimes provide critical data for the assessment of the status of these technologies. Several different charge/discharge cycling regimes are performed. Constant current and constant power discharge tests are conducted to verify capacity and measure degradation. A utility test is imposed on some units which consists of partial depths of discharge (pulsed constant power) cycles simulating a frequency regulation operating mode, with a periodic complete discharge simulating a spinning reserve test. This test profile was developed and scaled based on operating information from the Puerto Rico Electric Power Authority (PREPA) 20 MW battery energy storage system [1]. Another test conducted at SNL is a photovoltaic battery life cycle test, which is a partial depth of discharge test (constant current) with infrequent complete recharges that simulates the operation of renewable energy systems [2]. This test profile provides renewable system designers with critical battery performance data representative of field conditions.

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Two GNB batteries, prototype ABSOLYTE II and ABSOLYTE IIP 18 V units, both rated at 1200 Ah at C/8, have undergone extensive utility testing during the last year. In addition, a VRLA battery from Yuasa-Exide (three Dynacell DD modules, Type DD-35-7) has been tested under utility conditions to characterize the technology.

PV battery cycle life tests are being conducted on Trojan VRLA batteries. Four batteries were received in October 1996, all four batteries were put on test immediately. In another test, a flooded lead-acid starting, lighting, and ignition (SLI) battery from Community Power Inc. was received which is slated for use in PV systems in Indonesia. Although this type of battery is not proven in PV applications, because of restrictive import costs Community Power and their Indonesian customers elected to use locally produced Pafecta Yuasa SLI lead-acid batteries. The batteries arrived in September 1996 and were dry charged. The batteries were activated and placed on a PV cycle test in October, 1996.

This paper will provide results from these and other tests in progress at the time of the conference. Additional life cycle tests will be performed prior to the conference and some degradation information may be available at that time.

VRLA Battery Testing for Utility Applications

The lead-acid battery has been in existence for over 100 years and is used in a wide variety of energy and power storage applications, including engine starting, propulsion power, backup and standby power systems, and power conditioning applications. The widespread use of the lead-acid couple is the result of its good electrical performance under a wide range of conditions, relatively low cost of materials and components, and familiar and generally "user-friendly" characteristics. The great majority of experience in use has been with flooded-electrolyte lead-acid batteries, which have the disadvantage of requiring relatively frequent maintenance. This disadvantage can be overcome by the use of valve-regulated lead-acid (VRLA) technology. However, uncertainty about lifetime and reliability of the VRLA battery is a primary concern. Another concern is the cost of initial investment in large-scale systems such as utility applications.

A test cycle that simulates utility energy storage (UES) operations of frequency regulation and spinning reserve has been devised and is based on the Puerto Rico utility battery system operation. The first part of the cycle is composed of several sessions of constant power pulses of frequency regulation separated by intermediate charges. These are followed by a spinning reserve deep discharge and then a refreshing charge that brings the battery back to 100% state of charge (SOC). Although the battery

starts out at 100% SOC, it operates between 70 and 90 % SOC for most of the frequency regulation part of the test cycle. During the spinning reserve discharge, the first half is spent at constant power, and then the power ramps down to zero during the second half of the discharge. This test regime was implemented on several batteries being developed by the ESS Program for utility applications.

GNB ABSOLYTE Batteries

A cost-shared contract was established in 1991 between Sandia and GNB Industrial Battery Company to improve the performance and reduce the cost of VRLA batteries for utility applications. The approach was to pursue changes in battery design, improve materials and manufacturing processes, and to develop conceptual battery system designs and economic models for utility applications. Prototype deliverables were sent to SNL during the development project for evaluation to determine the status of the design improvements.

The first task in the program focused on engineering improvements to an existing GNB product, the ABSOLYTE II battery, marketed for telecommunications and other standby applications. The engineering improvements concentrated on vent valve reliability, positive plate growth (a consequence of anodic corrosion of the positive grid structure, a normal wearout mechanism), thermal management (more difficult in VRLA batteries than flooded electrolyte types because of reduced heat capacity and conduction, and a significant factor in battery lifetime), and ground fault elimination. Long-term life and characterization testing is being performed on an ABSOLYTE II battery at SNL. As the development project progressed, an improved design was attained in 1993 and was subsequently issued as a commercially available product, the ABSOLYTE IIP.

The ABSOLYTE IIP design was expected to provide a significant improvement in performance at all discharge rates. An ABSOLYTE IIP battery was delivered to Sandia for testing.

ABSOLYTE II Test Results

Testing of the ABSOLYTE II deliverable is ongoing with a total cycle count of 113. Due to tester problems, this battery was on open circuit from April 5, 1996, to November 5, 1996. Following the stand, several equalization cycles were performed. An equalization charge to 115% overcharge was attempted, but only 103% was achieved. A second equalization cycle to 120% was successful. Cycling was again resumed using the normal "E" charge parameters shown in Table 1.

The capacity of the battery gradually rose, but sometimes the charge was stopped by a high-temperature alarm. Figure 1 is capacity plot showing amp-hours removed and amp-hours returned for Cycles 95 through 113.

Recharge Regime Name	Recharge Regime Specifics	Required Time to Complete Regime	
		ABSOLYTE II	ABSOLYTE IIP
Normal Overcharge (A)	CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 7% overcharge, OC for 2 hr	—	25 hr
Normal Overcharge (B)	CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 24 A, CI (24 A) for 2 hr, OC for 2 hr	—	11.5 hr
Normal Overcharge (C)	CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 7% overcharge, OC for 8 hr	—	31 hr
Normal Overcharge (D)	CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 24 A, CI (24 A) until 7% overcharge, OC for 8 hr	16.5 hr	17.5 hr
Normal Overcharge (E)	CI (300 A) until 2.40 vpc, CV (2.40 vpc) until 24 A, CI (24 A) until 7% overcharge, OC for 8 hr	—	16 hr
Boost Charge (A)	CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 24 A, CI (24 A) for 8 hr, CV (2.35 vpc) for 48 hr	—	64 hr
Intermediate Charge (A)	CI (120 A) until 2.35 vpc, CV (2.35 vpc) until 90% SOC, OC for 5 min	—	3 hr
Refreshing Charge	CI (300 A) until 2.40 vpc, CV (2.40 vpc) until 24 A, CI (24 A) for 2 hr, OC for 8 hr	—	16.5 hr

CI = constant current CV = constant voltage OC = open circuit vpc = volts per cell SOC = state of charge

Table 1. Various Regimes Used for Recharging the ABSOLYTE II and IIP.

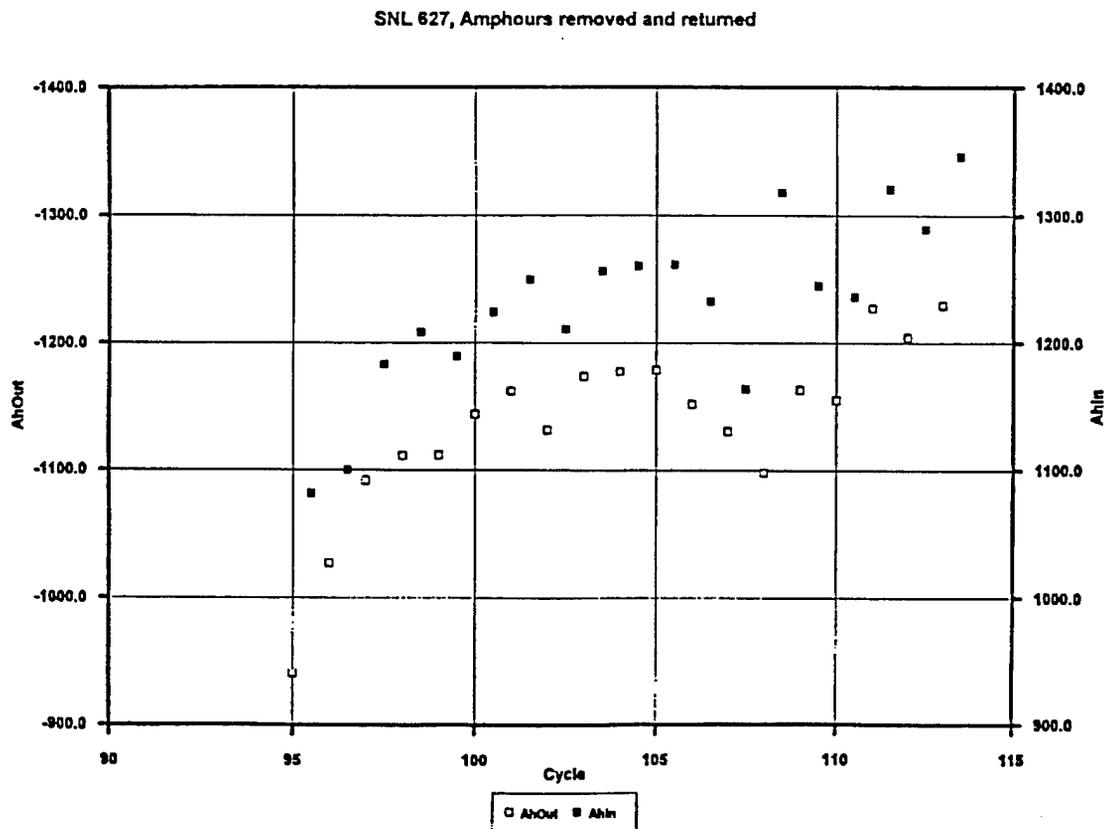


Figure 1. Amp-Hours Removed and Returned for the ABSOLYTE II Battery.

ABSOLYTE IIP Test Results

The first test objective was to confirm the electrical performance ratings under various constant current loads. Tests were made at C/8 (150 A), C/2 (428 A), and C/18 (74 A), which initially confirmed that the ABSOLYTE IIP performed as rated, but a trend of declining capacity with successive cycling was noted. This led to several studies aimed at determining a recharge regime that would be suitable for utility energy storage applications in terms of both completion time and discharge capacity stability. These charge regimes are shown in Table 1. Regime A was the initial routine, and regime B, tried next, resulted in an even higher degradation of capacity.

In general, the faster constant-current charges result in more capacity degradation than charge regimes that finish with a constant voltage and tapering current. The trade-off, however, is that the tapering current charge required nearly twice the time to complete.

Testing of the ABSOLYTE IIP continued with cycles performed to evaluate its capability to meet a defined frequency regulation/spinning reserve utility cycle. The results of the frequency regulation subcycles are summarized in Table 2.

In this test, 23, 160-min subcycles were accomplished in a 61-hr period during the first frequency regulation session, whereas 19, 160-min subcycles were accomplished in approximately 51 hr during the second and third sessions. With the battery at approximately 70% SOC, a spinning-reserve discharge test immediately followed the third frequency regulation session. For this part of the UES cycle, the ABSOLYTE IIP was discharged at a constant power rate of 11.38 kW for 16.7 min, followed by a linear ramp from 11.38 kW to 0 kW over a period of another 16.7 min. The spinning reserve test caused the battery SOC to drop an additional 24% from the 70% point. Then, with the battery at approximately 46% SOC, a refresh charge was applied to bring the battery back up to 100% SOC.

Life cycle testing is continuing on the ABSOLYTE IIP battery, with a total count of 265 cycles.

Yuasa-Exide Battery

In March, 1995, Yuasa-Exide provided Sandia with 10 Dynacell Type DD-35-7 VRLA modules for testing. Seven of these modules were forwarded to Pacific Gas and Electric Co. for testing in their Battery Test Lab. The remaining three modules were configured by Sandia into a series string. Each module consists of four series cells, except for the third module which contains only three. One cell was removed when received by Sandia because of very low open circuit voltage. Charge/discharge cycles were performed on the string to determine capacities at various discharge rates. Cycling is as summarized in Figure 2. The charge regimes used

are defined in Table 3. Testing is planned to continue until the battery reaches 80% of rated capacity.

Lead-Acid Battery Testing for Photovoltaic Applications

In addition to the testing of VRLA batteries intended primarily for utility applications, Sandia is testing batteries for photovoltaic and other renewable energy applications. The battery cycling scheme is based on available PV array power, user system load, and PV system control restraints. Array and user load are simulated by laboratory electronic power supplies and electronic loads. PV control restraints are ensured by laboratory data acquisition equipment. PV cycling consists of shallow discharges followed by a partial recharge thus simulating a PV day. This process is repeated several times until the battery reaches a minimum voltage called the low voltage disconnect, roughly equal to a 50% battery state-of-charge (SOC). At this point the battery is fully recharged to 120% of its discharged capacity and PV cycling is resumed. This process is repeated until the battery is unable to provide an adequate number of PV cycles.

Trojan 12-V VRLA Gel Batteries

Trojan Battery Company sent four sealed gel VRLA batteries to Sandia to be tested to confirm the electrical performance ratings, to evaluate the batteries' ability to meet Trojan customer requirements, and to determine the service life of the batteries. The life cycle test procedure was appropriate to a PV application, and is shown in the test regime below. The electrical characteristics of the four batteries are shown in Table 4. Battery temperatures (case) and capacities are shown in Figures 3-6.

1. Discharge at 25 A constant current to 10.5 V, recording Ah out.
 2. Rest 30 minutes.
 3. Recharge at a constant current of 20 A until the voltage rises to 14.40 v, then hold the voltage constant and allow the current to taper. Terminate recharge at 15% overcharge or after a total recharge time of 12 hr, whichever comes first.
 4. Rest 2 hours
- Repeat steps 1-4 for 50 cycles, then perform one boost cycle of a constant current charge at 1.0 A for 20 hr (1.4 A for battery types 2410 and 30H14). Battery case temperature is constantly monitored.

Session #	SOC at Start of Session (%)	No. of Subcycles Completed	Length of Session (hr)	Accumulated Ah Removed During Session (AhOut)	Accumulated Ah Returned During Session (AhIn)	SOC at End of Session (%)
1	90.0	23	60.9	2740	2496	69.5
2	90.0	19	50.9	2294	2053	69.8
3	90.0	19	50.2	2260	2017	69.6

SOC = state of charge

Table 2. Summary of Frequency Regulation Data of a UES Cycle on the ABSOLYTE IIP (Cycle 141).

"A" Charge	"B" Charge	"C" Charge	"D" Charge	"E" Charge	"F" Charge
Charge at 30 A to an 8% overcharge or cutoff at 25.3 V 5-min rest	Charge at 30 A to an 8% overcharge or cutoff at 25.85 V 5-min rest	Charge at 44 A to a 5% overcharge or cutoff at 26.4 V Charge for 2 hr at 2 A or cutoff at 26.95 V 5-min rest	Charge at 44 A to a 5% overcharge or cutoff at 25.85 V Charge for 2 hr at 3 A or cutoff at 26.95 V 5-min rest	Charge at 44 A to a 5% overcharge or cutoff at 25.85 V 5-min rest	Charge at 44 A to a 5% overcharge or cutoff at 25.85 V 5-min rest
Wait until one or more thermocouples show temperature below 29°C	Wait until one or more thermocouples show temperature below 29°C	Wait until one or more thermocouples show temperature below 29°C	Wait until one or more thermocouples show temperature below 29°C	Charge for 2 hr at 2 A or cutoff at 26.95 V	Charge for 8 hr at 2 A or cutoff at 26.95 V
				5-min rest	5-min rest
				Wait until one or more thermocouples show temperature below 29°C	Wait until one or more thermocouples show temperature below 29°C

Note: All cycles start with a C/8 (13.5 A) discharge to 19.25 V followed by a 5-min rest.

Table 3. Standard Charge Regimes for Yuasa-Exide Dynacell Battery.

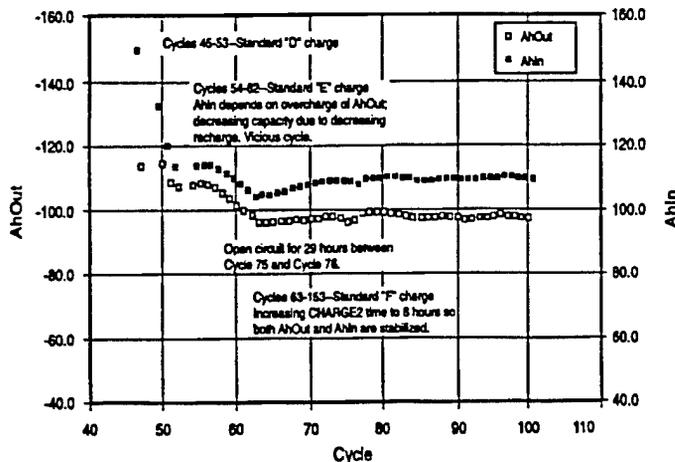


Figure 2. Life-Cycle Capacity Plot at C/8 Discharge Rate for Yuasa-Exide Dynacell Battery.

SNL Battery ID	722	723	726	727
Battery Type	2410GEL	2410GEL	30H14GEL	30H14GEL
Serial No.	1364	1365	1383	1384
Weight (kg)	21.37	21.27	28.75	28.86
Voltage	12	12	12	12
Capacity (8 hr)	60	60	80	80

Table 4. Trojan Batteries Undergoing Testing at SNL.

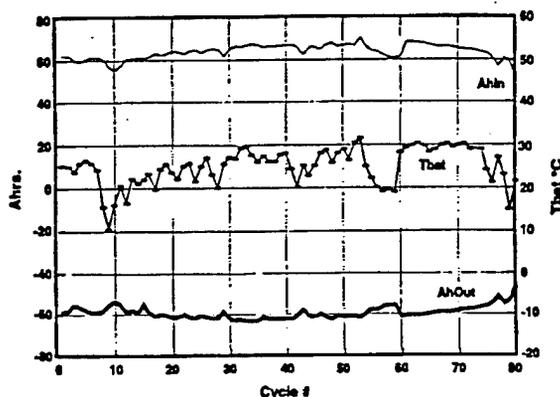


Figure 3. Trojan Capacity & Temperature Plot for Battery #727.

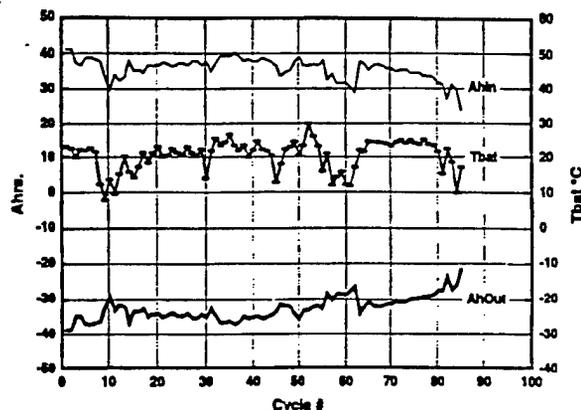


Figure 6. Trojan Capacity & Temperature Plot for Battery #722.

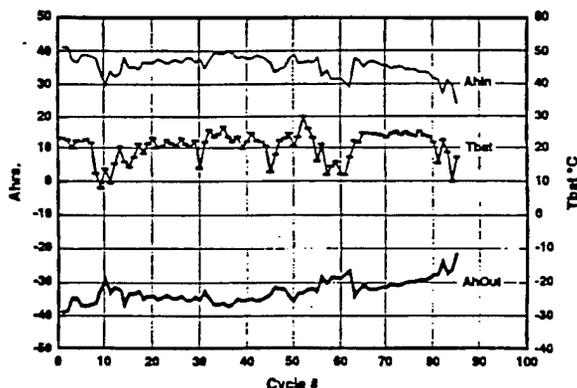


Figure 4. Trojan Capacity & Temperature Plot for Battery #726.

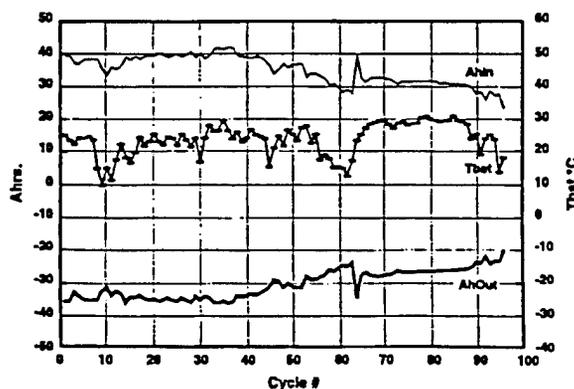


Figure 5. Trojan Capacity & Temperature Plot for Battery #723.

In the early cycles, through about cycle 80, depending on the battery, the test facility experienced temperature fluctuations associated with variations in the measured capacity. For the later testing, the batteries were moved to a laboratory in which the temperature is better controlled. The batteries have shown an expected gradual decline in capacity.

Yuasa Pafecta SLI Batteries

Late in 1996, Community Power Corporation proposed that SNL test a starting, lighting and ignition (SLI) type battery in a PV operating regime. The batteries would be intended for use in Indonesia in a government-sponsored electrification project. A locally-manufactured SLI battery must be used in this application because there are restrictions on importing batteries into Indonesia and no deep-cycling batteries are manufactured there. Prior experience has shown that SLI batteries do not perform well in a cycling environment, and there was high interest in seeing if an SLI battery, with proper care and management, could support a cycling application. Strong constraints were placed on charge and discharge rates, depth of discharge, and low-voltage disconnects.

Three batteries of rated capacities (at C/8) of 40 Ah, 65 Ah, and 100 Ah were placed on test. Before beginning life cycling, initial capacities were measured with the results shown in Table 5. The batteries were then

placed on test. Typical PV cycles are shown in Figure 7 for the 65 Ah battery and Figure 8 for the 100 Ah battery. Six PV days (12 days for the 100 Ah battery) of partial discharging and recharging drove the battery's capacity below the low voltage cutoff point. The PV controller then disconnected all loads until the battery was fully recharged to 120% of removed capacity, and the PV cycling was resumed.

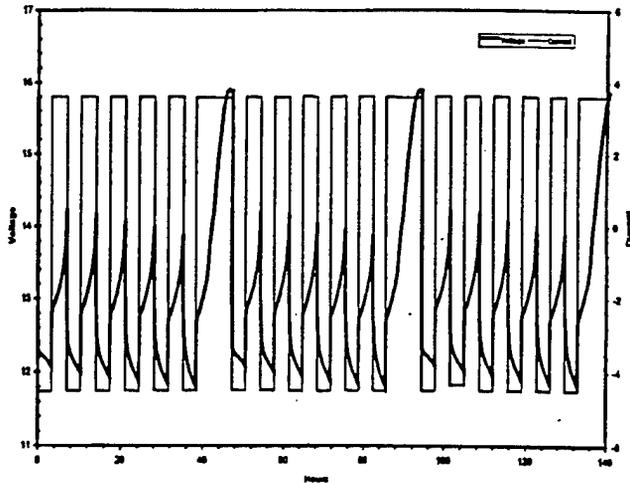


Figure 7. PV Cycles, Yuasa Pafecta NS-70, 65 Ah Lead-Acid SLI Battery.

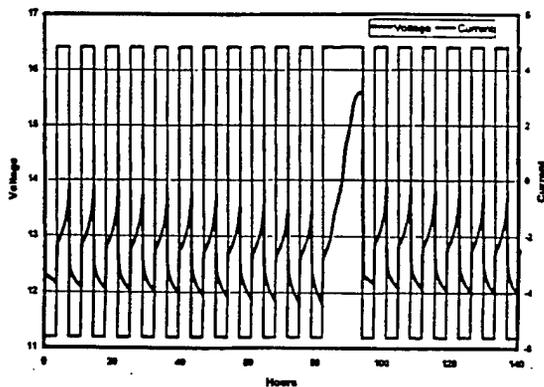


Figure 8. PV Cycles, Yuasa Pafecta NS-100, 100 Ah Lead-Acid SLI Battery.

After approximately 125 cycles (slightly different for each battery) the batteries were checked for capacity with the results shown in Table 6, and testing was resumed. The cycling of the 40 and the 65 Ah batteries was recently terminated, while the cycling of the 100 Ah battery continues.

All the batteries required additional deionized water during the cycling. This maintenance will be particularly important in the tropical environment in which the batteries will operate.

Conclusions

Testing of improved lead-acid batteries for utility and photovoltaic applications is in progress at SNL. A variety of charging regimes are being evaluated to determine optimized procedures for maintaining stable capacity in VRLA batteries. The measured capacity of the prototype ABSOLYTE IIP peaked at approximately 1300 Ah. Assuming that available capacity of the ABSOLYTE II does not increase from 1200 Ah further along in its life, the ABSOLYTE IIP now appears to provide an 8.3% improvement in capacity at the 8 hr constant-current rate. Over 100 constant current full discharge cycles have been performed on Yuasa Exide battery to date and capacity is stable. Several lead-acid designs have been tested successfully for photovoltaic applications. Stable capacities were achieved for flooded and VRLA technologies under partial depth of discharge conditions. Life testing will continue until pre-defined failure conditions are reached.

Acknowledgment

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References

- [1] P. C. Butler, "Utility Battery Storage Systems Program Report for FY95", SAND96-0532, March, 1996.
- [2] P. C. Butler, "Energy Storage Systems Program Report for FY96", SAND97-1136, April, 1997.

SNL Battery ID #	Rated Capacity Ah @ C/8	Discharge Rate	EOD Voltage	Ah Removed	EOC Voltage	EOC Current (A)	Ah Returned
728	40	C/5	10.44	31.22	16.28	8.132	39.11
729	65	C/5	10.34	51.55	16.63	12.370	62.85
730	100	C/5	10.88	83.75	16.47	20.489	98.52

Table 5. Capacity Cycles Run on Yuasa Pafecta Lead-Acid SLI Batteries to Verify Performance Prior to PV Cycling.

SNL Battery ID #	Rated Capacity Ah @ C/8	Discharge Rate	EOD Voltage	Ah Removed	EOC Voltage	EOC Current (A)	Ah Returned
728	40	C/5	10.47	28.73	15.80	8.133	34.52
729	65	C/5	10.49	50.61	16.29	13.179	60.81
730	100	C/5	10.48	82.52	15.98	20.510	99.18

Table 6. Capacity Cycles Run on Yuasa Pafecta Batteries to Verify Battery Condition After 100-125 PV Subcycles.

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