VRLA/GEL BATTERIES:
PV HYBRID SYSTEM EVALUATION AND RECOMMENDED TEST PROCEDURES

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INTRODUCTION

The Sandia National Laboratories, Energy Storage Systems Department[1] initiated a detailed and comprehensive analysis program for a new generation of Yuasa/Gel Batteries as well as a thorough study of the interaction of all system components (Inverter/controller, PV array, and generator) with the batteries[2]. The overall goal of the test and evaluation program was to develop a Renewable Generation and Storage (RGS) operational strategy to improve battery life cycle costs for off-grid hybrid systems and, at the same time, to evaluate the potential benefits of tubular gel VRLA batteries in RGS applications. The focus of this paper is on the evaluation of the Yuasa/Gel batteries.

In June 1997, 240 cells, model DT85-11 Yuasa VRLA/Tubular Gel batteries, were installed at the Arizona Public Service "*Solar Test and Research*" (STAR) Hybrid Test Facility. Each cell is rated at 2 Vdc nominal and 425 AH at the 8 hour rate. The battery was configured in two parallel 120-cell strings providing a total of 204 kWh of energy storage. These batteries were removed in June 2000 and sent to Sandia National Laboratories for additional testing.

A Campbell Scientific CR-9000 data acquisition system (DAS) was installed to monitor system operation, with 120 data parameters measured every 30 seconds.

A 30 KW bi-directional Omnion inverter, a 30 KW bi-directional Trace Technologies inverter, and a 30 KW Koehler generator were also evaluated as major components of the hybrid system. The system load varied from a 100 KW load bank to the hybrid test facility to the highly dynamic load of the entire STAR center. The load often varied during the day from a 3-KW base load to peaks loads up to 50 KW due to air conditioner motor starting requirements.

The following areas of evaluation are covered in this paper:

- State of health of individual cells based on monthly open-circuit cell reads and semi-annual battery-bank capacity tests.
- Correlation, if any, between internal cell resistance and state of health of each cell. Specifically, can internal cell resistance be used as an indicator of approaching end of battery life?
- Cell temperature variations during typical operating conditions. Temperature variations (profiles) across the two battery strings, including temperature spreads across the entire battery during slow discharge, fast discharge, early charge, finish charge, and equalization charge were monitored and evaluated. Voltage sensitivity to temperature variations was evaluated under these operating conditions.
- Recommendations for evaluating a large bank of batteries in a hybrid system.

Results and conclusions at the end of the initial three years of testing are presented in this paper. These results and conclusions apply specifically to the Yuasa Tubular Gel batteries and may or may not apply to other battery types or technologies.

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1 Under the sponsorship of the Department of Energy (DOE), Office of Power Technologies

2 The evaluation was conducted with the support and assistance of Arizona Public Service Company (APS) at their Solar Test and Research Center (STAR). APS, Yuasa/Exide and DOE cost shared the hardware.

BACKGROUND

The Arizona Public Service Company (APS) established a "Hybrid Test Facility" in 1997 to evaluate a variety of hybrid system components (e.g., batteries, inverters, charge controllers, PV arrays, engine generators, and wind generators), as well as the interaction between these components. This paper focuses on the three-year evaluation of the Yuasa DT85-11 Tubular Gel cell in a typical PV-Genset hybrid configuration (Figure 1).

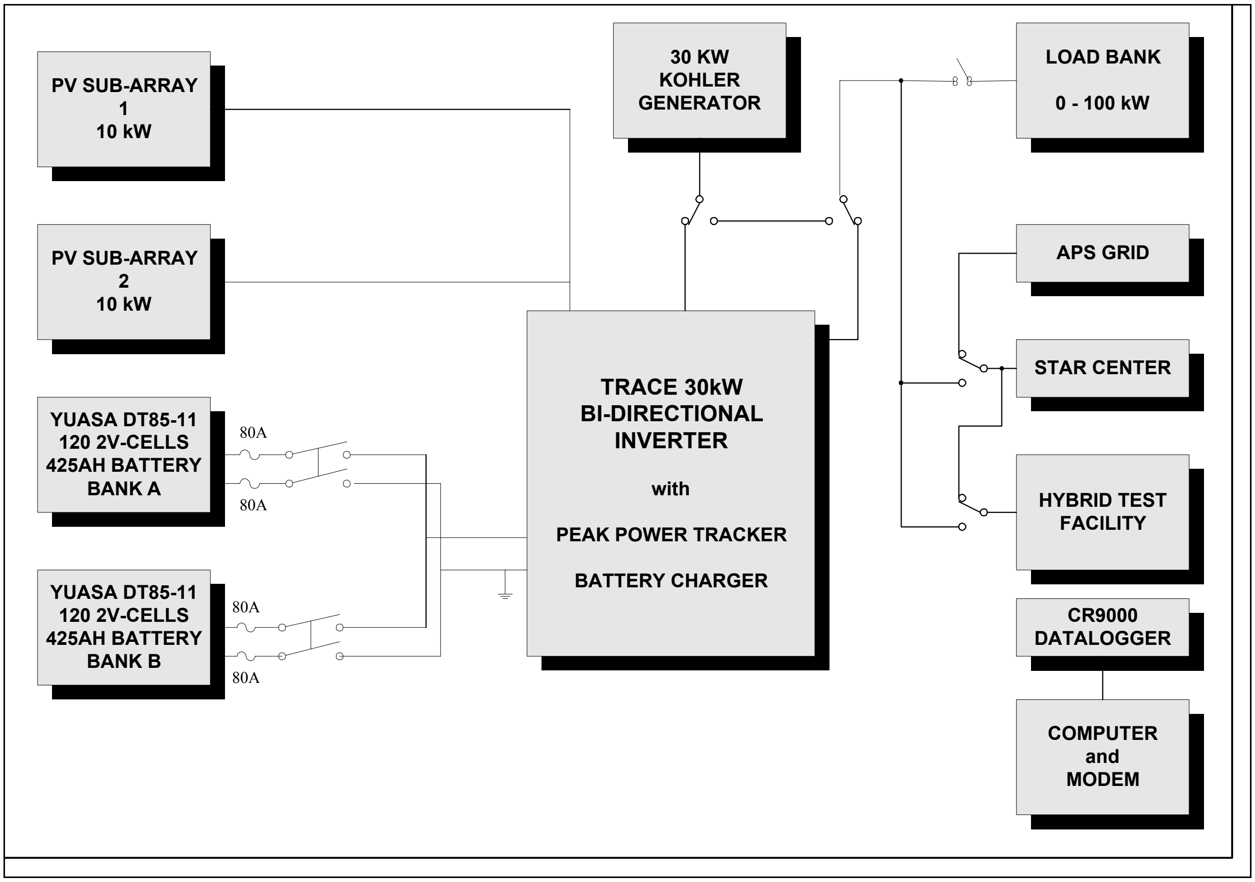

Figure 1. Hybrid System Diagram

Batteries were configured as two strings of 120 cells each for a 240-Vdc (nominal), 850-Amp-hour, battery bank (Figure 2). Battery bank A is on the left in Figure 2; battery bank B is on the right.

Physical layouts of battery banks A and B are shown in Figures 3 and 4. All cells are identified in the layouts, including pilot cells (as of May 2000).

Battery instrumentation included battery-bank voltage, module voltages (20 modules of 12-series cells each), four pilot cells (the highest and lowest open-circuit cell voltages in each string) and string currents (A and B). Twenty thermocouples were bonded to cell interconnects at locations defined in Figures 3 and 4 to determine temperature profiles for the entire battery bank. Thermocouple #17 was relocated from cells 211-212 to open air in order to measure ambient temperature in the battery room.

Figure 2. Photo of Battery Banks A and B

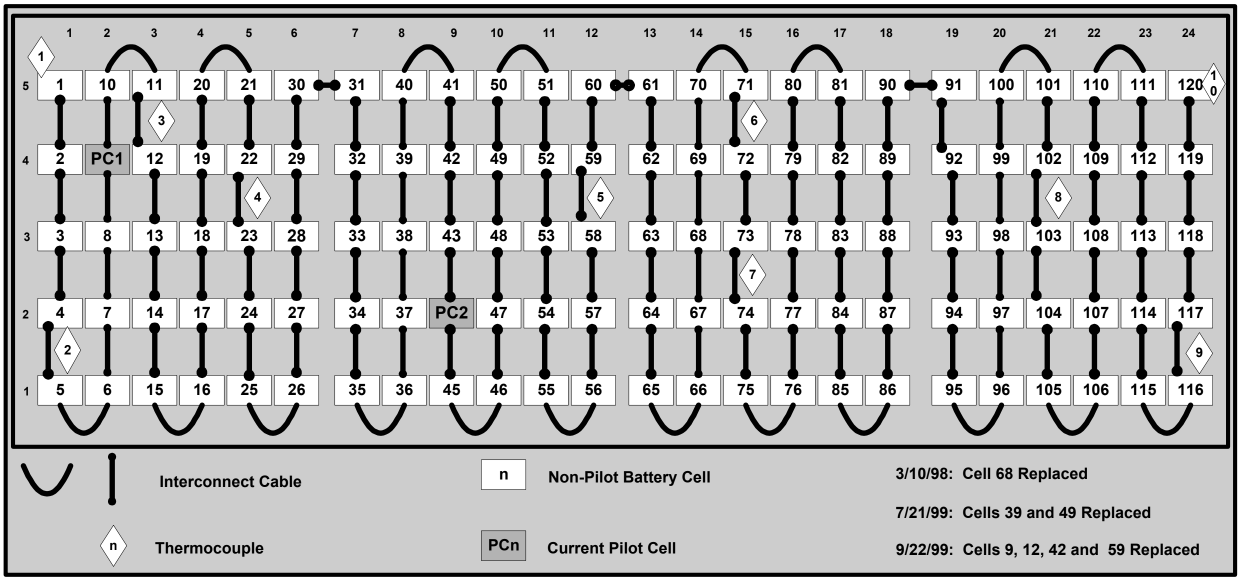

Figure 3. Battery Bank A

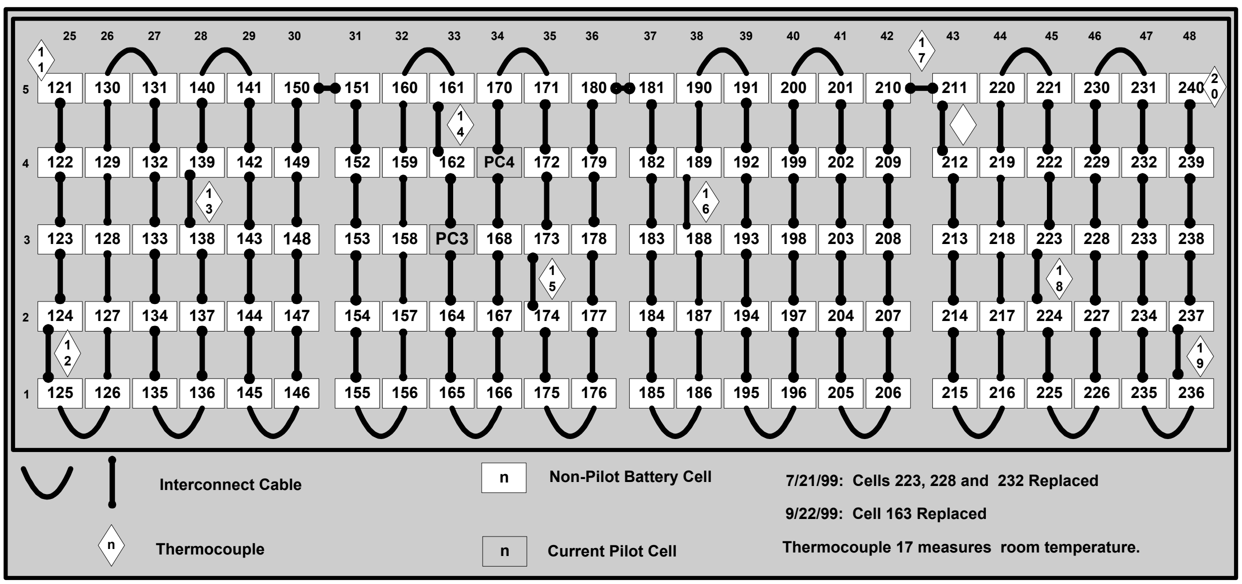

Figure 4. Battery Bank B

BATTERY STATE OF HEALTH

Battery state of health was monitored by measuring open-circuit cell voltage monthly (Figure 5) and battery capacity semi-annually (Figure 6). Cells with the lowest open-circuit voltage were always the weakest cells. The weakest cell in a string limits the capacity of the entire string (120 cells in this case). Weak cells that were replaced are identified in the lower right corner of Figures 3 and 4. It was common for a weak cell to reverse bias during the capacity tests, even though the average cell voltage was 1.75 volts at the end of the capacity test. Not only do weak cells limit battery bank capacity, they also pose a safety and fire risk hazard if not monitored when reverse biased.

Weak cells were identified (i.e., those cells having the lowest open-circuit voltage) and replaced periodically since the original installation in June 1997. These weak cells were identified by cell voltage measurements, not by resistance measurements. Experience with these cells showed that cells with the lowest open-circuit voltages were the cells that would experience voltage reversal first during a capacity test. The following cells were replaced: 3/10/98, **#68**; 7/21/99, **#39, #49, #223, #228, #232**; 9/22/99, **#9, #12, #42, #59, #163**

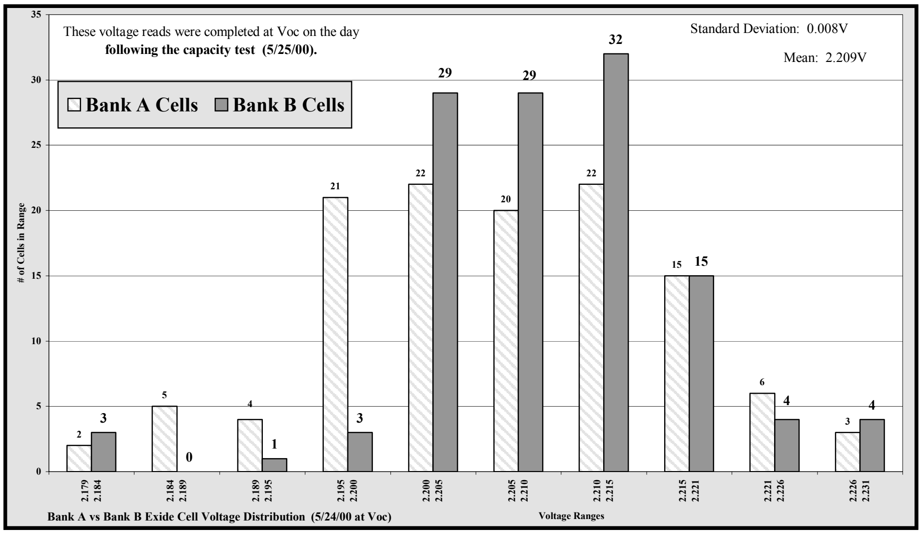

Figure 5. Cell Voltage Distribution

Parameter	9/10/98	10/7/98	5/6/99	8/5/99			10/5/99			5/23/00		
	AB	AB	AB	Bank-A	Bank-B	Bank-AB	Bank-A	Bank-B	Bank-AB	Bank-A	Bank-B	Bank-AB
AH Capacity, Measured	**607.0**	**575.0**	**495.0**	**293.2**	**441.1**	**734.3**	**438.6**	**440.4**	**879.0**	**429.1**	**429.7**	**858.9**
Percent of Rated Capacity	**71%**	**68%**	**58%**	**69%**	**104%**	**86%**	**103%**	**104%**	**103%**	**101%**	**101%**	**101%**
Test Duration (hrs)	4.60	5.25	5.87	6.17	7.82	7.00	9.07	9.07	9.07	8.85	8.85	8.85
Average Battery Current (Adc)	-66.3	-55.3	-42.4	-47.1	-55.7	-102.7	-48.3	-48.5	-96.8	-48.4	-48.5	-96.9
Load Power (kW)	25.0	25.0	22.5	12.5	12.5	25.0	11.3	11.3	22.5	11.3	11.3	22.5
Min Battery Voltage (Vdc)	214.6	226.6	232.7	221.8	207.9	214.9	209.9	210.6	210.3	209.9	210.7	210.3
Min of Pilot Cell #1 & 3 Voltage	1.84	1.93	1.97	1.95	1.87	1.91	1.87	1.87	1.87	1.87	1.85	1.85
Min of Pilot Cell #2 & 4 Voltage	?	0.13	0.50	0.15	1.83	0.99	0.39	0.65	0.39	0.29	0.36	0.29
Ave. cell voltage at end of discharge	1.78	1.88	1.94	1.85	1.78	1.82	1.75	1.76	1.75	1.75	1.76	1.75
Note:	**Bank A pilot cells are #1 (highest) and #2 (lowest); Bank B pilot cells are #3 (highest) and #4 (lowest)**											

Figure 6. Battery Capacity Test Results

During the first three capacity tests (Figure 6), the tests were terminated when any cell in either string approached zero volts. Starting 8/5/99, the first string with a cell that reached zero volts was disconnected and the load on the remaining string was adjusted to one-half of the original load current. By 10/5/99, all weak cells (11) had been replaced and both strings remained on-line until the average cell voltage dropped to 1.75 Volts. Both strings delivered more than rated capacity. Seven months later, 5/23/00, both strings again delivered more than rated capacity.

CELL RESISTANCE

Individual cell internal resistance, (R_i), was measured periodically with an Alber Cellcorder to determine how cell resistance changed over time and to determine if such data could be used to determine the state-of-health of each cell. It was hoped that these data could be used to identify weak cells so that they could be replaced before they adversely affected string performance. Cellcorder readings were taken:

1) June 16, 1998
2) January 4, 1999
3) January 11, 1999
4) April 26, 1999
5) August 30, 1999
6) December 22, 1999

Cell voltage measurements were recorded during cell resistance measurements (Figure 7). This chart is typical of all six Cellcorder reads. The first Cellcorder reads were taken one year after installation of the batteries, so there is no baseline resistance data for the original batteries at the time of installation.

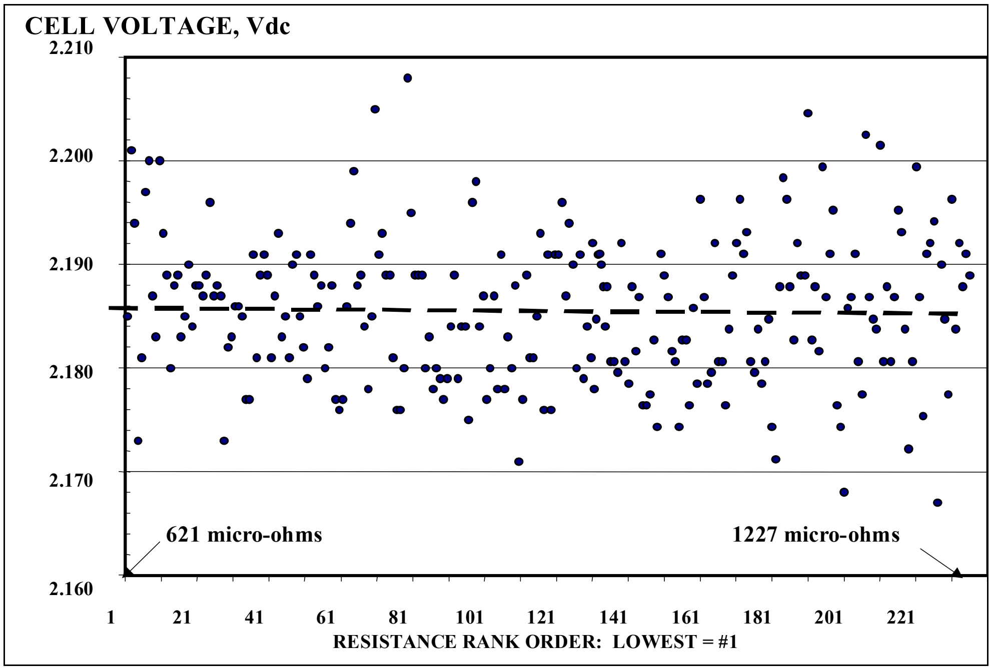

Figure 7. Cell Voltage vs Cell Resistance

During the three years that the 240 Yuasa Tubular Gel cells were in operation at the APS Hybrid Test Facility, there appears to be little, if any, correlation between cell resistance and open-circuit cell voltage. On the other hand, there appears to be a direct correlation between open-circuit voltage and health of the cell. The cells with the lowest open-circuit voltage were always the first cells to reverse bias during a capacity test. One can therefore conclude that there is little or no correlation between cell resistance and health of the cell at this point in time. However, as the cells age and lose water through normal hydrogen and oxygen loss (not attributed to venting), cell resistance may help to predict the onset of end of life for the battery. The continuation of this study is expected to yield that information at some time in the future.

The state of charge of the cells during Cellcorder reads appears to have a significant impact on cell resistance values. Cells near zero state of charge measured 50-60% higher in resistance than cells at 20-80% state of charge. Cells at 100% state of charge were about 20% higher in resistance than cells at 20-80% of full charge.

It is recommended that state of charge during Cellcorder reads be between 20% and 80% of full charge. The variations in readings from 1/4/99 to 12/22/99 could be due to cell temperature variations (17°C to 26°C) and variable state of charge conditions (20% to 100%). Thus, it cannot be assumed that the 25% increase in average cell resistance from 1/11/99 to 12/22/99 is due to cell aging. Since the Hybrid Test Facility was established to test systems under actual operating conditions (i.e., not a testing laboratory), the variable operating conditions are not always controllable.

According to data provided by the manufacturer, the battery, if properly managed, is expected to deliver 1000, 80% DOD cycles. At the 8-hour rate, the battery will discharge 340,000 Ah during its cycling lifetime. Data accumulated to date indicates that a nominal 27,998 Ah have been discharged through normal use. One may then conclude that the current age of the battery is at 8% of expected life. Tracking variance in cell resistance as a function of age is expected to provide insight into the manner in which a gel electrolyte VRLA battery ages and ultimately reaches end of life.

SPATIAL CELL TEMPERATURE VARIATIONS

A study of temperature variations (profile) across the two battery strings during slow discharge, fast discharge, early charge, finish charge, and equalization charge was conducted to determine voltage sensitivity to temperature variations during these operational segments.

Figure 8 shows a plot of one day of temperature data for each of four seasons of the year by battery column (from east to west). While the average battery temperature varies about eight degrees over the four seasons, cell-to-cell temperature variations vary only ± one degree centigrade across the entire battery bank. These low temperature variations on a given day were much lower than expected and indicated voltage changes due to spatial thermal variations for this battery configuration (physical location) are insignificant.

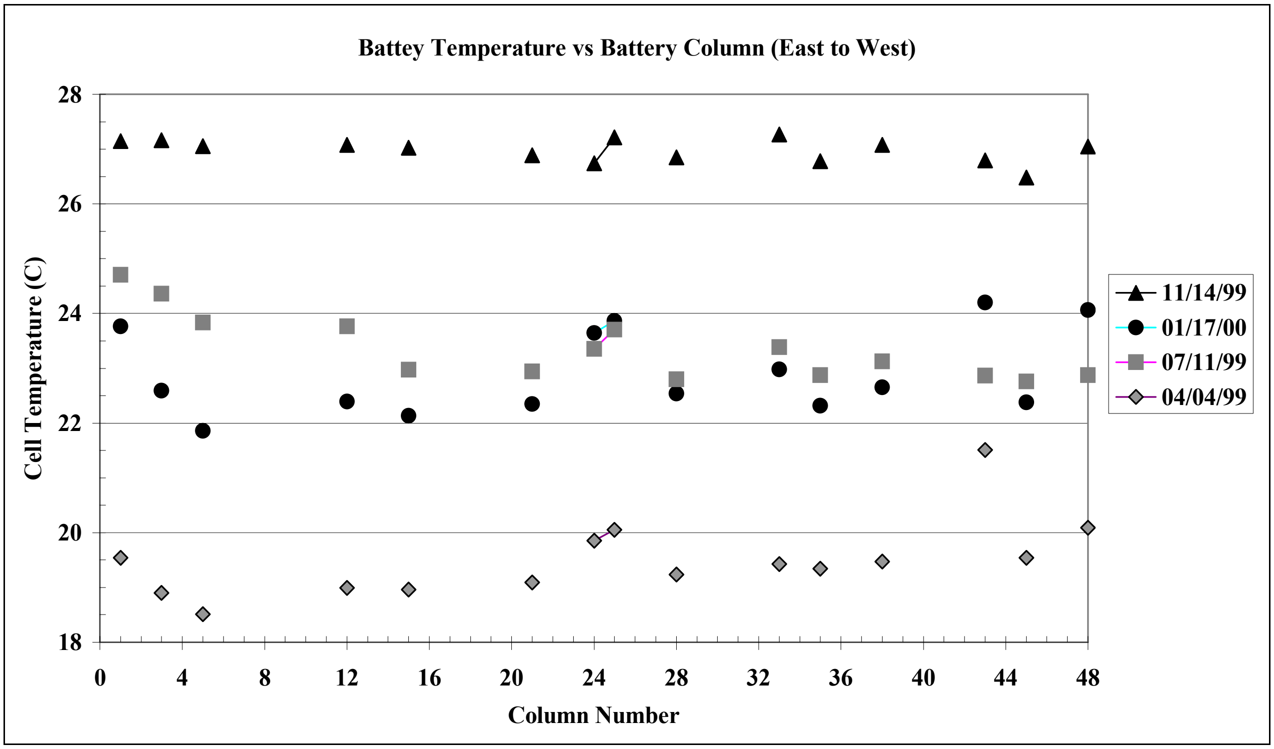

Figure 8. Battery Temperature vs. Battery Column (East to West)

RECOMMENDATIONS FOR TESTING VRLA BATTERIES

The following steps are recommended in order to effectively monitor and evaluate batteries such as the Yuasa VRLA-Gel batteries. Although most of these recommendations would apply to flooded lead-acid batteries, they are specific to VRLA-Gel batteries.

1. Maintain a detailed historical record (i.e., log of all significant events) regarding the batteries, including the date of installation, cells replaced, cell reads, capacity tests, and any other events that affect battery life or performance. Record and sum all amp hours removed from the battery in order to maintain a continual "capacity age" via amp-hour counting.
2. Install a data acquisition system that will continuously monitor battery-bank current and voltage and operating conditions such as cell temperature (two percent of cells, minimum) and ambient temperature. Also define and monitor pilot cells (one percent of cells in each string, minimum).
3. If possible, define battery "modules" such that each string is segmented into two or more equal parts for monitoring purposes. These modules voltages will help isolate and identify weak cells during a capacity test.
4. Measure open-circuit cell voltages quarterly (monthly preferred). Measurements should be made after cells have been at open-circuit condition for a minimum of one hour. Identify the cells with the lowest voltages (one percent of cells in each string, minimum) and monitor these cells as pilot cells. Measure Voc at approximately the same state of charge each time (e.g., 80%).

5. Perform a capacity test at least once per year, but no more often than twice per year, as a capacity test places a great deal of stress on the batteries. Begin the test immediately after an equalization charge. Always test under the same conditions (i.e., at the same constant discharge current and at the same battery temperature (e.g., 25°C, ± 3°C). Terminate the test at the same average "volts per cell," i.e., 1.75 vpc. Identify and monitor the cell in each string that has the lowest voltage. Terminate the capacity test is this cell (or any cell) reaches 45°C.
6. Follow the manufacturer's recommendations for operation and maintenance. Most importantly, never exceed the maximum equalization voltage. Unlike flooded lead-acid batteries, the requirement for equalization is much less critical for VRLA-Gel batteries.
7. Re-torque inter-connect nuts every six months or as recommended by the battery manufacturer.
8. Ensure that all cells within the battery bank are within ± 3°C of the average cell temperature during normal operation (other than equalization or during the last 25% of a capacity test).

CONCLUSIONS

Three years of cycling operation of the model DT85-11 Yuasa VRLA/Tubular Gel batteries has shown this technology to be robust and reliable:

- Capacity tests showed that one or more weak cells in a string of 120 cells could reduce the effective capacity to 60% of rated value.
- Measuring cell voltages under open-circuit conditions is an effective method to identify weak cells.
- Cells will the lowest open-circuit voltage were always the first cells to reach zero volts during the semi-annual capacity tests.
- Eleven of the 240 cells (5%) were replaced during the three-year period, and this process brought the full battery bank from 60% of rated capacity to above rated capacity.
- The tubular-plate gelled-electrolyte spare cells were able to remain at open-circuit conditions for one year with no apparent degradation. An equalization charge was all that was needed to bring the cells back to rated capacity.
- Spare tubular-plate gelled-electrolyte cells were idle (no charging current) for over a year with no apparent degradation. The entire 240-cell battery bank remained at open-circuit for six months with no apparent degradation. One may conclude that this technology is less prone to sulfation than the VRLA-AGM cells and is far less susceptible than flooded lead-acid batteries.

Other general conclusions are:

- Amp-hour counting is a more reliable charging algorithm than algorithms that are based on battery voltage.
- The tubular-plate gelled-electrolyte battery requires a six percent overcharge (amp-hours) for an effective finish charge.
- For a meaningful capacity test, equalization is required prior to a capacity test.
- Cell resistance reading proved to be of little or no value in identifying weak cells during the three-year test period. However, it is anticipated that cell resistance values will increase rapidly and substantially as the cells approach end of life. Quarterly Cellcorder readings provide a valuable historical record that may provide a warning that batteries are approaching end of life, especially when tracking amp-hour accumulation throughout the life of the battery.
- The physical battery environment at the APS STAR Center provided for a uniform cell-temperature profile (± one-degree C) during typical operating conditions. Voltage imbalances in individual cells were negligible with these uniform cell temperatures across the battery bank.

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