IMPROVING LIFE EXPECTANCY OF VRLA BATTERIES INSTALLED IN OUTDOOR CABINETS

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INTRODUCTION

S&C Electric Company is a manufacturer of switching and protection equipment for the electric power industry. S&C's Remote Supervisory Pad-Mounted Gear, illustrated in Figure 1, is utilized for automated switching of medium-voltage underground distribution feeders. This gear is typically installed outdoors. The low-voltage enclosure that houses a switch operator and the controls is mounted on the left-hand side of the high-voltage enclosure, as shown. (It is the smaller of the two enclosures.)

Remote operation of the feeder switches is effected by means of a radio or fiber-optic communication link. One requirement of this gear is the ability to operate switches when the feeder is de-energized, thus creating the need for a battery-operated power supply. The focus of this paper is automated switching equipment utilizing 5-ampere-hour, 12-volt-dc, valve-regulated, lead-acid (VRLA) batteries as a backup source of control power.

Figure 1. S&C Remote-Supervisory Pad-Mounted Gear.

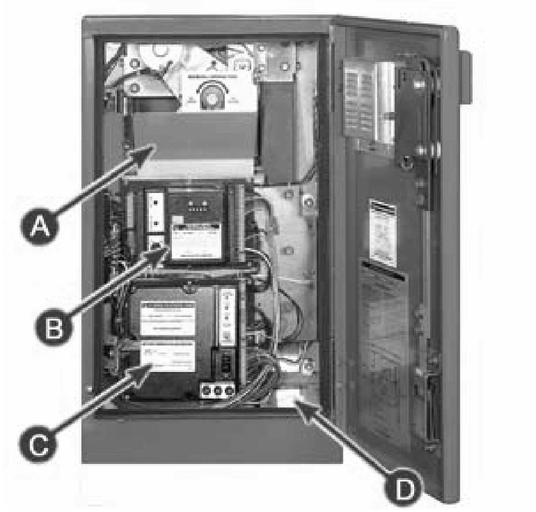


Figure 2. Switch operator and controls.

Figure 2 illustrates the typical locations of various components within the low-voltage enclosure. The switch operating mechanism is at location A. The switch control is at location B and the battery charger is at location C. The batteries are at the lower right-hand side of the enclosure at location D. The low-voltage enclosure includes venting for air circulation but has no other provision for cooling the batteries.

Several customers reported that they were experiencing unsatisfactory battery life in such gear. S&C's initial investigation of the problem identified a number of ways in which battery life could be improved. To insure that the areas identified for improvement would indeed address the root cause of short battery life, a large sample of batteries taken from the field were analyzed under contract with Sandia National Laboratories. This paper describes the findings and recommends ways to improve the life of batteries installed in outdoor cabinets. In addition, a simplified method of finding bad batteries in the field is identified.

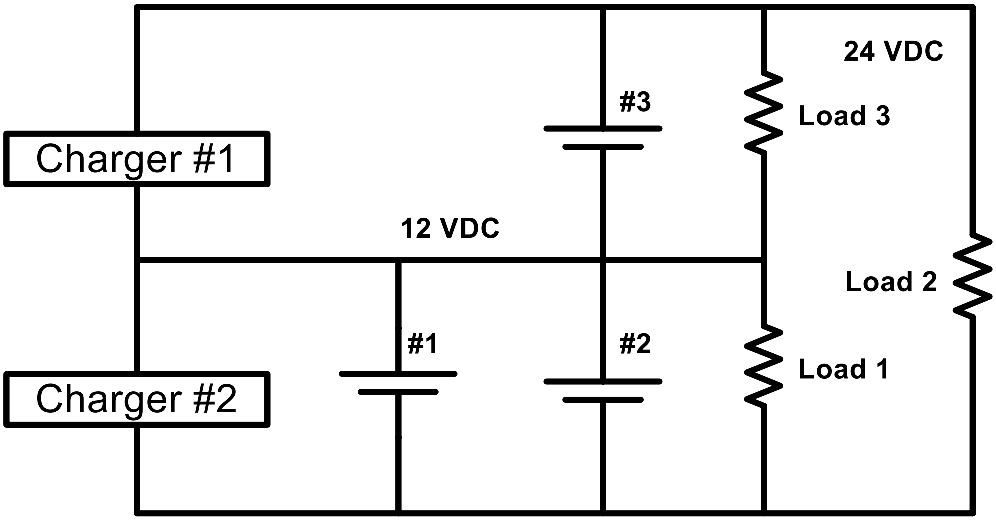
HISTORY

Customer feedback indicated that battery life in their gear was considerably less than desired. Gear located in colder northern climates was reported to have battery life on the order of 3 to 5 years, while gear located in warmer southern climates reported only 18 to 24 months of service. One customer, located in the southern United States, reported only 12 months of battery life. Yet the battery system had been conservatively designed to provide 30 months of service under worst-case conditions. In early 2000, S&C initiated an investigation to identify the root cause of this problem.

BATTERY SYSTEM CONFIGURATION

The circuit diagram in Figure 3 illustrates a battery system consisting of 3 batteries connected in series and parallel. Loads 1 and 3 are each 12 volts dc and Load 2 is 24 volts dc. Two temperature-compensated battery chargers are utilized.

Figure 3 Battery System



INITIAL INVESTIGATION

Choice of battery supplier

S&C's review of available battery technologies reconfirmed that the selection of VRLA batteries for the application was a good choice. The fact that good battery life was experienced in cooler northern climates was taken as an indication that the problem was not likely caused by the battery selection. Differences between various manufacturers' specifications for this type of battery appear to be minimal. So while it is possible that changing to batteries of other manufacture could yield improved performance, it was decided not to pursue this avenue unless subsequent evidence pointed in that direction.

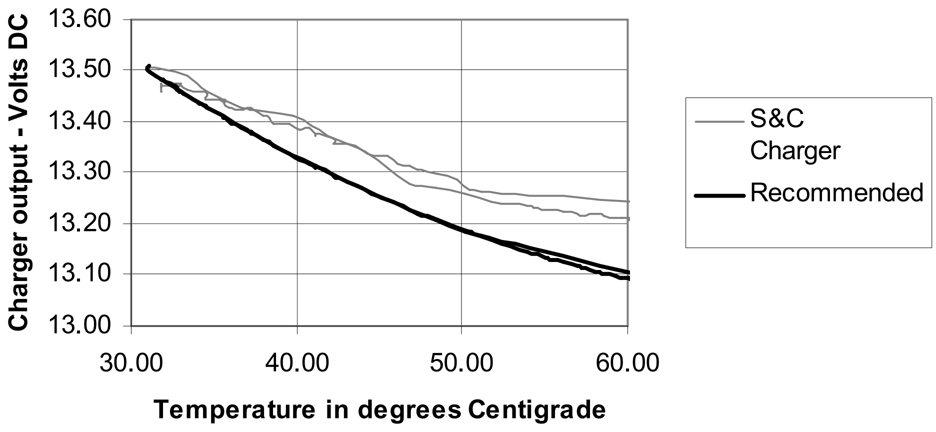


Figure 4. Charger Output Voltage versus Temperature

Battery charging system

The S&C Battery Charger is temperature compensated, current limited, and has a constant voltage output. Early on in the investigation, the charging system was considered to be a highly likely cause of the shortened battery life. Of major concern were the temperature compensation of the output voltage and the output voltage setting. Tests were conducted to verify the compensation curve and, as illustrated in Figure 4, the plot of charger output voltage versus battery temperature does follow the battery manufacturer's recommended compensation curve reasonably well. Two curves are provided for the charger to show the difference between an increasing versus a decreasing temperature profile. Also the charger curves have been shifted from nominal setting to make it easier to compare the curves.

Investigation of the method for setting the charger output voltage did, however, reveal that a less-than-optimum situation existed. Depending on the specific application, it was possible for the factory setting to be higher or lower than the battery manufacturer's recommended 2.27 to 2.35 volts per-cell setting at 25 degrees Centigrade. Fortunately, this situation was easily corrected with the development of a new procedure for setting the charger output voltage. The big question was: "Is this the cause of shortened battery life?"

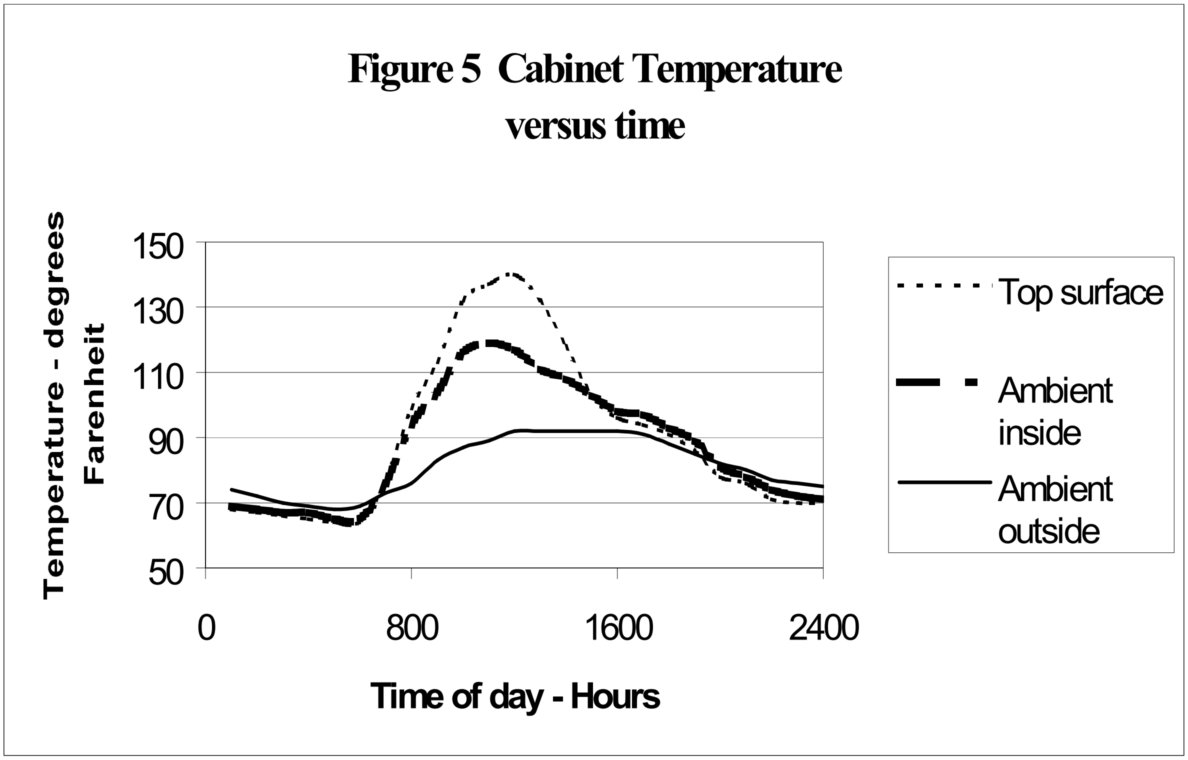
Cyclic loading

The charging system is designed for a float application. For the most part, the loads have a fixed current draw. One exception is the transceiver load. Transceivers typically draw a few hundred milliamperes continuously. But when they transmit, every few seconds to a minute, they draw up to an ampere for about 200 milliseconds. So while the average load is always within the output capability of the charger, short intervals of battery current draw are encountered during radio transmit.

Field reports indicated no difference in battery life expectancy between float and cyclic applications in either hot or cool climates. It was thus concluded that cyclic loading, while suspicious, was not a primary cause of shortened battery life. To be on the safe side, however, all future designs will assure that the charging system can deliver full current, to keep up with the load, even when the radio is transmitting.

Cabinet temperature

S&C contracted for a study of internal temperatures of low-voltage enclosures exposed to solar heating. Tests were conducted at a laboratory in Phoenix Arizona. Figure 5 illustrates a typical 24-hour pattern of temperature variation in the enclosure. On the average, the internal cabinet temperature seems reasonable. Locating the batteries at the bottom of the cabinet is consistent with the lowest temperature readings within the enclosure. Note, however, the temperature of the



cabinet surface. At midday, the top surface temperature can be 20 to 25 degrees Fahrenheit hotter than the inside ambient temperature. Since the batteries are mounted against the outside cabinet wall, shortened life could result. Insulating the batteries to reduce peak temperature excursions would seem to be a cost-effective way to solve the problem.

INITIAL CONCLUSIONS

The most likely causes of shortened battery life appeared to be the charger output voltage setting and the internal temperature within the cabinet. While several quick fixes were implemented, a root cause analysis was needed to know with certainty whether these remedies actually cured the core problem.

FINDING THE CAUSE

A basic tenet of root cause analysis is “Let the parts teach you”. With the cooperation of a large investor-owned utility located in the southern United States, a significant number of batteries judged to be near their end of life were obtained. Recognizing that expert help would be needed, S&C contracted with Sandia National Laboratories in Albuquerque to perform diagnostic testing and autopsies on these samples.

DATA FROM THE FIELD

As the batteries were removed from service at the aforementioned utility, each was identified with a unique ID number and information specific to that battery, and the field site location was recorded. A sampling of the collected data is shown in Table 1. The batteries determined to be defective after the Sandia analysis are shown in bold.

The charger voltage measurements taken in the field generally appear to be on the high side when compared to the charging voltage recommended by the battery manufacturer for the specific operating temperature. The difference between the recommended and the measured charger output voltage is likely greater than that shown since the temperature rise inside the cabinet due to solar heating is not taken into account.

Using the newly developed procedure, the customer recalibrated the charger output voltage settings to the battery manufacturer's recommended setting as the replacement batteries were installed.

Table 1. Field data

Utility Switch ID	Battery Manufacturer's Recommended Charging Voltage*	As Found Charging Voltage Battery #1	As Found Charging Voltage Battery #2	As Found Charging Voltage Battery #3	Direction Cabinet Faces	Date of Battery Installation	Amount of Sun	Temperature at Site, Degrees Fahrenheit
665	13.42	13.77	13.77	13.95	East	04/23/1999	Full	95
711	13.48	**12.89**	12.89	13.26	South	?/1999	Unknown	90
918	13.48	13.77	**13.77**	13.93	North	Unknown	Partial shade	90
1009	13.50	13.96	13.96	14.09	South	04/23/1998	Full	88
1149	13.49	14.09	14.09	14.2	West	Apr-98	Full	89
1873	13.56	14.04	14.04	13.93	North	04/23/1998	Partial	83
4792	13.42	13.85	**13.85**	14.13	East	11/04/1998	Shade	95
7675	13.49	**13.91**	13.91	**14.06**	North	Apr-98	Unknown	89
7779	13.56	14.01	14.01	14.05	East	04/23/1998	Full	83
8126	13.53	14.17	14.17	14.22	West	04/23/1998	Full	85
8144	13.49	**13.77**	13.77	13.89	South	04/23/1998	Full	89
8226	13.57	14.02	**14.02**	**14.22**	West	04/23/1998	Full	82
9540	13.48	12.96	12.96	13.18	South	May-99	Full	90
9537	13.62	13.9	13.9	**14.16**	South	Apr-98	Shade	78

*These recommended voltages are based on the outside air ambient and do not take into account heating of the battery due to solar radiation.

SANDIA'S FINDINGS

Initial non-destructive tests were conducted by Sandia to determine the as-received condition of the batteries. First, the open-circuit voltage and the weight of each sample were measured. Next, the capacity of each sample was tested following standard conditioning recommended by the battery manufacturer. This data is summarized in Table 2.

Table 2. Weights and capacities of batteries as received

SNL ID	Utility's ID	Battery Location Number	Date of Manufacture, Week/Year	Weight, kg	Pre-Test Open-Circuit Battery Voltage	Open-Circuit Battery Voltage (After rest)	Capacity, as received Ampere-Hours	Full Capacity as Tested, Ampere-Hours
866	NEW	N/A	300	2.2640	12.29	12.87	2.245	3.809
867	NEW	N/A	300	2.2644	12.41	12.89	2.499	3.858
868-1	665	1	1298	2.2054	12.84	13.05	3.502	4.051
869-1	**711**	**1**	**1298**	**2.2375**	**12.64**	**12.88**	**0.818**	**1.365**
870-2	**918**	**2**	**1298**	**2.2354**	**12.62**	**12.86**	**1.677**	**2.538**
871-3	918	3	1298	2.2263	12.75	13.07	3.521	4.131
872-1	1009	1	1298	2.2418	12.80	13.09	3.759	4.225
873-3	1009	3	1298	2.2310	12.79	13.09	3.661	4.152
874-1	1873	1	1298	2.2376	12.78	13.09	3.670	4.272
875-1	4610	1	3798	2.2386	12.86	13.10	3.979	4.369
876-1	4710	1	3798	2.2389	12.87	13.03	4.022	4.403
877-1	4792	1	3798	2.2596	12.84	13.02	3.840	4.341
878-1	6001	1	1799	2.2245	12.80	13.00	3.758	3.759
879-1	**7675**	**1**	**1298**	**2.2336**	**12.65**	**12.80**	**0.477**	**0.975**
880-1	7779	1	1298	2.2370	12.77	13.00	3.631	4.241
881-3	7779	3	1298	2.2481	12.74	13.06	3.430	4.064
882-1	8008	1	1799	2.2045	12.79	13.08	3.141	3.649
883-1	8116	1	5099	2.2370	12.88	13.13	3.831	4.249
884-1	8126	1	1298	2.2380	12.78	13.07	3.496	4.182
885-1	**8144**	**1**	**1298**	**2.2368**	**12.59**	**12.89**	**0.137**	**0.479**
886-1	8226	1	1298	2.2368	12.78	12.82	3.559	4.070
887-1	9537	1	1298	2.2374	12.85	12.88	3.853	4.205

The batteries are rated 3.9 ampere-hours at the 1-hour rate and are considered to be defective at 80% of capacity, or 3.12 ampere-hours. In this sampling, 4 batteries are judged to be defective and are identified in bold. The weight and open-circuit voltage of the batteries are plotted in Figures 6 and 7, respectively, along with capacity.

Examination of Figures 6 and 7 shows that neither battery weight nor open-circuit voltage give any indication of battery capacity. Why this is true became apparent after the batteries were disassembled. More on that later.

Another observation of interest from Figure 6 is that a high percentage of the batteries are at or above full capacity. So some batteries are very bad . . . but most batteries are very good and have many months of remaining life.

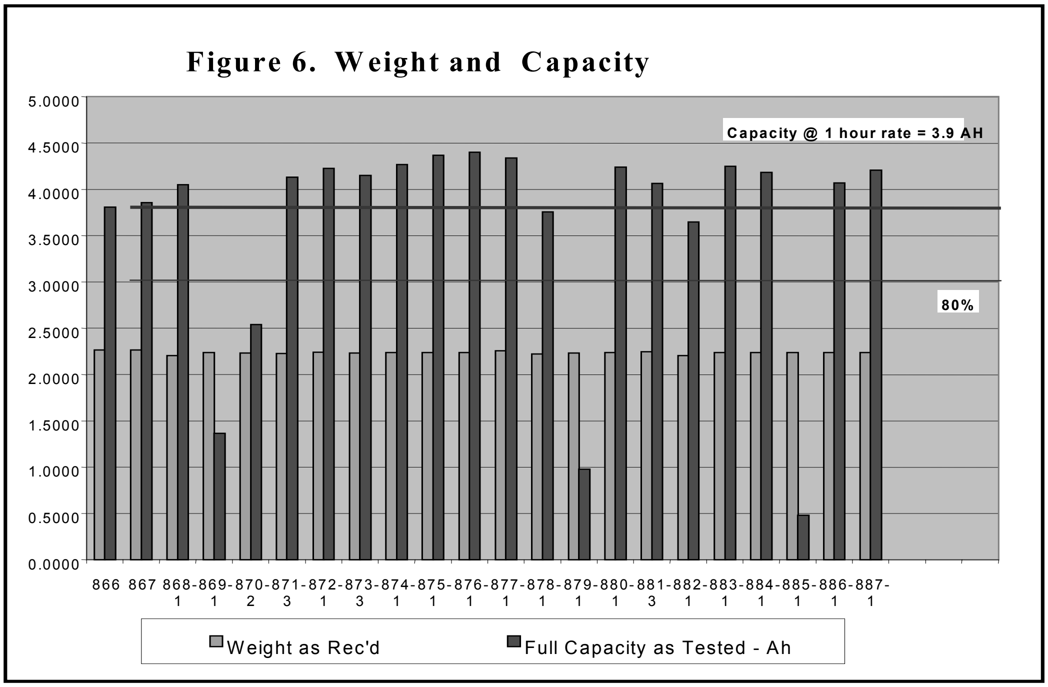


Figure 6. Weight and Capacity

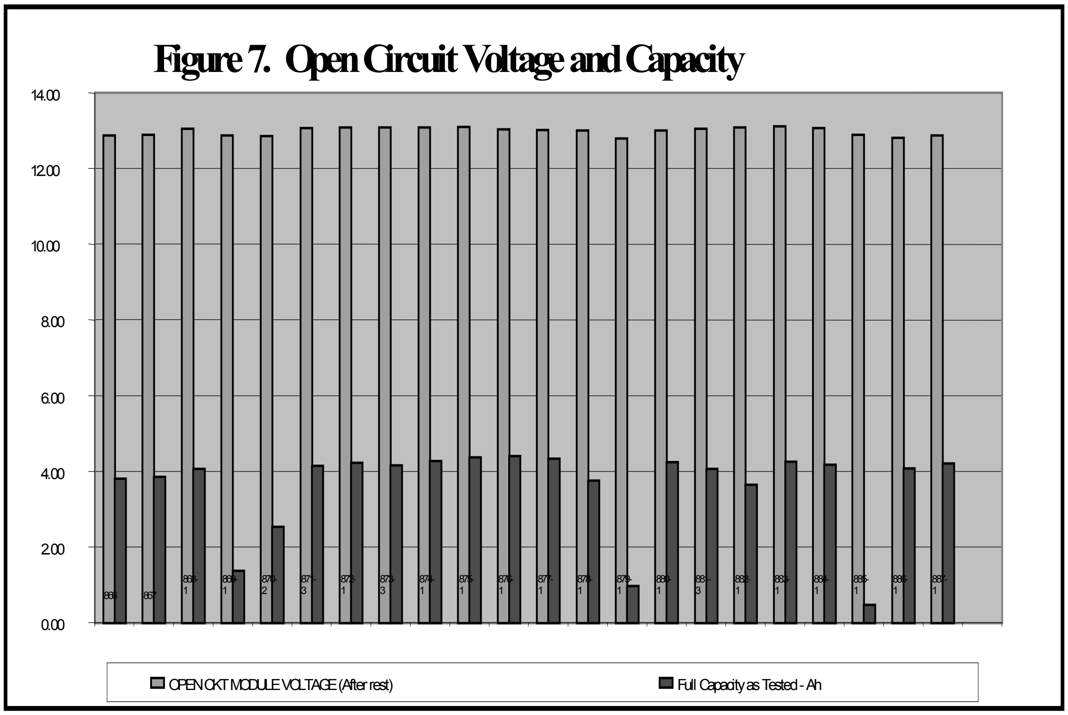


Figure 7. Open Circuit Voltage and Capacity

Measurements of impedance and conductance were made and compared to tested capacity. These measurements are shown in the scatter plot in Figure 8 and indicate a very strong correlation with tested capacity. This finding is significant because a method of quickly and easily measuring relative battery capacity would be very useful to customers, and would help them determine the remaining life of units in the field. Potentially, batteries could be replaced as they near end of life, instead the present method of mass changeout at fixed intervals.

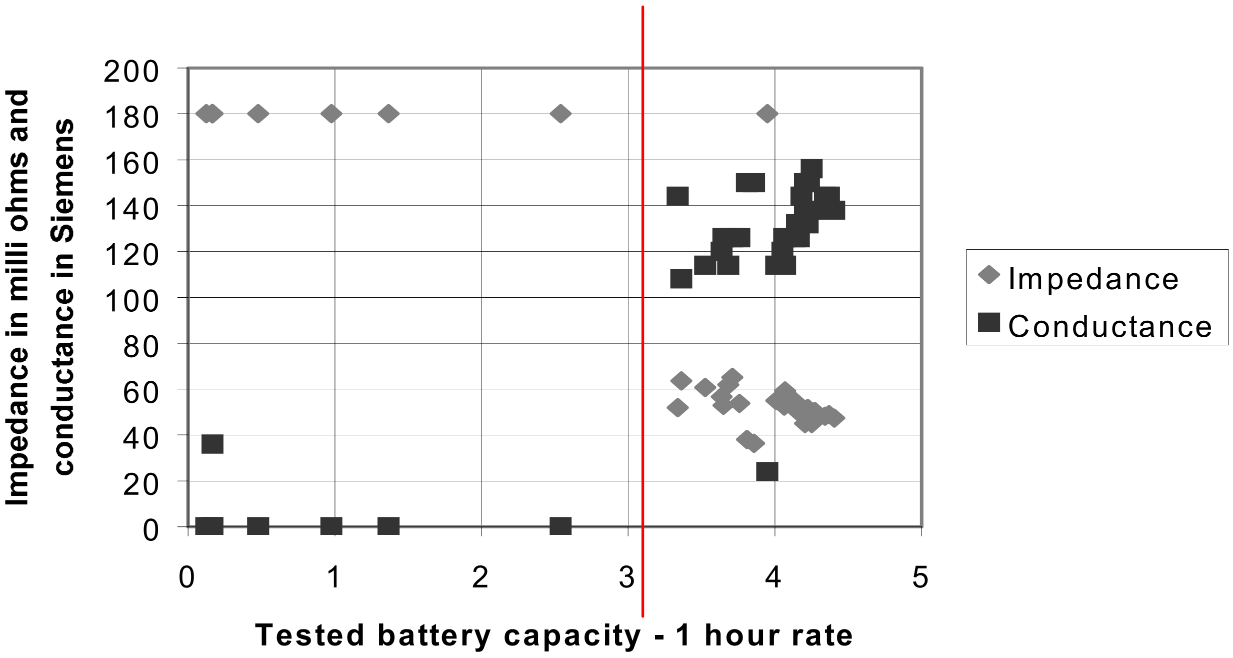


Figure 8. Impedance and Conductance variation versus tested battery capacity

Note the single low reading of conductance and high reading of impedance at nearly 4 ampere-hours. This was the result of a poor intercell connection and points out the ability to find problems other than low capacity. The zero Siemens readings from the conductance tester and the 180 ohm readings for the impedance tester represent out of range indications from the meters.

At this point it was decided to disassemble some of the defective batteries and compare them with one new battery. Individual cell voltages of the defective batteries are summarized in Table 3.

Table 3. Cell voltages of failed Monoblocs

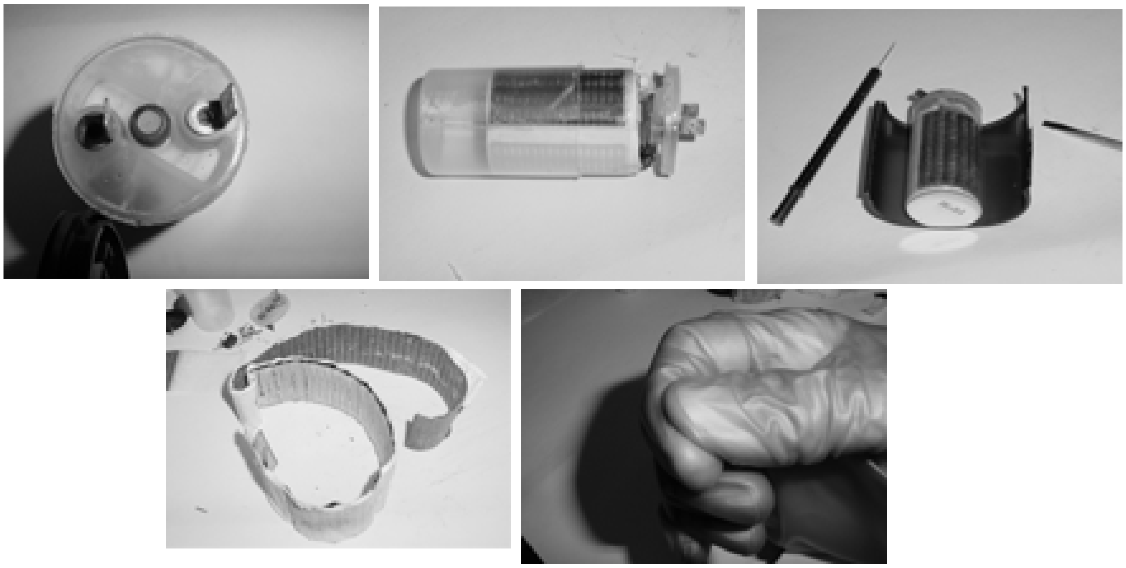
Cell No.	1	2	3	4	5	6
869-1	1.86	1.87	1.87	1.85	1.87	1.14
870-2	-0.54	1.94	1.47	1.95	1.96	1.95
879-1	-0.85	1.87	1.88	1.87	1.88	1.87
885-1	-0.36	1.87	1.87	1.87	1.86	1.87
891-3	2.14	2.14	2.15	2.14	2.14	1.28
898-2	1.13	2.16	2.16	2.16	2.16	2.16
900-2	2.15	2.16	2.16	2.15	2.15	0.98
905-3	2.16	2.15	2.16	2.16	2.16	1.10

Notes: Cells in the first four rows were discharged for disassembly

Cells in bottom four rows are fully charged

Note that in every defective battery, one of the end cells had a very low open-circuit voltage, while the remaining cells were essentially the same. Further disassembly of the end cells was the next step, and is illustrated in Figure 9.

Figure 9. Typical details of a defective cell



In all the failed cells, the separator appeared to be very dry and electrolyte could not be extracted by compressing the glass mat separator (the photo showing the gloved hand). It was also noted that the paste material on the positive and negative plates was very brittle and cracked easily, indicating a dryout condition. No signs of active corrosion were noted in any of the defective cells. In addition, although the plates appeared dry, there were no signs of sulfation. No sign of dendrites were noted in any of the defective cells.

Figure 10. Typical details of a new cell

In contrast, disassembly of a new cell, shown in Figure 10, indicated that the glass mat was saturated with electrolyte. The electrolyte was easily squeezed out of the mat, as shown by the puddle in the lower right hand corner of the photo. The glass mat was easily separated from both the positive and negative plates. The plates themselves were very pliable and did not show the cracking noted in the failed cells. It was also very easy to slip the inner cylinder out of the outer plastic shell. In the failed units, the plastic shell had to be cut and peeled off the cylinder in order to remove the cell components.

The most remarkable observation made during the disassembly of this cell was the apparent saturation of the glass mat with electrolyte and the pliability of the plates observed during the unrolling of the cell “jelly roll.” None of the failed cells exhibited these qualities. There were also no signs of corrosion in any area of the cell, including the post areas. It was also noted that the glue used to hold the cells together was very pliable and quite soft. In the field-returned units, after removal of the shrink-wrap, it was noted that many of the glue blocks were detached from the individual cells, and had become stiff and hard. This may also be evidence of operation at elevated temperatures.

CONCLUSIONS

Upon review of the operational data provided from the field, the average charging voltages appear to be a bit on the high side, but not excessively high, even in higher temperature environments. The fact that no signs of corrosion were found during the tear down would seem to indicate that these batteries have a good tolerance of higher than recommended charging voltage. It does not appear that the units analyzed were chronically undercharged since sulfation typically associated with undercharging was not observed in any of the batteries tested at Sandia.

Cell dryout was seen to be the primary cause of failure of the field-returned batteries. Of even greater importance is the cause of cell dryout. It was noted that all units operate at elevated temperatures, typically in the 32 to 35 degrees C range. Using the standard rule of thumb of one-half expected life for each 10 degrees C above 25 C, one would expect that the batteries should have an operational life of at least 4 years. (This is based on a life of 8 years at 25 degrees C for float applications, as specified by the manufacturer.) With that in mind, one might assume that dryout of an individual cell is caused by something other than the operational temperature environment of the entire battery. Considering the orientation of the batteries within the enclosure, cells located next to the South- or West-facing wall of the enclosure may be exposed to high radiation heating directly from the wall of the enclosure. The remaining cells not in direct contact with the outside wall would be somewhat insulated from radiation heating. If so, the end cell(s) would operate at much higher temperatures than the remaining cells, leading to premature failure as was found in the test group.

If indeed dryout of the end cells is caused by radiation heating, a solution would be to eliminate the source of the radiated heat with some form of insulation on the South- or West-facing wall. An alternative would be a factory modification that insulates the entire battery from radiation heating.

RECOMMENDATIONS TO IMPROVE BATTERY LIFE

- Modification of the way the batteries are installed in the cabinet, to preclude single cell heating from cabinet wall-radiated heat, including thermal isolation between the battery and the walls of the cabinet.
- More precise control of battery charger float voltage.
- Improvement in the operating environment for the batteries, through better air circulation around the batteries.
- Development of a simple field test procedure to be implemented by customers, to identify weak batteries that may be replaced prior to failure (rather than wholesale replacement of batteries on a scheduled basis).

PLANS FOR FUTURE WORK

- Full implementation of Sandia's recommendations.
- Further work to understand the benefits of insulating the batteries and to explore the effectiveness of various insulating methods.
- More field data will be collected to develop guidelines for determining remaining battery life based on impedance or conductance measurements.
- Lastly, a battery maintenance program will be developed utilizing what has been learned to optimize performance while reducing cost of replacement.