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Evaluation of Bipolar Pb-Acid Batteries for Aircraft Applications

GARY LOEBER
JAMES MALONE
CAMERON RIEPENHOFF

Battery Branch
Power Division
Air Force Research Laboratory
Wright-Patterson AFB OH 45433-7650

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Gary Loeber
GARY LOEBER
Project Engineer

Richard A. Marsh
RICHARD A. MARSH
Chief, Battery Branch

Michael D. Braydich
MICHAEL D. BRAYDICH, LtCol, USAF
Chief, Power Division
Air Force Research Laboratory

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Gary Loeber
James Malone
Cameron Riepenhoff

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Power Division
Air Force Research Laboratory
Wright-Patterson AFB OH 45433-7650

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This report describes the results of in-house evaluation of bipolar Pb-Acid batteries which have the potential to be used for 270V power. Batteries from two manufacturers were evaluated in this effort

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1.0 Introduction

An effort was undertaken by WL/POOB to evaluate bipolar lead-acid (Pb-Acid) batteries for high power density, high voltage applications such as the more electric aircraft (MEA). This technology is also being studied for use as the power source for electric vehicles. These batteries were delivered under developmental programs with Pinnacle Research Institute (PRI) and Johnson Controls, Inc. (JCI). The PRI program was jointly funded by Wright-Patterson Air Force Base and Eglin Air Force Base. Results of these programs are described in WL-TR-95-2111, "Development of a Bipolar Lead/ Acid Battery for the more Electric Aircraft" and WL-TR-97-2041, "Advanced Bipolar Lead-Acid Battery." This report describes the results of the evaluations performed at WL/POOB.

The bipolar Pb-Acid technology was chosen as a candidate for the MEA due to its inherently high power density and relatively compact size. Results of these contracts and the WL/POOB evaluation task clearly show that much developmental work remains to be done if this technology is to be used.

2.0 Experimental

2.1 Test Articles

PRI delivered two 12V, 3Ahr batteries at the end of the first year. These test articles had individual sensing leads for each of the six cells, in addition to the standard battery tabs. This gave us the capability to monitor individual cells and also allowed us to bypass cells to charge/ discharge an individual cell if necessary. This was done on battery PR602 to balance a cell that had a significantly lower voltage than the others. Each cell also had a fill port to allow for the addition of water and a vent for gassing on overcharge. Table 1 shows the PRI battery specifications and Tables 2 and 3 show the PRI contract goals. Two 12V and one 24V valve-regulated batteries were received from JCI. Unlike the PRI batteries these did not include individual cell tabs, making it impossible to monitor or control individual cells. Table 4 shows the JCI battery specifications and Tables 5 and 6 show the JCI near and far term goals. Representative batteries from PRI and JCI are shown in Figures 1 and 2 respectively.

Table 1. PRI Battery Specification

BATTERY ID	PR 602	PR 603
Nominal Voltage	12V	12V
Number of Cells	6	6
Rated Capacity (Ahrs)	3.0	3.0
Dimension Length (in) Height (in) Thickness (in)	 9 8 1.25	 9 8 1.25

Table 2. Contract Goals for PRI Batteries - Wright-Patterson AFB Requirements

Parameter	Value	Notes/ Conditions
Voltage	48V	6 and / or 12 V preliminary
Capacity	3 to 5 Ahr	1 C rate at room temperature
Gravimetric Power Density	> 1 kW/kg	10 s rate and 10% duty cycle at room temp
Gravimetric Energy Density	30 Whr/kg	1 C rate at room temperature
Volumetric Energy Density	> 60 Whr/1	1 C rate at room temperature
Charging Conditions	Constant Potential	Current limited
Float Charge	> 10 hours	Would prefer 100 hours
Cycle Life	> 200 cycles	1 C rate, 80% DOD at room temperature
Calendar Life	> 2 years	From open circuit decay

Table 3. Contract Goals for PRI Batteries - Eglin AFB Requirements

Parameter	Value	Notes/ Conditions
Voltage	6 or 12 V	
Capacity	0.125 Ahr for 1" x 1" design	1 C rate at room temperature
	0.5 Ahr for 2" x 2" design	1 C rate at room temperature
Gravimetric Power Density	> 5 kW/kg	1 s rate and 10% duty cycle at room temp
Design	Flexible	May need 1 surface for C collector mounting

Table 4. JCI Battery Specifications

DELIVERABLE IDENTIFICATION	WPG-6	WPG-8	WPG-11
Nominal Voltage	12	24	12
Number of Cells	6	12	6
Open Circuit Voltage	12.637	25.466	12.960
Dimensions Length (in) Height (in) Thickness (in)	 10 7.125 1.325	 10 7.125 1.86	 10 7.125 1.325
Mass (kg)	3.512	5.515	3.491
Resistance (ohm)	9.1	18.5	12.0
Cycles to Date	8	6	5

Table 5. Near Term (5 year) Goals for JCI Bipolar Batteries

Requirements Met	Battery Dimensions	Battery Volume	Battery Weight	W/kg	W/cm^3	W-hr/kg	W-hr/cm^3
Main Engine Starting APV Starting Hybrid Emergency	17.6"x 15.5"x 15.5"	2.45 ft^3	450lbs	747.9	2.2	12.25	0.036
Main Engine Starting Ground Power Emergency Power APU Starting Hybrid Emergency Scenario 1 30 minute ground power capacity	27.4"x 19.7"x 19.7"	6.15 ft^3	1000lbs	62.2	0.16	31.08	0.081
Scenario 2 45 minute ground power capacity	36.2"x 19.7"x 19.7"	8.13 ft^3	1349 lbs	46.1	0.12	34.56	0.092
APU Starting	16.5"x 4.33"x 4.33"	0.18 ft^3	33 lbs	705.0	2.1	11.75	0.036

Table 6. Far Term (10 year) Goals for JCI Bipolar Batteries

Requirements Met	Battery Dimensions	Battery Volume	Battery Weight	W/kg	W/cm3	W-hr/kg	W-hr/cm3
Main Engine Starting APV Starting Hybrid Emergency	14.4"x 15.5"x 15.5"	2.00 ft^3	389lbs	895.	2.8	14.17	0.044
Main Engine Starting Ground Power Emergency Power APU Starting Hybrid Emergency							
Scenario 1 30 minute ground power capacity	21.6"x 19.7"x 19.7"	4.85 ft^3	864 lbs	72.0	0.21	35.97	0.103
Scenario 2 45 minute ground power capacity	29.9"x 19.7"x 19.7"	6.72 ft^3	1235 lbs	50.6	0.15	37.77	0.111
APU Starting	15.2"x 4.33"x 4.33"	0.16 ft^3	31 lbs	772.0	2.3	12.87	0.041

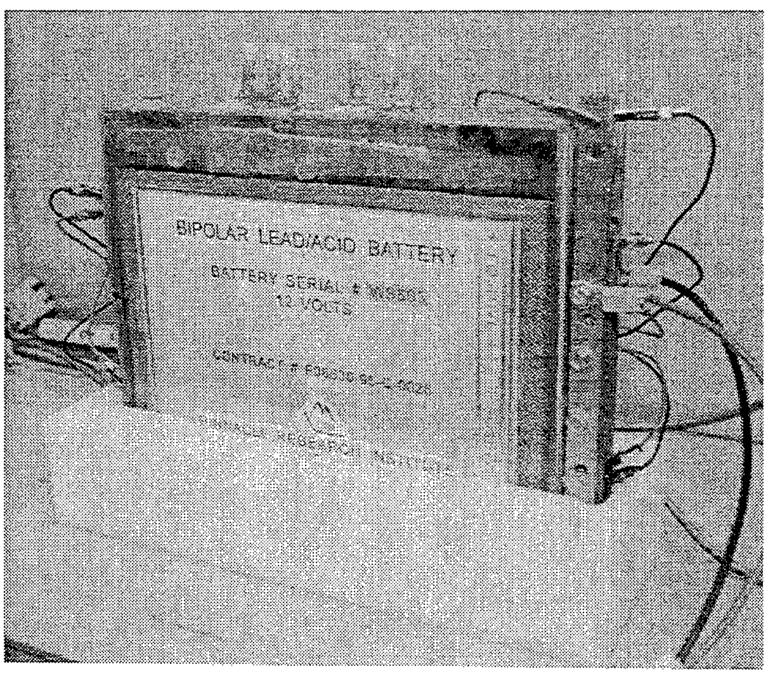

Figure 1. Pinnacle Bipolar Lead/Acid Battery

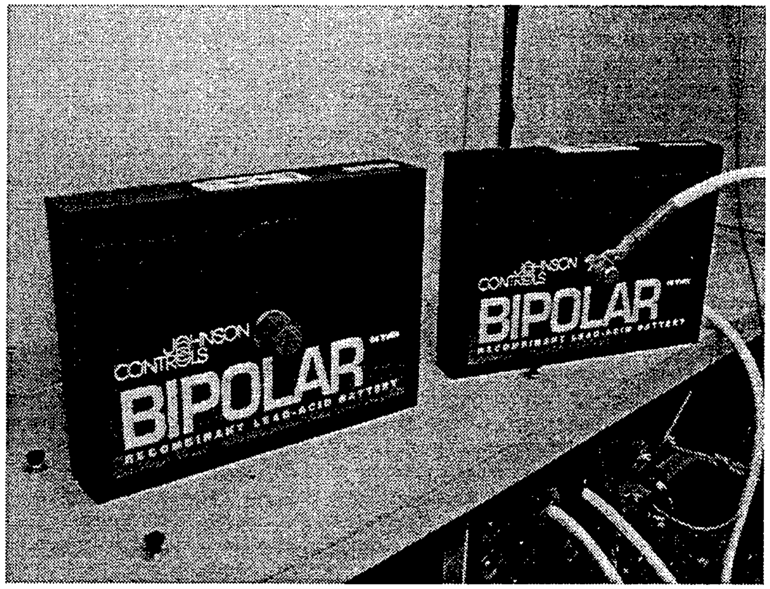

Figure 2. Johnson Controls Bipolar Lead-Acid Battery

2.2 Test Facility

The electrochemical section in-house facility was designed to allow different technologies to be tested with relatively minor modification to the test stands. Each test stand is equipped with appropriate electronic loads, power supplies, strip chart recorders, current and voltage displays, a data acquisition unit (DAQ) and some degree of backup protection circuitry such as voltage set point meters. Figure 3 shows a typical test stand. In addition, there are 7 temperature chambers capable of controlling temperature in the range -40°C to 70°C. A typical chamber is shown in Figure 4. Each test stand is connected through the DAQ to the computer system which controls and monitors all aspects of the tests. If the computer system locks up or crashes, backup protection is provided by the set point meters included in the test stands. These meters cannot control such cycling limits as overcharge but can place a test on open circuit if a voltage or current limit is exceeded. The computer system is capable of stopping a cycle when any type of limit such as voltage, current, temperature, overcharge, or pressure is reached or of completely stopping a test if a condition occurs that requires intervention by lab personnel. Such a condition might be a power supply that stops functioning correctly.

Prior to beginning a new test and when equipment is replaced a check on the calibration of the instrumentation is performed. This procedure involves setting a known valve on each DAQ channel and taking a reading at the computer. If these values do not match, the necessary instrumentation is replaced and a new check is made.

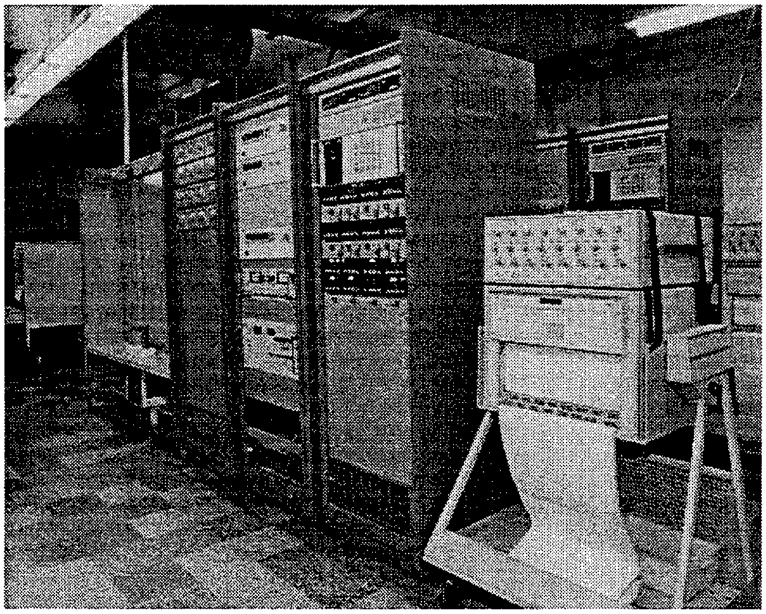

Figure 3. In-House Test Stand

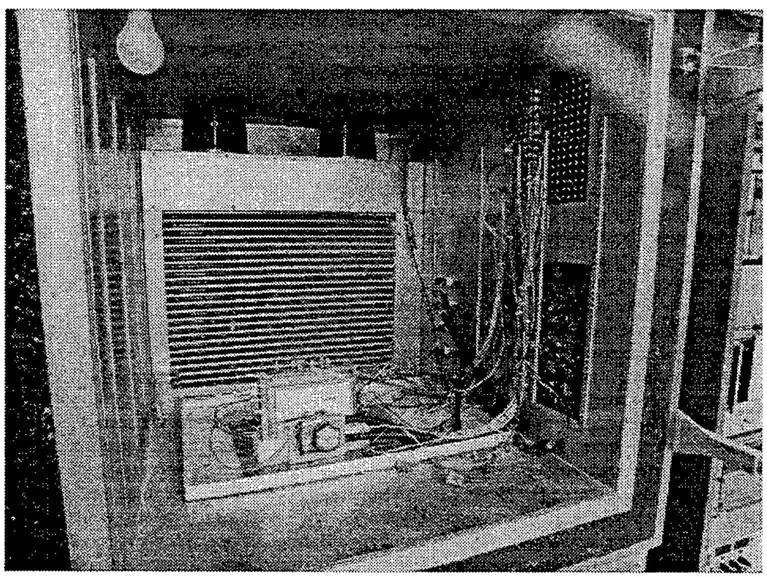

Figure 4. In-House Temperature Chamber

2.3 Test Plan

Prior to beginning the tests it was critical to develop a test plan for each battery. The types of tests run were based partly on specific aircraft applications and partly on the number of test articles received. Further consideration needed to be given to manufacturer recommendations for such parameters as maximum rates, voltage/ temperature compensation limits, extreme operating temperature limits, and maximum recommended cycles per day.

A suggested test plan was included with the JCI batteries and a decision was made to follow this plan as closely as possible for battery WPG6. Battery WPG8 was placed on life cycle test at 1.5C. Electrical performance characterization was planned for battery WPG11. This electrical characterization was to include constant current discharge at various rates, pulse discharge, charge/discharge cycles at various temperatures from -40 °C to 50 °C and self discharge studies. Although aircraft requirements call for an upper operating temperature of 70 °C, JCI recommended limiting the operating temperature to 50 °C to prevent irreversible damage to the bipolar plate. Test plans for batteries WPG6, WPG8, and WPG11 are shown in Tables 7-9. Note that Table 9 is incomplete since testing was terminated after the self discharge test.

Table 7. Test Plan for JCI Battery WPG6

DESCRIPTION	RATES and TEMPERATURES
Constant Current	3 A, 30 A, 180 A, 500 A
Single Pulse Power Capability	1, 3, 5, 10, 15, 30 second
Main Engine Starting	2X 30 second constant power
APU Starting	4X 15 second constant power
Emergency Power	10 minute constant power
Ground Power	30-45 minute constant power
100% DOD C- Rate Capacity versus Temp	-54, -30, 0, 30, 49°C [-65, -22, 32, 86, 120°F]
Rapid Recharging	10 minute max (Main and APU)
Stand Loss	1 week
Temperature Shock	MIL-STD-810E, Method 503.3
Vibration	MIL-STD-810E, Method 514.4

Table 8. Test Plan for JCI Battery WPG8 - Life Cycle Test at Room Temperature

1. Discharge at 1.5C to 9.6V
2. 0.25C constant current charge to 28.8V followed by constant potential charge at 28.8V to 110% return
3. Open current for a period equal to 24 hours - (discharge time + charge time)
4. Repeat until battery fails to deliver 75% of its initial capacity

Table 9. Test Plan for JCI Battery WPG11 - Electrical Performance Testing

1. Capacity check cycles at 22°C
   -same as the life cycle testing performed on battery WPG8
2. High rate performance at 22°C
   -10 C discharge to 5.7V
   -Standard recharge according to life cycle regime
   -Open circuit for 1 hour
   -Capacity check cycles
3. Run two consecutive 10C discharges at 22°C according to the procedure outlined in step 2 above. The purpose of this test is to determine the effects on capacity of consecutive high rate discharges with no reconditioning between the cycles.
4. Self discharge test
   -Place charged battery on open circuit at 22°C
   -After 5 weeks perform a 1.5 C discharge and calculate percent loss
   -Capacity check cycles
5. High rate performance at 40°C. Same as number 2 above except run at 40°C

No test plan was included with the PRI batteries so it was decided to perform room temperature life cycle testing at 80% DOD on battery PR602 and electrical performance characterization on battery PR603 at various rates and temperatures. Table 10 shows the test plan for battery PR602 and Table 11 shows the test plan for battery PR603.

Table 10. Test Plan for PRI Battery PR602

1. Capacity Check
   - -C/10 discharge to 1.8V per cell
   - -Rest 1 hour
   - -C/10 charge to 120% return
   - -Rest 1 hour

Go to step 2 when capacity stabilizes

2. Life cycle test at room temperature to 80% DOD
   - -C/3 discharge to 1.86V per cell or 2.4 Ahrs
   - -Rest 30 minutes
   - -C/10 charge to 120% return
   - -Rest 1 hour

Repeat step 2 until battery fails to deliver 2.3 Ahrs before reaching the voltage limit

Table 11. Test Plan for PRI Battery PR603

1. Capacity vs. Discharge Rate
   Perform one each of the following cycles with at least two capacity check cycles after each. All testing is at room temperature.
   - -C/6 to 1.75V/cell
   - -C/3 to 1.65V/cell
   - -C/1.25 to 1.60V/cell
   - -C-rate to 1.5V/cell

   All recharges are C/10 to 120% return.

2. Temperature Performance
   Perform one each of the following cycles with at least two capacity check cycles after each. The following temperatures should be used at each discharge rate: 10°C, 40°C, 0°C, 70°C, -40°C, -55°C.
   - -C/6 to 1.75V/cell
   - -C/3 to 1.65V/cell
   - -C/1.25 to 1.60V/cell
   - -C-rate to 1.5V/cell

3. Charge Retention Study
   Perform three capacity check cycles prior to storing at each of the following temperatures: 22°C, 40°C, 0°C, 70°C and -40°C. At each temperature the battery should be stored for the following time periods: 1 day, 1 week, 4 weeks, 10 weeks and 20 weeks. At the end of each time period return the battery to 22°C and run a C/10 discharge to 1.8V/cell.

In addition to the test plans, specific testing guidelines were supplied by both JCI and PRI. Below is the list of guidelines for the JCI batteries.

1. Discharge voltage cutoff determined by discharge rate. See Table 11 and Figure 5.
2. Charge voltage cutoff determined by temperature. See equation 1.
3. No more than one cycle per day.
4. No rest after discharge.
5. Maximum operating temperature of 50°C

Table 12. Discharge Cutoff Voltage Criteria

Discharge Rate	10hr	5hr	3hr	2hr	1hr	40min	30min	20min	10min	5min
Cutoff volts/cell	1.77	1.75	1.73	1.71	1.64	1.60	1.54	1.46	1.26	0.95

Plotting the values in Table 12 resulted in the graph shown in Figure 5 which was used for intermediate discharge rates.

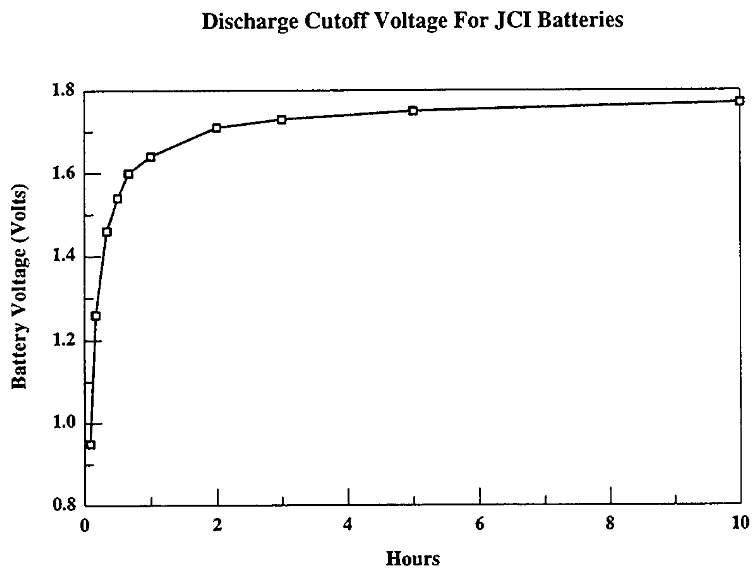

Figure 5. Discharge Cutoff Voltage for JCI Batteries

$$V_{lim}, T \neq 25°C = V_{lim}, T=25°C + [K * (25-T)]$$

Where V_{lim}, $T \neq 25°C$ = Temperature corrected voltage limit

V_{lim}, $T=25°C$ = 2.4V per cell

T = Operating temperature in °C

K = Compensation factor:

$T < -20°C$ K = 0.036V/°C

$T \geq -20°C$ K = 0.024V/°C

Equation 1 - Charge voltage cutoff/temperature relationship for JCI batteries

The following list is the guidelines for the PRI batteries:

1. If any cell voltage falls below 2.0V while on open circuit, a boost charge at 100ma for up to 15 hours should be performed.
2. Water level should be checked approximately every five cycles and adjusted as necessary.

3. Discharge voltage cutoff is rate and depth of discharge dependent. See Table 13.

Table 13. Discharge Voltage Cutoff as a Function of Rate and DOD

Rate	C/10	C/6	C/3	C/1.25	C
Current (Amps)	0.30	0.5	1.0	2.4	3.0
Depth of Discharge	Minimum	Cell	Cut	Off	Voltage
20%	2.05	2.00	2.00	1.90	
40%	2.01	1.98	1.96	1.86	
60%	1.98	1.95	1.92	1.82	
80%	1.93	1.90	1.86	1.75	
100%	1.80	1.75	1.65	.60	11.5

The first step performed on these batteries was a capacity determination using manufacturer supplied profiles for this specific purpose. A minimum of three cycles was planned with more if necessary.

One problem encountered with the PRI batteries was the lack of a standard charge algorithm. This resulted in running many cycles to try to determine correct overcharge rates and voltage limits. With more time or additional batteries an effort could have been undertaken to determine these values. Ideally, this would have been done before proceeding with the other tests.

3.0 Test Results

In this section specific results from each of the tests will be discussed. PRI results are detailed in section 3.1 and JCI results in section 3.2.

3.1 PRI Results

Testing on PR602 began in Oct 96. In accordance with the test plan we started with the capacity verification procedure. This involved C/10 discharges to 100% DOD or 10.8V and C/10 recharges to 10% overcharge. On the first discharge it was observed that cell #2 limited the capacity delivered to 0.58 Ahrs due to its being significantly out of balance compared to the other cells. This is shown in Figure 6. Following a discussion with PRI personnel we attempted to balance cell #2 with the others using the following procedure:

1. Recharge the full battery at C/10 to 0.58 Ahrs (the amount removed on discharge #1).
2. Continue charging cell #2 only at 100mA for 15 hours to return a total of 2.1 Ahrs to that cell.

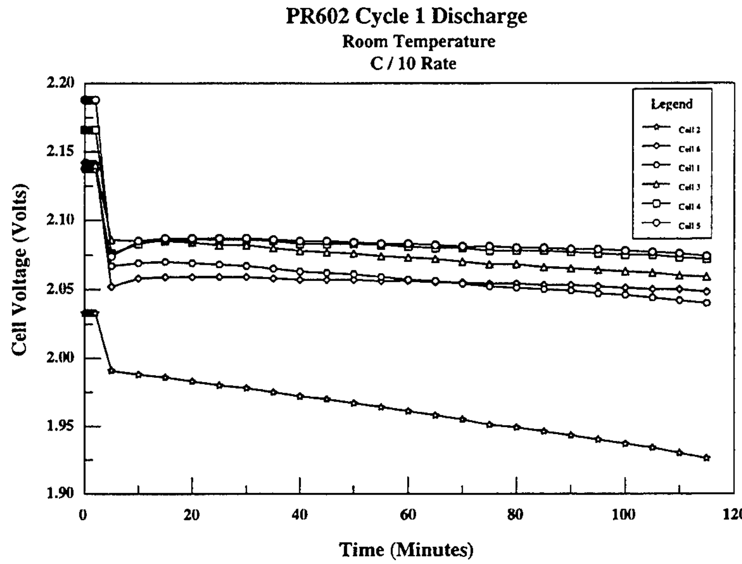

Figure 6. PR602 Cycle 1 Discharge

This improved the discharge capacity to 2.1 Ahrs by cycle #4. However, on cycle #5 cell #5 limited the capacity which continued to fade until water levels were adjusted. Within 2 to 3 cycles of adding water the capacity would again fade. This continued until testing was terminated at cycle 36 when the battery delivered less than 10% of its rated capacity. In addition to adusting water levels, some of the actions taken during cycling included adjusting overcharge rates to as high as 40% and cell charge voltage limits to 2.8V. On cycle 19 it was observed that the battery was delivering 1.53 Ahrs or just more than 50% of the rated capacity and by cycle 28 only 22% of rated capacity was being delivered.

Initial performance of battery PR603 was significantly better than battery PR602 delivering 2.9 Ahrs on cycle 1. The recharge resulted in a 115% return with no cell exceeding the 2.7V limit. Capacity rose to 3.1 Ahrs on cycle 2 and then began falling rapidly until no capacity was delivered at cycle 29 due to cell 5 which appeared to be failing. Water levels were adjusted at cycles 8, 15, 21, 32, and 36. However, this action had no lasting effect as capacity on subsequent cycles faded rapidly. On cycle 36 water levels were adjusted and capacity rose to 0.55 Ahrs; however cell #5 was now completely dead. See Figure 7. It was decided to remove this cell and continue testing as a five cell battery. However, the capacity continued to fall and at cycle 50 testing was terminated. One interesting point concerning this battery is the frequency at which water levels were adjusted. Although overcharge rates on this battery never exceeded 20%, water was added at the same frequency as battery PR602 which was given 40% overcharge.

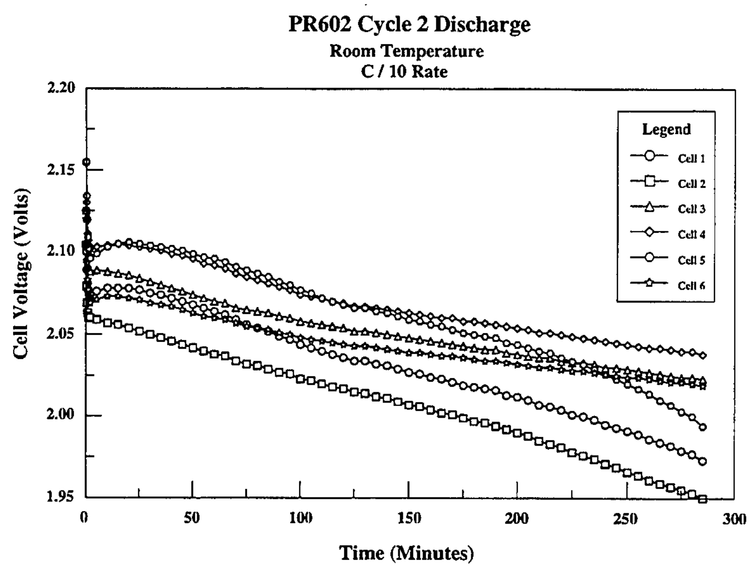

Figure 8. PR602 Cycle 2 Discharge

Therefore, it would appear that excessive overcharging alone cannot account for all of the water loss. Representative voltage curves from batteries PR602 and PR603 are shown in Figures 8-14. Capacity vs. cycle is shown in Figures 15 and 16 for batteries PR602 and PR603, respectively.

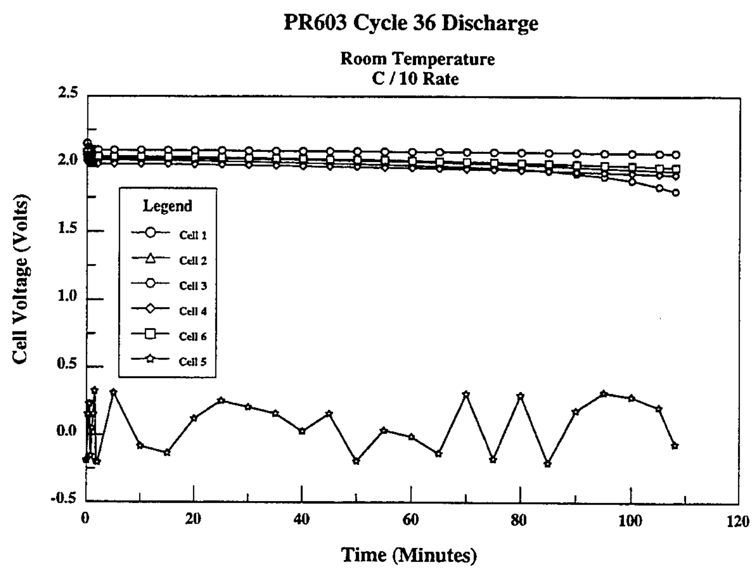

Figure 7. PR603 Cycle 36 Discharge

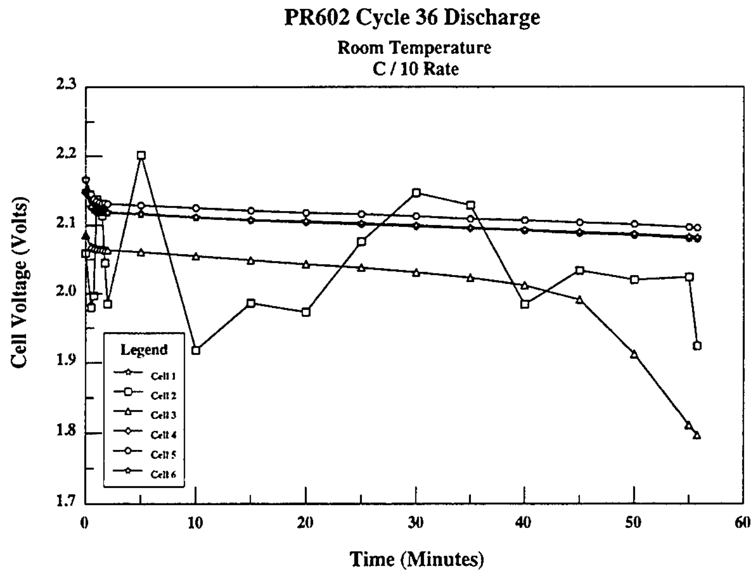

Figure 9. PR602 Cycle 36 Discharge

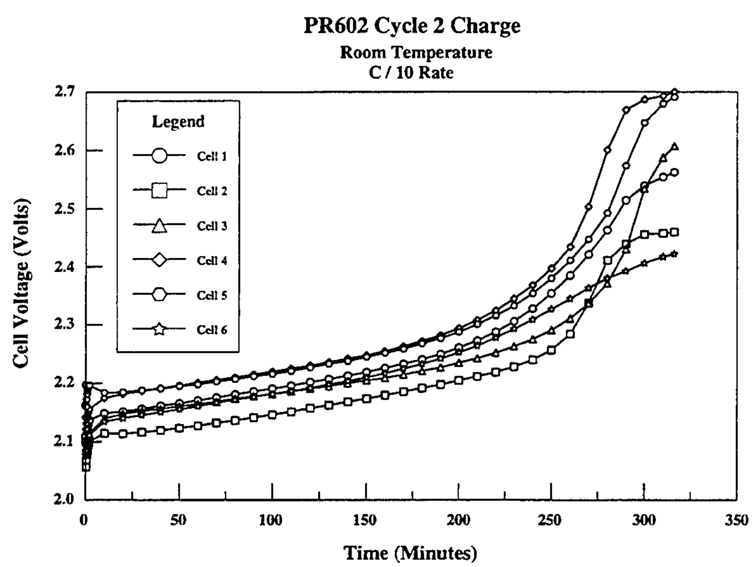

Figure 10. PR602 Cycle 2 Charge

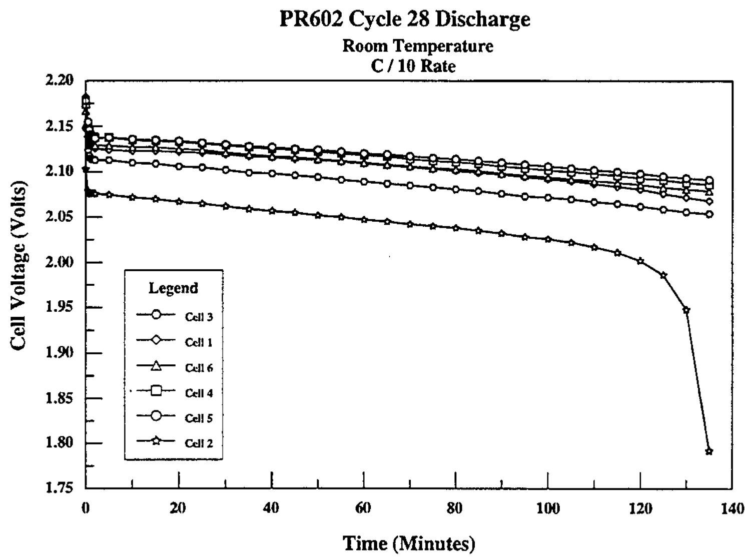

Figure 11. PR602 Cycle 28 Discharge

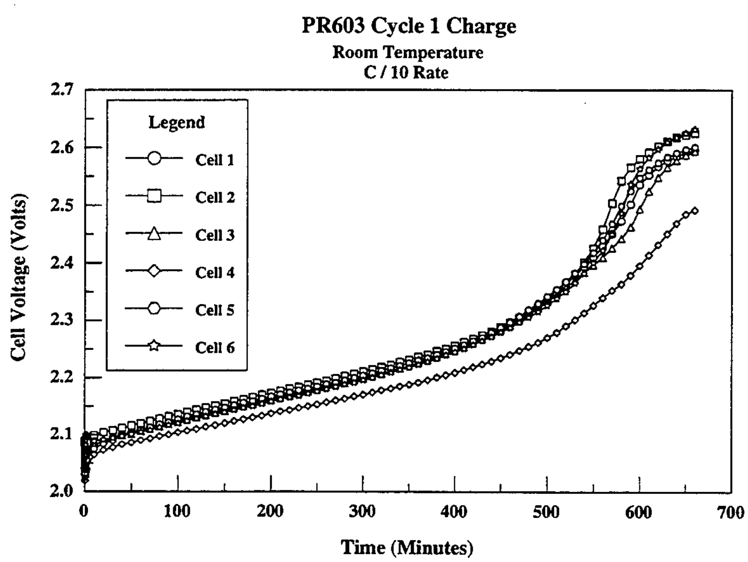

Figure 12. PR603 Cycle 1 Charge

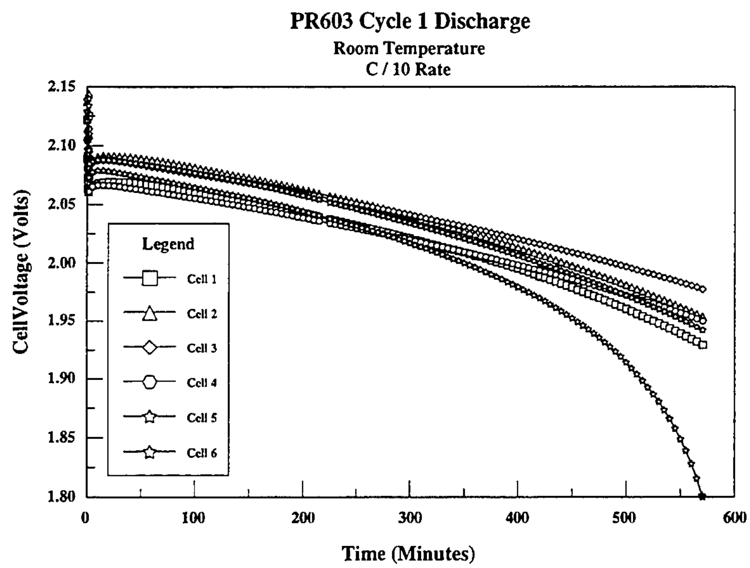

Figure 13. PR603 Cycle 1 Discharge

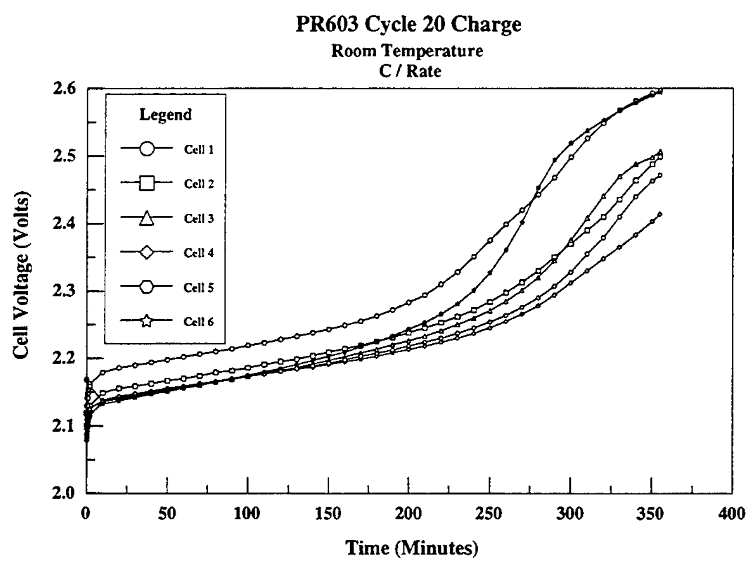

Figure 14. PR603 Cycle 20 Charge

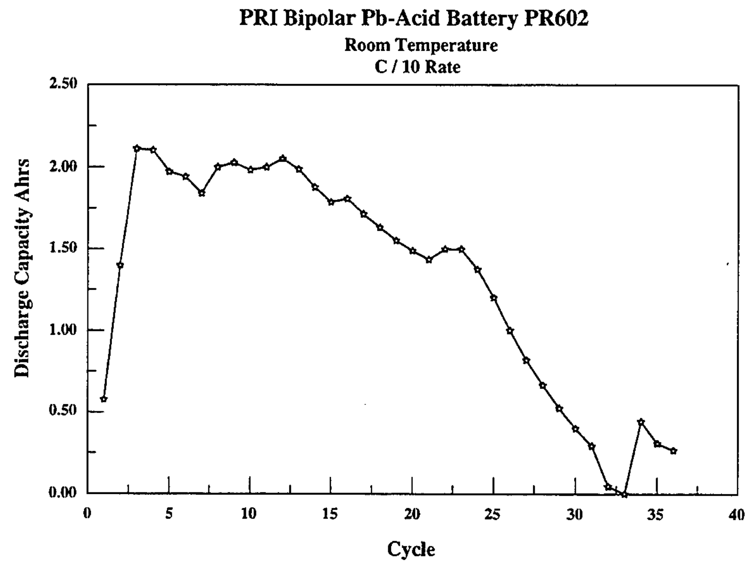

Figure 15. PR602 Discharge Capacity Versus Cycle Number

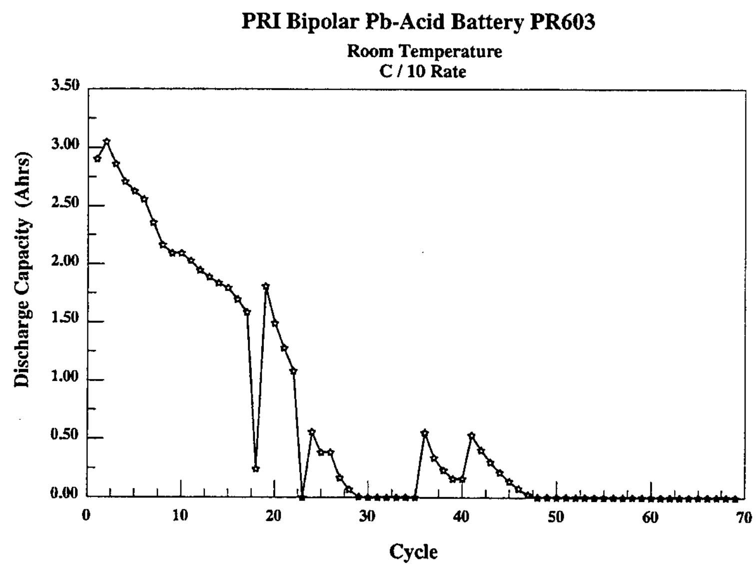

Figure 16. PR603 Discharge Capacity Versus Cycle Number

3.2 JCI Results

3.2.1 Battery WPG-11

Overall this battery performed well delivering more than the rated capacity at the 1.5C rate and the rated capacity at the 10C rate. Testing began with a 1.5C discharge based on a 2Ahr rated capacity. Recommended recharge consisted of a 500mA constant current charge to 14.4V followed by a constant potential charge to 110% return of the discharge capacity. At cycle 15 a 3A, 16% duty cycle pulse discharge was performed. See Figure 17.

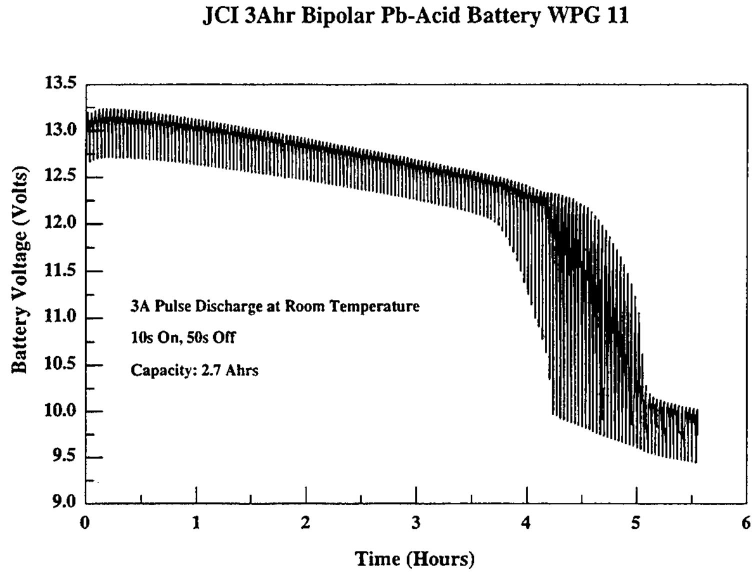

Figure 17. Pulse Discharge of Battery WPG 11

3.2.2 Battery WPG-8

Battery WPG8 underwent life cycle testing at the 1.5C discharge rate at room temperature. Recharge was a 500mA constant current charge to 28.8V followed by a constant potential charge to 110% return of the discharge capacity. Capacity started at 90% of the rated 2.0Ahr capacity, fell an average of 50mAhrs over the next few cycles and then began rising to 125% of rated capacity at cycle 19 before failing at cycle 23. The reason for failure remains unknown; a post mortem analysis should be performed to make this determination.

3.2.3 Battery WPG-6

Battery WPG-6 was to be evaluated for electrical performance using most of the suggested regimes supplied by JCI. The battery failed at cycle 36 before many of these tests were done. Listed below are the tests that were performed.

1. 1.5C discharge
2. 1.5C pulse discharges, 16.7% duty cycle
3. 62C discharges
4. A 15C discharge

Cycles 1-10 consisted of 1.5C discharges to 100% DOD at room temperature and 500mA constant current charges to 14.4V followed by constant potential to 110% return. These 10 cycles performed very well delivering between 108% and 150% of the rated 2Ahr capacity. At cycle 11 a 3A, 16% duty cycle pulse discharge was performed. Cycles 12-20 were run the same as cycles 1-10 to serve as a comparison. These cycles delivered even higher capacity ranging from 158% to 188% of rated. A 62C discharge was performed on cycle 21 and was followed by a single 1.5C discharge and then another 62C discharge. The 62C discharge delivered 78% of the rated capacity. Two more 1.5C discharges were followed by the 15C discharge which delivered 120% of the rated capacity. After this the battery began to fail and testing was terminated at cycle 36. See Figures 18-21. Representative plots for the JCI batteries are shown in Figures 22-23.

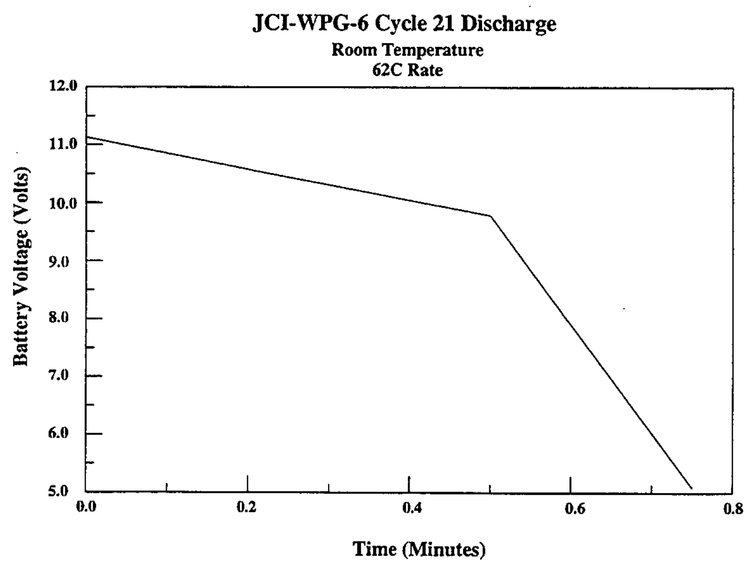

Figure 18. WPG-6 Cycle 21 Discharge

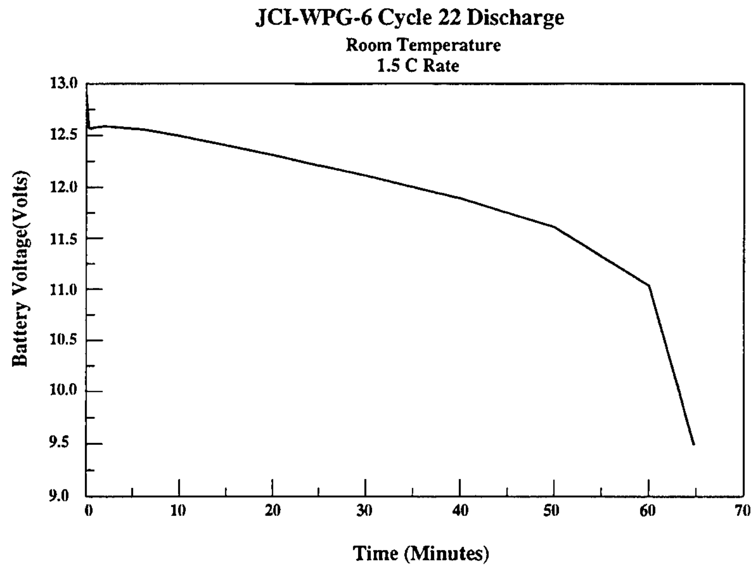

Figure 19. WPG-6 Cycle 22 Discharge

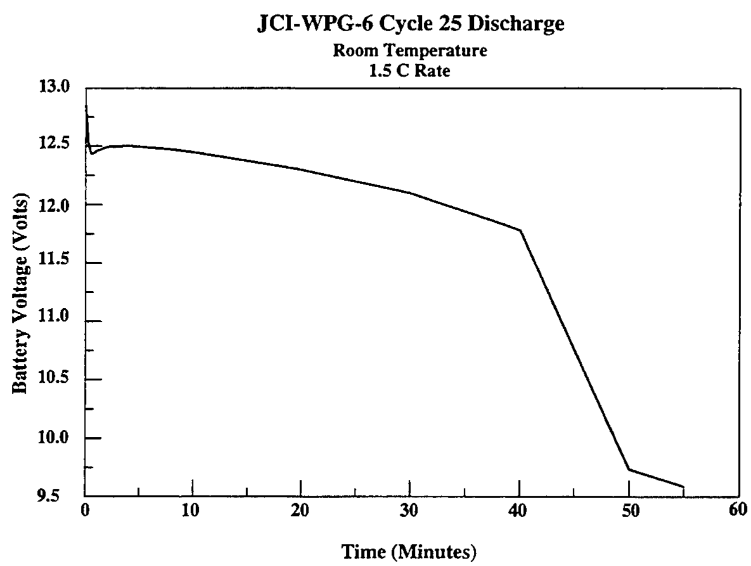

Figure 20. WPG-6 Cycle 25 Discharge

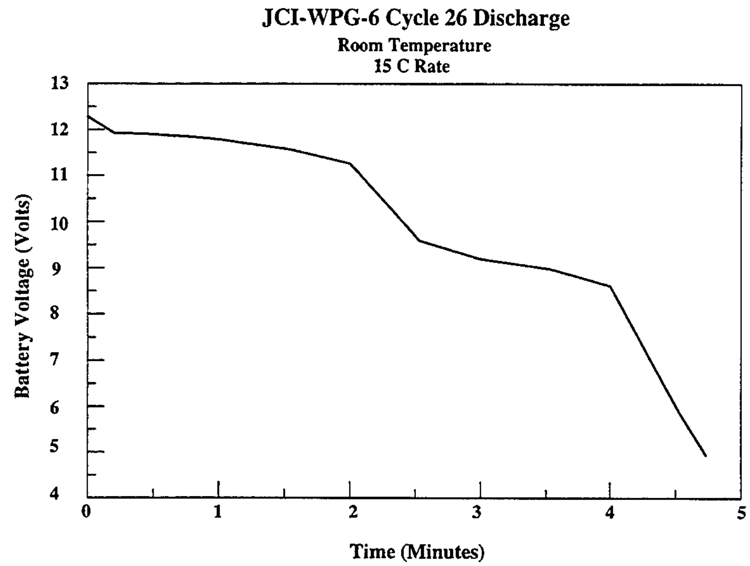

Figure 21. WPG-6 Cycle 26 Discharge

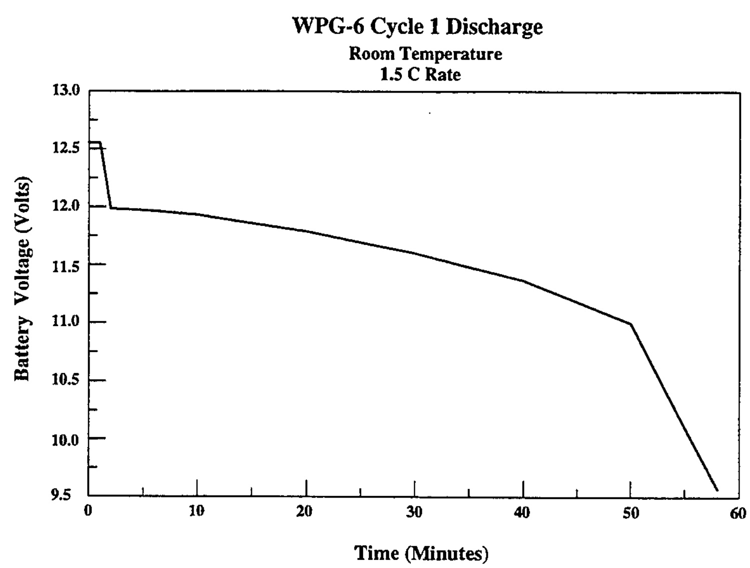

Figure 22. WPG-6 Cycle 1 Discharge

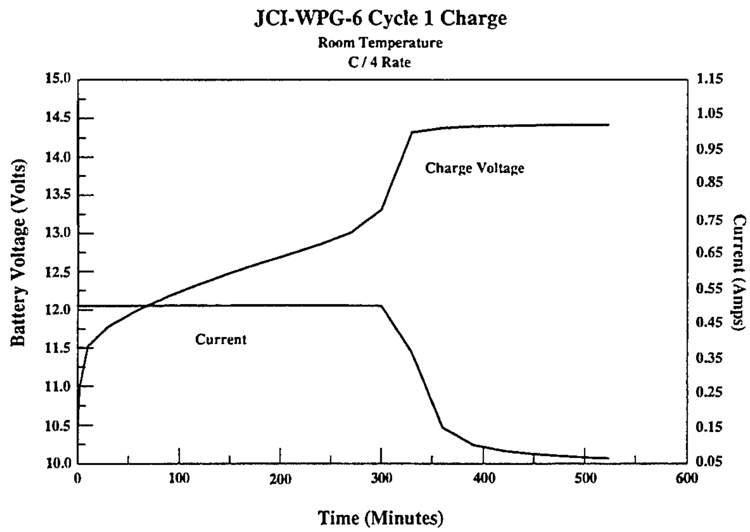

Figure 23. WPG-6 Cycle 1 Charge

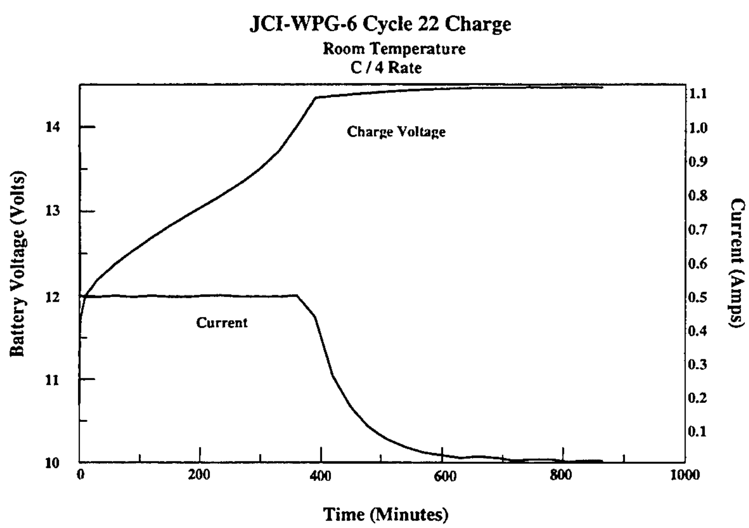

Figure 24. WPG-6 Cycle 22 Charge

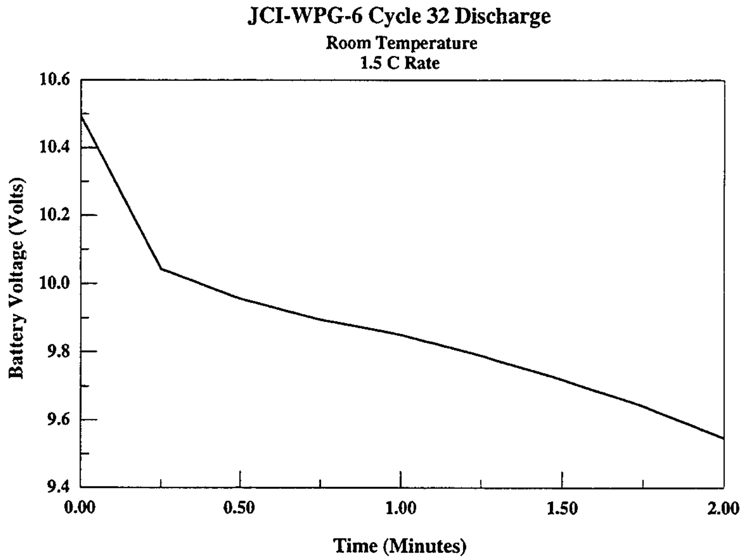

Figure 25. WPG-6 Cycle 32 Discharge

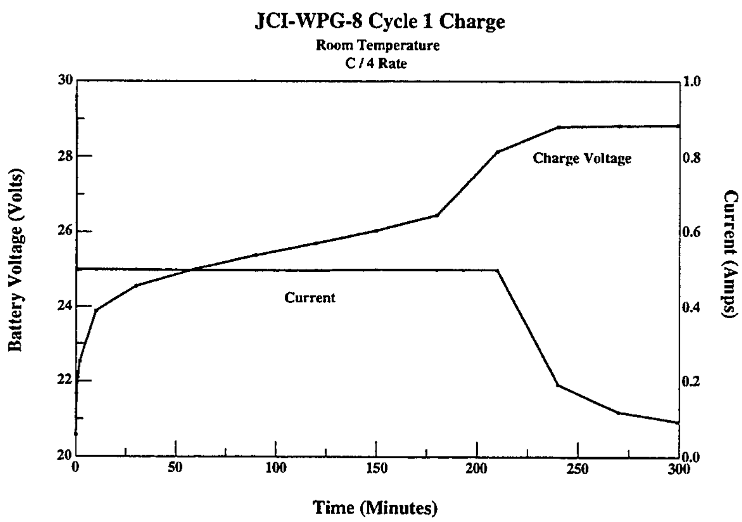

Figure 26. WPG-8 Cycle 1 Charge

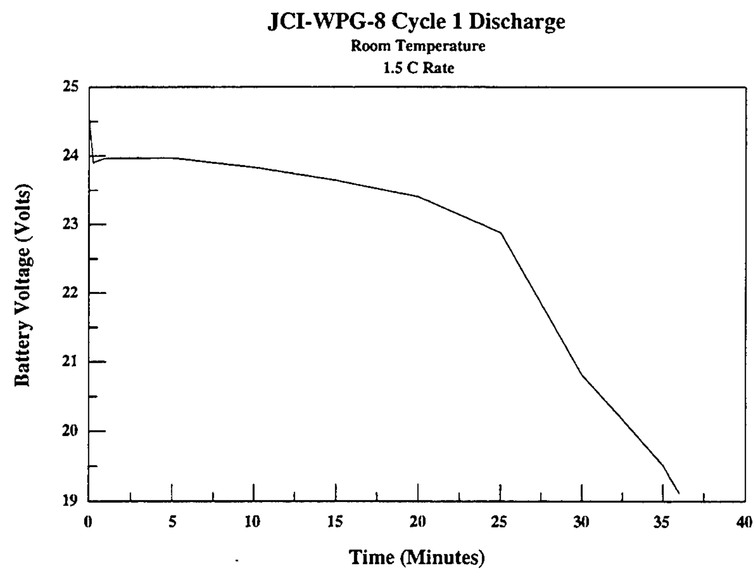

Figure 27. WPG-8 Cycle 1 Discharge

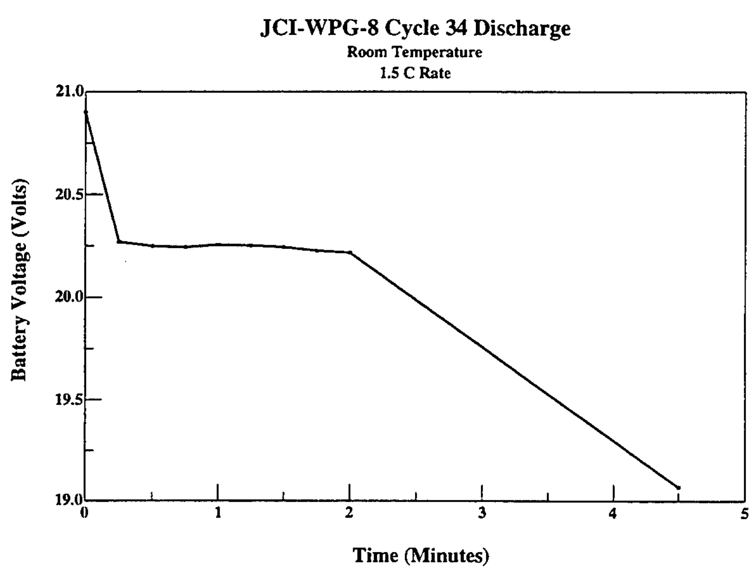

Figure 28. WPG-8 Cycle 34 Discharge

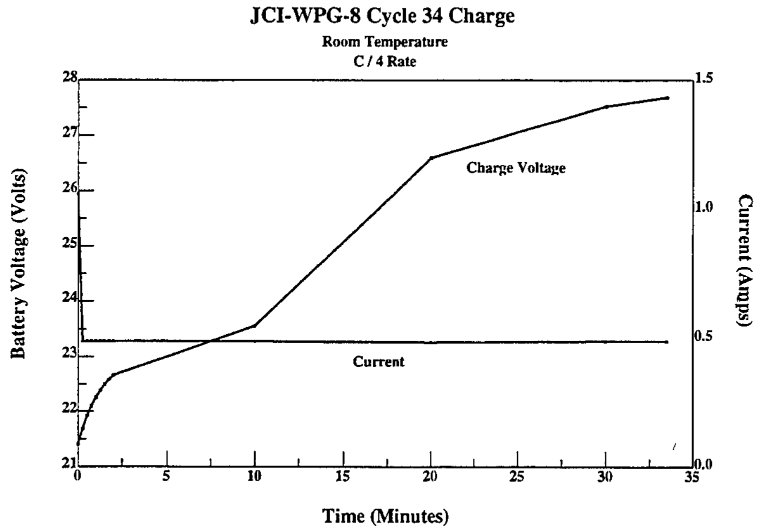

Figure 29. WPG-8 Cycle 34 Charge

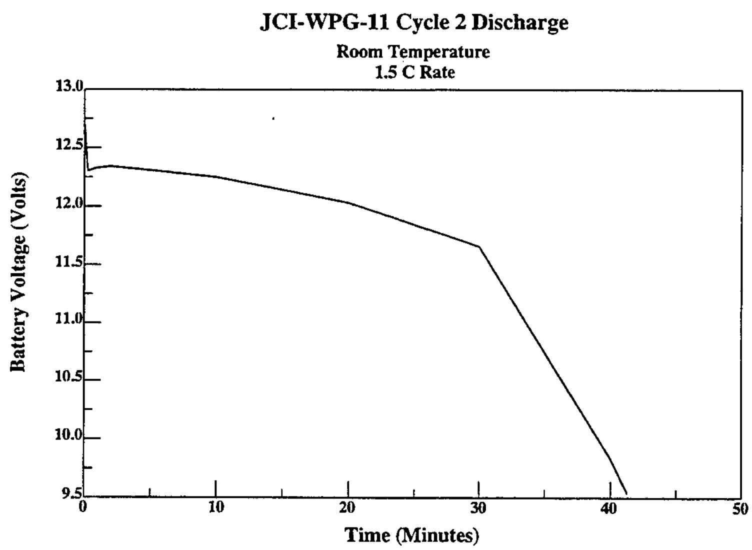

Figure 30. WPG-11 Cycle 2 Discharge

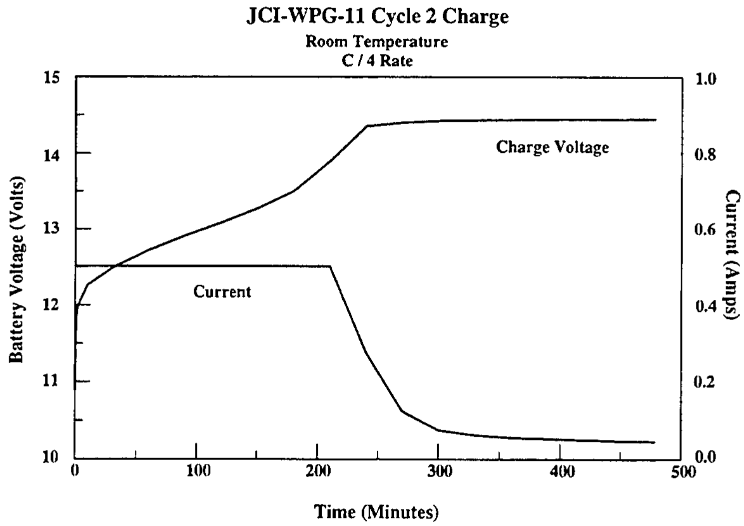

Figure 31. WPG-11 Cycle 2 Charge

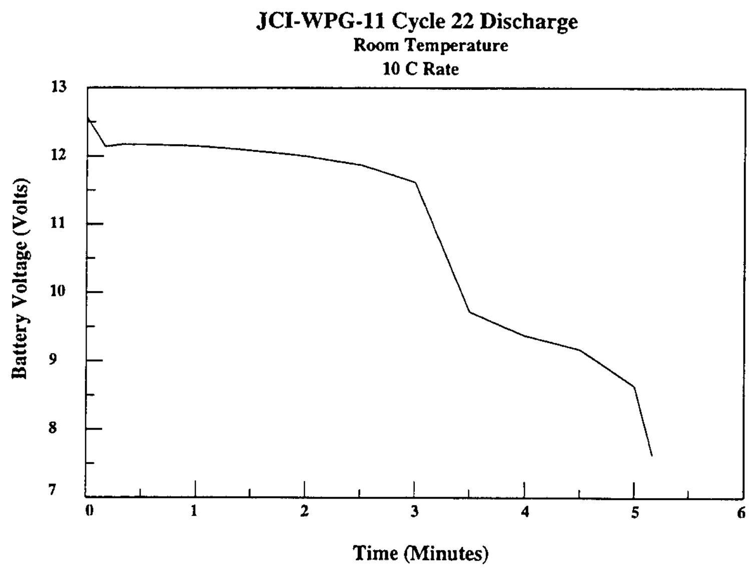

Figure 32. WPG-11 Cycle 22 Discharge

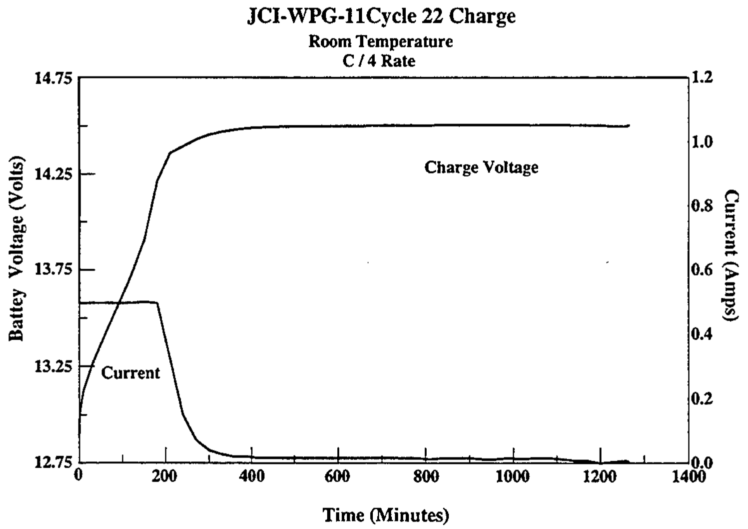

Figure 33. WPG-11 Cycle 22 Charge

4.0 Conclusions

All five batteries that were evaluated in this program exhibited very limited cycle life. In addition the PRI batteries showed great water loss needing water approximately every 5 cycles. One possible explanation is severe overcharging; however, battery PR603 was never subjected to greater than 20% overcharge yet showed the same amount and frequency of water loss as battery PR602 which was overcharged to 40%. Therefore, it is not believed that overcharging alone can account for the water loss. Ths JCI batteries exhibited very good high rate behavior but unfortunately failed quickly. Individual cells of the PRI batteries showed significant imbalances. The JCI batteries could not be monitored individually.

5.0 Recommendations

To gain greater understanding of the failure mechanisms of these batteries a post mortem analysis should be performed. However, at this point funding is not aavailable to perform an analysis.

Some known problems that need to be addressed before the bipolar Pb-Acid battery can be considered as a candidate for Air Force applications include:

1. Breeching of the seal material around individual cells and the entire battery package.
2. The strength of the bipolar plate needs to be increased without increasing its thickness. Currently the plate tends to flex during cycling causing the active material to break apart