SANDIA REPORT
SAND2012-1352
Unlimited Release
Printed February 2012

Initial Test Results from the RedFlow 5 kW, 10 kWh Zinc-Bromide Module, Phase 1

David M. Rose and Summer R. Ferreira

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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David M. Rose
Energy Storage and Transmission Analyses Department 06113

Summer R. Ferreira
Advanced Power Sources R&D Department 02546
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-1140

Abstract

In this paper the performance results of the RedFlow zinc-bromide module (ZBM) Gen 2.0 are reported for Phase 1 of testing, which includes initial characterization of the module. This included physical measurement, efficiency as a function of charge and discharge rates, efficiency as a function of maximum charge capacity, duration of maximum power supplied, and limited cycling with skipped strip cycles. The goal of this first phase of testing was to verify manufacturer specifications of the zinc-bromide flow battery. Initial characterization tests have shown that the ZBM meets the manufacturer's specifications. Further testing, including testing as a function of temperature and life cycle testing, will be carried out during Phase 2 of the testing, and these results will be issued in the final report, after Phase 2 testing has concluded.

ACKNOWLEDGMENTS

This work is funded by Dr. Imre Gyuk of the Department of Energy Office of Electricity, Energy Storage Program. We would like to thank RedFlow limited for supplying the zinc-bromine module that was the subject of these tests. We also thank Steven Hickey, Redflow Limited's lead test engineer, for commissioning the system and providing operator training.

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FIGURES

TABLES

ACRONYMS

A	Ampere
AC	alternating current
Ah	Ampere hour
BSM	Battery Management System
CC	constant current
cm	centimeter
DAS	Data Acquisition System
DC	direct current
DOE	Department of Energy
kW	kilowatt
kWh	kilowatt hour
L	liter
NI	National Instruments
RISE	Research Institute for Sustainable Energy
SDK	System Development Kit
SMES	superconducting, magnetic electrical energy storage
SNL	Sandia National Laboratories
V	volt
V_{oc}	open circuit voltage
W	Watt
Wh	Watt hour
ZBM	zinc-bromine module

1. INTRODUCTION

This work was supported by the U.S. Department of Energy (DOE) Office of Electricity Delivery & Energy Reliability. The DOE program goals are directed at supporting industry and utilities in the areas of

- Developing and evaluating integrated electrical energy storage systems;
- Developing batteries, superconducting magnetic electrical energy storage (SMES), flywheels, super capacitors and other advanced energy storage devices;
- Improving multi-use power electronics, controls, and communications components;
- Analyzing and comparing technologies and applications; and
- Encouraging program participation by industry, academia, research organizations, and regulatory agencies.

The work reported here is part of Sandia National Laboratories' (SNL's) effort to characterize the performance parameters of advanced energy storage technologies, and this report details the preliminary findings characterizing a zinc-bromide flow battery.

Advanced energy storage technologies are of interest to the DOE Office of Electricity in addressing the varied needs of electricity generation and deployment on and off the grid and in the future "Smart Grid." Energy storage is seen as part of the solution to address applications in providing remote area power, to address grid instability and reliability and in the "Smart Grid." In particular, large emphasis has been placed on energy storage to facilitate renewables integration, in order to make integration of wind and solar viable at the large scale. It has been reported that the analysis of renewable integration suggests that above 10 to 30% renewable sources of energy storage will destabilize the grid, with the critical percent dependent on factors such as grid size, renewable profiles, and use profiles.[1]

Advanced energy storage technologies commercially available and under development for addressing these challenges include secondary (rechargeable) batteries such as lead-acid, sodium-sulfur and lithium-ion batteries, as well as flow batteries, including vanadium-redox and zinc-bromine designs. These battery technologies also are competing with alternative commercial energy storage technologies such as capacitors, flywheels, compressed air storage and pumped hydro. Flow batteries are widely seen as a very promising category of energy storage technology to respond to present and future electricity needs; slated to address a wide range of applications including energy shifting, renewable generation firming and smoothing, and off grid generator run-time minimization. Some advantages of flow batteries include capability of being located anywhere, in contrast to compressed air or pumped hydro; having millisecond output response time as opposed to conventional generation; high round-trip efficiency as compared to fuel cells.[2] They are also forecast to have lower capital cost per kWh than many of the competing technologies.[2]

Flow batteries have an electrolyte containing electroactive species, which flows through an electrochemical cell, converting chemical energy to electricity. Flow batteries are characterized by tanks located external to the electrode. In redox-flow batteries the battery capacity is determined only by the size of these external tanks and the charge and discharge occur as oxidation and reduction of the species in the electrolyte take place. One category of flow battery is the hybrid flow battery. A hybrid flow battery is defined by one or more electroactive species being deposited as a solid.[3] In the zinc bromide battery the capacity is determined both by electrolyte volume and electrode area on which the solid zinc is deposited. Therefore, the tank and battery stack must be sized together to dictate capacity.

The Zinc-Bromide Battery Module (ZBM) is a flow battery developed by RedFlow Limited. RedFlow Limited was founded in Australia in 2005 by Mr. Chris Winter and Dr. Alex Winter. Since then, they have developed the RedFlow flow battery into a turnkey product, targeting broad applications. In 2010 they commissioned third-party testing by the Research Institute for Sustainable Technology (RISE) [4]. The RISE report was released in May 2010 and consisted of the results of characterization and performance testing of a RedFlow zinc-bromide battery module. In November 2011 RedFlow provided SNL with a System Development Kit (SDK) (which includes a ZBM) for additional third-party testing. Sprint and Jabil Circuits Inc. are also interested parties in this testing. Sprint is interested because they could make use of an energy-shifting battery in grid-connected telecommunications applications to offset peak load. Jabil is interested because they intend to manufacture RedFlow systems.

A detailed description of the SDK and its use and applications can be found in the RedFlow T510 System Development Kit Installation and Operation Manual [6]. Figure 1 shows the components of the SDK as it arrived at SNL. The module is housed in an enclosure with the power electronics and control circuitry in the top compartment. The ZBM is the electrochemical storage device in the SDK, which sits in the bottom compartment. This plastic tank is based on a nested design such that the bromide tank is held inside the zinc tank for added safety. Leak detectors are present and temperature sensors monitor the internal battery stack temperature and ambient temperature in the enclosure to provide engineering safety measured. The SDK delivered to Sandia is a generation 2.0 kit. The battery stack is made up of three stacks of 33 cells with a rated power of 5 kW, and 10 kWh. Auxiliary system includes the pumps and a fan. These pumps deliver electrolyte from the tanks through tubing into the stacks to circulate during charge and discharge.

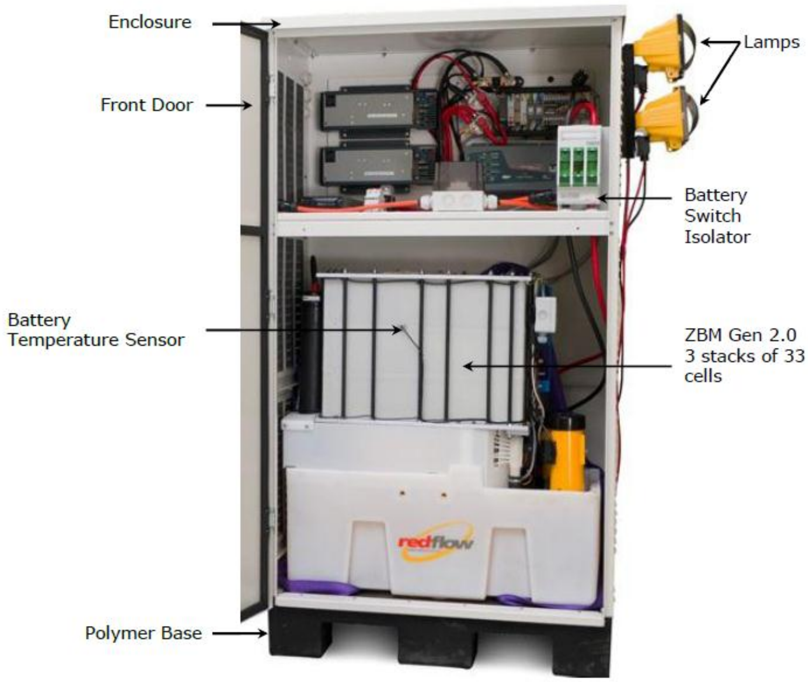


Figure 1. RedFlow T510 System Development Kit [3].

The connection diagram as it arrived at SNL is shown in Figure 2. In this configuration the mains power (generator) will support the lamps (Telecom DC load) and charge the ZBM simultaneously until the ZBM reaches a maximum state of charge. At this time the mains power is disconnected and the ZBM will begin to discharge into the lamps. The 600W inverter is connected to the DC output of the cell stack and is used to power the parasitic loads of the system. Note: This is not how the SDK was tested at SNL; see Section 2 for those details.

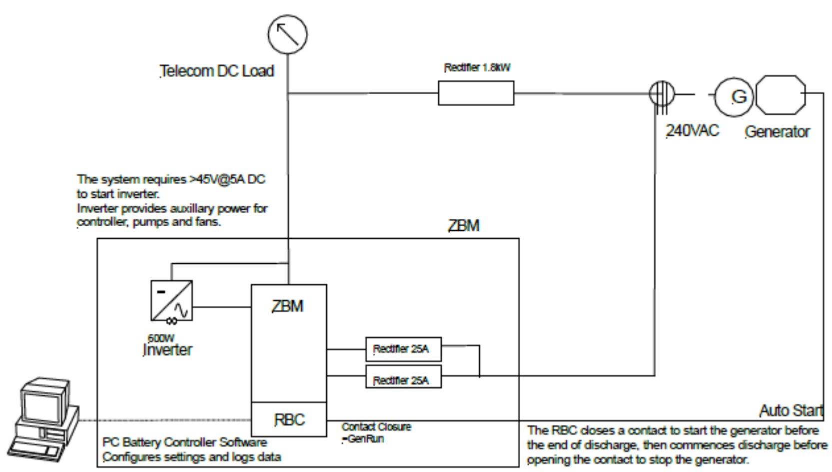
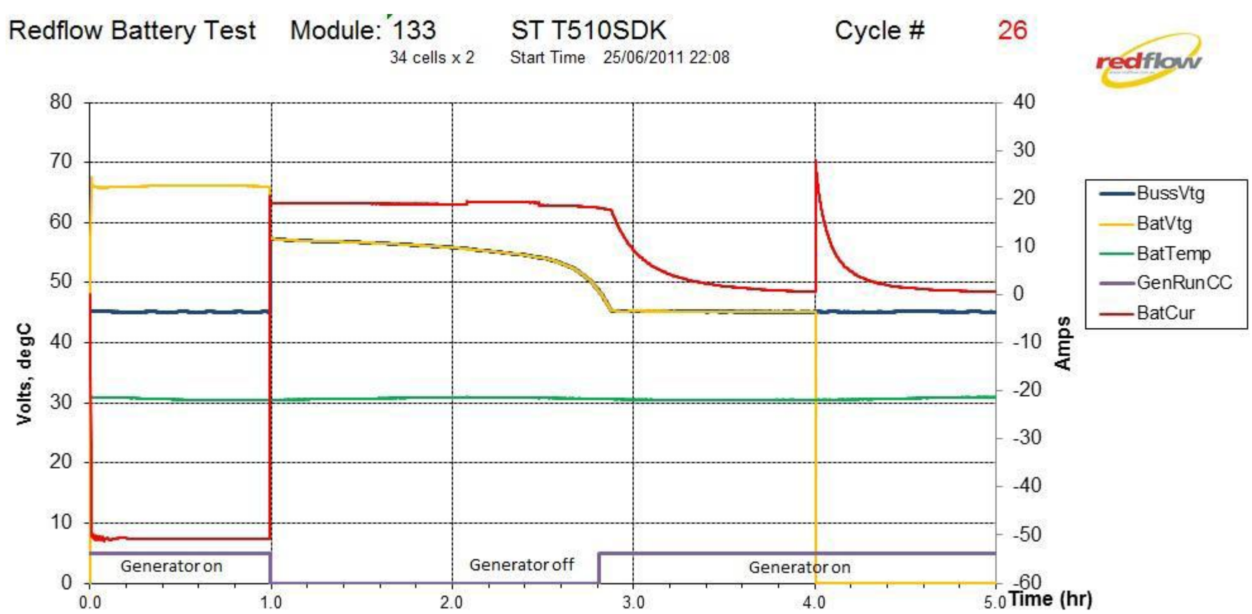


Figure 2. T510 SDK Schematic [3].

A sample charge discharge profile is shown in Figure 3. In Figure 3 the battery voltage, temperature and current are plotted, with generator run cc. Generator run cc simply indicates whether the generator is on or off at a given time. During this cycle the module is charged for the first hour, here using a generator. During charge the stack is being charged at 50 A, and the stack is experiencing voltages between approximately 66 to 68 volts, the next hour and 50 minutes is spent supporting the approximately 20 A load while the generator is off resulting in a drop in voltage from 58 to the cut-off voltage of 45 V. The cut-off voltage is specified by the operator to optimize use of the battery charge but there is no minimum voltage limit for the zinc-bromide battery. Then the generator comes on to support the load but it keeps the voltage low enough (around 45 V) to continue to discharge the battery, to fully utilize its remaining energy; and last the battery disconnects from the generator and strips itself of its remaining zinc for the final hour. The battery should be stripped after a full discharge following each cycle to prevent dendrite formation. Dendrite formation can damage the separator and cause battery failure. Subsequent charge cycles that skip the strip cycle must account for a loss in total capacity following manufacturer specified operations to ensure damage does not occur as a result of the dendrite formation. There are two methods of battery strip: a passive and an active strip. Section 2 describes the conditions under which these are used and the procedure.



25/06/2011 22:08	Avg Amps	Usef Ahr	Tot Ahr	Voltage	Energy (Wh)	Time (hr)	Resistance	26
In	50.7	50.0	50.0	66.0	3303	1.0	0.20	
Out	16.2	39.7	41.9	52.8	2121	2.4	Discharge efficiency	
Avg Temp	30.7	**79.4%**	**83.8%**	**80.0%**	**64.2%**	**1.05**	94.7%	

Note: Gen Run at 4% SOC

Figure 3. Sample Charge-Discharge Profile [3].

2. METHODS

For laboratory testing, the SDK had to be reconfigured to allow for control over charge and discharge rates. Figure 4 shows the testing circuit schematic. The battery charge/discharge profile is set through the RedFlow controlled laptop and battery controller. For testing purposes Sandia is controlling and metering the 5 kW DC power supply and 10 kW DC load bank as outlined in Section 2.5. The following two devices were used as supply and load for these tests:

Programmable Power Supply
Chroma 62050P-100-100 Programmable DC Source 100 VDC/100 A/5,000 W

Programmable Load
Chroma 63206 Programmable DC Load 80 VDC/600 A/10,000 W

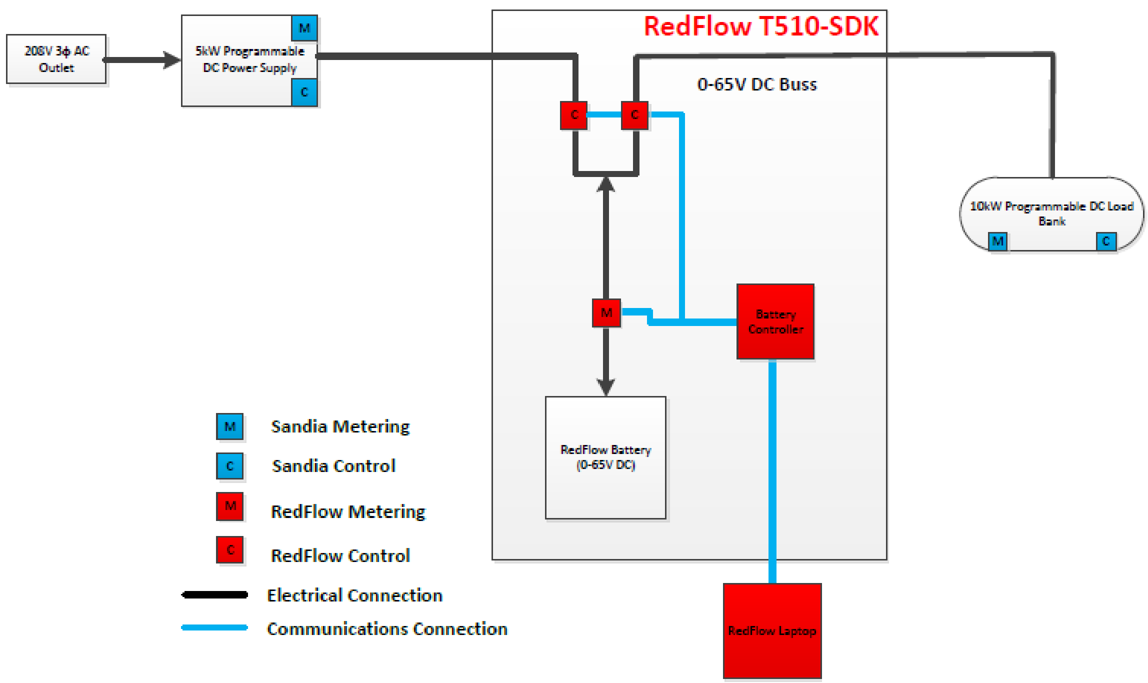


Figure 4. Interconnection Schematic for RedFlow Testing.

During initial commissioning under normal operation, an unexpected elevated temperature rise was observed and addressed by modifying the test setup. While cycling at 45 A charge and discharge over 40 hours of testing the module temperature rose to 23 °C above ambient. To address the temperature rise, the door to the SDK was left open during further testing to allow maximum heat to dissipate from the battery module. Additionally the parasitic loads (electrolyte pumps, cooling fan, and BSM controller) were connected on a separate circuit to the cell stack. This SDK was designed for laboratory testing and does not have the same cooling mechanisms as the system-level field units sold by RedFlow. The testing results in this report are therefore to be considered results of the battery module, rather than a complete system.

This must be noted in reporting efficiencies of the module, as efficiency levels would be reduced with increased parasitic loads. Future testing on a system level may be conducted during Phase 2, which incorporates cooling mechanisms at the system level; however, this is beyond the scope of this work in Phase 1.

After the SDK was reconfigured the RedFlow data acquisition system (DAS) was analyzed. This consisted of verifying the voltage, current, and time.

2.1 Data Logging

The data reported here were taken from the RedFlow DAS after calibration conducted at SNL was carried out as described in Appendix A.

2.2 Test Procedures

In Phase 1 Test Program, charge rates were adjusted between tests using the power supply front panel. Discharge rates were adjusted using the load bank front panel. All other settings such as maximum charge, stripping time/conditions, or maximum current and temperatures were set using the battery controller software interface described in the SDK manual [3].

2.3 Battery Strip Procedure

Stripping can be achieved by a passive or active method. Passive stripping involves continually pumping electrolyte through the cell stack in order to strip any remaining zinc off of the plates. This is a very slow process, sometimes taking days to remove the plated zinc and reduce voltage levels. An active strip (as shown after hour 4.0 in Figure 3) occurs when the terminals of the battery are shorted across a low impedance shunt in order to more quickly remove the remaining zinc (this normally takes 0.5 to 2 hours).

3. PHASE 1 TEST PROGRAM

Phase 1 of the test program consists of characterization of the DC system.

3.1 Initial Battery Conditioning

Before the system was tested it was conditioned to assure optimal and consistent performance. This consisted of five 100% (240 Ah) charge/discharge/strip cycles at 30 A charge and 30 A discharge to the end of discharge conditions described in Table 1 followed by a two-hour active strip.

3.2 Characterization

The tests described here were developed to characterize the zinc-bromide flow battery module.

- Physical Measurement Test
  - Measurements of the physical characteristics
- Rate Sensitivity Test
  - Storage efficiency parameterized by rates of charge and discharge
- Efficiency as a Function of Capacity Test
  - Storage efficiency (net and gross) parameterized by Ampere-hours (Ah) of charge
- Power Test
  - Duration of rated peak power delivery (5 kW)
- Strip Cycle Skipping Test
  - Confirm safe operation without battery failure with skipped strip cycling following the manufacturer's recommendations and determine the effect (if any) on efficiency

All tests were performed at ambient room temperature and the temperature was logged.

3.3 Operating Parameters

The ZBM operational specifications are listed in Table 1. Note, during all testing at Sandia the manufactuer specified limits are observed, and the unit is not subjected to abuse testing condition.

Table 1. ZBM Test Specifications.

Company	RedFlow Limited
System Name	Zinc-Bromide Module
Software Version	BC Manager 2.10.03 EXPERIMENTAL
Firmware Version	2.04.00
Discharge Power Rating	5 kW
Energy Rating	10 kWh
Max Charge Current	60 A
Max Charge Voltage	66 V
Max Charge Capacity	250 Ah
Ambient Temperature Range	0-45°C
End of Discharge Conditions	Stack voltage drops below 2.0 V and current drops below 0.5 A
Strip Cycle Operation	Before every characterization test, two-hour minimum active strip unless testing cycling with skipped strip cycles
Capacity Reduction Rate *	-3 Ah/hour of operation
*The capacity reduction rate applies when performing tests without stripping the ZBM between cycles. For such testing, if strip cycles are skipped, the maximum charge capacity is limited to prevent zinc dendrites from causing damage during charging. This is done by reducing the maximum charge capacity by 3 Ah for every hour of operation. This number holds only under the specific operating conditions described in this section and in the SDK Manual [3] and will change depending on the zinc and bromide pump duty cycles and the battery temperature.	

3.4 Physical Measurement Test

The weight of the ZBM was measured without including the enclosure, and physical dimensions of the ZBM were recorded in SI units.

3.5 Rate Sensitivity Test

This test is conducted to determine how sensitive the efficiency of the system is to the charge and discharge rates. The procedure for this test follows (see also Table 2).

1. Initialize the electrochemistry before testing by performing stripping.
2. Charge the battery at the rate specified in Table 2.
3. Discharge on a constant current (CC) load to end of discharge conditions.
4. Repeat for each element in Table 2.
5. Table 2 was repeated twice, once to 150 Ah and second to 240 Ah to compare the efficiency between a partial and full charge of the system as a function of the rate.

Table 2. Rate Sensitivity Matrix.

	Charge at 15 A	**Charge at 30 A**	**Charge at 60 A**
Discharge at 15 A	Test 1	Test 4	Test 7
Discharge at 30 A	Test 2	Test 5	Test 8
Discharge at 60 A	Test 3	Test 6	Test 9

3.6 Efficiency as a Function of Capacity Test

The purpose of this testing is to determine how maximum charge capacity influences efficiency of the ZBM. This was done in ten stages (levels 1 to 10 in Table 3). Using the results from this test, the efficiency at each charge capacity can be determined. During all tests, both the charge and discharge currents were maintained at 30 A.

Table 3. Charge Levels for Efficiency Test.

Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**	**Level 6**	**Level 7**
25 Ah	50 Ah	75 Ah	100Ah	125 Ah	150 Ah	175 Ah
Level 8	Level 9	Level 10				
200 Ah	225 Ah	250 Ah				

3.7 Power Test

This test is to determine the duration that the system can support a load at its maximum rated power. The system is fully charged and then discharged on a 5 kW constant power load. The procedure for this test is:

1. Initialize the electrochemistry before testing by performing stripping;
2. Charge at 30 A to 250 Ah; and
3. Measure duration of 5 kW constant power discharge.

3.8 Strip Cycle Skipping Test

The purpose of this test is to (1) confirm safe operation without battery failure with skipped strip cycling following the manufacturer's recommendations and (2) determine the effect (if any) on efficiency. As stated in the battery operating parameters, if strip cycles are skipped, the maximum charge capacity MUST be limited to prevent zinc dendrites from causing damage during charging. The capacity starts at 240 Ah (baseline) for an initial charge and must be decreased at a minimum of 3 Ah per hour that the system is running. During these tests the charge and discharge currents are maintained at 30 A. This equates to approximately 15 hours to discharge and charge the system to a capacity of 240 Ah, resulting in approximately 45 Ah capacity decrease per cycle. This is a very conservative test with a wide safety margin and so it has a reduction rate higher than 3 Ah per hour. Future tests will be performed that come closer to the 3 Ah per hour rate. The procedure for this test is (see also Table 4):

1. Initialize the electrochemistry before testing by performing stripping;
2. Charge the system at 30 A to the level shown in Table 4;
3. Discharge the system at 30 A until the voltage drops below 50 V; and
4. Repeat Steps 2 and 3 for three more cycles without stripping the system in between.

Table 4. Strip Cycle Skipping Progression.

Cycle 1	Cycle 2	Cycle 3	Cycle 4
240 Ah	195 Ah	150 Ah	105 Ah

4. TEST RESULTS

In this section several metrics for efficiency are used, three of which are coulombic efficiency, energy efficiency, and voltaic efficiency. Coulombic efficiency is calculated by Equation 1, energy efficiency by Equation 2, and voltaic efficiency by Equation 3. For the voltaic efficiency calculation the discharge voltage average includes data with values above a low useful voltage limit chosen during data processing. In this paper the low-voltage limit was chosen to be 34 V; this value would change in applications depending on the low-voltage requirements of a given load.

Equation 1: Coulombic Efficiency

$$\gamma_c = \frac{Charge\ in\ (Ah)}{Charge\ out\ (Ah)}$$

Equation 2: Energy Efficiency

$$\gamma_e = \frac{Energy\ in\ (kWh)}{Energy\ out\ (kWh)}$$

Equation 3: Voltaic Efficiency

$$\gamma_v = \frac{Average\ Voltage\ During\ Discharge\ (V)}{Average\ Voltage\ During\ Charge\ (V)}$$

The coulombic efficiency is a better measure of the expected operational efficiency in DC applications where the power draw reduces somewhat with the voltage of the system (such as such as with resistive loads). The energy efficiency is a better measure of the expected operational efficiency in AC applications (or whenever power conversion is used) where the power draw remains constant despite DC voltage of the system (such as such as with grid connected applications). The voltaic efficiency is a measure of the internal DC Ohmic resistance of the system (not normalized to charge and discharge current). For some chemistries this can be tracked over time and used to detect or predict system failure.

4.1 Physical Measurement Test

Table 5 shows the results of measurements taken on the physical system. The ZBM (empty) entry describes the system as it arrived at SNL having been filled, tested, and emptied for transport. This means that there are likely a few liters of electrolyte still in the stack left over from the first filling.

Table 5. Physical Measurements and Calculations.

Component Name	Weight		
ZBM (empty)	113.78 kg		
Total Electrolyte	122.20 kg		
Total System	235.98 kg		
	Length	**Width**	**Height**
ZBM	82.5 cm	40.0 cm	86.4 cm
	Calculated System Volume		
ZBM	285 L		
	Rated System Energy Density (10 kWh)		
ZBM	42.376 Wh per kg		
	Rated System Power Density (5 kW)		
ZBM	21.188 W per kg		
	Rated System Specific Energy (10 kWh)		
ZBM	35.1 Wh per L		
	Rated System Specific Power (5 kW)		
ZBM	17.5 W per L		

4.2 Rate Sensitivity Test

Table 6 shows the numeric efficiency results of the rate sensitivity test at 150 Ah. Figures 5, 6, and 7 show effect of charge rate and discharge rate on the Coulombic, energy and voltaic efficiencies. The coulombic efficiency stayed in the band from 83.0% and 93.4% and increased with increases in both charge rate and discharge rate. These trends in increased efficiency with rate are true when charging to both 150 Ah (Figure 5) and to 240 Ah (Table 7 and Figure 8) with greater overall efficiencies at the lower, partially charged, capacity. Therefore, the highest coulombic efficiency observed in this test was 93.4% at 60 A charge and 60 A discharge to 150 Ah. These results suggest that it may best optimize the system to design systems to operate at maximum charge and discharge rates when targeting DC applications.

The energy efficiency stayed within the band of 73.6% to 78.5% when charging to 150 Ah, as shown in Table 6, and was highest in the middle of each range for charge and discharge rates, with efficiencies dropping off both above and below 30 A rates as seen in Figure 6. Again this trend is also observed for cycling at the higher, 240 Ah capacity tested (Figure 9), but with the highest efficiencies observed at the partially charged, 150 Ah capacity. The highest energy efficiency observed in this test was 78.5% at 30 A charge and 30 A discharge to 150 Ah.

The voltaic efficiency stayed in the band between 83.4% and 93.3% as shown in Table 6, and increased with both reduced charge rate and reduced discharge rate (Figure 7). The highest voltaic efficiency observed in this test was 93.3% at 15 A charge and 15 A discharge. In contrast with coulombic and energy efficiencies, under voltaic efficiency, while again the trends in efficiency with rate remain consistent at different capacities (Figure 10) a greater total efficiency is observed for the higher capacity test to 240 Ah as seen in Table 7.

Table 6. Rate Sensitivity Test Results (150 Ah).

Coulombic Efficiency	**Charge at 15 A**	**Charge at 30 A**	**Charge at 60 A**
Discharge at 15 A	83.0	86.4	87.3
Discharge at 30 A	86.2	90.4	91.4
Discharge at 60 A	88.9	92.0	93.4

Energy Efficiency	**Charge at 15 A**	**Charge at 30 A**	**Charge at 60 A**
Discharge at 15 A	75.4	77.1	75.3
Discharge at 30 A	76.1	78.5	77.4
Discharge at 60 A	73.6	76.1	75.6

Voltaic Efficiency	**Charge at 15 A**	**Charge at 30 A**	**Charge at 60 A**
Discharge at 15 A	93.3	91.3	88
Discharge at 30 A	90.7	88.9	86.5
Discharge at 60 A	86.1	84.4	83.4

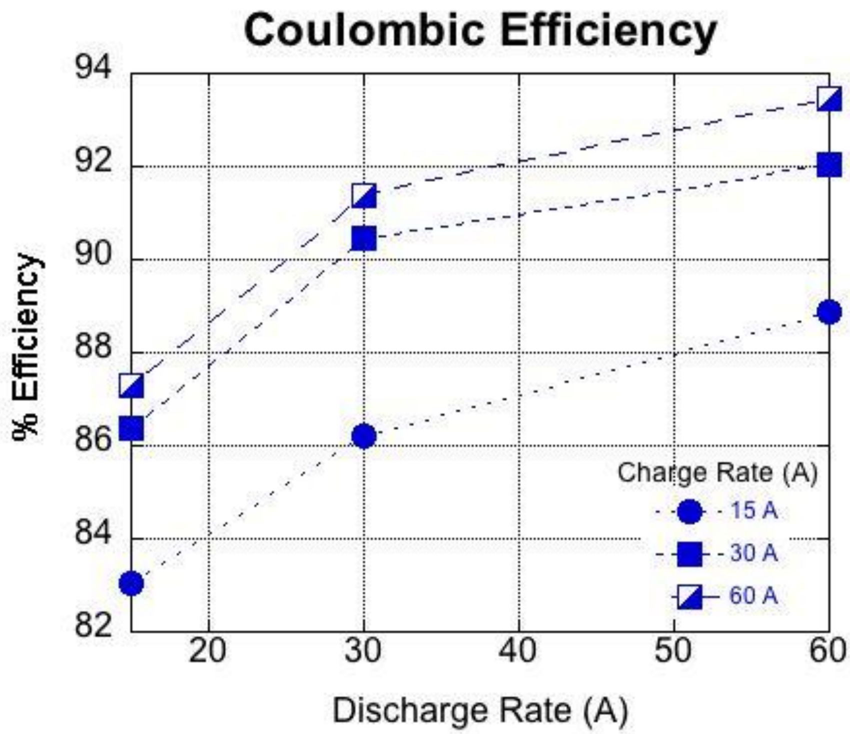


Figure 5. Rate Sensitive Coulombic Efficiency (150 Ah).

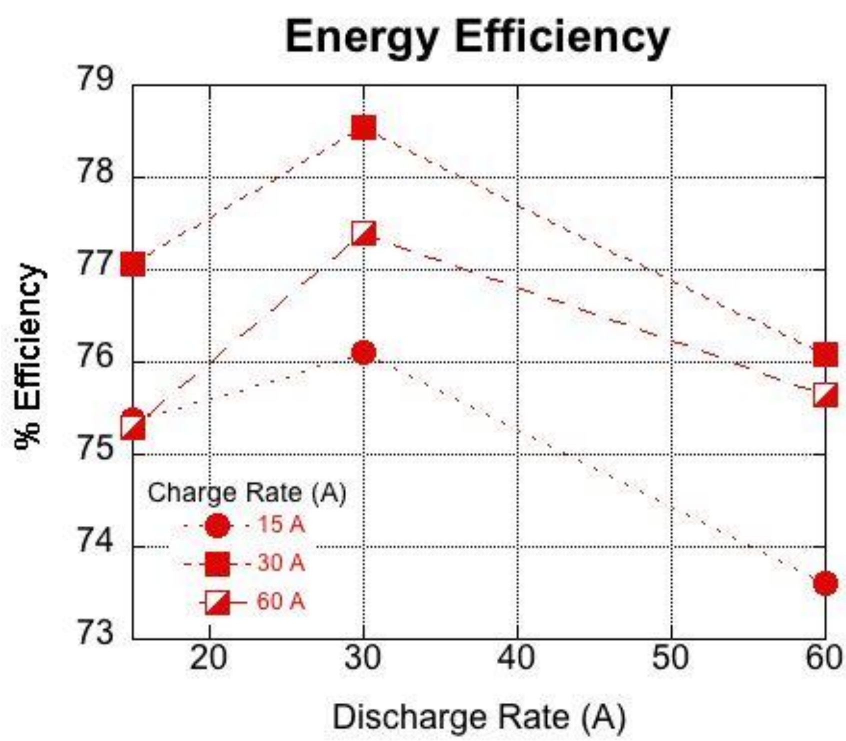


Figure 6. Rate Sensitive Energy Efficiency (150 Ah).

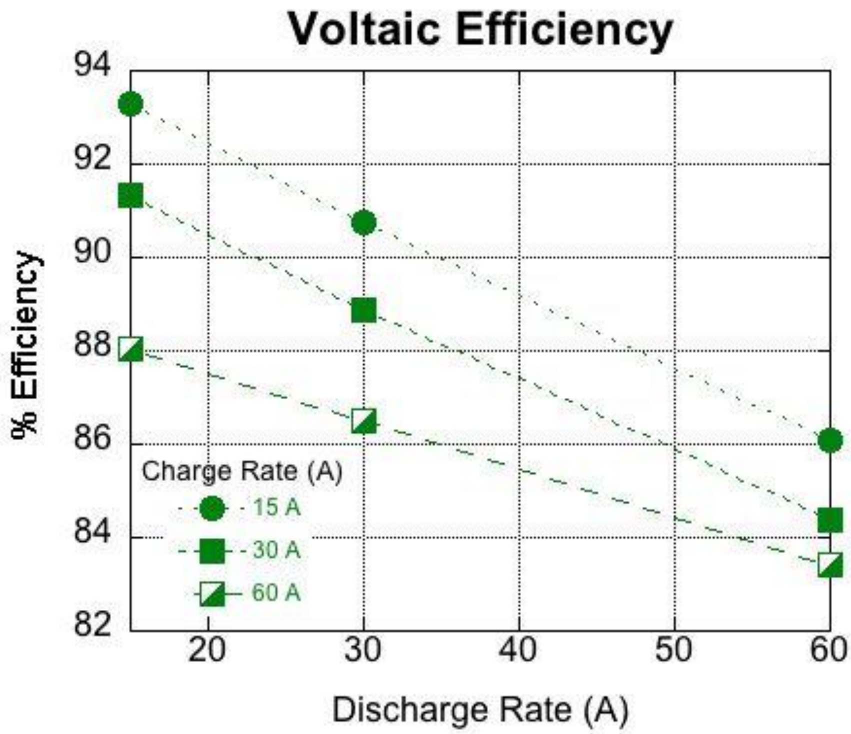


Figure 7. Rate Sensitive Voltaic Efficiency (150 Ah).

Table 7. Rate Sensitivity Test Results (240 Ah).

Coulombic Efficiency	Charge at 15 A	Charge at 30 A	Charge at 60 A
Discharge at 15 A	78.1	81.9	82.7
Discharge at 30 A	82.4	87.2	88.3
Discharge at 60 A	85.1	90.0	91.9

Energy Efficiency	Charge at 15 A	Charge at 30 A	Charge at 60 A
Discharge at 15 A	71.3	73.1	71.4
Discharge at 30 A	73.2	76.0	74.5
Discharge at 60 A	71.6	74.8	73.7

Voltaic Efficiency	Charge at 15 A	Charge at 30 A	Charge at 60 A
Discharge at 15 A	93.5	91.3	88.0
Discharge at 30 A	90.9	88.9	85.9
Discharge at 60 A	85.1	83.9	82.0

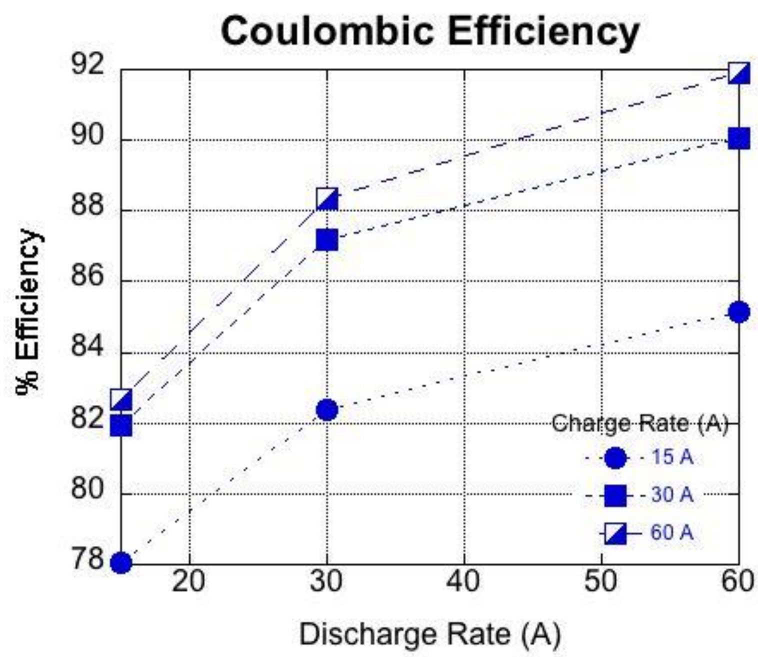


Figure 8. Rate Sensitive Coulombic Efficiency (240 Ah).

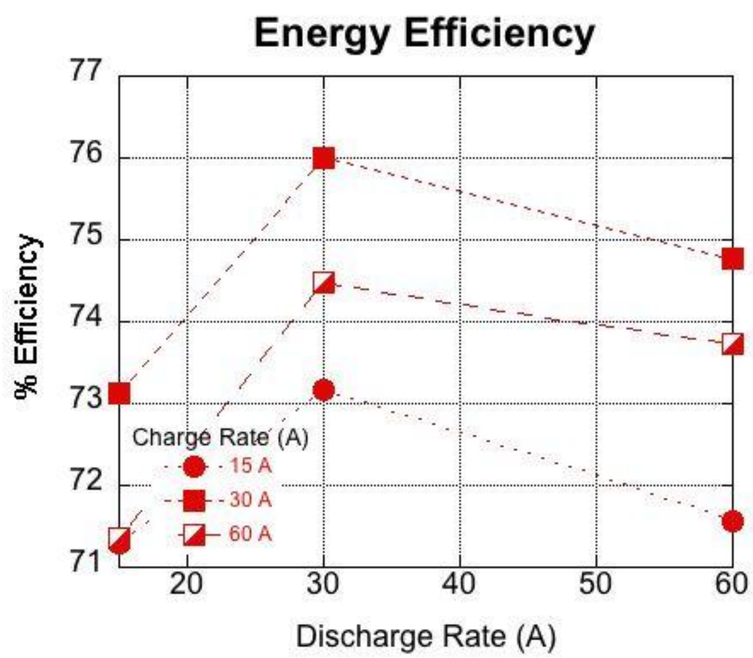


Figure 9. Rate Sensitive Energy Efficiency (240 Ah).

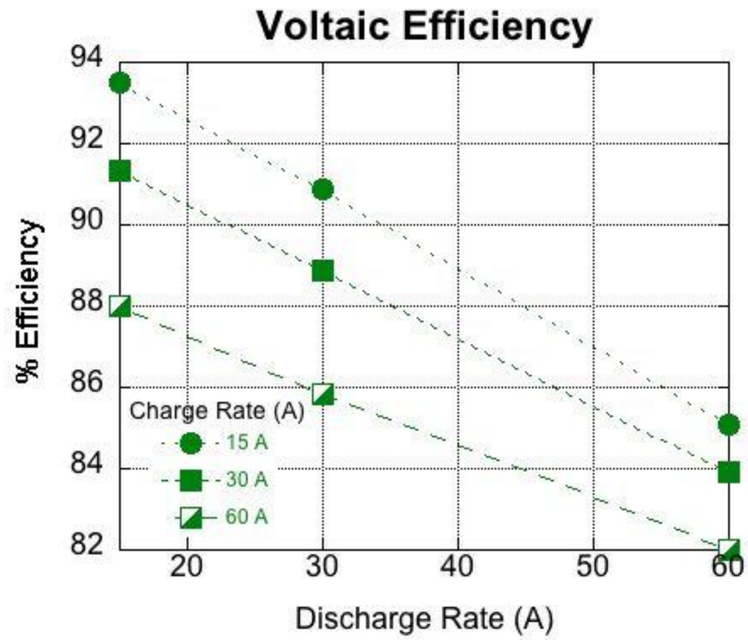


Figure 10. Rate Sensitive Voltaic Efficiency (240 Ah).

4.3 Capacity and Efficiency Test

Table 8 shows the numeric results from the Efficiency as a Function of Capacity Test. Figure 11 plots these results. Coulombic efficiency stayed between 86.8% to 92.5% with a negative correlation to maximum charge. Energy efficiency stayed in the band of 75.3% to 78.9%. The highest energy efficiency was 78.9% observed at two points in the middle of the range, both 100 Ah and 125 Ah maximum charge. Voltaic efficiency stayed relatively constant between 88.6% and 89.8% with a small positive correlation to maximum charge. Two more noteworthy observations: first, the 150 Ah Cap Test was repeated from the rate sensitivity test and yielded efficiency values consistent within 0.05%; second, the energy extracted in total discharge from both the 225 Ah Cap Test (10.5 kWh) and the 250 Ah Cap Test (11.5 kWh) exceeded the 10 kWh energy rating of the system.

Table 8. Efficiency as a Function of Capacity Test Results.

	25Ah Cap	50Ah Cap	75Ah Cap	100Ah Cap	125Ah Cap	150Ah Cap	175Ah Cap	200Ah Cap	225Ah Cap	250Ah Cap
Coulombic Efficiency	92.9	91.6	90.7	90.8	90.7	90.2	89.7	89.3	87.8	86.8
Energy Efficiency	75.3	78.0	78.2	78.9	78.9	78.7	78.4	77.9	77.1	76.5
Voltaic Efficiency	88.6	89.2	89.5	89.4	89.3	89.3	89.4	89.3	89.4	89.8

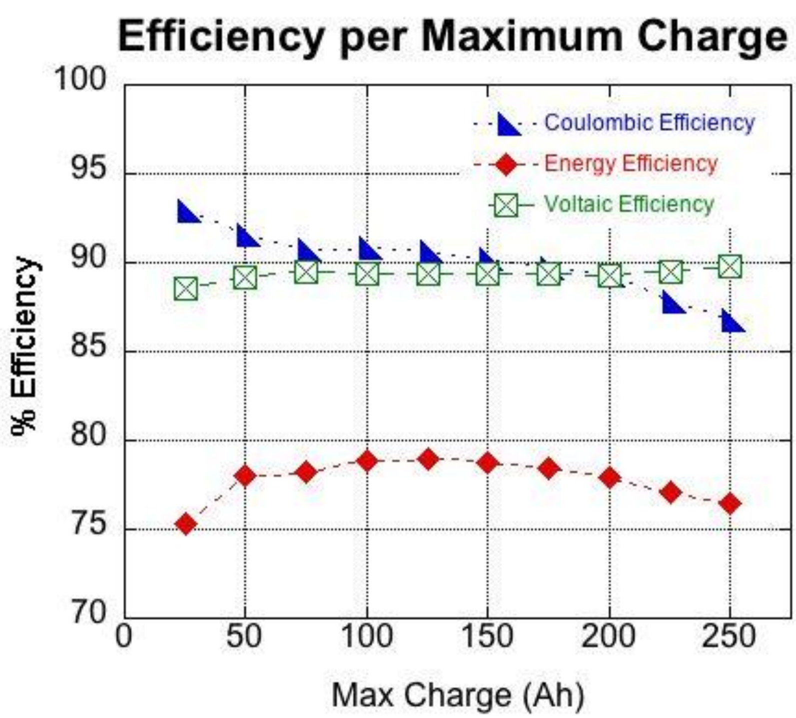


Figure 11. Efficiency Test Results Plot.

Further calculation was done to find the marginal efficiency of each stage between 0 and 250 Ah. The marginal efficiency is a measure of how efficient each charge/discharge stage is (say from 100 Ah to 125 Ah). This is useful in determining the optimum (most efficient) range for partial SOC cycling. By subtracting each element from the element before it, the slope of this efficiency curve can be found. Table 9 shows the numerical results of this calculation and Figure 12 plots these.

The marginal coulombic efficiency stayed in a band from 76.2% to 92.5% with a negative correlation to maximum charge. This means that the last 50 Ah to go into the system are significantly less efficient than the first 50 Ah. The marginal energy efficiency stayed in a band from 70.3% to 80.8%, also with a negative correlation to maximum charge; however, the first 25 Ah are observed as significantly less efficient than the second 25 Ah. This shows an effect of the low voltage tail on the end of each discharge; at high maximum charges the energy contained is relatively insignificant but it has more of an effect at low maximum charges. These data show the most efficient rage for partial SOC cycling to be in the low range of SOC (below 200 Ah) with a nominal operating SOC of 100 Ah.

Table 9. Marginal Efficiency Calculations.

	25Ah Cap	50Ah Cap	75Ah Cap	100Ah Cap	125Ah Cap	150Ah Cap	175Ah Cap	200Ah Cap	225Ah Cap	250Ah Cap
Marginal Coulombic Efficiency	92.9	90.2	89.0	91.3	89.9	87.8	86.7	86.3	76.2	77.3
Marginal Energy Efficiency	75.3	80.7	78.6	80.8	79.1	77.7	76.9	74.1	70.3	71.2

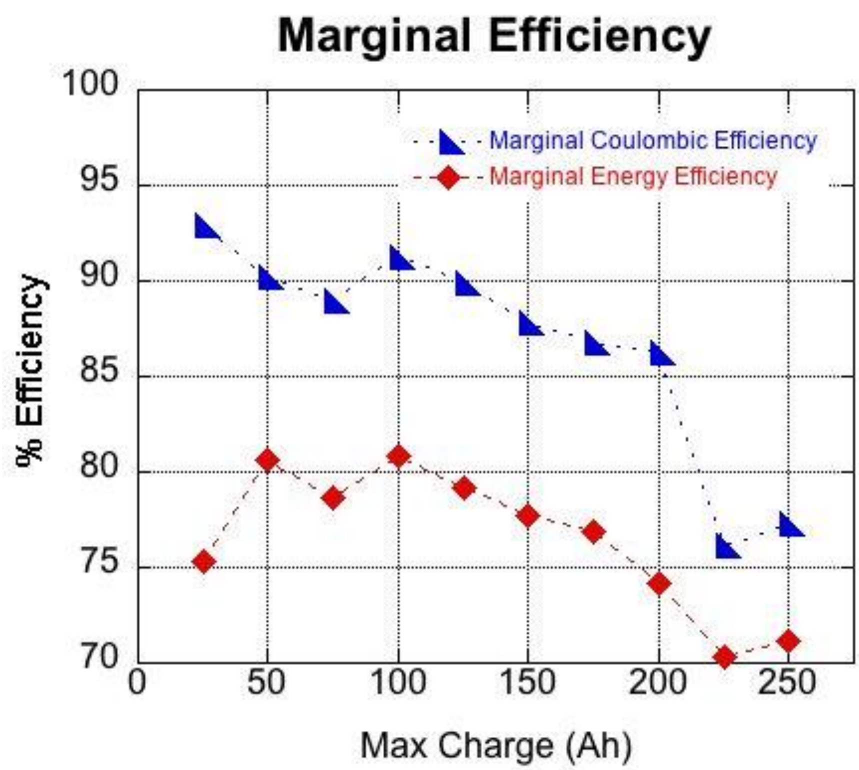


Figure 12. Marginal Efficiency Plot.

4.4 Power Test

The system was operated at the nameplate load of 5 kW to determine the time for which it would support this load. Figure 13 plots the cycle data from this power test. The system supported a 5 kW load for a total of two hours and three minutes. It satisfied both the power and the energy ratings from the manufacturer in a single test by supplying 10.5 kWh of energy at a 5 kW rate. The voltage fell to 35 V at the lowest and at this point the current draw of a 5 kW load exceeded what the protective programming would allow at 149.1 A. This caused the system to trip off line on overcurrent. The battery did have some remaining charge, as apparent from the battery voltage climbing after its initial decline. The results from this test and corresponding efficiencies are found in Table 10 with coulombic efficiency, energy efficiency, and voltaic efficiency of 86.0, 68.8, and 80.6 respectively.

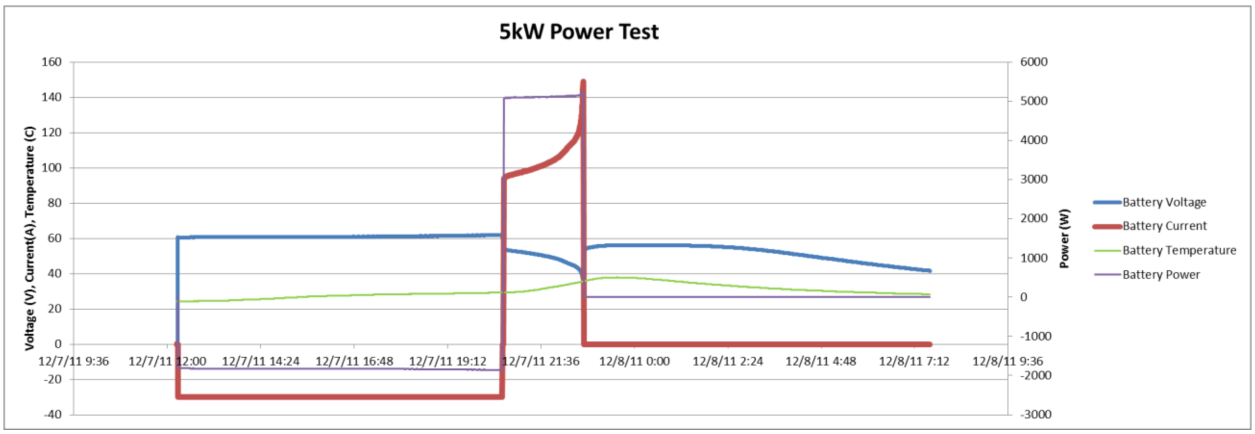


Figure 13. Power Test Charge/Discharge Curve.

Table 10. Power Test Results.

Total Charge (Ah)	250.0
Total Discharge (Ah)	215.0
Coulombic Efficiency	86.0
Total Charge (kWh)	15.3
Total Discharge (kWh)	10.5
Energy Efficiency	68.8
Voltage Charge (V)	61.1
Voltage Discharge (V)	49.3
Voltaic Efficiency	80.6
Maximum Temperature (C)	38.0
Total 5 kW Time (min)	123.0
Total 5 kW Time (hours)	2.05

4.5 Strip Cycle Skipping Test

The battery was operated over four cycles without stripping the system between cycles. Figure 14 plots the charge/discharge curve for this set of cycles. Table 11 shows the results of the strip cycle skipping test with individual and cumulative efficiencies. The coulombic efficiency is calculated to be lower in this test than in the Efficiency as a Function of Capacity Test because the charge in the low voltage tail is not removed after each cycle here. The energy efficiency is almost identical to results from the Efficiency as a Function of Capacity Test, suggesting that skipping stripping cycles has little to no effect on the energy efficiency. Figure 15 plots the efficiency for the strip cycle skipping test, which show nearly uniform efficiencies across cycles for voltaic efficiency, and increases in efficiency with successive skipped cycle as the total capacity is decreased. This test does not decouple the effect on efficiency of cycling without strip and decreasing the total charge in these successive cycles.

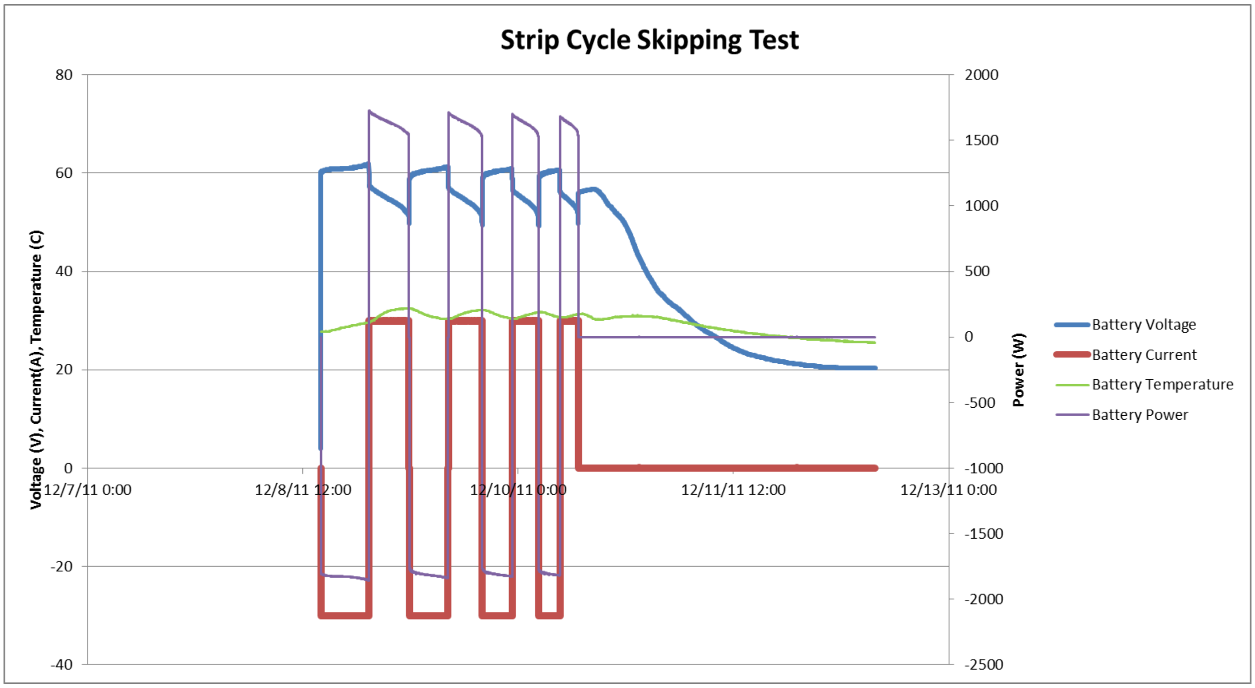


Figure 14. Strip Cycle Skipping Test Charge/Discharge Curve.

Table 11. Strip Cycle Skipping Test Results.

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Over All
Coulombic Efficiency	83.6	86.9	87.7	87.8	86.0
Energy Efficiency	74.8	78.3	79.0	79.2	77.4
Voltaic Efficiency	89.5	90.1	90.1	90.2	90.0

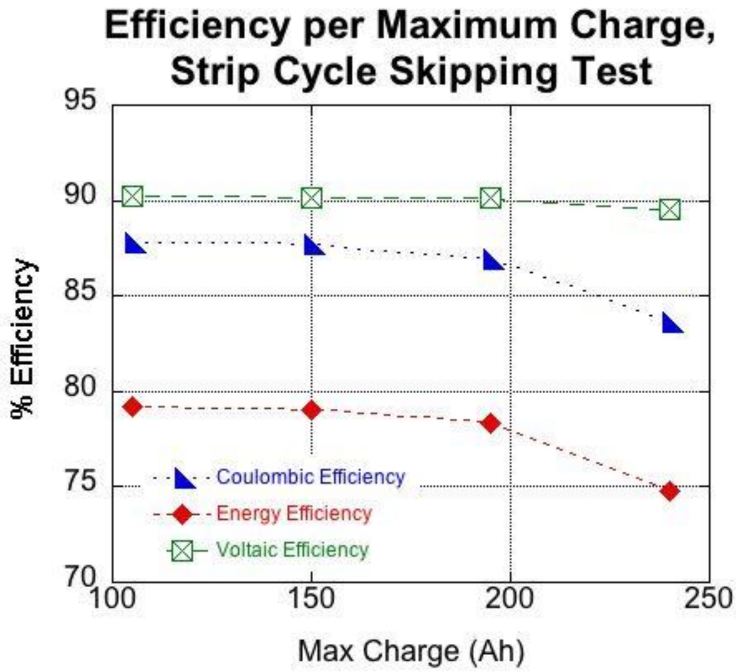


Figure 15. Efficiency Plot for the Strip Cycle Skipping Test.

5. CONCLUSIONS

To date, the testing of the RedFlow Gen 2 ZBM SDK has included measuring physical dimensions and weight of the battery module, as well as performing initial characterization testing. While the name of the unit under test is system development kit (SDK), this unit is considered a battery module for the purposes of these test, rather than a system, because the SDK does not include the mechanisms to self-cool within the cabinet enclosure. All testing reported here is carried out at ambient room temperature of nominally 25 °C with the door to the system cabinet open to provide cooling to the unit by the ambient room temperature. External forced air cooling was not employed. Additionally the parasitic loads (electrolyte pumps, cooling fan, and BSM controller) were connected on a separate circuit to the cell stack. Hence the characteristics reported here are for the ZBM cell stack only and any system application calculations using these data would need to account for the parasitic loads necessary in a given application.

The module has performed to the manufacturer specifications or better for the testing to date. The system has provided the rated 5 kW of power and 10 kWh of energy. It should be noted that the battery module was able to achieve both the power and energy ratings within the same test at an energy efficiency of 68.8% although the manufacturer does not claim both nameplate values can be achieved in the same test.

The module voltaic, coulombic, and energy efficiencies were calculated for the characterization tests. Excluding the power test at 5 kW, the test parameters for module characterization explored between 15 and 60 A charge and discharge currents and between 25 Ah and 250 Ah capacity. For this testing, the energy efficiency stayed within the band of 73.6% and 78.5% and was highest in the middle of each range of charge and discharge rate. The highest observed was 78.9% at 30 A charge and 30 A discharge to 125 Ah capacity.

A skipped strip test was performed on the module for four successive charge/discharge cycles at 30 A charge/discharge rates, with the allowed capacity decreased by the manufacturer-recommended 3 Ah per hour of operation. The battery was able to perform the set of cycles with skipped strips.

Overall, the battery module has performed according to the manufacturer’s specifications during characterization. Further conclusions will be held until the final report is issued after Phase 2 testing has concluded.

As only one ZBM has been supplied for testing thus far no statistical conclusions or extrapolations can be made to the many ZBMs in production. However, as these data can be compared to previous third party testing such as the RISE report [4] and to future SNL testing on other ZBMs the final report may include a statistical analysis.

6. FUTURE WORK

The future work with the RedFlow ZBM SDK will include further characterization tests under controlled temperature, including thermal-dependent self-discharge, tracking the rate of self-discharge over time and temperature. Furthermore, the Phase 2 testing will be carried out to evaluate the module under long-term cycling. The delivery of an R510 system is expected in 2012, and characterization and cycling of this system will also be carried out at the DC and the AC level.

7. REFERENCES

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Appendix A: Measurement and Control Verification

As part of these testing activities the RedFlow Battery Management System (BSM) underwent validation testing for measurement and control accuracy.

Voltage

In the voltage verification test the battery module was disconnected from the DAS and an external voltage was applied to the DAS using the Chroma Power Supply. This voltage could be read on the power supply, on the RedFlow Laptop, and on a calibrated HP 34401A voltmeter. The recorded values are displayed in Table A-1. Observe that the RedFlow Laptop voltage measurement error stays below 0.05%.

Table A-1. DAS Analysis, Voltage.

Setpoint (V)	Meter	Power Suply	Power Suply %Error	RedFlow Laptop	RedFlow Laptop %Error
20	20.01	20.00	-0.04998	20.0	-0.0350
30	30.01	30.00	-0.04998	30.0	-0.0400
40	40.01	40.00	-0.03249	40.0	-0.0250
50	50.02	50.00	-0.04598	50.0	-0.0400
52	52.02	52.00	-0.04229	52.0	-0.0384
54	54.02	54.00	-0.04258	54.0	-0.0370
56	56.02	56.00	-0.04284	56.0	-0.0357
58	58.02	58.00	-0.04137	58.0	-0.0345
60	60.02	60.00	-0.03999	60.0	-0.0333
62	62.03	62.00	-0.05481	62.0	-0.0484
64	64.03	64.00	-0.05310	64.0	-0.0469
66	66.03	66.00	-0.04998	66.0	-0.0454
68	68.03	68.00	-0.05145	68.0	-0.0441
70	70.03	70.00	-0.04998	70.0	-0.0428

Current

In the current verification test the battery module was reconnected to the DAS and an external current was applied to the battery module using the Chroma Power Supply or the Chroma Load. This current could be read on the power supply or on the load, on the RedFlow Laptop, and on the calibrated voltmeter, which displayed the voltage across a calibrated 0.999856 mOhm shunt. The recorded values are displayed in Table A-2. Observe that the RedFlow Laptop voltage measurement error stays below 1%.

Table A-2. DAS Analysis, Current.

Setpoint (A)	Meter (mV)	Meter (A)	Power Suply	Power Suply %Er	RedFlow Laptop	RedFlow Laptop %Error
-60	-59.99	-60.00	-59.98	-0.04107	-60.1	0.166
-50	-49.99	-49.99	-49.98	-0.02640	-50.0	0.012
-40	-39.98	-39.99	-39.99	-0.006898	-40.0	0.028
-30	-29.98	-29.98	-29.99	0.01895	-29.9	-0.278
-20	-19.98	-19.98	-19.99	0.04565	-19.9	-0.425
-10	-9.98	-9.98	-9.99	0.110	-9.9	-0.80
0 (off)	0.03	0.03	0.00	n/a	0.0	n/a
			Load			
10	9.82	9.82	9.90	0.821	9.9	0.311
20	19.92	19.92	19.99	0.3471	20.0	0.412
30	29.86	29.87	29.93	0.1965	30.0	0.448
40	39.96	39.97	40.01	0.1094	40.1	0.330
50	49.90	49.91	49.93	0.03869	50.1	0.377
60	60.00	60.01	60.04	0.04726	60.3	0.486
70	69.95	69.96	70.01	0.07851	70.4	0.633
80	80.03	80.04	80.06	0.02558	80.5	0.573
90	89.99	90.00	90.04	0.03893	90.7	0.776
100	100.08	100.09	100.09	-0.00241	100.8	0.7069
110	110.01	110.03	110.06	0.03104	110.9	0.7945
120	120.10	120.12	120.15	0.02723	121.1	0.8181

Time

In this test the system was externally monitored by routing through an independent DAS using a National Instruments (NI) cDAQ-9188. LabView was used to record a charge and discharge profile to verify time data. Figures A-1 and A-2 show the voltage and current respectively as measured by the RedFlow DAS and the NI DAS over two consecutive cycles, including a 10-Ah cycle and a 60-Ah cycle. The RedFlow DAS was set to a data acquisition rate one point every 15 seconds. The NI DAS was set to a data acquisition rate of one point every 5 seconds. There is no discrepancy in the data observed within the data rate of the RedFlow DAS from the calibrated NI DAS within the data acquisition rate chosen for recording results.

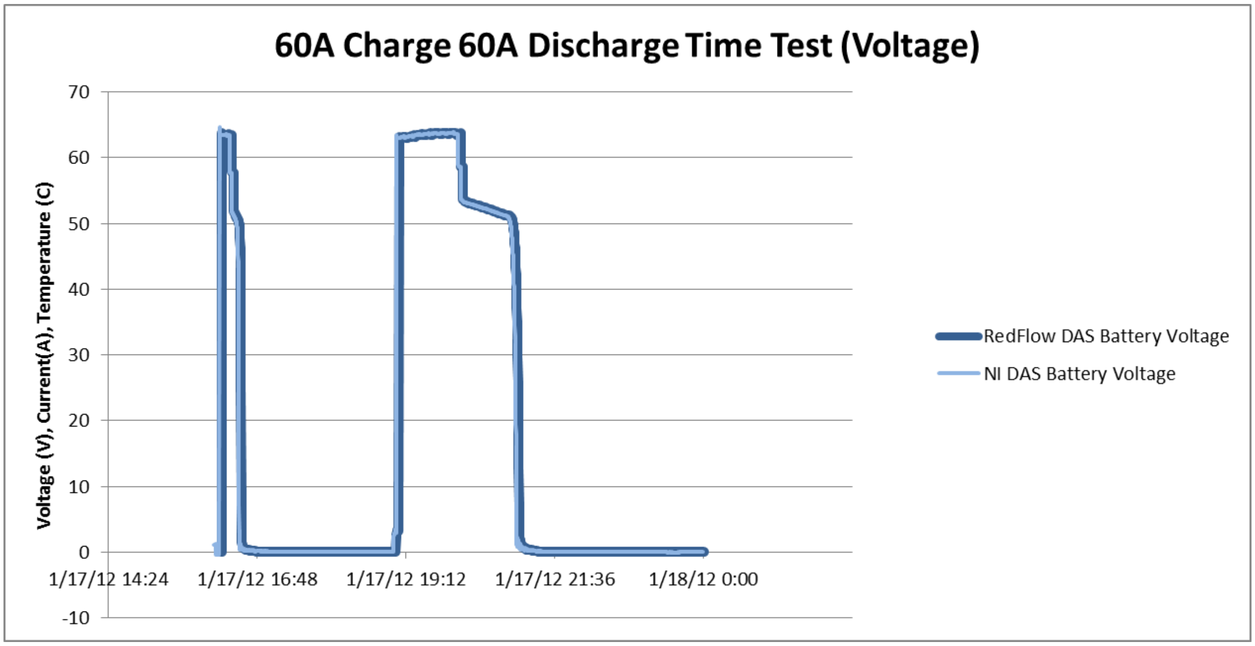

Figure A-1. Time Test (Voltage).

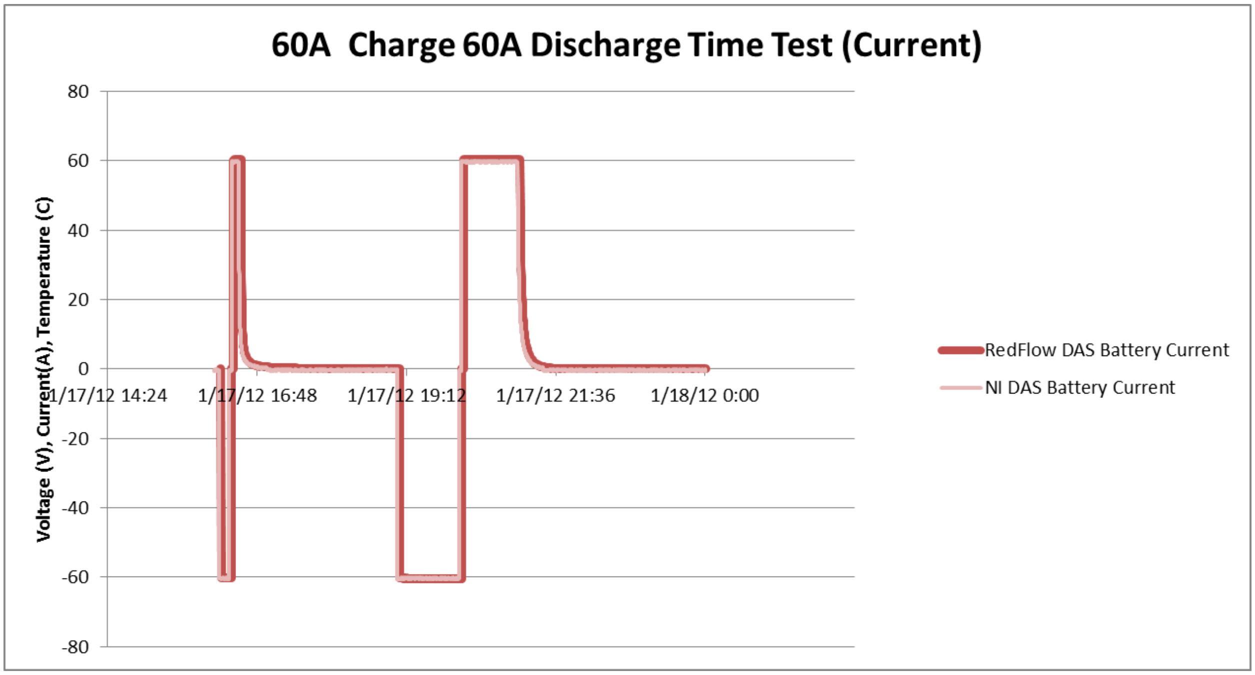

Figure 16. Time Test (Current).

Initial Software Settings

The performance of the module will depend on many factors set by the battery controller software interface. The default settings for this phase of testing are listed in Table A-3 and shown the screen capture in Figure A-3. Detailed descriptions of the software interface and operation can be found in the SDK Manual [3].

Table A-3: Default Software Settings

Setting Name	Default Value
Strip Section	
Max Time	120min
End Run Time	120min
End Amps	0.3
Pump Run	0.00hr
Joules In	0.0MJ
SOC	0.00%
Charge Section	
Purge Time	120sec
Flush Time	120sec
End Amp-Hours	240Ah
End SOC	100%
End Time	1000min
End OC Volts	0.0V
Charger Fail Time	20min
Purge on Time	20tics
Purge off Time	2tics
Discharge Section	
End Amps	0.5A
End Volts	2.0V
Bus Trip Volts	66.0V
End Run Time	1min
Float Section	
Pump on Time	120
Pump off Time	0
Amps Section	
Trip	150A
Trip time	5sec
Offset	-6
System Section	
Nom KW Hours	10.00
Nearest Zero	55.8

Nearest Gain	0.032
Leakage Current	2.20
Temperature Section	
High	25.0
High High	55.0
Other Settings Section	
Leak Fail	20
Leak Trip	80
Nom Resist	0.145 Ohm
End Resist	0.300 Ohm
Offset Resist	0.000
Soc Factor	54
Service Soc	0.00
Cpu Temp Offset	0
Mode	Off
Zn SetPnt	0.0
Br SetPnt	0.0
Charge, At	0.0 Volts, at 0.0 Amps
Discharge, At	Volts, 6.4 Volts
Strip, At	Amps, 0.00 Amps

Figure A-3. Initial Software Settings Screen Capture.

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