High Performance Accumulator for Hybrid Power Plant to Repower RTG Cranes in Port of Houston

Task 1 Report

for:

New Technology Research and Development Program

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Submitted by:

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Abstract/Executive Summary

Ecopower Hybrid Systems designs efficient hybrid power plant for RTG Cranes. The goal of this project is to develop and demonstrate the technical performance and the commercial viability for a new hybrid power plant using lithium-ion (Li-ion) energy accumulator. This development will provide the ability to replace a conventional diesel generator used on Rubber Tire Gantry (RTG) cranes, leading to important emission reductions and significant improvements in fuel economy.

This report presents result of the testing work performed during the first task of the program. The main objective at this phase was to demonstrate that a battery technology could meet the technical requirements and could deliver enough power to carry crane duty cycle only on battery for a time corresponding to a hybrid cycle. TCEQ has requested to have a go-no-go milestone after a first phase in order to have technical confirmation of the feasibility of the project.

Eight different cells were procured and evaluated for capacity, power capability, heat rejection and aging. One cell was rejected because high impedance and poor results at incoming inspection. Two cells were rejected to the poor quality of manufacturing and quality inconsistency during Ecopower visit. Two high end cells were rejected because high price that could not be justified.

The 3 remaining cells were assembled in configuration test modules: 1 format 26650 and the two prismatic cells (~16 Ah, ~40Ah).

The modules were tested under 3 different duty cycles corresponding to:

- Intensive RTG crane operation obtained from direct monitoring to demonstrate cell performance using real operational data,
- Standardized very severe duty cycle to show limit of technologies, and
- A model duty cycle use for calculation; as real world operation is too complex to extract required parameters.

All manufacturers that could be used as cells supplier for this project were visited and audited.

We are pleased to confirm from results obtained the feasibility of using Li-Ion; Graphite/$LiFePO_4$ for the application.

Introduction/Background

A Rubber Tired Gantry (RTG) crane is a mobile gantry crane used for stacking shipping containers within the stacking areas of a container terminal. RTGs are used at container terminals and container storage yards when straddling multiple lanes of rail/road and/or container storage, or when maximum storage density in the container stack is desired.

Conventional RTGs utilize a 400 to 700 kilowatt (kW) conventional diesel generator to provide power to the electric motor drives. The hybrid power plant developed by Ecopower Hybrid Systems will replace a conventional power plant with a smaller diesel generator set (GenSet) between 80 and 225 kW, combined with batteries. It will reduce RTG's fuel usage and greenhouse gas emissions by 55% to 80% and is expected to reduce NO_x and particulate matter (PM) by 55% to 90%. The hybrid power plant enables the aforementioned efficiency gain for the following reasons:

- Significantly smaller engine: The conventional RTG cranes idle a significant portion of the time, run one large engine at low power, and have no capability for energy storage. Even in a very high duty cycle, a RTG equipped with a conventional GenSet requires, on average, the full power of the GenSet for only 15 seconds of every 120 seconds, which is equivalent to 12.5% of the time. In the hybrid system, the GenSet is sized to deliver required average power. The peak power required to lift a container is supplied by the batteries. For the RTG application, the hybrid power plant's GenSet size is 4 to 5 times smaller than the original engine required to provide the maximum peak power demand.
- Battery acts as capacitor bank: The conventional RTG diesel power plant is oversized in order to provide enough voltage stiffness. In the hybrid system, however, the batteries can provide the same voltage stiffness while allowing the smaller diesel GenSet to be used in optimal conditions for efficiency.
- Recovering potential energy: The crane application is a natural application for an hybrid system. Efficiency increases by capturing regenerative power as the hoist on the crane lowers containers and storing it in the batteries. The potential energy of the container is maximized when at the top level; the crane essentially turns the electric motors into generators as the load is lowered, charging the batteries and further reducing the amount of time that the genset must operate.
- Engine running only part time: The smaller diesel generator installed on the hybrid power plant is turned on and off only as required to maintain the batteries' state of charge. Depending on application, the batteries' low state of charge is defined to deliver enough maximum power. This represents a supplementary fuel reduction when compared with a conventional RTG power plant in which the engine runs all the time during operation.

In addition to the technology using smaller and cleaner engine, the fuel reduction is significant enough to drastically reduce pollutants such as NO_x, carbon monoxide (CO), volatile organic compounds (VOC), and PM. Using a more efficient accumulator will permit Ecopower to increase the proportion of time that the motor is shut-off, leading to higher fuel reduction and ensuring the diesel generator is running only when required at optimal levels for fuel efficiency, which helps to better control emissions.

Project Objectives / Technical Approach

The main goal of the project is to develop and demonstrate a new hybrid power plant with using Li-ion accumulator to be retrofitted as an efficient repower solution for RTG cranes. This development will provide the ability to replace a conventional diesel generator used on RTG cranes used in the port of Houston, leading to important emission reductions and significant improvements of fuel economy.

This deliverable report covers only task one of the project; this step was designed as a go-no-go milestone. The objectives of the task were to develop and build three Li-ion modules using different commercially available cells, to test them to demonstrate the performance of each Li-ion modules when subjected to a standardized RTG duty cycle.

Task 1: Selection of Battery Technology, Assembly in Sub-packs and Testing

This report covers only results of work performed during task one of the project; this task was designed as a go-no-go milestone. The goal of the task was to demonstrate from test modules developed and built from commercial cells that the technology was able to be used as accumulator when subjected to a standardized RTG duty cycle and to confirm capability and sufficient performances.

The report will demonstrate that task one is satisfactory completed and that the li-ion technology tested is suitable to build the hybrid power plant to replace conventional genset on an RTG Crane.

Technology Choice

From the Grant Activities (Scope of Work):

> *"Task 1: Selection of and assembly of battery sub-pack*
>
> *2.1. Task Statement: The PERFORMING PARTY will procure and test different commercially available battery technologies then select and test the technology best suited for the prototype RTG crane power plant.*
>
> *2.1.1. The PERFORMING PARTY will procure and fabricate at least three commercially available battery technologies into sub-packs for performance testing.*
>
> *2.1.2. The PERFORMING PARTY will contract with an accredited technological or research and development center to test the performance of the battery sub-packs. TCEQ approval of the technological or research and development center is required before the PERFORMING PARTY enters the contract or authorizes testing to begin."*

As mentioned, the objective of the phase one was to determine if a viable solution of energy storage that is safe and compact enough existed.

The formal criteria were formulated as follows, from the Grant Activities (Scope of Work):

> *"2.1.3. The PERFORMING PARTY will select the preferred battery technology from the tested sub-packs. The selected technology will demonstrate the following characteristics, as compared with lead acid battery technology: at least two times smaller than the lead acid battery accumulator used on the first prototype version; recharging two times faster; presenting a power/energy ratio of at least 5 at peak power."*

For safety reason, we have searched of solution and focus on technology using $LiFePO_4$ active material as cathode. This technology is safer and resists higher temperature, is not susceptible to thermal runaway in over charge. Overall this technology is recognized as a safer alternative than other technologies but presents a lower energy density. We did preliminary calculations and demonstrate that this lower energy density permitted to reach our objectives of reduction in size to fit smaller cranes and to significantly simplify retrofit when compared to lead acid battery technology requiring crane structure modification and complex installation.

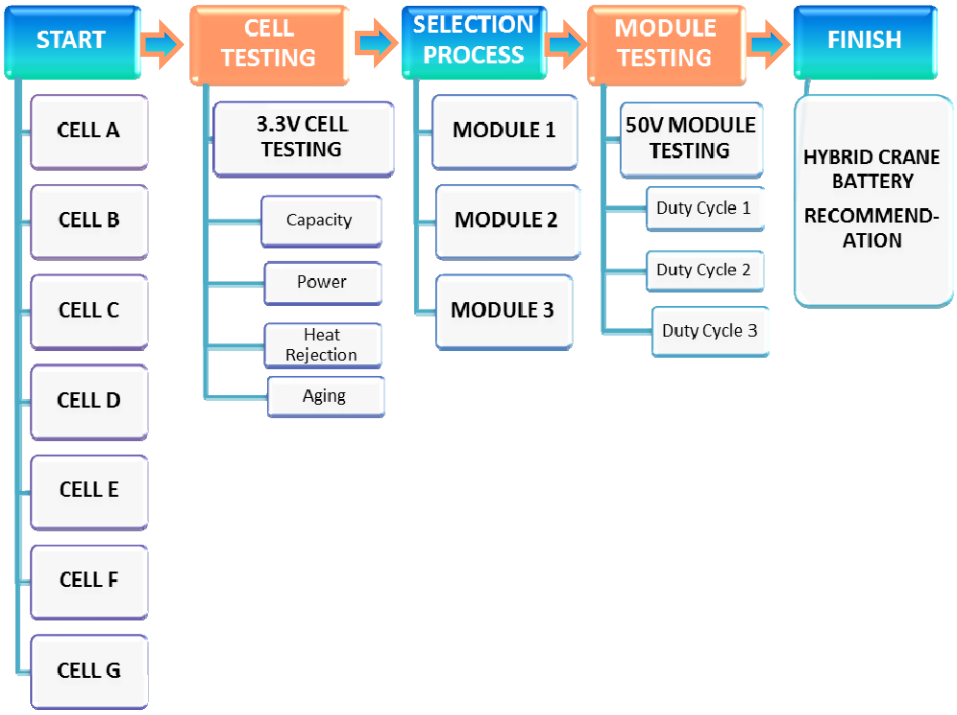
Results of characterization are presented in the following sections. These results will be summarized at the end to demonstrate that the Task 1 is completed. From the results obtained, we are able to conclude that target characteristics are met.

Overview of Testing and Purpose

The objective of this test plan was to evaluate eight different lithium ion battery using $LiFePO_4$ cathode chemistry in order to down-select the best possible solution for hybrid RTG crane application. The program is broken up into two phases: Cell Characterization and Module Characterization.

Before starting characterization phase, all the cells have passed an incoming inspection.

Figure 1. Testing methodology used for Task 1



As illustrated at Figure 1, the cell characterization phase includes testing all seven different battery types (Cell A to G) against a capacity, power, heat rejection, and aging test regiments. The outputs of the cell testing phase will down-select the best three candidates for the hybrid crane application.

The module test phase entails evaluating the performance of the top three cells (Module 1 – Module 3) by cycling them against three different crane-style drive profiles, as shown in Figure 1. The evaluation is based on temperature rise, cell resistance, voltage limitations, energy efficiency and number of cells to be assembled to build a pack of required size for the application.

Finally, recommendations about the suitability of the various cell types for the crane application are made based on the testing results.

Cell Tested

Eight different cells based on $LiFePO_4$ chemistry were procured and tested. Table 1 below lists the eight different battery/cell types under evaluation for the hybrid crane application.

Table 1. List of cells evaluated

Cell Identifier	Shape	Nominal Capacity	Nominal Voltage
Cell A	**Cylindrical**	**2.5Ah**	**3.2V**
Cell B	**Cylindrical**	**4.4Ah**	**3.2V**
Cell C	**Cylindrical**	**3.3Ah**	**3.2V**
Cell D	**Cylindrical**	**2.6Ah**	**3.2V**
Cell E	**Cylindrical**	**3.2Ah**	**3.2V**
Cell F	**Prismatic**	**16Ah**	**3.2V**
Cell G	**Prismatic**	**42Ah**	**3.2V**
Cell H	**Cylindrical**	**3.0Ah**	**3.2V**

Incoming Inspection: Cell Testing Lot

Prior to starting the cell testing phase, each test sample underwent an incoming inspection process. The process entails measuring the cell's 1kHz AC impedance (mOhm), open circuit voltage (Volts), and weight (grams). Figure 2 and Figure 3 below illustrate the incoming inspection data collected on the cells slated for the Cell Testing Lot. Only cells within the highest and lowest 5% of cell impedances were used for the process. Due to the very high impedance values observed on cells H, it was decided to stop testing this cell.

Figure 2. Impedance normalized to capacity for each cell lot

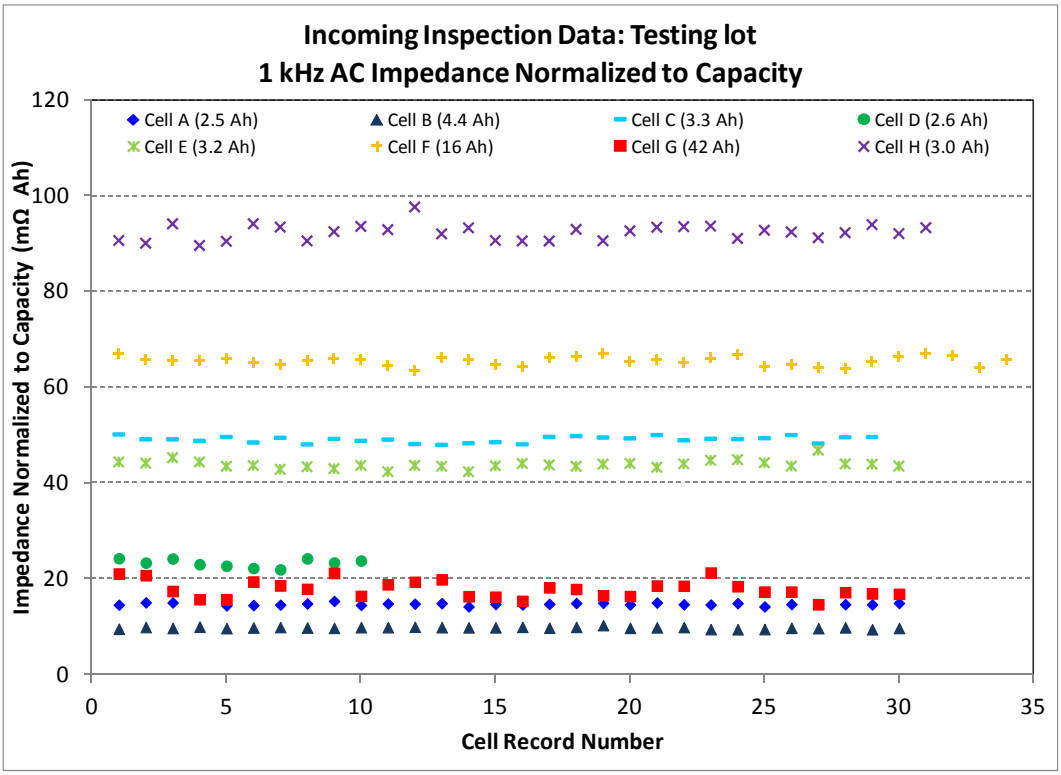
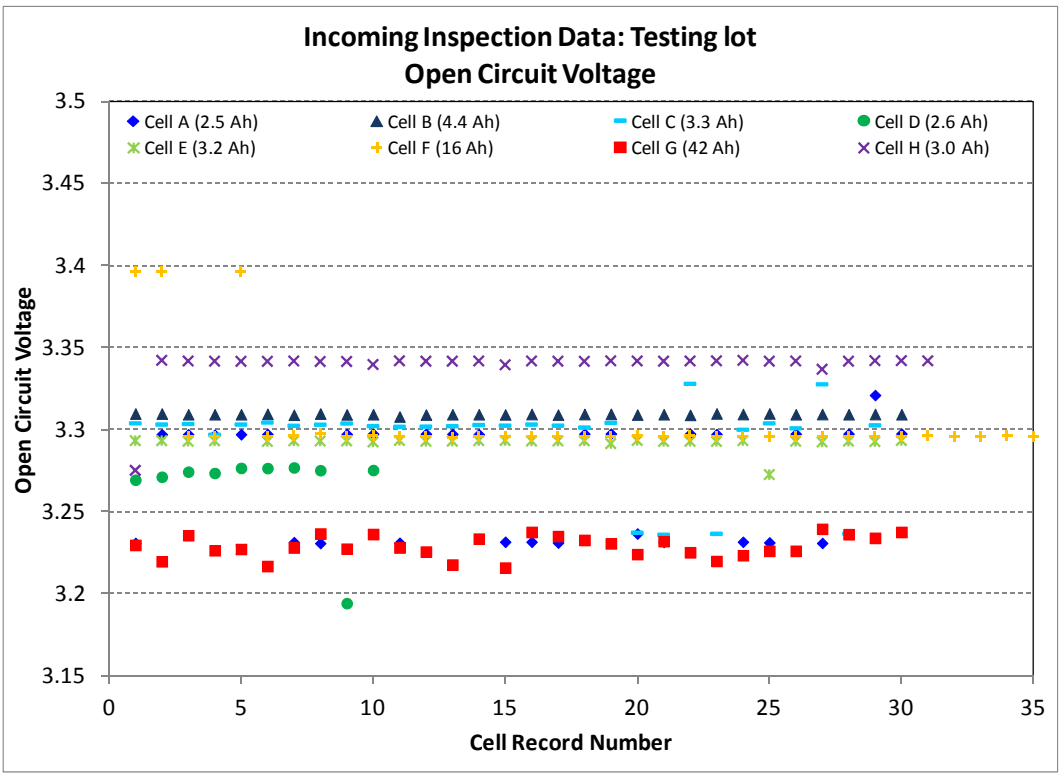


Figure 3. Open Cell Voltage (OCV) measured on each cell lot



The cells were removed from the packaging material and inspected visually for damage. Although no damaged cells were found, they would have been removed from the lot. A Hioki BT3562 Battery Tester and Kelvin connection probes were used to measure the cell open-circuit voltage and AC impedance at 1 kHz.

Figure 2 summarizes 1kHz AC Impedance normalized for each cells and Figure 3 presents the open cell voltage of each cell as received. Cells A, B, D and G show the lowest impedance as expected as these cells are sold as power cells for HEV application in comparison with Energy Cells for EV applications. Cell G and H show more variability in the impedance and Open circuit voltage.

Incoming Inspection: Module Testing Lot

Figure 4 to Figure 6 presents the incoming inspection of the cells used to build the modules. Cell C required 480 cells for 30P 16S configuration for the module. The impedance and open circuit voltage were measured for 520 cells. 500 cells respected the criteria; within 1σ for voltage and 2σ for impedance. Cell C presents the highest standard deviation for open circuit voltage.

96 cells were required to build the module with Cell F and 104 cells were inspected; 98 cells respected the criteria. The cells were received in pre-assembled cassettes of 5S and 6S. Impedances were measured for cassettes and normalized by the number of cells per cassette. Cell F shows the highest stability in impedance and voltage.

Cell G required 32 cells and were received from manufacturer pre-assembled. Nevertheless, an incoming inspection was performed and the result is presented in Figure 6.

Figure 4. Cell C incoming inspection for module

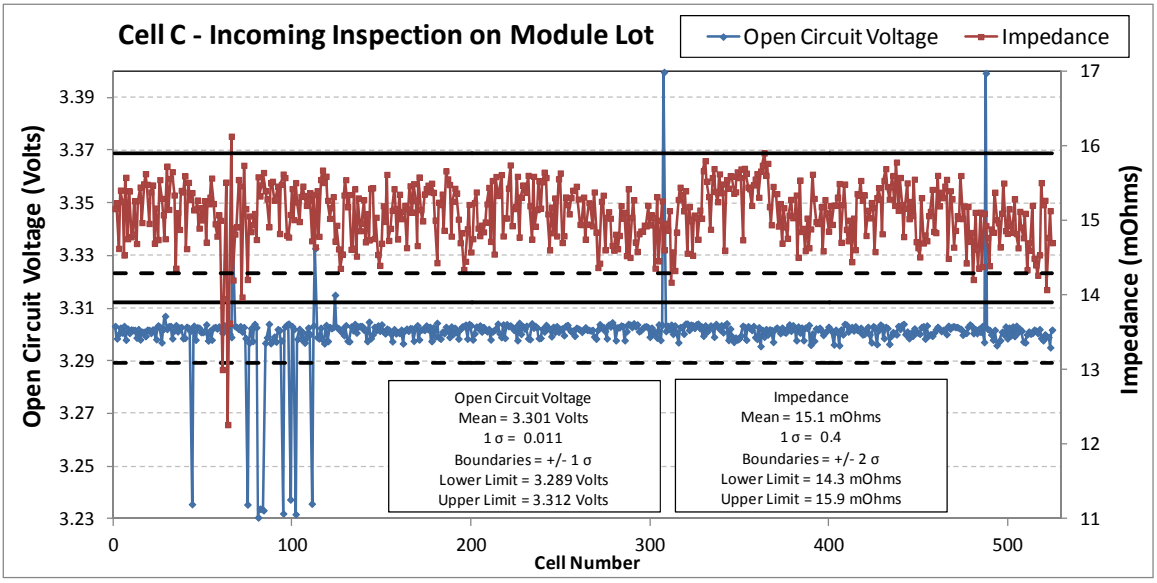


Figure 5. Cell F incoming inspection for module

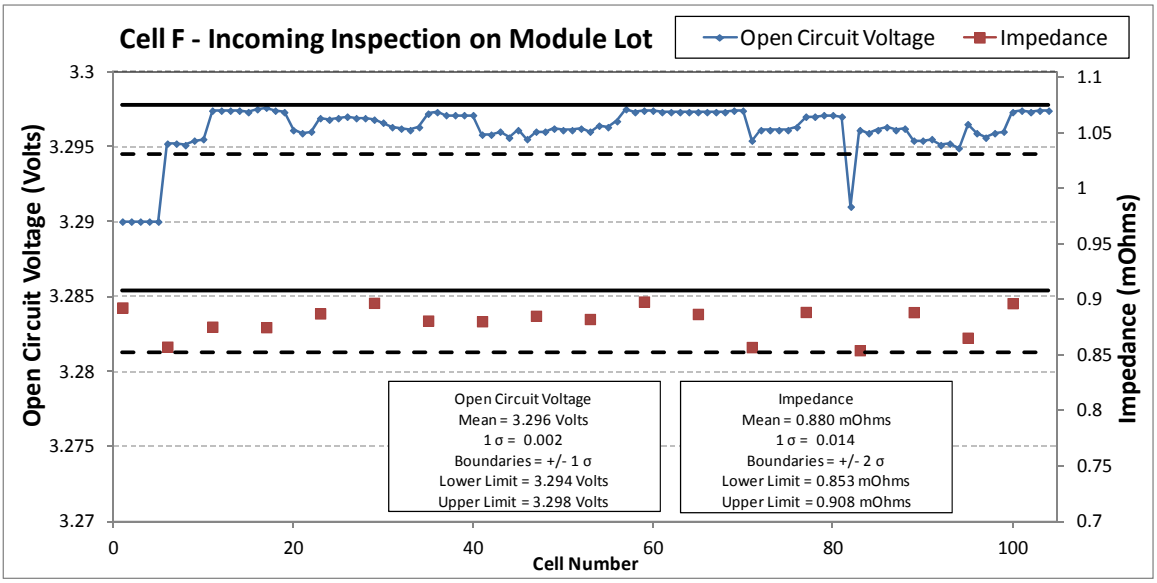
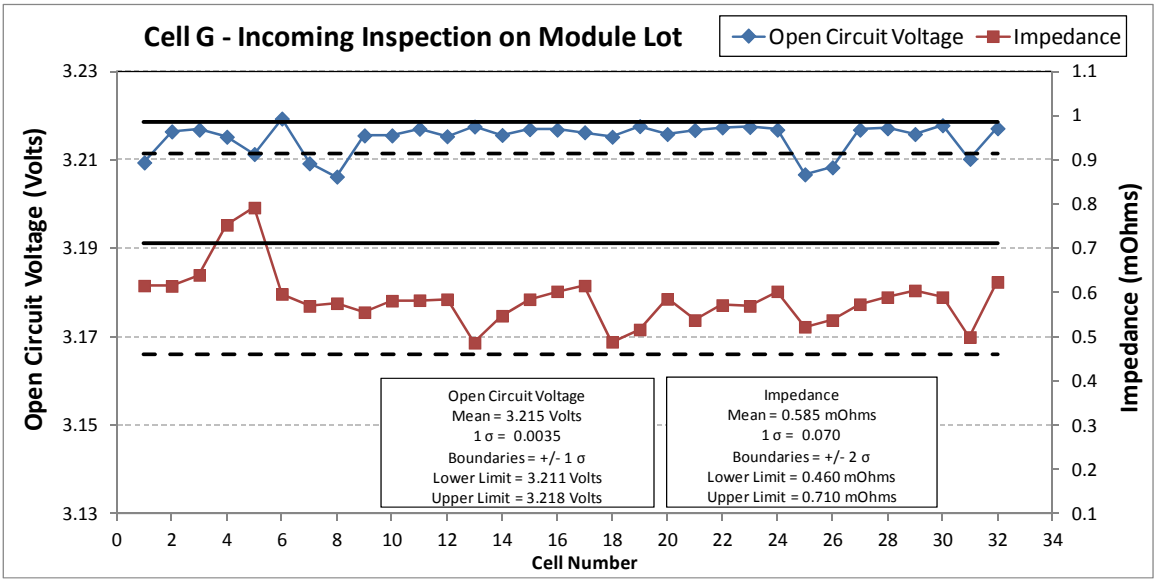


Figure 6. Cell G incoming inspection for module

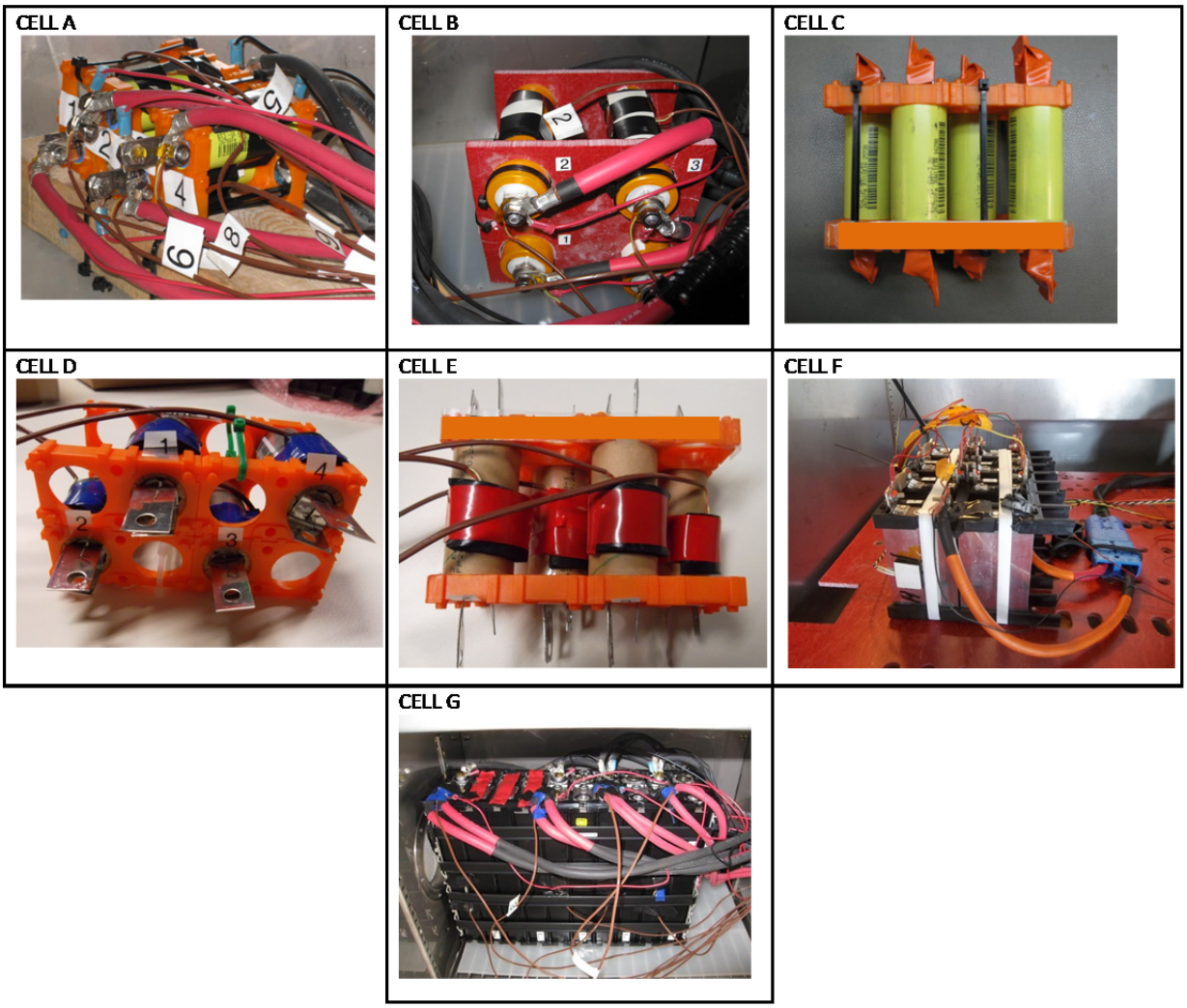


Test Setup

Cell Testing: Test-Setup

The cell testing is conducted on individual 3.2 V cells using a Maccor 4200 battery cycler. Four cells from each group (Cell A – Cell G) are tested. Each cell is connected to a Maccor channel and is instrumented with a Maccor voltage and temperature sensor (K-type thermocouple). The temperature sensor is attached on the side of the can using thermally conductive tape and separated from other cells using insulating foam tape. The ambient temperature is maintained using either a Test Equity or Thermotron thermal chamber.

Figure 7. Cell testing setup pictures



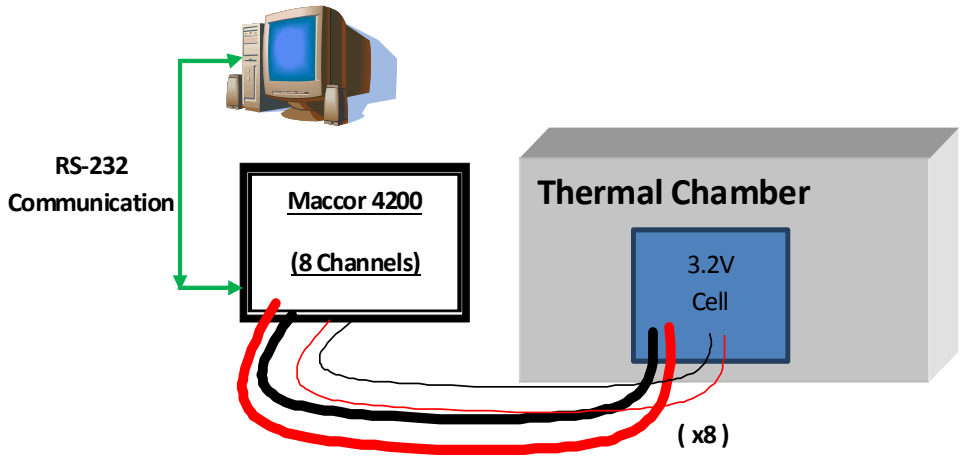
Cell testing: Equipment Required

Equipment required includes:
Maccor 4200 Battery Cycler,

Digital Multimeter, and

PC running Maccor 4200 Battery Cycler.

Figure 8. Cell testing: equipment setup block diagram



There are a couple of deviations to the above setup in order to execute some of the cell tests on the higher capacity cells. The required amperage for Cell F (16Ah) and Cell G (42Ah) is outside the capabilities of the Maccor cycler. These tests were conducted using an Aerovironment ABC-150 in order to supply/accept the necessary loads. Cell F and G utilized the ABC-150 to perform the power testing (±96A and ±252A required respectively) and heat transfer testing (±48A and ±126A required, respectively). The setup for these tests is consistent with Figure 8.

Maccor accuracy is:

- Voltage: 0.02% of full scale reading or 1 mV
- Current: 0.05% of full scale reading or 7.5 mA
- Temperature: 0.1°C

During testing, cell temperature was limited to maximum of 55°C or the manufacturers recommended temperature, whichever was lower.

Module Testing: Test Setup

The module testing is conducted on a series/parallel string of cells configured to represent a scaled down system of the full battery pack. The full system is estimated at 120kWh. The sub pack module under test is sized at ~5% of the nominal energy. To match battery management system (BMS) and battery cycler capabilities, it was decided to use a series string of sixteen cells or 51V, corresponding to an assembly of 4 independent modules of ~1.5 kWh. With the specified energy and voltage values, the capacity (or the number of cells in parallel) is easily derived. The three configurations are presented at Table 2.

Table 2. Description of each test module fabricated and tested

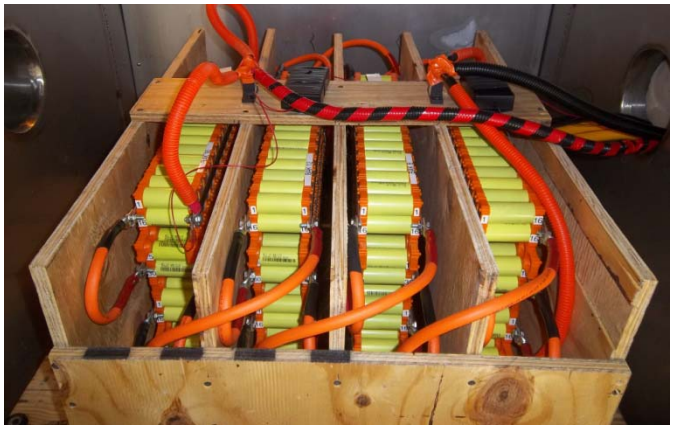
Module Identifier	Cell Identifier	Shape	Module Capacity (# of Parallel Cells)	Module Voltage (# of Series Cells)	Module Energy
Module 1	**Cell C**	**Cylindrical**	**99Ah (30P)**	**51.2V (16S)**	**5.07 kWh**
Module 2	**Cell F**	**Prismatic**	**96Ah (6P)**	**51.2V (16S)**	**4.92 kWh**
Module 3	**Cell G**	**Prismatic**	**84Ah (2P)**	**51.2V (16S)**	**4.30 kWh**

To reduce testing time, the modules were configured in a 4 x 4S for a total 16S and each level of 3.2 V was monitored using a BMS. Module 2 was configured differently due to availability of standard trays used in other applications for that specific cell. Configuration used was (2 x 5S) + (1 x 6S), total voltage remains the same and as each 3.2V group of cells are all monitored independently, final results can be compared easily.

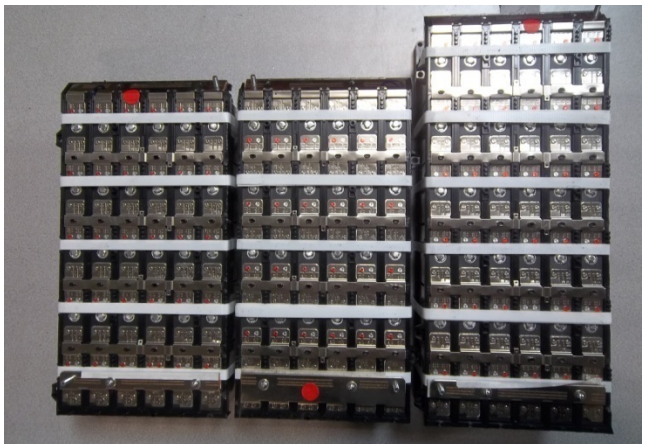
We mention the basic configuration to relate the work done to the original budget were 3 or 4 modules of 1.5 kWh were planned to be built. The configuration presented here is equivalent.

Figure 9. Picture of the three test modules assembled and tested

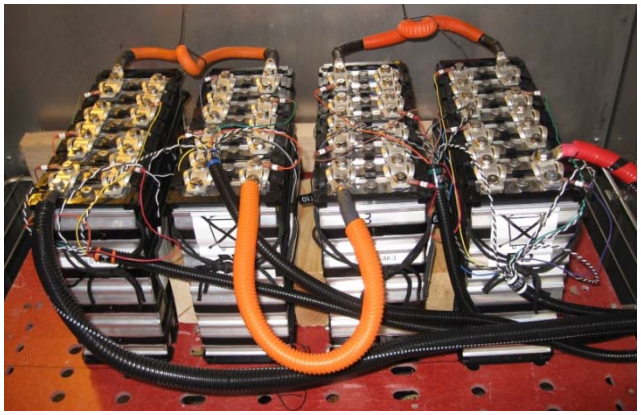
Module 1 (4 X 4S30P)



Module 2 (2 X 5S6P) + (1 X 6S6P)



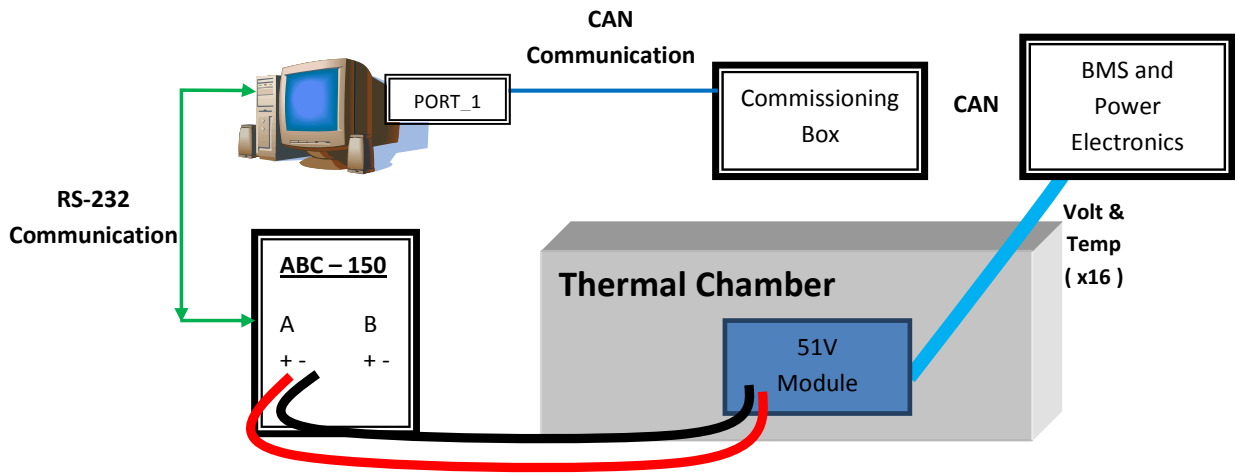
Module 3 (4 X 4S2P)



Module Testing: Equipment Required

- ABC-150 Cycler with PC
  - PC running Win XP with a NI CAN card
  - ROS software installed on PC
- ECS Commissioning Box (100246 Rev C)
- Digital Multimeter

Figure 10. Module testing: equipment setup block diagram



ABC-150 accuracy is:

- Voltage accuracy: 250 mV
- Current: 100 mA or 0.25% of reading, whichever is larger

BMS:

- Cell Voltage accuracy: 6 mV
- Temperature: 1°C.

Test Procedure

Cell Testing: Test Flow and Procedures

Each test fixture is setup with four cells from each manufacturer; therefore eight cells from each manufacturer are required for the cell testing phase. For each manufacturer, the power and capacity is characterized at three temperatures: 5°C, 20°C, and 40°C. The Heat Rejection test is conducted at 20°C and the accelerated aging test is conducted at 45°C.

Table 3. Cell testing: Fixture 1 test flow

Cell Test Fixture 1	Capacity (5°C, 20°C, 40°C)
	Power (5°C, 20°C, 40°C)
	Heat Rejection (20°C)

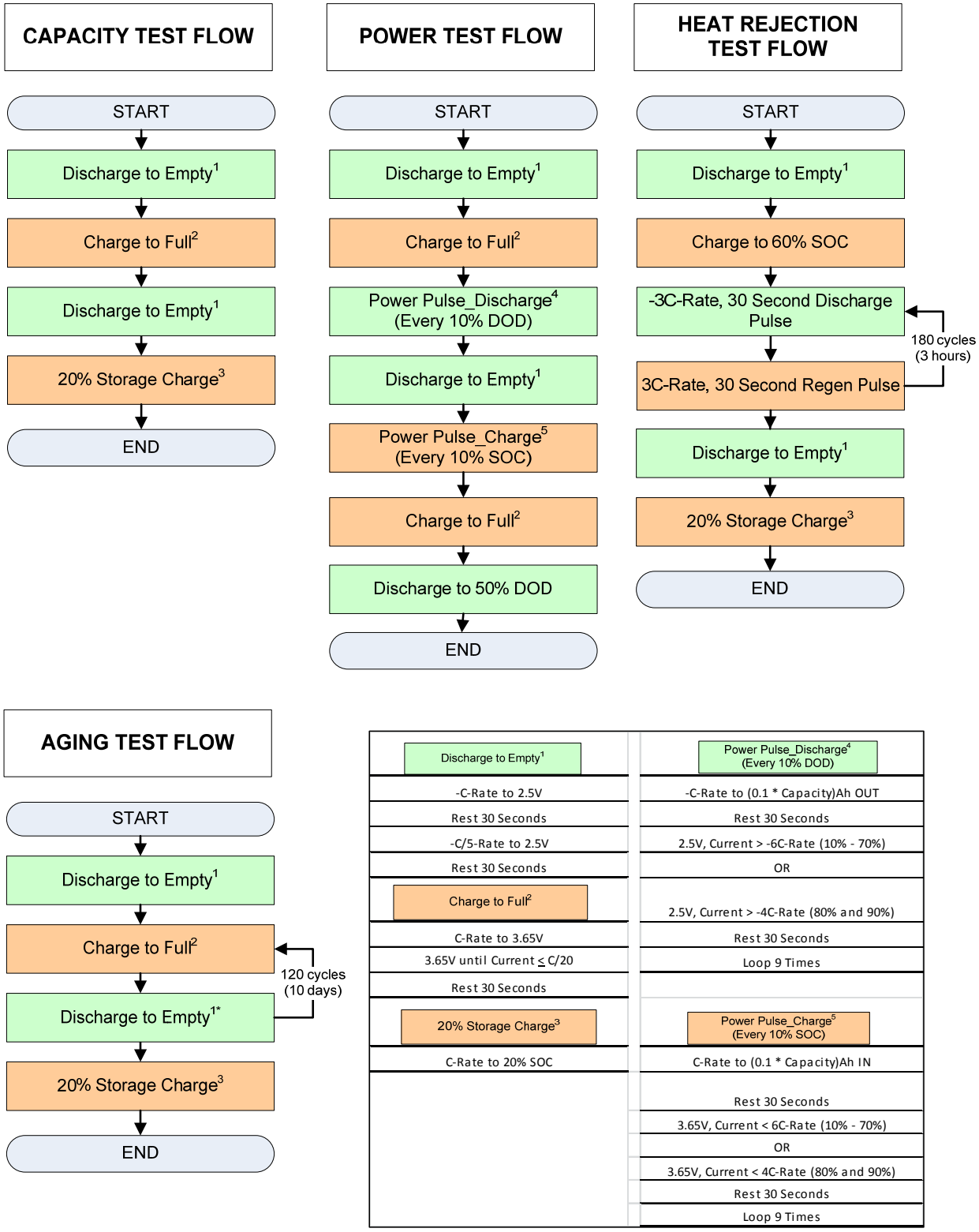
Table 4. Cell testing: Fixture 2 test flow

Cell Test Fixture 2	Capacity (20°C)
	Aging (45°C)
	Capacity (20°C)

For all tests conducted in an environmental chamber, the following temperature stabilization procedure is followed:

1. Set chamber to desired temperature.
2. Allow chamber to stabilize for 1 hour.
3. Place module/cells in center of chamber.
4. Allow cells to stabilize for 4 hours.

Figure 11. Cell testing: test procedures



Module Testing: Test Flow and Procedures

As mentioned in test setup section, module testing is conducted on prototype sub-packs referred to as the module. Each module is tested in an environmental chamber controlled at 20°C and is subjected to three different duty cycles repeated continuously for a minimum of 8 hours. Each duty cycle is illustrated in following figures and is presented as the equivalent power in respect with time. The power sized at:

- Duty Cycle :1
  - Generated utilizing real time data collected off of the Rubber Tire Gantry (RTG)
  - Cycle is 3,000 seconds long
  - RMS power of 104 kW on the system level
  - Shown in Figure 12

- Duty Cycle 2
  - Represents worst case lifting conditions characterized by the heaviest containers and the highest elevation (four containers high)
  - Cycle is 120 seconds long

RMS power of 173 kW on the system level

  - Figure 13

- Duty Cycle 3
  - Represents average lifting conditions
  - Cycle is 120 seconds long
  - RMS power of 117 kW on the system level
  - Shown in
  - Figure 14

The duty cycle testing is conducted between 50% and 85% state of Charge (SOC). Each of the duty cycle in its original state is referred to as 'charge depleting'. The duty cycle is repeated until the module drops from 85% down to 50% SOC. To charge the module back up, the duty cycle is compensated by adding the equivalent contribution of the generator to be used in operation (80kW on the system level).

Table 5. Module testing: module test flow

Module Test Fixture 1	Duty Cycle 1 (20°C)
	Duty Cycle 2 (20°C)
	Duty Cycle 3 (20°C)
	Duty Cycle 2 without Rest (20°C)

Figure 12. Duty Cycle 1 charge depleting and charge increasing

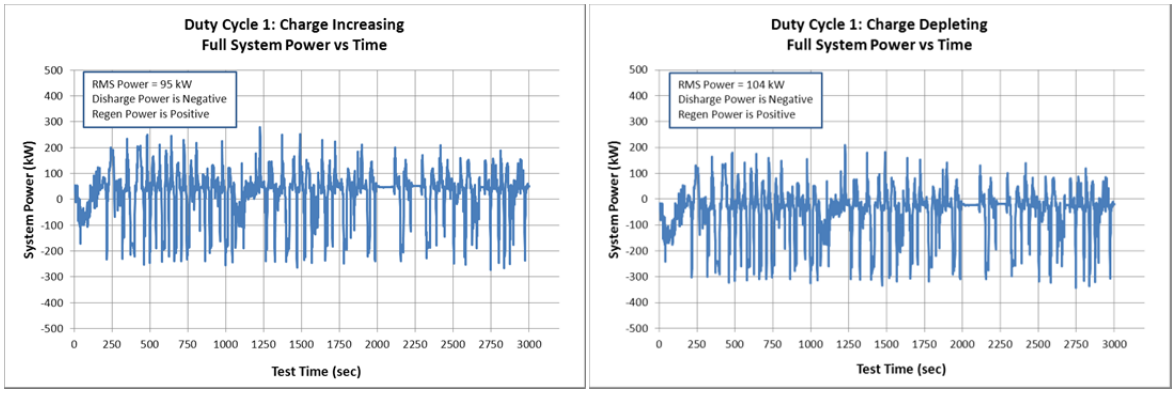


Figure 13 Duty Cycle 2 charge depleting and charge increasing

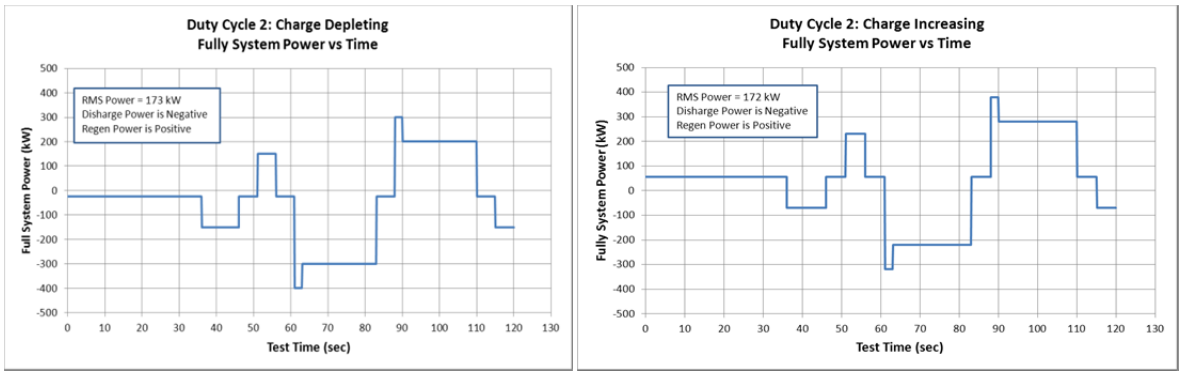


Figure 14 Duty Cycle 3 charge depleting and charge increasing

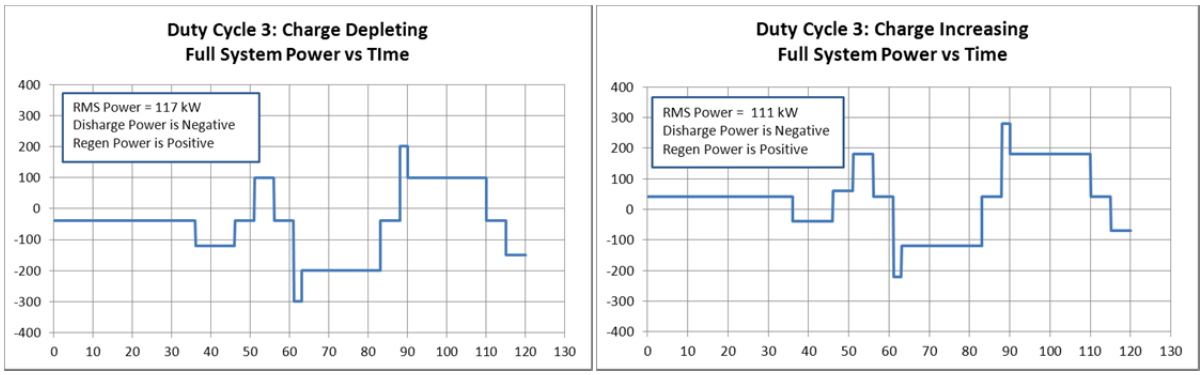
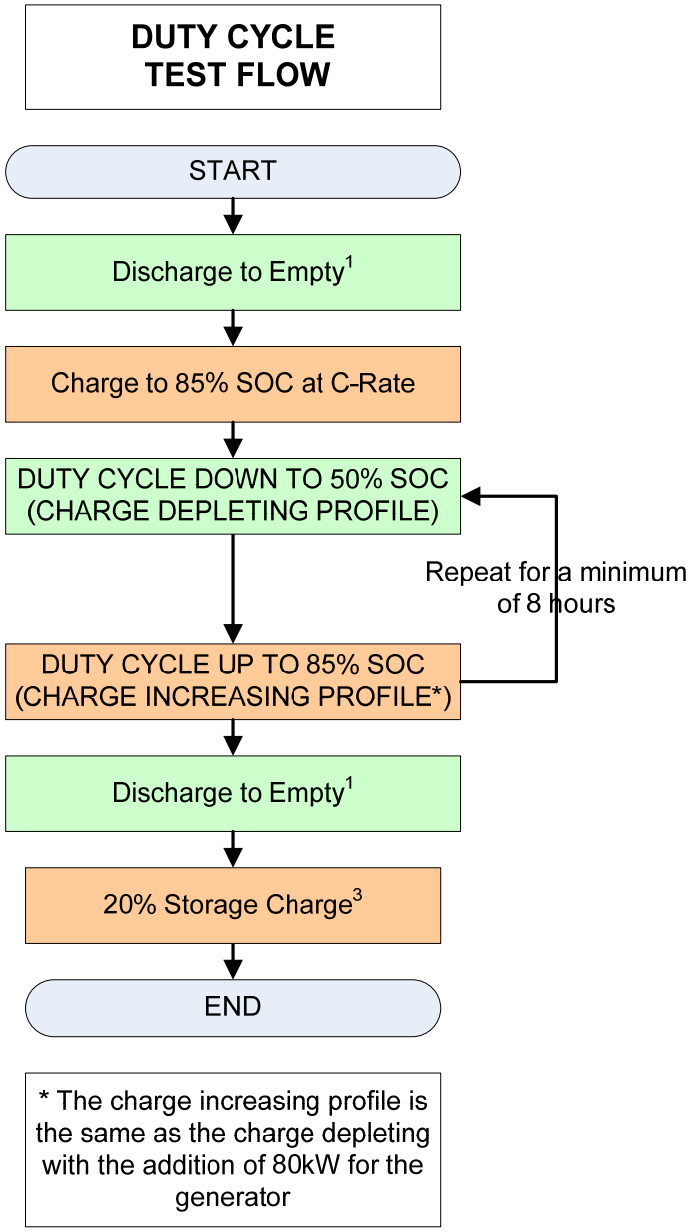


Figure 15 Module Testing: Test procedure



The test procedure sequence illustrated above in

Figure 15 is the same test procedure for each of the three Duty Cycles.

Test Results

Cell Testing Results

Cell Testing Results: Capacity

Four cells from each manufacturer were analyzed for capacity using a 1C charge/discharge cycle from 0 to 100% SOC (2.5 to 3.65V) at three temperatures (5°C, 20°C and 40°C). The capacity data from the four cells was averaged to generate average capacity data for the seven cell manufacturers, which are shown in Figure 16. Figure 17 presents these capacities normalized by rated capacity for each cell (Capacity expected from specification sheet of the manufacturer). These Figures show that cells D and E have less than 95% of the capacity available at C/1 rate and 20°C. At C/5 rate, their capacities remain lower than rated capacities. All the other cells have higher capacity than the rated one for C/5 rate and at 20°C, especially for cell G. At 5°C and C/1 rate, the power cells (Cell A, B, D and G) have more than 80% of the capacity available. At 5°C and C/5 rate, only cell E is still showing capacity under 80% of the rated capacity.

The coulombic efficiency (Capacity Discharged / Capacity Charged) was calculated for each group of the cell manufacturers; four cells from each manufacturer, and the four values averaged. Results are reported at Figure 18. Cells A, B and D have shown the best coulombic efficiency with temperature and C rate. Cells C, F and G present poor coulombic efficiency at C/1 rate and 20°C. For Cell G, further results show coulombic efficiency improvement after few cycles (power and aging) as if the formation cycles were not completed.

Figure 19 shows the calculated resistance after 30 sec rest at the end of discharge. The resistances have been normalized by the capacity of each cell. Cell G presents a high resistance for a power cell. The other power cells (A, B and D) show the lowest resistances at 20°C. The high resistance explains the low capacity available for various cells. As the resistances decrease at 40°C and lower discharge rate (C/5), this demonstrates that the high resistance is related to the electrochemistry of the cells (Diffusion resistance) and not the connections (ohmic resistance).

Figure 16. Average discharge capacity

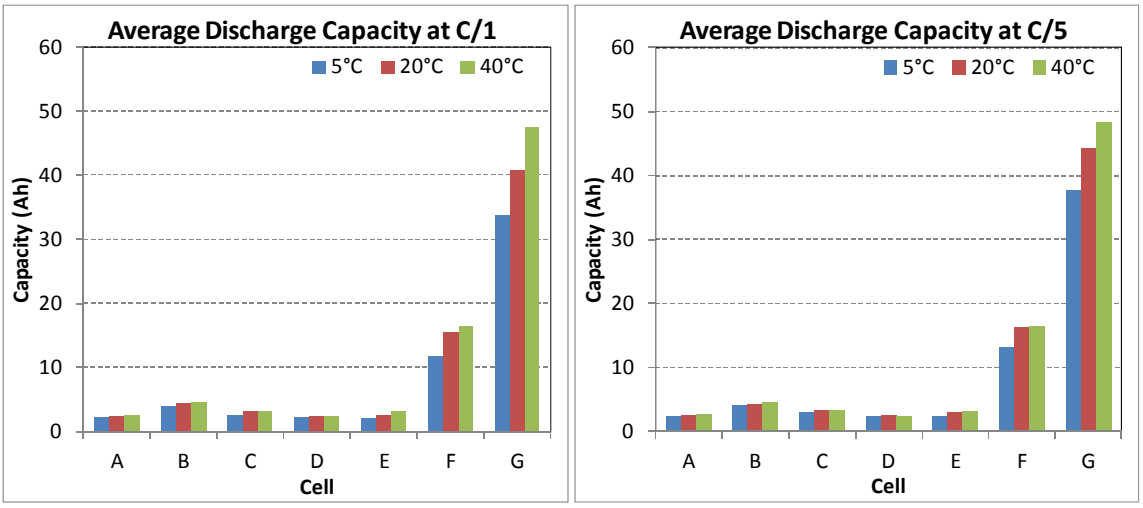


Figure 17. Normalized discharge capacity to rated capacity

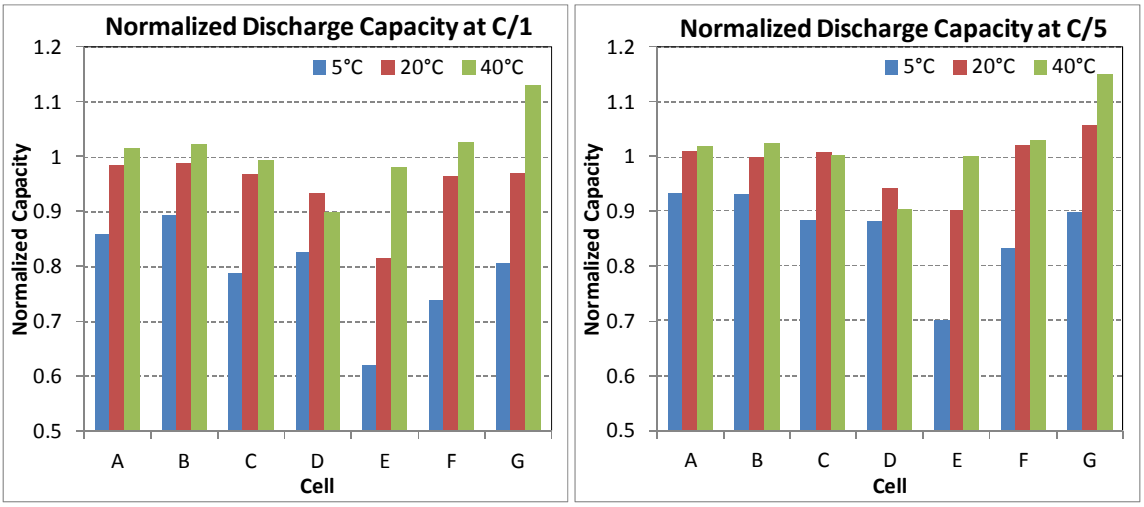


Figure 18. Coulombic efficiency

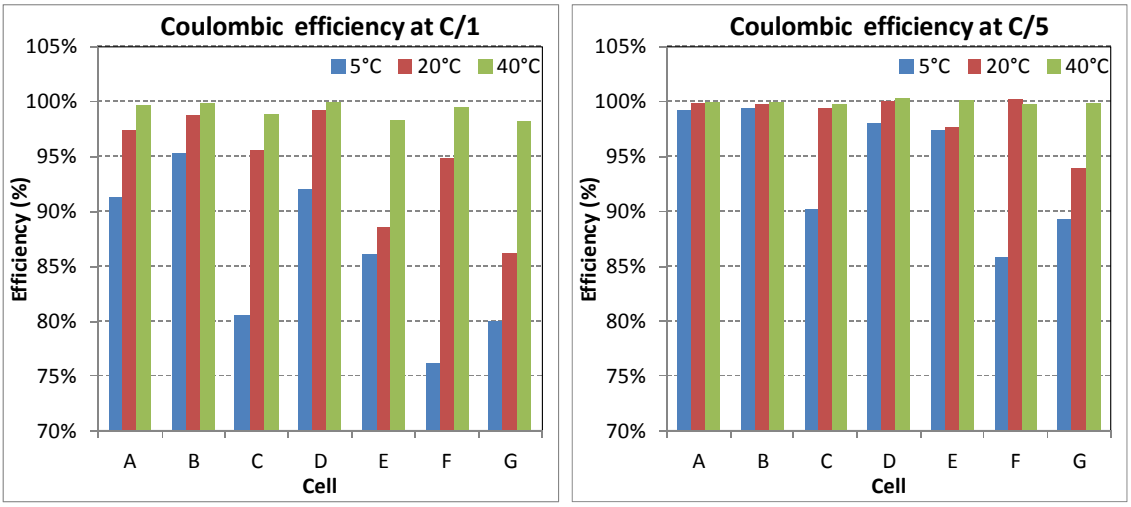
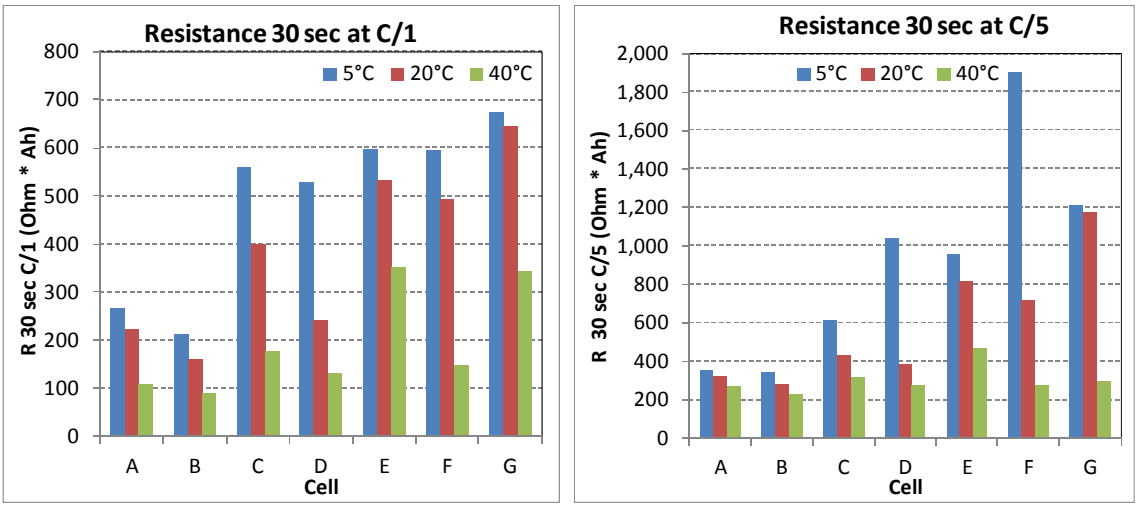


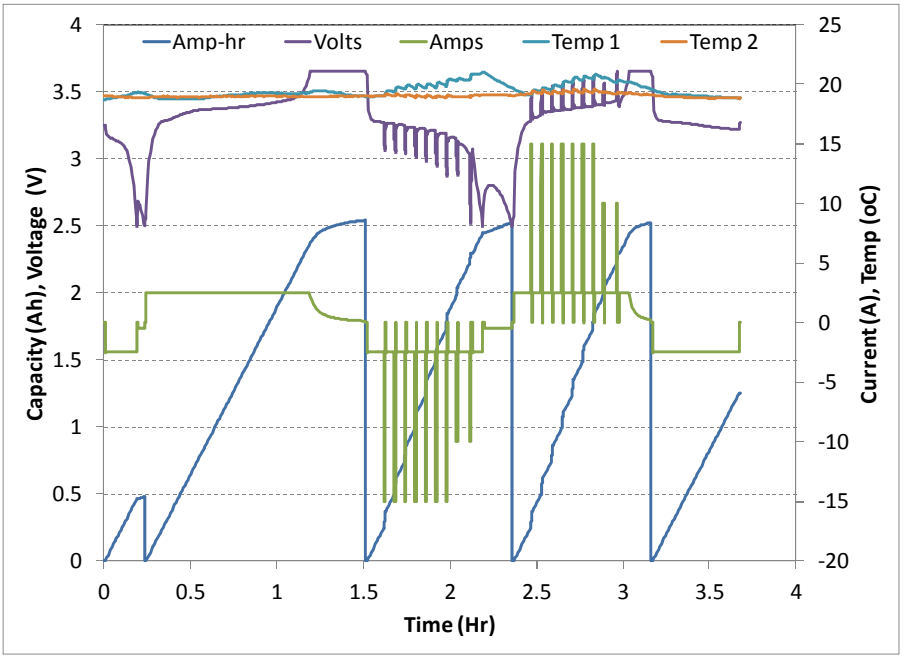
Figure 19. End of discharge resistance after 30 sec



Cell Testing Results: Power

The power capability was determined by setting the cycler to perform a charge/discharge pulse in voltage mode and setting the target voltage to the maximum charge/discharge voltage. The resultant current is multiplied by the voltage, and this provides the peak power capability for the given cell at a given temperature and SOC. This test was performed on all cells at three temperatures and for SOC from 10% to 90% in 10% increments. An example of the test is presented in Figure 20.

Figure 20. Pulse power test example



The power capability was extracted at 2, 5, 10, 20 and 30 seconds from each 30 seconds pulse. Only the data at 2 and 20 sec are presented in this report, which are the most representative for crane operation power demands. Power capability represents the maximum power that can be charged/discharged for a given pulse time. However, to avoid damaging the cells, maximum current for discharge pulse was set to 6C for SOC between 30 to 90% and 4C for lower SOC. For charge pulse, the maximum current was set to 6C for SOC from 10 to 70% and 4C for higher SOC. Then, in some case the cell could have given more power but was limited by the maximum current involving that the voltage limit was not reached.

The power capability was scaled up to an Equivalent Crane Power based on the cell size. Pulse Power values were normalized for a complete module of 120kWh as follow:

$$\text{Equivalent Crane Power (kW)} = \frac{\text{Pulse Power(W)} * 120\text{kWh}}{\text{Cell Nominal Voltage} * \text{Cell Rated Capacity}}$$

Table 6. Power testing limitations and power requirements at crane level

State	Battery Pack Voltage Limit	Corresponding Cell Voltage Limit	Pulse duration	Crane Power requirement	Crane Power Requirement + Burden of 1.5
Discharge	**520V**	**2.5 V**	**2 sec**	**400 kW**	**600 kW**
			20 sec	**300 kW**	**450 kW**
		3.80V	**2 sec**	**350 kW**	**525 kW**
Charge	**790V**	**But 3.65 V used for safety**	**20 sec**	**250 kW**	**375 kW**

The worst case for crane power requirement in discharge is 400kW for 2 sec and 300 kW for 20 sec and in charge the maximum peak power are 350kW for 2 sec and 250kW for 20 sec (see

Figure 13). A burden of 1.5 from cells to pack is used to include the effect of wiring, unbalance between cells and the aging that reduced power capability with time. Table 6 summarizes the voltage and power requirement for crane battery pack. The Figure 21 to Figure 23 can be used to show the approximate range of temperature and SOC where the power requirement can be met. Both 2 sec and 20 sec power requirement should be met in the power capability windows.

Figure 21. Power equivalent for each cell vs. %SOC at 5˚C at 2 and 20 sec

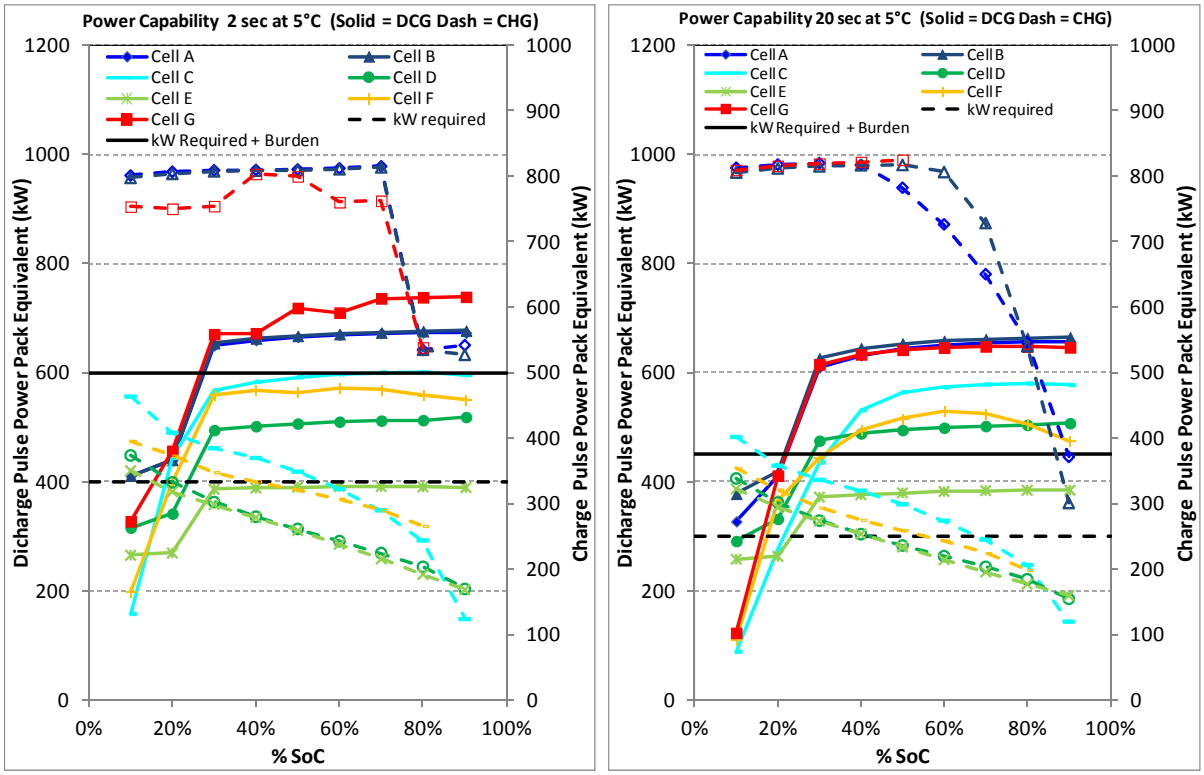


Figure 22. Power equivalent for each cell vs. %SOC at 20˚C

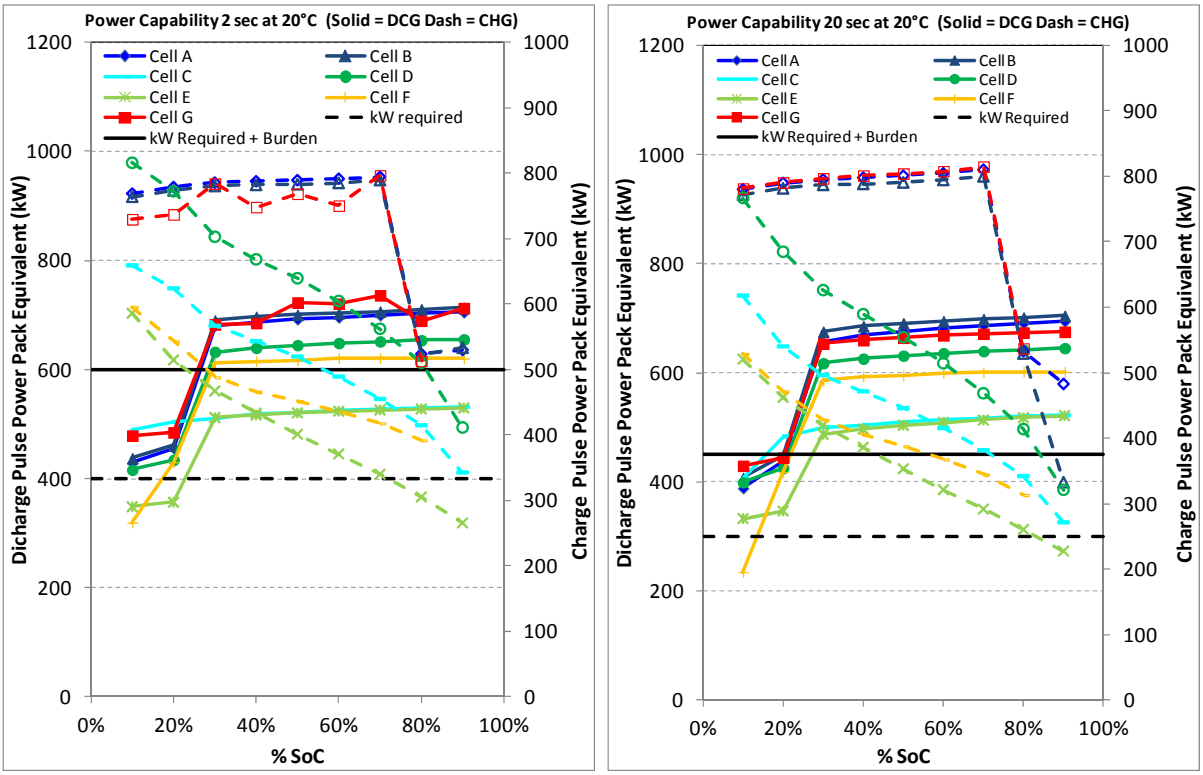


Figure 23. Power Equivalent for each cell vs. %SOC at 40˚C

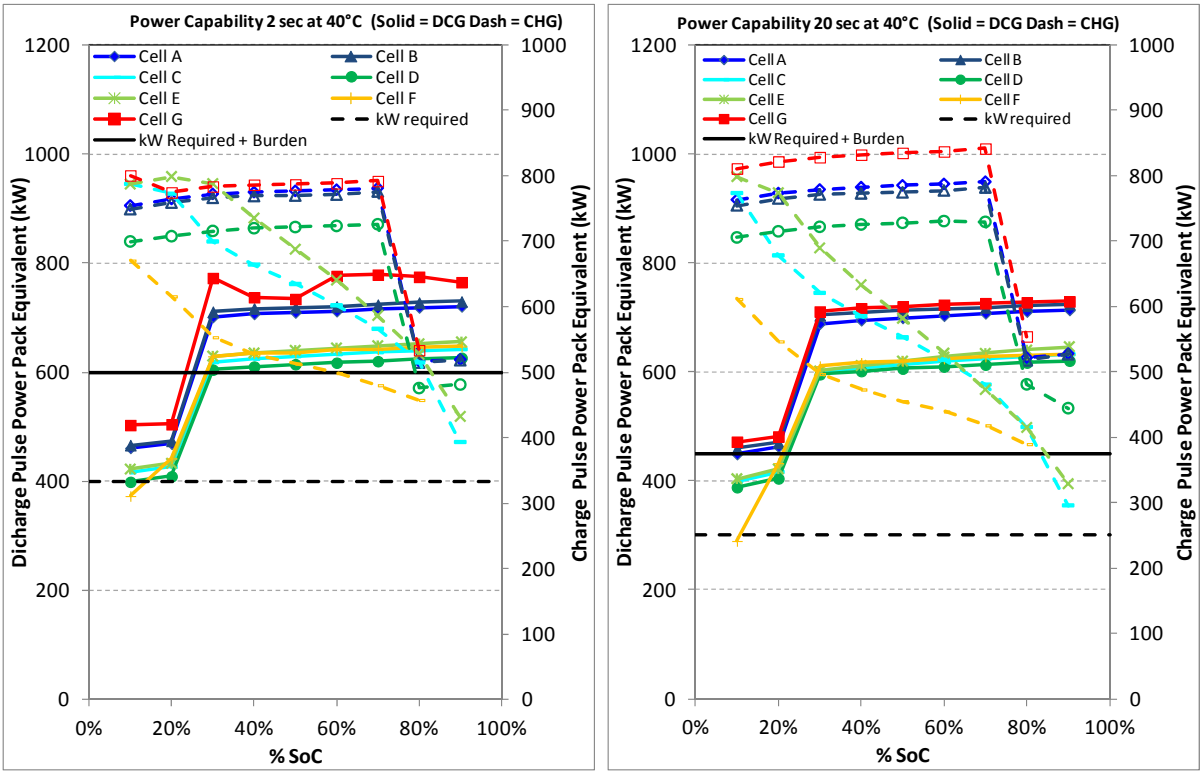


Table 7. Power capability windows for crane operation

Cell	5°C Discharge Limit SOC	5°C Charge Limit SOC	20°C Discharge Limit SOC	20°C Charge Limit SOC	40°C Discharge Limit SOC	40°C Charge Limit SOC
A	30%	90%	25%	>90%	25%	> 90%
B	30%	85%	25%	85%	25%	> 90%
C	-	-	30%	55%	30%	80%
D	-	-	30%	80%	30%	80%
E	-	-	-	25%	30%	85%
F	-	-	30%	30%	30%	60%
G	30%	>70%	25%	80%	25%	> 90%

For the 2 sec pulse power capability, a higher variability is observed for cell G due to the lag in data acquisition from the ABC-150. Table 7 presents the power capability windows for each cell at the three temperatures. Figure 24 summarizes the power capability in charge and discharge for each cell. Again, the power cells present the highest power capability at all temperatures. The difference is more important for charge power capability. Only the power cells show a useable SOC window at 5°C from 30% to 80% SOC.

Figure 25 presents the resistance extracted after each power pulse during the 10 sec rest. Again, the power cells show lower resistance. The resistance increase rapidly in discharge at SOC lower than 40% at 5 and 20°C. In charge, the increase begins after 80% SOC. For this reason, an operation window between 40% and 80% SOC is more appropriate with all these cells.

Overall cell E displayed very poor performance on the power test.

This data can be used (with an appropriate margin of safety) for sizing the pack to meet power requirements. Final validation will be performed at final design after final cell is chosen and commercial agreement with the supplier is concluded.

Figure 24. Power capability at 50% SOC

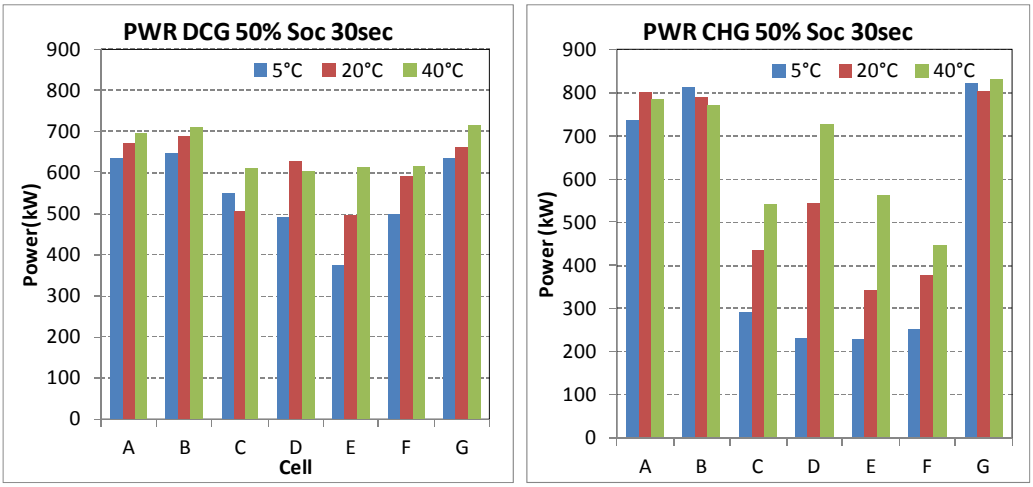
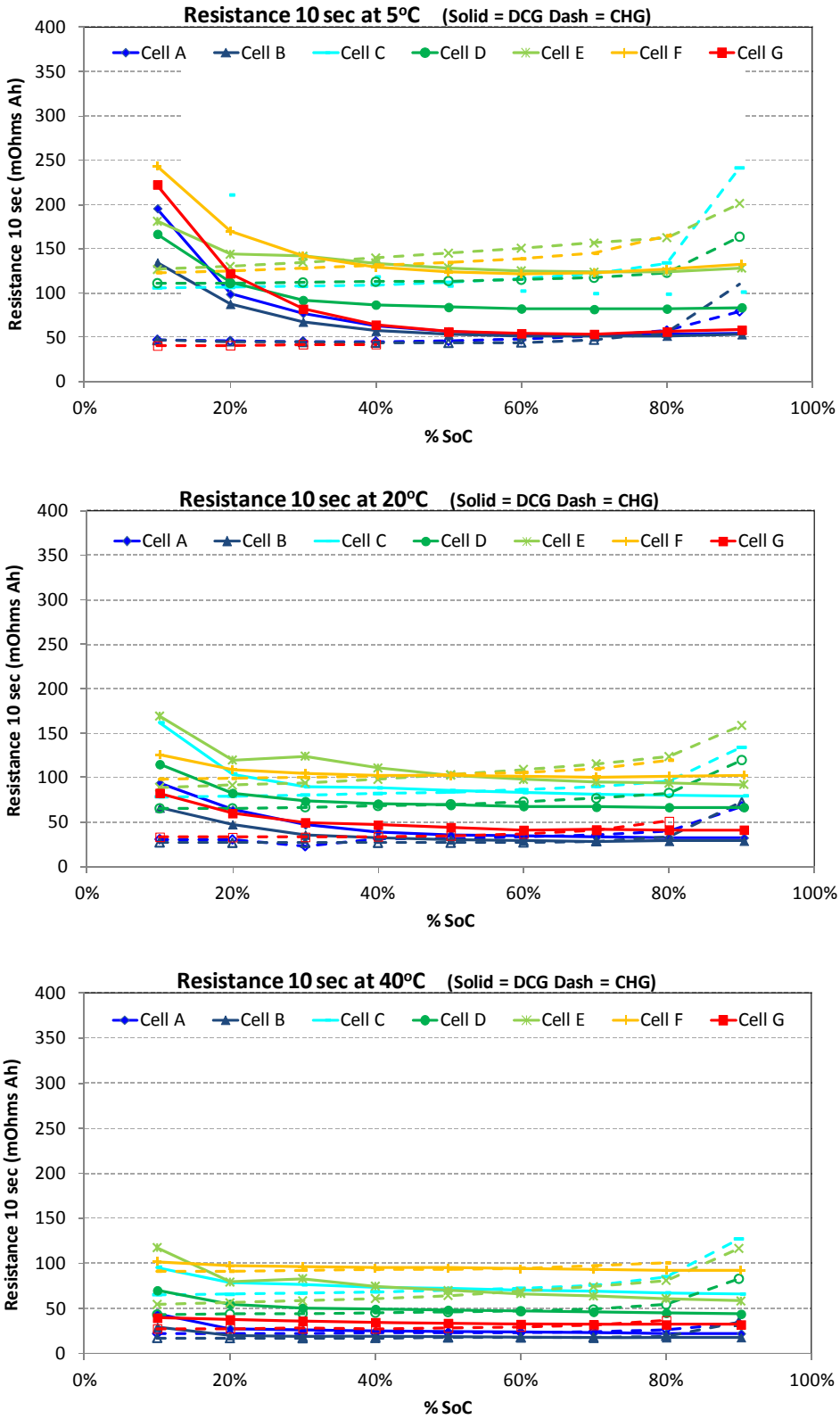


Figure 25 Resistance for 10 sec rest after power pulse at different SOC for 5, 20 and 40°C.



Cell Testing Results: Heat Transfer Coefficient

The heat transfer coefficient (hA) is measured by the amount of heat expelled (q) divided by the temperature difference of the cell temperature and the ambient air temperature, as shown in Figure 26. The experiment is designed to cycle the cell using an amp-hour neutral profile until the cell reaches thermal equilibrium. The amp-hour neutral profile consists of a +3C rate pulse for thirty seconds followed by a -3C rate pulse for thirty seconds. This sequence is repeated for two and a half hours to ensure thermal equilibrium. It should be noted that:

- Electrical power is measured and that thermal power was not directly measured.
- Heat losses by cables and connections are assumed negligible.
- Temperature is measured in one point on the cell casing; this temperature is assumed even for all cell exchanged surfaces.
- Thermocouples readings accuracy is 0.1°C for Maccor setup (Cell A to E) and 1°C for ABC-150 setup (Cell F and G).
- Because their higher capacities, Cell F and G had to be tested as a block of seven cells to work at minimal voltage requested on ABC-150 and to deliver required higher current 45A for cell F and 126A for cell G. Configuration of stacked cells was not advantageous when compared to single small cylindrical cells tested independently with higher natural convection efficiency. We considered these tests as a worst case scenario for cell F and G.

Figure 26. Heat transfer test profile

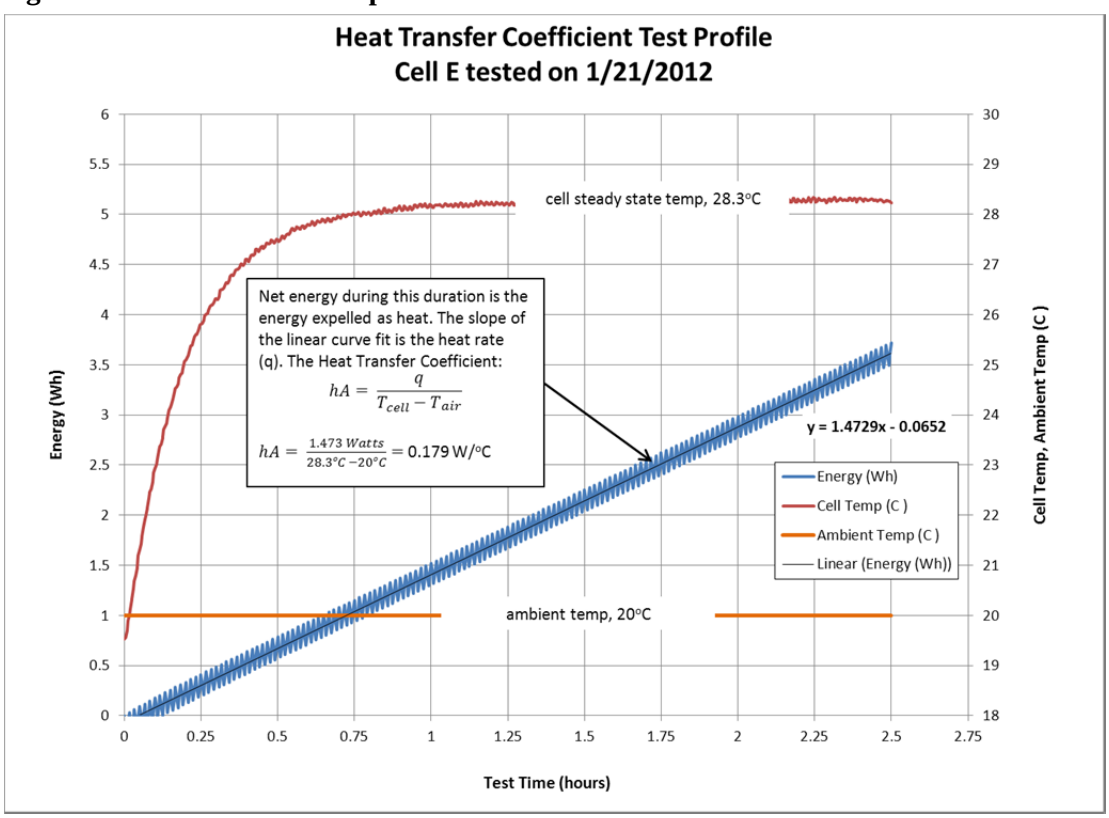


Figure 27 below illustrates the average heat transfer coefficient for each of the seven cell types. The two prismatic cells performed well at 0.65 W/°C for Cell G and 0.85 W/°C for Cell F. However, those cells show higher heat transfer surface area (A) than the regular 26650 cylindrical cells.

Based on the Equivalent Thermal Resistance (Power/ Current square) presented at Figure 28, we could grade Cells from best to worse in the following manner: G, F, B, A, C-E and D.

Figure 27. Average heat transfer coefficients

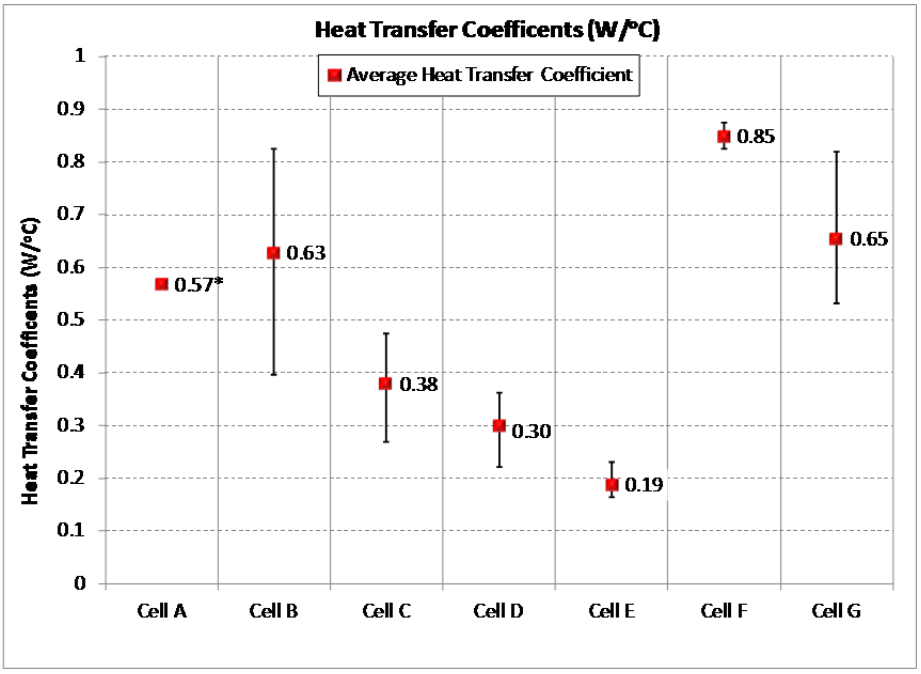
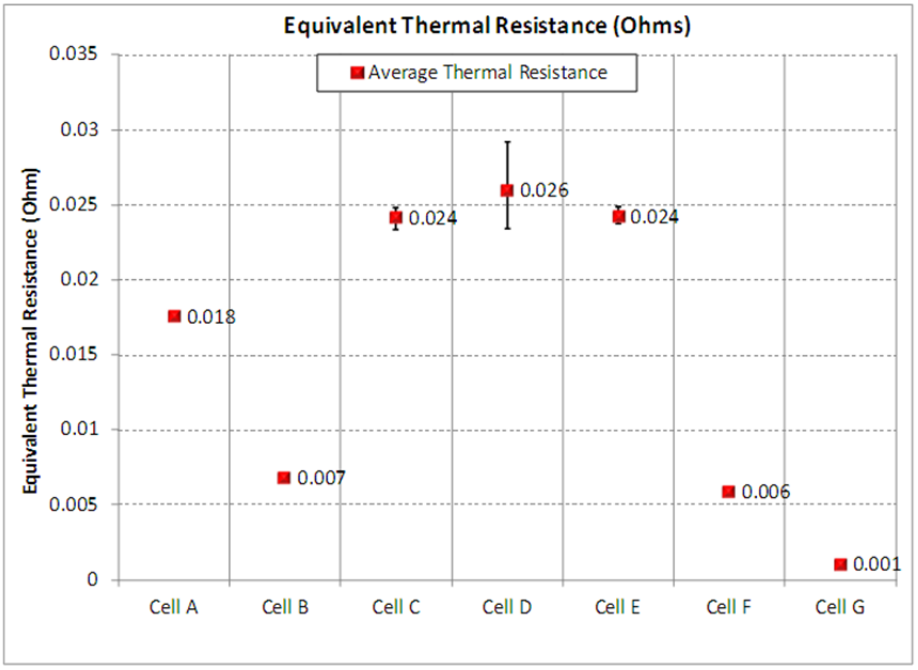


Figure 28. Equivalent thermal resistance (Ohms)



Cell Testing Results: Accelerated Aging

All charge and discharge current is defined from the nominal capacity of the cells or the modules. Is is generally expressed as a ratio between the capacity and the time taken to charge or discharge. As example: C/1 rate corresponds toa current to perform a charge or a discharge of the full capacity in one hour, C/5 in 5 hours, C/20 in 20 hours, 2C in 30 minutes, 6C in 10 minutes.

As presented in Table 4 and Figure 11, the aging test was done by first performing a capacity characterization at 20°C, which includes:

- Full charge at C/1 followed by a taper at 3.65V until the current reached C/20
- Discharge at C/1 to 2.5V
- Discharge at C/5 to verify the remaining capacity in the cells.

Then, accelerated aging was performed by cycling the cells at 45°C from 3.65V to 2.5V with C/1 rate in charge and discharge for 120 cycles. After the aging, a capacity characterization at 20°C was done again. The capacity variation at 45°C for the 120 cycles is presented in Figure 29. Cells C, E and G display the worst performance on the aging for the capacity loss at 45°C.

Figure 29. Accelerated aging at 45°C

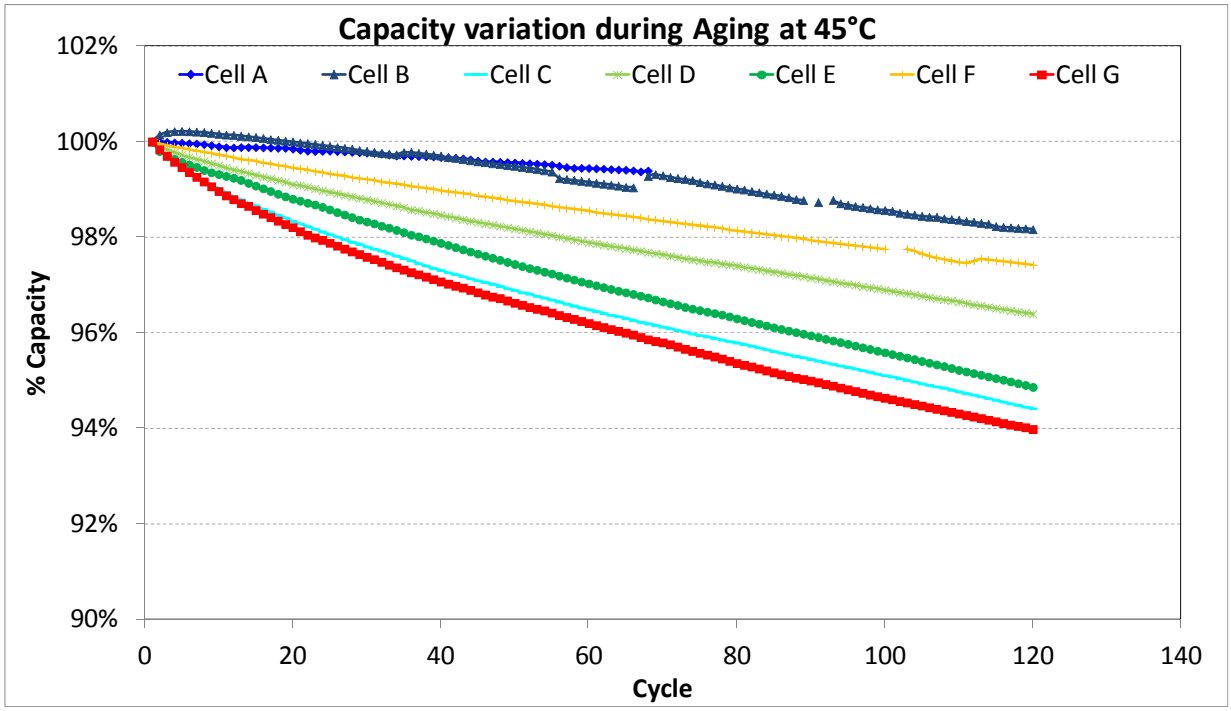


Figure 30 compares the capacity loss at 45°C (C/1) and 20°C for C/1 and C/5. Cells E, F and G have a negative capacity loss at 20°C and C/1 rate meaning that more capacity is available after the aging then before. This is related to an important decrease in resistance at end of discharge as presented in Figure 31. This also is reflected by an increase in coulombic efficiency at C/1 (Figure 32).

A fast aging represents the higher risk of premature failure in the application. Extrapolation of the cycle life for 80% capacity remaining gives the following order: Cell A (~2000 cycles), Cells B and F (~1000 cycles), Cell D (~800 cycles) and Cells C, E and G (>600 cycles). These values are lower than the one given by the manufacturer because of the temperature effect (45°C) to accelerate the aging. However, this extrapolation accounts only for the capacity loss. In hybrid application, in addition to capacity loss, increase in resistance should be considered but required longer aging. Important increase in resistance limits the power capability.

Figure 30. Capacity loss at 45°C (C/1) and 20°C (C/1 and C/5)

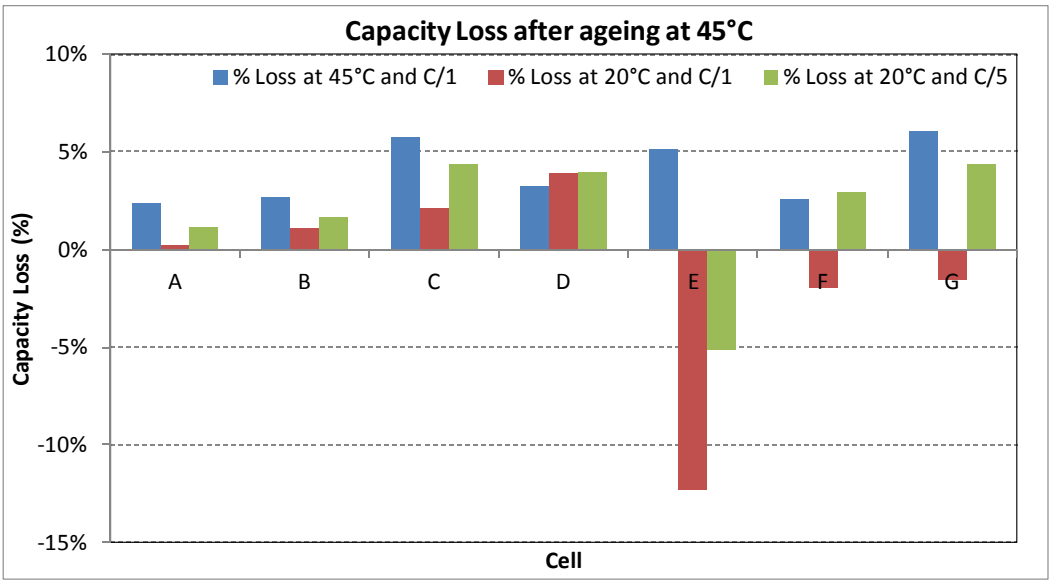


Figure 31. Coulombic efficiency at 20°C (C/1 and C/5) before and after aging at 45°C

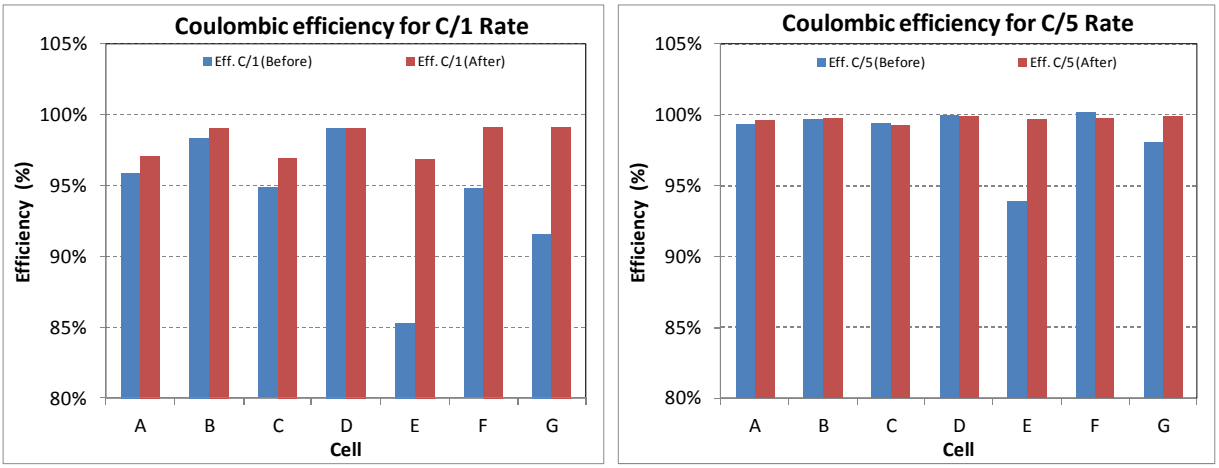
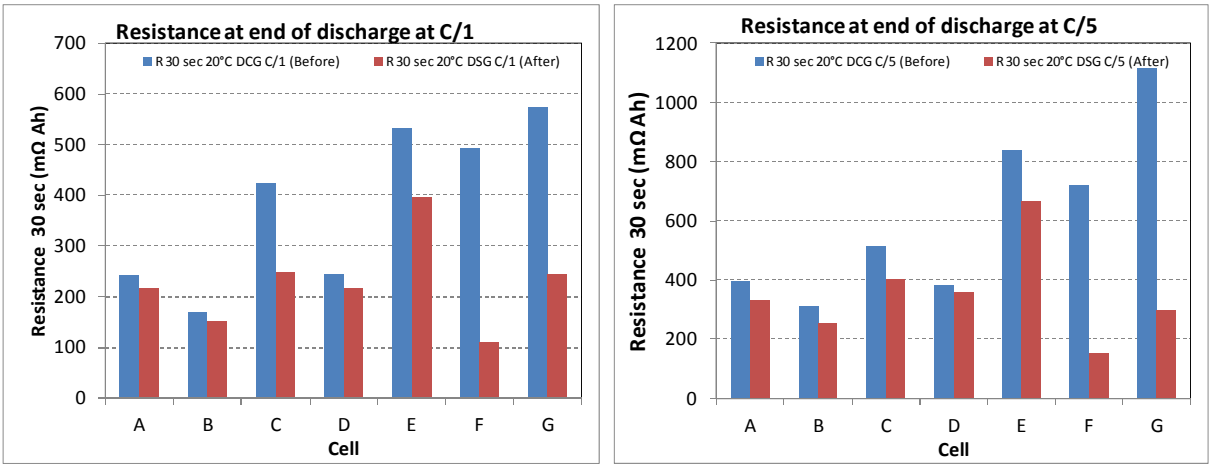


Figure 32. Resistance at end of discharge at 20°C (C/1 and C/5) before and after aging at 45°C



Module Testing Results

Cells selection for Module Testing

It was required to select cells to be mounted in module configuration (prototype sub-pack) and evaluate the performance against typical RTG crane duty cycles. This selection has been made by Ecopower and was settled for cells C, F and G:

- Cells A and B performed very well at cell level testing but they were finally rejected because of their high cost.
- Cell E performed poorly at power testing
- Cell D was rejected after conducting a quality audit of the manufacturing site.

Prismatic cells were retained (F and G) and cell C kept as a representative of the cylindrical cell format.

The three module types were cycled with three duty cycles as described in the section Module Testing: Test Flow and Procedures.

Figure 33 presents an example of the cycling performed on the module. In the following test, a cycle refers to a discharge (DCG) starting at 85% SOC and ending at 50%SOC followed by charging (CHG) back to 85% SOC. A lift refers to one repetition of the duty cycle and the steps are each power demand for a given time as presented in Figure 34. Duty Cycle 2 and 3 are composed of 12 steps, which are repeated for 10 min followed by 10 min rest at power equivalent to 30kW at crane level, until 50%SOC is reached. Then, the duty cycle is switched to charge mode, which corresponds to the same duty cycle but where 80kW equivalent crane is added to simulate the genset charge. During the 10 min rest, the charge is done at 50kW corresponding to 30kW auxiliary power subtracted to 80kW charge.

For all modules, 16 temperatures and voltages were recorded corresponding to each layer connected in series. The minimum, maximum and average values of these 16 "layers" are presented in the following figures.

Figure 33. Module cycling example

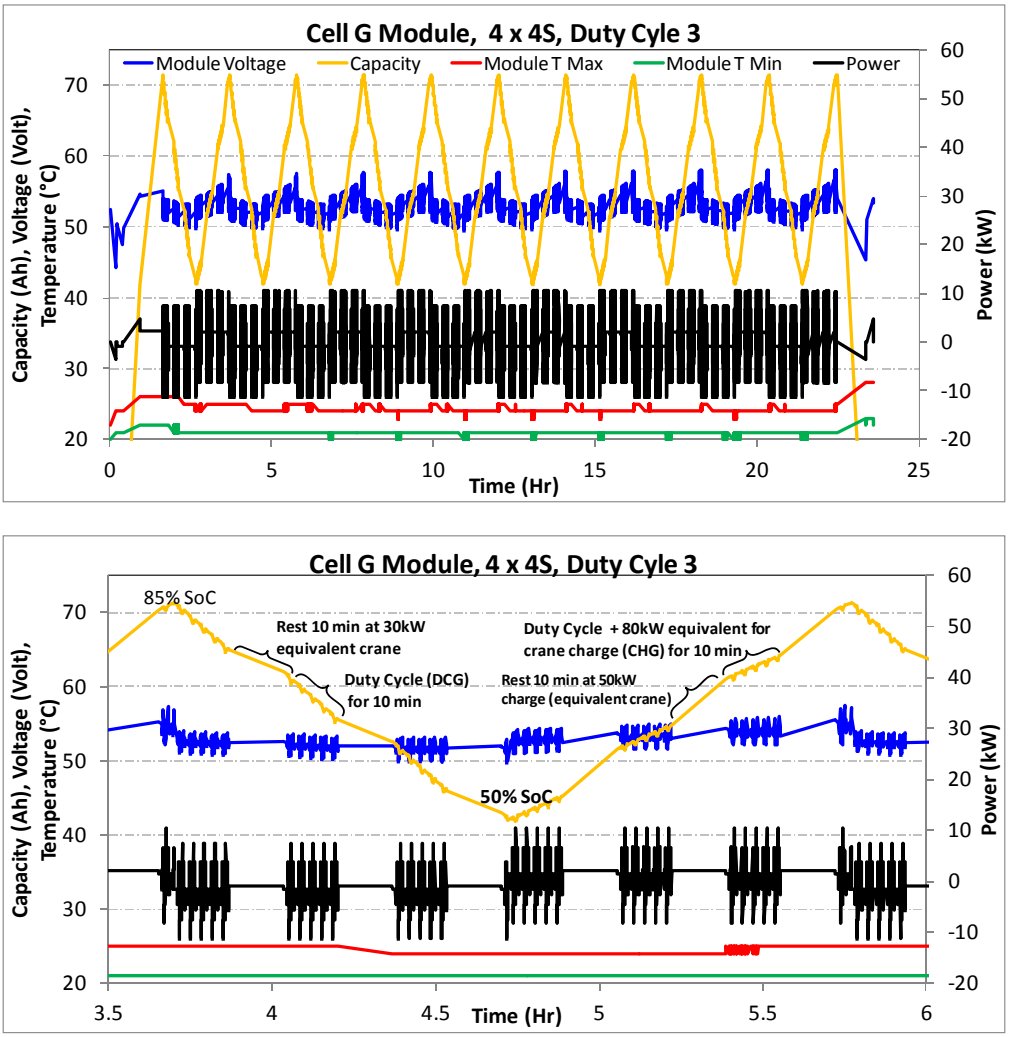
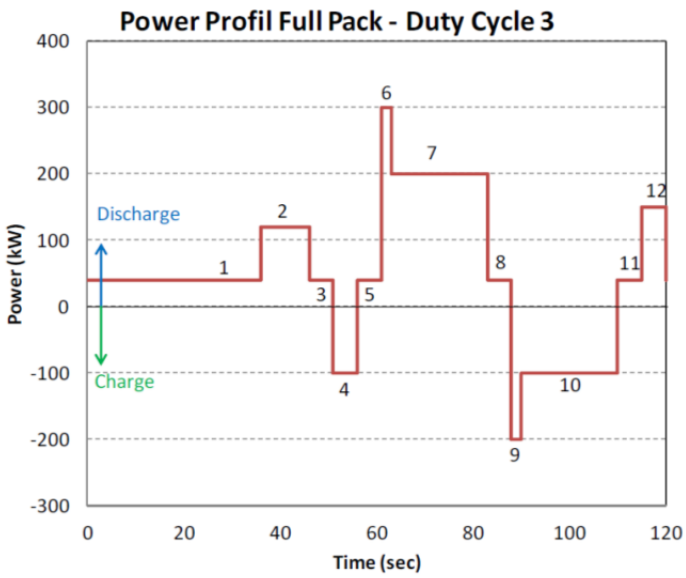


Figure 34. Module cycling step identification in Duty Cycle 2 & 3



Cell Voltages for high power demand

For duty cycle 1, the cell voltages were extracted for the high power demands in charge and in discharge as presented Figure 35 and Figure 38. For duty cycles 2 and 3, these voltages were extracted at end of each step. Figure 36 and Figure 37 show the cell voltages at end of step 6 as the module is discharging. Figure 39 and Figure 40 show the cell voltages at end of step 10 as the module is charging. These two steps have been the most demanding on the cells. Module built with Cell C shown poor performances for all duty cycles. The maximum voltage of 3.65V is exceeded for all duty cycles. The voltages go lower than the minimum limit of 2.5V during duty cycle 2. Cells F and G have well performed in discharge; Cell F has voltages slightly lower than cell G. During charge, Cell G shows a fast increase of the voltage at high SOC, involving that the SOC window has to be limited to lower SOC for this cell.

Figure 35. Cell voltage for high discharge power for Duty Cycle 1 without Rest

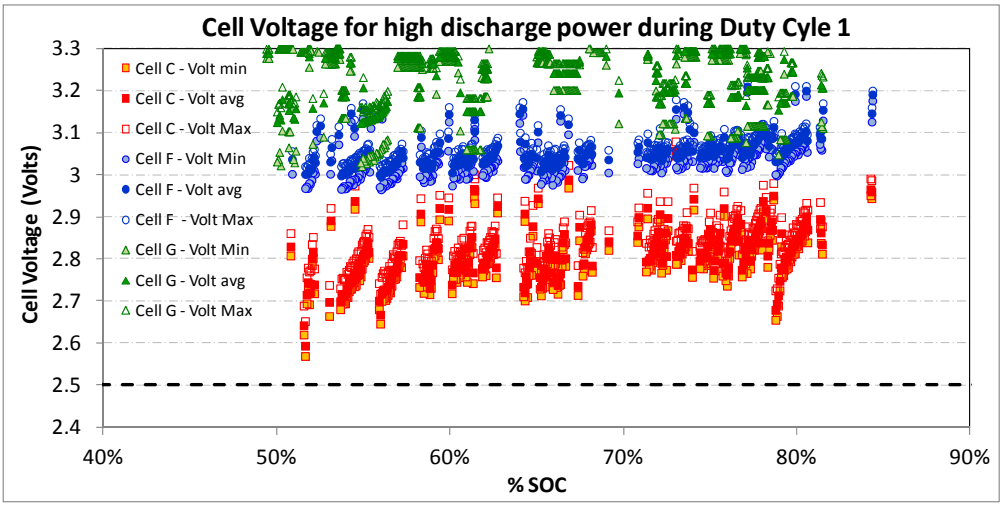


Figure 36. Cell voltage at end of Step 6 for Duty Cycle 2 with Rest

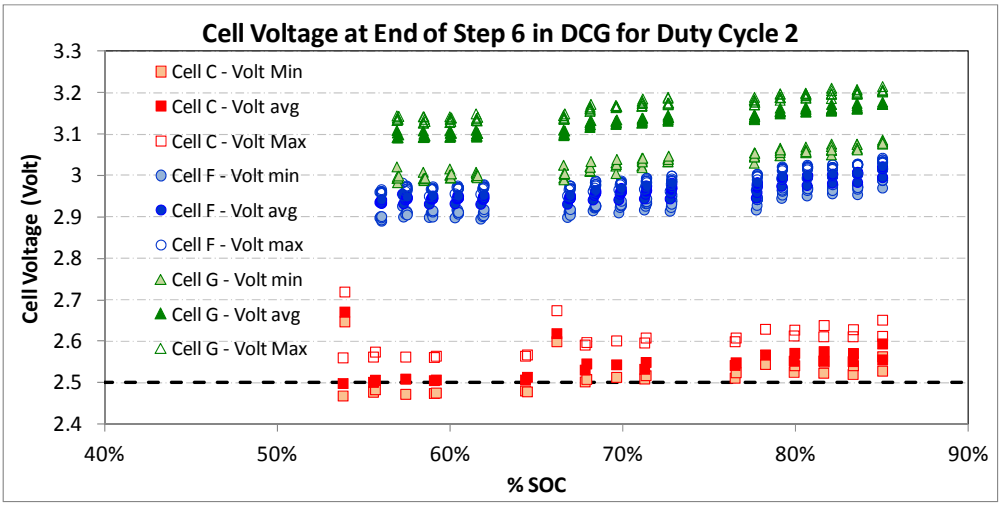


Figure 37. Cell Voltage at end of Step 6 for Duty Cycle 3 with Rest

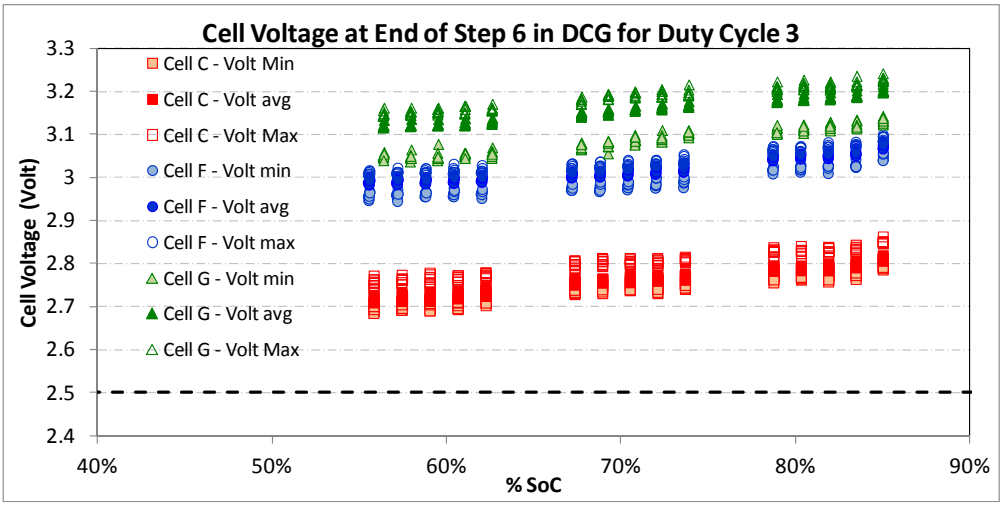


Figure 38. Cell voltage for high charge power for Duty Cycle 1 without Rest

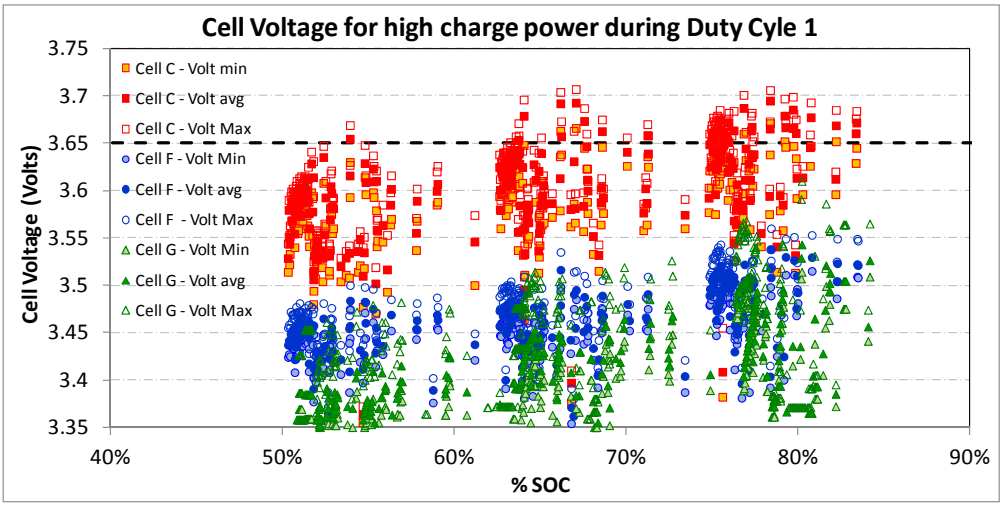


Figure 39. Cell voltage at end of Step 10 for Duty Cycle 2 with Rest

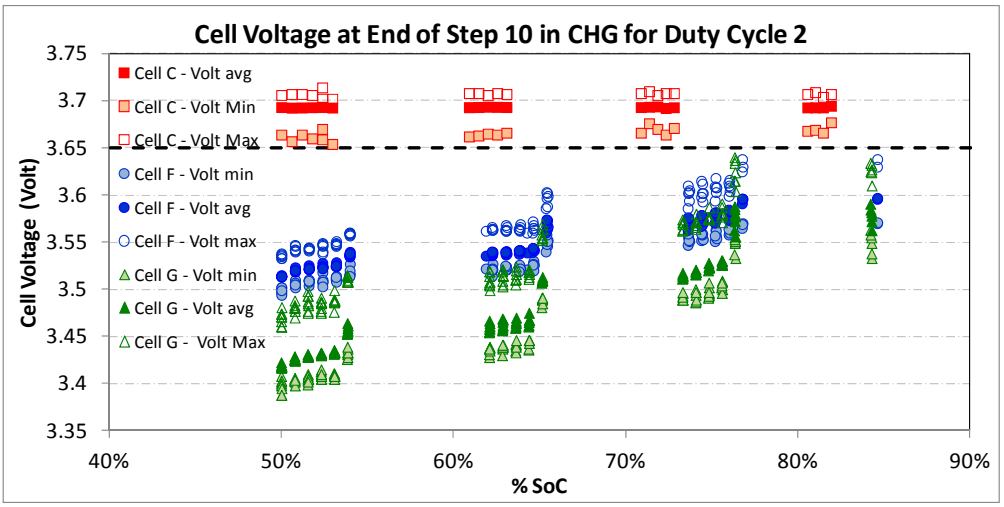
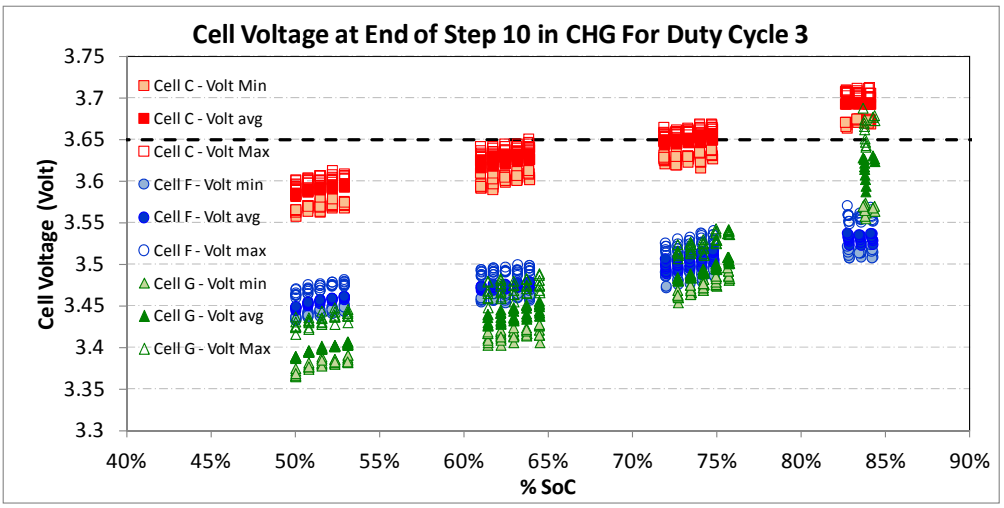


Figure 40. Cell voltage at end of Step 10 for Duty Cycle 3 with Rest



Energy Efficiency and Temperatures

The Energy efficiency (Energy Discharged (Wh Out)/Energy Charged (Wh In)) was calculated at end of each cycle for all the duty cycles and are shown in Figure 41 to Figure 43. As the Energy Efficiency represents the percentage of energy that can be used in operation, the rest of the energy being lost mainly as heat, the lowest is the energy efficiency, the higher is the heat generated. The temperatures are presented in Figure 44 to Figure 46 for each duty cycle. For duty cycle 1, minimum, maximum and average temperatures were extracted at end of each cycle and only one complete cycle is presented in Figure 44. For duty cycles 2 and 3, the temperatures were extracted at the end of each lift.

Cell G shows the best efficiency and also the lowest temperature during all duty cycle.

Cell F has shown less efficiency in duty cycle 2 and the maximum temperature stabilized around 37°C.

The cycling of Cell C with Duty Cycle 2 had to be stopped for safety reason due to the high temperature reached during testing. The temperatures of cell C vary during charge and discharge. These cells generate more heat during discharge and cool down during charge. The Energy Efficiency is less than 85% for all duty cycles involving that 15% of the energy is lost as heat.

Figure 41. Module energy efficiency for Duty Cycle 1 without Rest

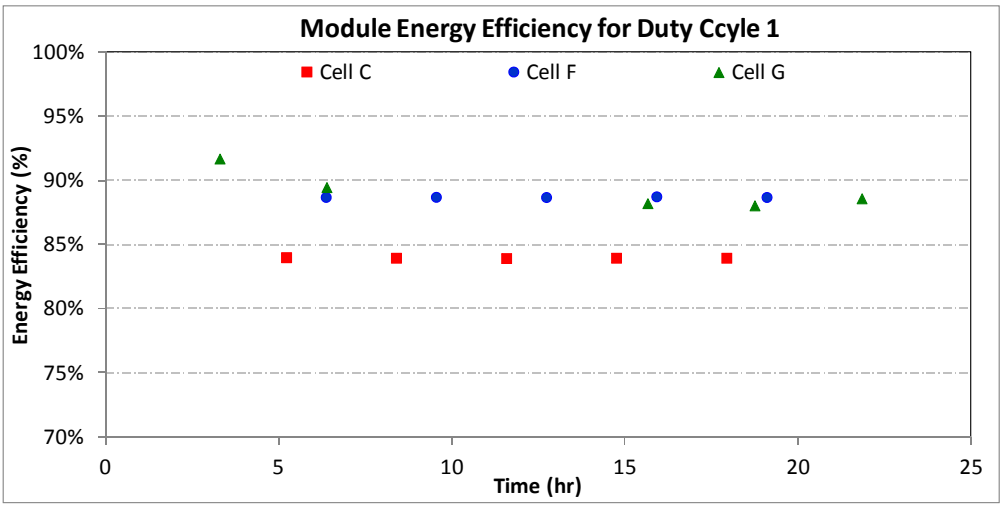


Figure 42 Energy Efficiency for Duty Cycle 2 with Rest

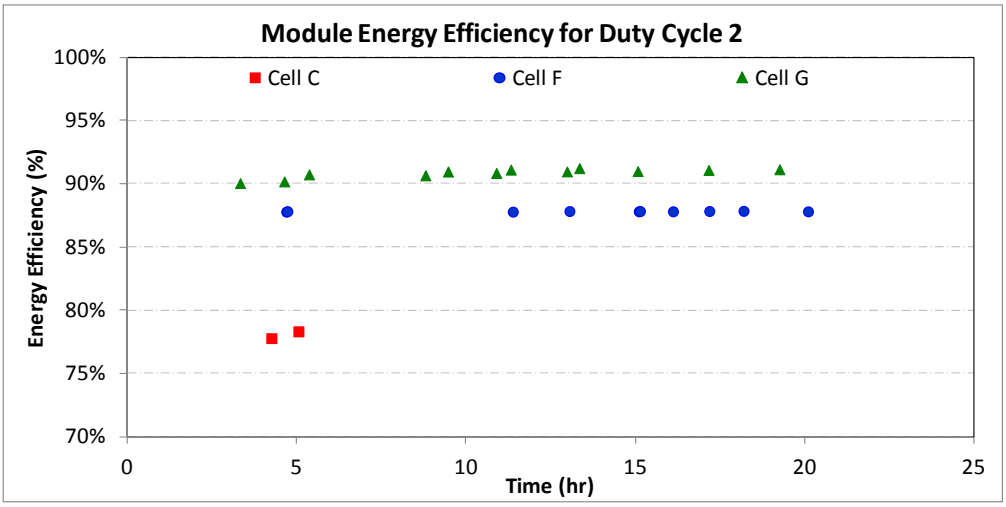


Figure 43. Energy efficiency for Duty Cycle 3 with Rest

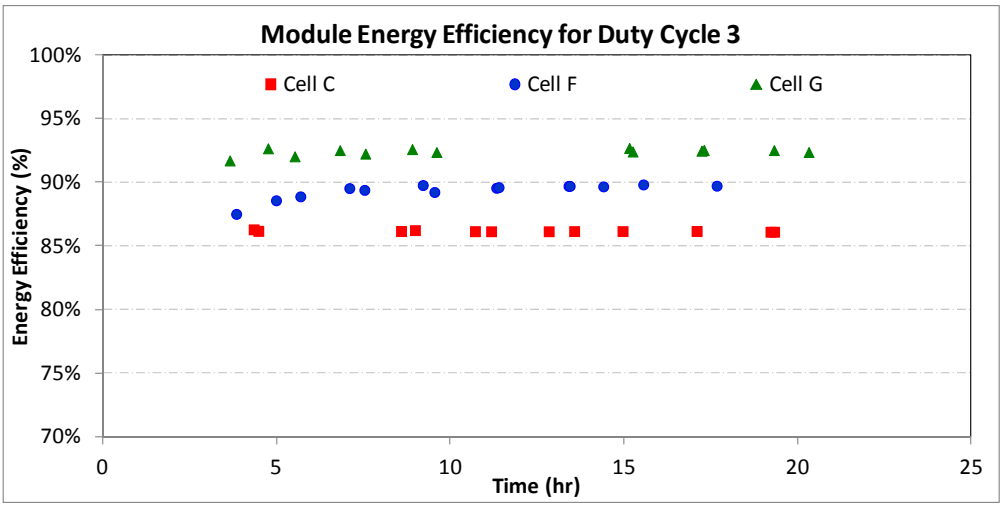


Figure 44. Temperatures for Duty Cycle 1 without Rest

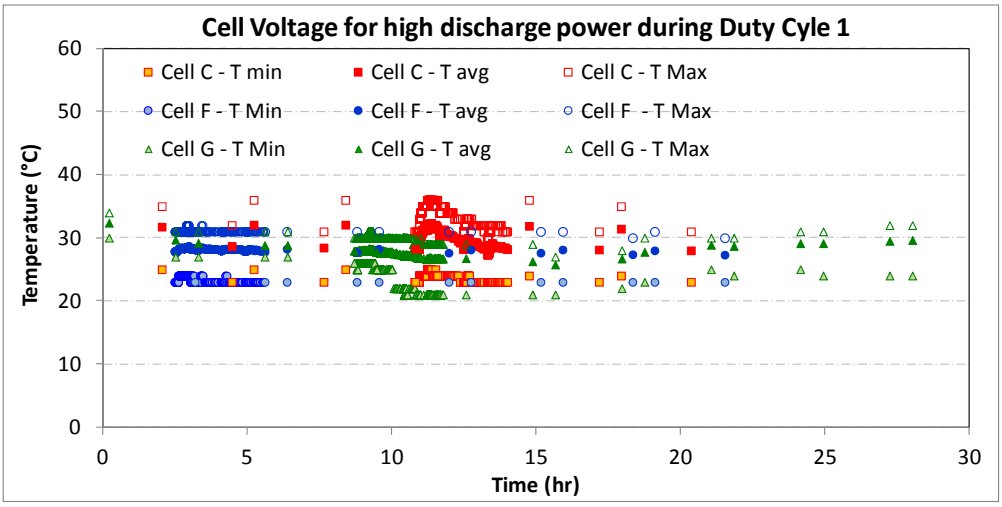


Figure 45. Temperature rise for Duty Cycle 2 with Rest

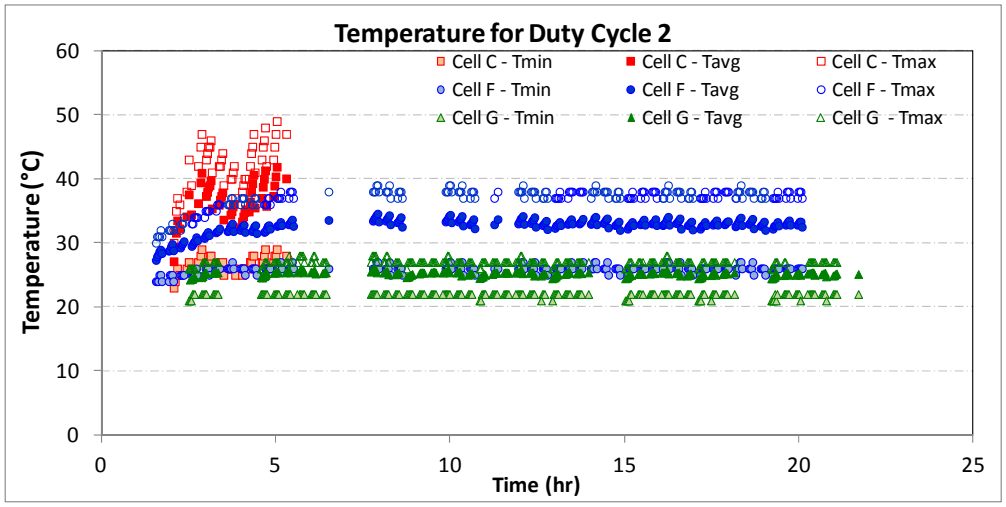
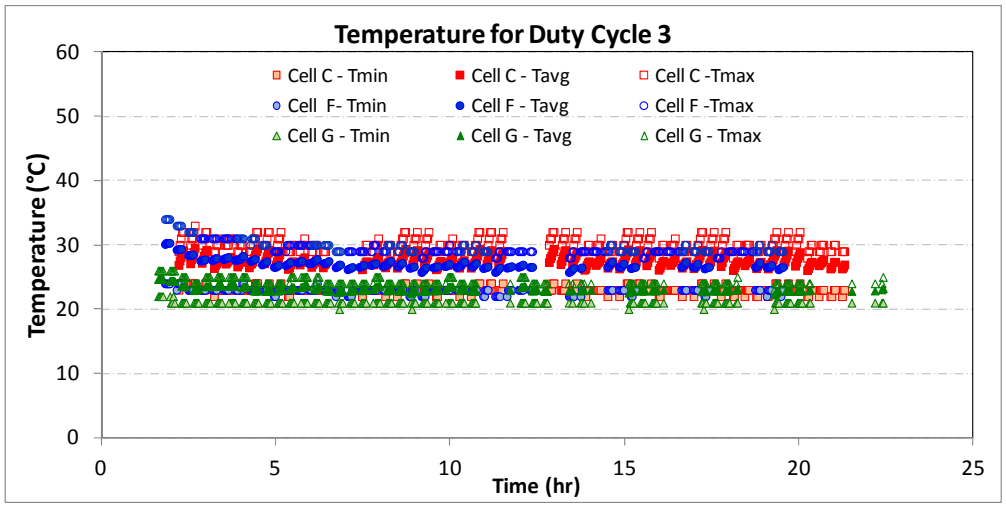


Figure 46. Temperature rise for Duty Cycle 3 with Rest



Resistance

For Duty Cycle 2 and 3, voltages and currents were extracted at end of each step, allowing calculation of resistance for specific step as followed:

$$R_{4-5}(Ohm\ Ah) = \frac{V_5 - V_4}{I_5 - I_4} \times Module\ Capacity\ (Ah)$$

where V is the voltage and I the current at the end of a step. The lower scripts (4 and 5) refer to the step number as presented in Figure 34. The resistance is normalized by the capacity to be compared for all cells and modules.

Resistances have been calculated for all high peak currents in charge and discharge, but remain barely constant overall SOC, except for $R_{10\text{-}11}$, and this is the case for duty cycle 2 and 3.

Cell G presents the lowest resistance during cycling except at end of charge. Cell F shows higher resistances but remain constant for the entire SOC window.

Figure 47. Resistance calculated between steps 10 and 11 ($R_{10\text{-}11}$) for Duty Cycle 2 with Rest

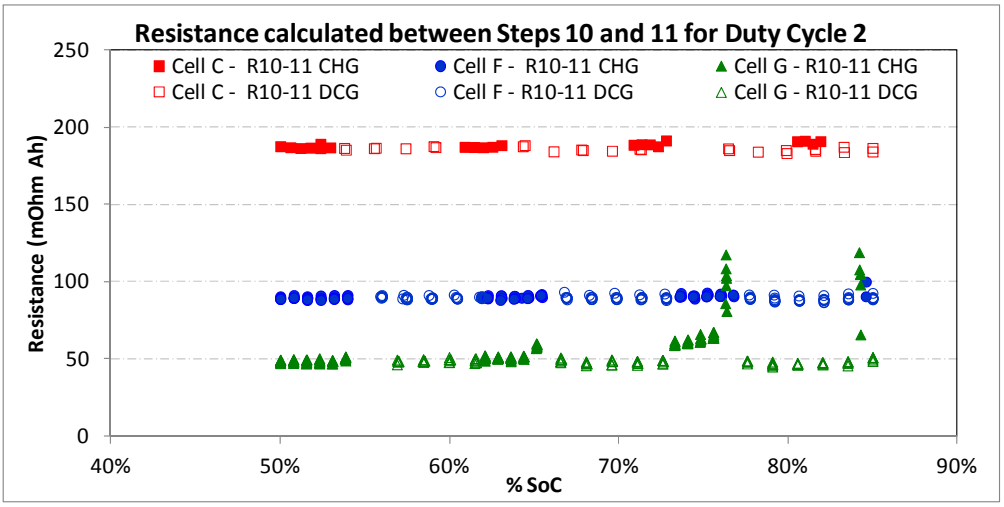
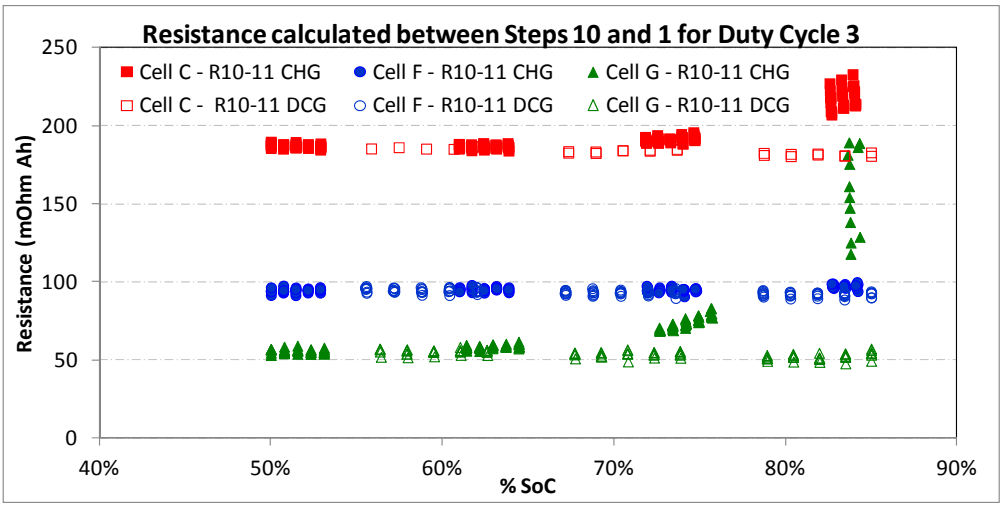


Figure 48. Resistance calculated between steps 10 and 11 ($R_{10\text{-}11}$) for Duty Cycle 3 with Rest



Module Testing Discussion

Modules have been tested following 3 duty cycles and the following parameters have been recorded and analyzed: high power discharge capability, high power charge capability, energy efficiency, temperature rise and resistance of the different modules.

For each duty cycle, the main conclusions are the following:

Duty cycle 1 (real field operation as monitored)**:**

- Module with Cells C did not pass the test; voltage limits were exceeded in charge
- The maximum temperature reached was at 36˚C for Modules C, 30˚C for module F and 27˚C for module G

Duty cycle 2 (worst case lifting conditions; heaviest containers and highest elevation):

- Module with Cells C did not pass the test:
  - Voltage limits were exceeded in charge and discharge
  - The maximum temperature reached was at 50˚C for Modules C after 3 hours; test has been stopped at this temperature for safety reasons
- The maximum temperature reached was at 38˚C for module F and 27˚C for module G;
- Module G shows an increase in resistance for SOC higher than 75% which will limit the state of charge window for operation.

Duty cycle 3 (average lifting conditions):

- Module with Cells C did not pass the test; voltage limits were exceeded in charge;
- The maximum temperature for all modules stayed below 32˚C ;
- Module G cannot take the full regen for higher state of charge than 80 %.

Modules F and G have passed all duty cycles in an equivalent configuration of 120kWh at pack level.

To use Cell C in crane operation, the pack should be at least 150kWh.

Discussion/Observations

Objectives vs. Results

From the Grant Activities (Scope of Work):

> *"Task 1: Selection of and assembly of battery sub-pack*
>
> *2.1. Task Statement: The PERFORMING PARTY will procure and test different commercially available battery technologies then select and test the technology best suited for the prototype RTG crane power plant."*

As mentioned, the objective of the phase one was to determine if a viable solution of energy storage that is safe, compact enough and economically viable existed.

The formal criteria were formulated as follows, from the Grant Activities (Scope of Work):

> *"2.1.3. The PERFORMING PARTY will select the preferred battery technology from the tested sub-packs. The selected technology will demonstrate the following characteristics, as compared with lead acid battery technology: at least two times smaller than the lead acid battery accumulator used on the first prototype version; recharging two times faster; presenting a power/energy ratio of at least 5 at peak power."*

Each criterion was addressed as described below.

At least two times smaller than the lead acid battery accumulator used on the first prototype version

- We did preliminary calculations and demonstrate that this higher energy density permitted to reach our objectives of reduction in size to fit smaller cranes and to significantly simplify retrofit when compared with lead acid battery technology requiring crane structure modification and complex installation.
- From the battery testing performed, we are planning to build a 120 kWh battery pack. This is 3.5 times less capacity of the first Ecocrane prototype and 2.2 times less than the last unit installed in Port of Los Angeles using lead acid battery. The energy density of Li-ion based on $LiFePO_4$ chemistry being 2 times higher than the one of VRLA technology. The reduction in size will represent a reduction of pack size somewhere between 4 and 7 times.
- Preliminary design shows that the complete new hybrid power plant using Li-ion batteries system will have the same size than conventional genset cabinet to be replaced.

Safe regarding thermal run-away in over charge and over discharge

- For safety reason, we have researched solutions and focus on technology using $LiFePO_4$ active material as cathode. This technology is safer and resists higher temperature, is not susceptible to thermal runaway in over charge. Overall this technology is recognized as a safer alternative than other technologies but presents a lower energy density. We have demonstrated that Li-ion technology using $LiFePO_4$ invented by *Goodenough* at University of Texas in Austin and patented by Hydro Quebec

represents a safe solution and can be used as energy accumulator in the RTG Crane to be retrofitted at APMT port of Houston.

Authorizing recharge current at least two times higher with 80% efficiency

- We have demonstrated during our test that all cells could be recharged at 2C at least; recommendation for charging VRLA batteries is much lower forcing to install much more capacity to manage the power.

Presenting a power (kW)/energy (kWh) ratio of at least 5.

- All cells were tested in power up to peak power of 5C.

Designed and sized to have a minimal life expectancy of 7 years or 4 times the one of a lead acid battery for this type of application.

- Knowing that $LiFePO_4$ technology lose 20% of capacity at every 2000 full cycles. Considering an average power of 40 kW during operation. We calculate 18 hybrid cycles of 14kWh in average every day. This corresponds to 600 full cycles per year. By extrapolation, the remaining energy of the pack would be around 90kWh after the 7th year.
- We need to install the pack in order to validate this assumption.

Critical issues

- Special care will be taken to minimize all contact resistances.
- Welding analysis will be incorporated in module manufacturing process.

Technical and commercial viability of the proposed approach

The work done for the task one was to evaluate which cell technology, cell format and cell resistance could be used to equip practically an RTG Crane and to evaluate the size of the pack required for the application.

We have demonstrated that high capacity prismatic cells could be used for the application, making easier to demonstrate commercial viability. Some work remains to be completed before the final ROI evaluation.

We have answered all these questions up to a level that permits to complete design and to manufacture the battery pack and the complete hybrid power plant.

The goals of the project are technically achievable. It will be possible to replace a tier 2; 500kW engine with a tier 4i smaller than 100kW and a pack of li-ion batteries. Basic calculations show that objectives regarding fuel and emission reduction can be reached.

Scope for future work

Future work is essentially related to task 2 to 4 of the current project: to complete engineering of the Li-ion hybrid power pack, to manufacture and to install the power plant on a RTG crane at APMT terminal at Port of Houston. This development could lead to Li-ion pack development for other applications.

Intellectual Properties/Publications/Presentations

No new IP or invention disclosure was filed during the Task 1 of the project. Concepts were patented before the application for this demonstration project.

Summary/Conclusions

Cells based on $LiFePO_4$/graphite chemistry were tested; 2 power cells (~2.5Ah) and 3 energy cells (~3.2Ah) in format 26650, one power cell (~4.5Ah) in format 32113, and two custom prismatic cells (~16 Ah, ~40Ah). All 8 cells were packaged in sealed metal enclosure.

- 1 cell was rejected because high impedance and poor results at incoming inspection.
- 2 cells were rejected to the poor quality of manufacturing and quality inconsistency during EcoPower Audit
- 2 high end cells were rejected because high price that could not be justified.
- The 3 other cells were assembled in configuration test modules: 1 format 26650 and the two prismatic cells (~16 Ah, ~40Ah).

For the RTG crane application, the pack nominal voltage is targeted at 700V. The results obtained during characterization confirmed that pack energy shall be in the range of 120kWh. This represents between 11000 and 12 000 cells format 26650 (cylindrical cell of 26mm of diameter and 65 mm length). There is an obvious interest to go with higher capacity cells to limit the complexity and the number of connections. Cells of 15 and 40 Ah would require respectively 8000 and 3000 units. On the other hand, it is more challenging to cool bigger cells. For cost reason and due to the feasibility on a RTG, it is planned to use convection air cooling to cool the batteries. Test performed at ECS confirmed that bigger prismatic cells can deliver required power and still be cooled by air convection. Both prismatic cells can be used for the application.

In the module test phase, Cell C demonstrated extremely high temperature rise and could not perform Duty Cycle 2. Cell F exhibits a good balance of a number of characteristics but would need to be used in an oversized pack or used with active thermal management due to poor performance at low temperatures. CellG, despite its poor performance on the aging test, could be used in this application with appropriate precautions to ensure that impedance growth and capacity degradation do not represent a significant failure risk.