Summary of Test Results

True Balancing – Generation 3

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Overview

This is a summary of test results on the Gen 3 True Balancing system as of 2021-June-6.

A detailed report on test results is in a separate (much longer) document.

All test results are empirical measurements of True Balancing performance in 12-cell NMC battery packs with nominal capacity of 2.4Ah.

We are testing in three phases:

- Phase 1: One 12-cell module with 2.4Ah NMC cells
- Phase 2: Two 12-cell modules connected in series, also with 2.4Ah NMC cells
- Phase 3: Two or three 12-cell modules in series, with 19Ah LFP cells

All test results in this report are from Phase 1.

Key Results

- True Balancing can add between 6% and 14% to the capacity of the pack
  - This represents about a thousand dollars of added value in an EV battery pack
- True Balancing is at least 95% efficient
  - The two most important goals in battery management are maximizing battery capacity and maintaining optimum efficiency of energy transfer. Achieving these goals maximizes the value and life of the battery.
  - Our test results confirm that True Balancing delivers greater battery capacity at higher efficiency than any other battery management technology we know of.

Note: All tests performed to date are prior to optimization of True Balancing operating parameters. As we progress with the tests, we are modifying the operating parameters to steadily improve performance. When parameters are optimized, added capacity and operating efficiency should be higher.

Contents

Separate Report (available upon request): Detailed Description of Every Test in Phase 1

- Description of test set up and test parameters
- Analysis of sources of error in the test system
- Complete description of each test performed to date
- Comments on the results and/or significance of each test

Section 1: Tests to Measure Efficiency of True Balancing

Test 2 measured the efficiency of True Balancing in worst case conditions.

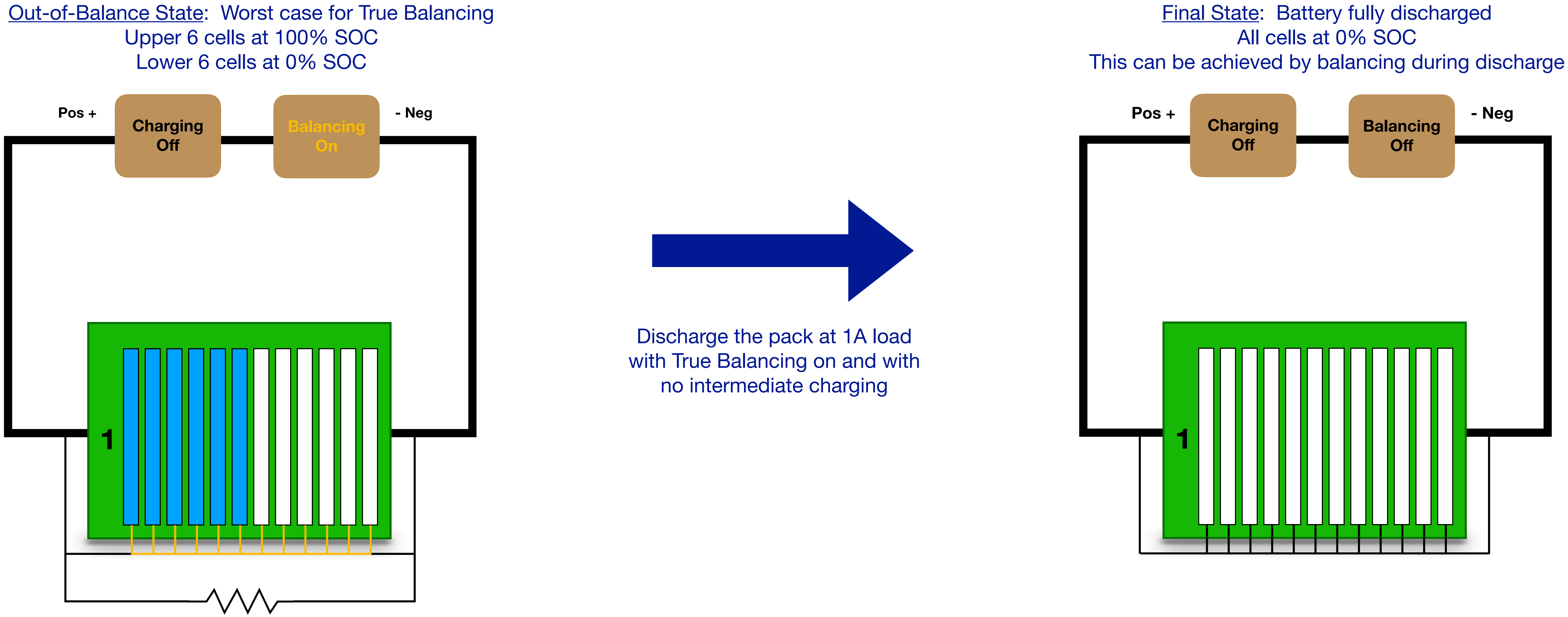
Test 3 measured the efficiency of True Balancing in an extremely out-of-balance condition (but not worst case)

These tests quantify how efficiently True Balancing can balance a battery that is extremely out-of-balance.

To make these tests challenging, we set the cells to extreme out-of-balance conditions that would never be encountered in the real world.

Results are on the following two pages.

Test 2: Measure the efficiency of True Balancing in a worst case scenario



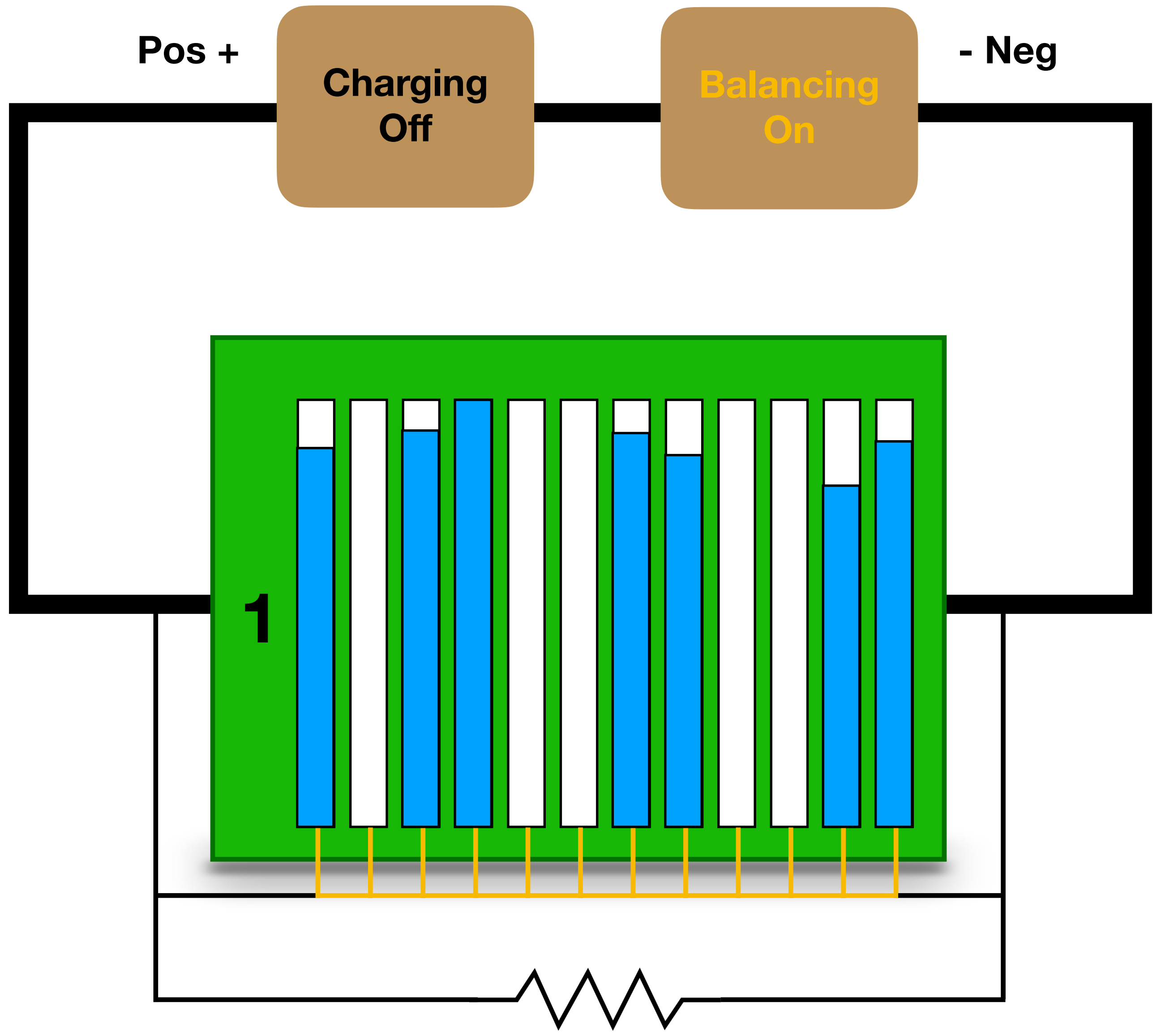
Result: 82.5% of the pack's energy was delivered to the load

Comments: This test is an absolute worst case scenario for measuring the efficiency of True Balancing. The initial out-of-balance state is extreme, and the test hardware and firmware had not yet been optimized – this was only the 2nd test we ran. So True Balancing was operating well below maximum efficiency.

Delivering more than 80% of the battery's energy to the load in this test case is a good demonstration of the capabilities of True Balancing. All other balancing systems that we know of would treat this situation as a dead battery — i.e. no energy could be delivered to the load until the battery had completed a cycle of recharging and pre-balancing.

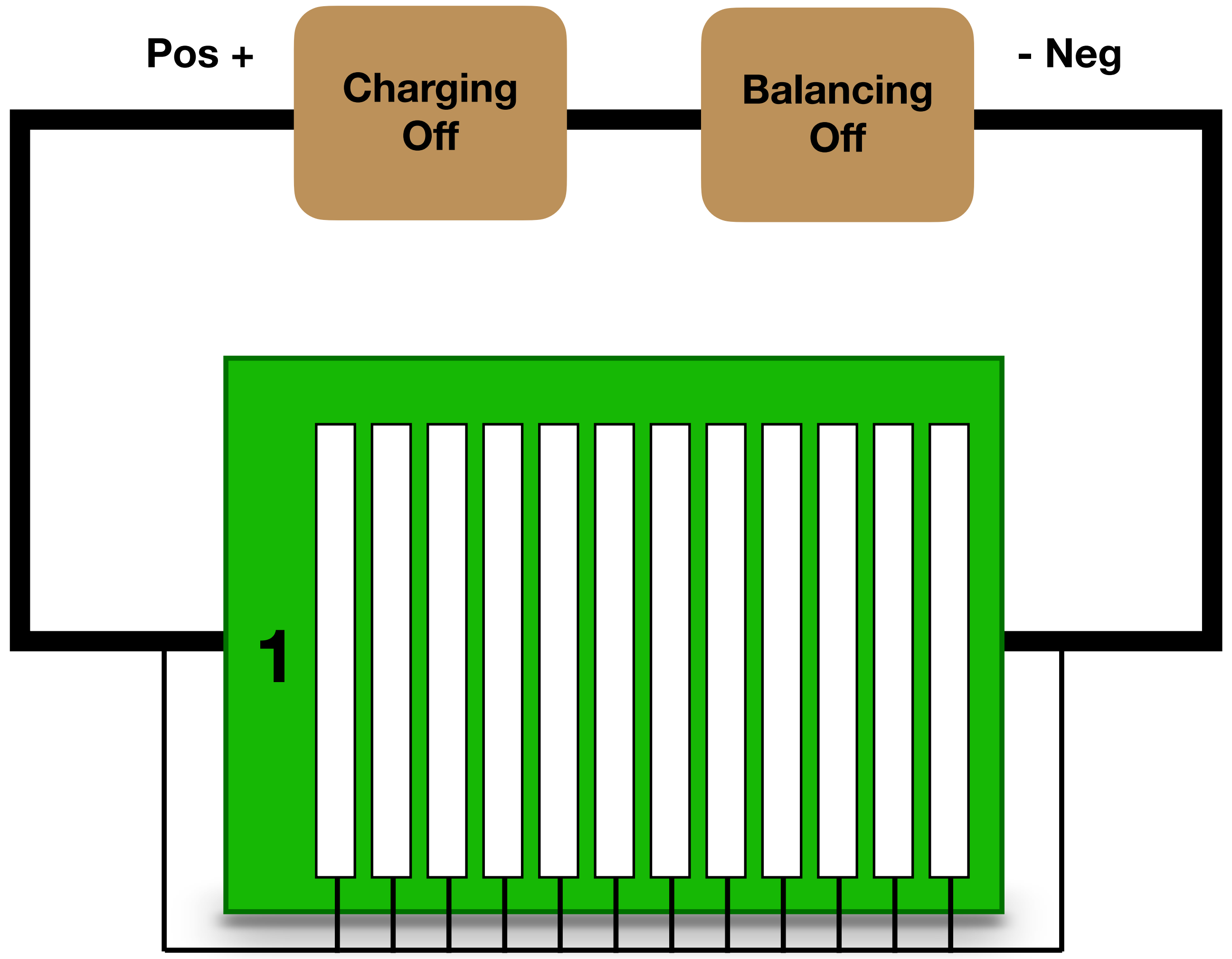
Test 3: Measure the efficiency of True Balancing with extremely out-of-balance cells

Out-of-Balance State:
Cells 3, 4, 7, 8 and 11 at 0% SOC
All other cells at high SOC, but not balanced



Discharge the pack at 1A load
with True Balancing on and with
no intermediate charging

Final State: Battery fully discharged
All cells at 0% SOC
This can be achieved by balancing during discharge



Result: 95% of the pack's energy was delivered to the load

Comments: We created an extremely out-of-balance battery, and the test hardware and firmware had still not been optimized. In this test case True Balancing had 95% efficiency in terms of delivering the battery's energy to the load.

We know of no other balancing technology that can achieve 95% efficiency in best case conditions (as opposed to the condition in this test). Existing balancing technologies would treat this as a dead battery that requires charging and balancing before it could start a discharge cycle.

With True Balancing, this battery did not need to be charged and pre-balanced. True Balancing could immediately start balancing the cells and then start powering the load and deliver 95% of the battery's energy to the load.

Section 2: Measure How Much Energy True Balancing Adds to the Pack

Test 5 measured the additional energy True Balancing could get out of the pack following a discharge cycle that simulates passive balancing.

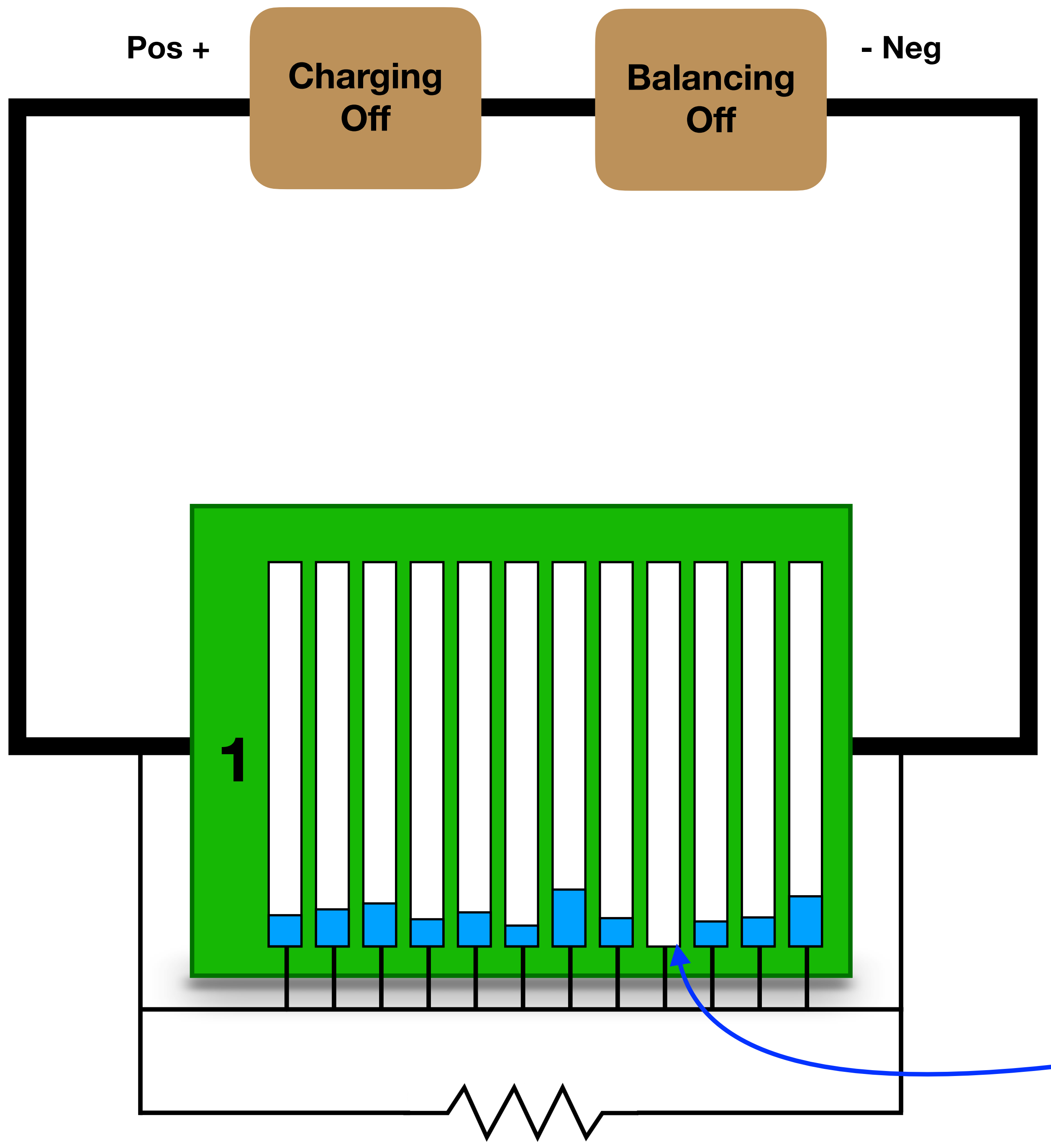
Test 7 measured how much energy True Balancing adds to the pack during consecutive charge and discharge cycles at different cut-off currents

The purpose of these tests is to quantify one of the most important features of True Balancing: The additional energy it can get into the pack during charge cycles and the additional energy it can get out of the pack during discharge cycles.

Note: In these tests, charge and discharge current are around 0.5C, so we simulate passive balancing by leaving True Balancing off. At these charge/discharge rates, the net impact of passive balancing is negligible.

Test 5: Measure the additional capacity True Balancing adds to the battery at the end of a full discharge cycle

Initial State:
The pack was discharged to COV with True Balancing off

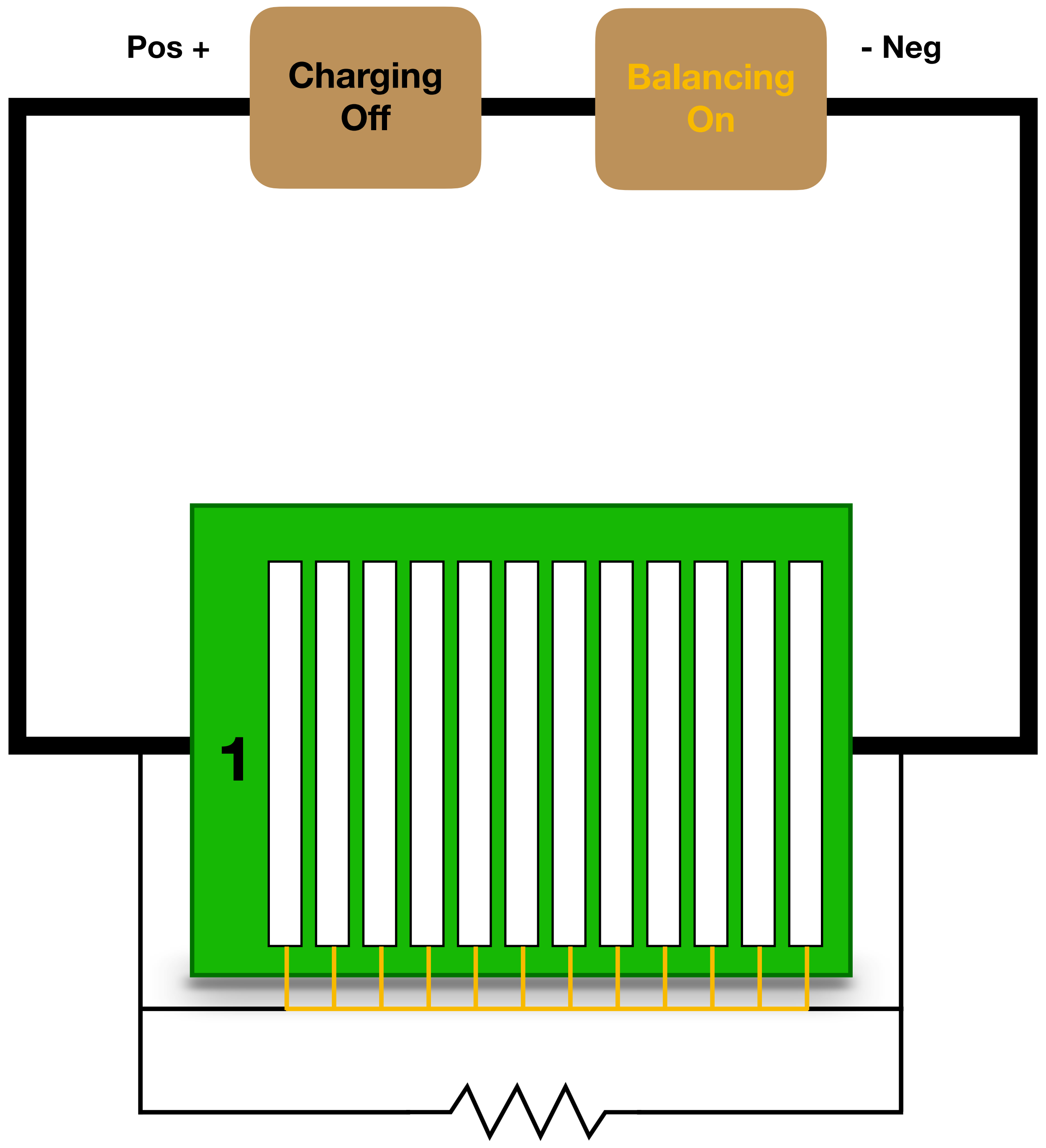


We discharged with balancing off. Cell 4 reached COV first. If this pack had passive balancing, the battery would be dead at this point.

This is when we turned on True Balancing.

Discharge the pack at 1A load with True Balancing on and with no intermediate charging

Final State:
We used True Balancing to extract the residual energy from the pack



Result: True Balancing added 11% to the capacity of the pack

True Balancing extracted 0.23Ah of additional energy from a pack that has a measured capacity of 2.06Ah. A passive balancing system would treat the initial state in this test as a dead battery that must be recharged.

If this were an EV battery pack with a nominal range of 300 miles, True Balancing could add 33 miles of range to the vehicle based on this test result.

Test 7: Measure the capacity that True Balancing adds with changes to the cut-off current (COC)*

In all of these tests, COV = 2800mV and FCV = 4150mV

Cycle #1: Charge

TB	COC (mA)	Capacity Ah
OFF	370	1.92
OFF	200	2.01
ON	200	2.13
Capacity Gain		6%

Cycle #2: Discharge

TB	COC (mA)	Capacity Ah
OFF	900	1.94
ON	900	2.11
Capacity Gain		9%

Cycle #3: Recharge

TB	COC (mA)	Capacity Ah
ON	200	2.12
N/A		
Capacity Gain		N/A

Cycle #4: Discharge

TB	COC (mA)	Capacity Ah
OFF	900	1.93
ON	900	2.12
Capacity Gain		9%

Cycle #5: Recharge

TB	COC (mA)	Capacity Ah
OFF	200	2.02
ON	50	2.31
Capacity Gain		14%

Result: True Balancing added between 6% and 14% to the capacity of the pack

COC is a parameter that can be set in firmware. True Balancing has a number of parameters that can be set to optimize operating conditions for any kind of battery in any use environment. As of test 7, we have not yet optimized all of True Balancing's operating parameters. (We're adjusting and improving operating parameters with each round of tests.)

*COC (cut-off current) is the current on the primary charge path at which charging or discharging is terminated (or cut off). At the end of charge and discharge cycles, cell impedance begins to rise so primary charge current begins to drop. With True Balancing you can specify how low you want primary charge current to drop before you terminate the charge or discharge cycle.

Two other parameters that can be set are full charge voltage (FCV) and cut-off voltage (COV). These are the upper and lower limits, respectively, of cell voltages that are allowed to occur during charging and discharging.

Test 7 — More Comments

Cycle #1: Charge

TB	COC (mA)	Capacity Ah
OFF	370	1.92
OFF	200	2.01
ON	200	2.13
Capacity Gain		6%

Cycle #2: Discharge

TB	COC (mA)	Capacity Ah
OFF	900	1.94
ON	900	2.11
Capacity Gain		9%

Cycle #3: Recharge

TB	COC (mA)	Capacity Ah
ON	200	2.12
N/A		
Capacity Gain		N/A

99%

100%

Cycle #4: Discharge

TB	COC (mA)	Capacity Ah
OFF	900	1.93
ON	900	2.12
Capacity Gain		9%

Cycle #5: Recharge

TB	COC (mA)	Capacity Ah
OFF	200	2.02
ON	50	2.31
Capacity Gain		14%

Result: Maximum utilization of battery capacity

Note that in cycle 2, True Balancing delivered 99% of the battery's energy to the load. In cycle 4, True Balancing delivered 100% of the battery's energy to the load. Actually, it's impossible to deliver 100% of the battery's energy to the load, especially when balancing is occurring.

There is inherent noise in our test and measurement system which adds an error term to all measurements. So these results can't be interpreted literally, but they are an indication of the efficiency and effectiveness of True Balancing.

Test 7 — Final Comments (For Engineers Only!)

Two aspects of test 7 that might be interesting to battery and BMS engineers:

(1) This was the first set of tests on pack 2. Some of the cells in pack 2 had been dormant for more than two years. We did not measure the capacities of the cells in the pack prior to starting test 7. It was a blind test.

We measured cell capacity after we completed the test. The two weakest cells had capacities of 1.91Ah and 1.95Ah. The strongest cell had capacity of 2.34Ah. That's a range of 22.5% between the strongest weakest cells. So test 7 is a good demonstration of one of the key advantages of True Balancing:

> *With passive balancing systems, the usable capacity of the pack is limited to the capacity of the weakest cell in the pack. With True Balancing, the usable capacity of the pack is approximately equal to the total capacity of all of the cells in the pack, and the total capacity of all of the cells is the theoretical maximum capacity of any battery pack. With True Balancing, the usable capacity of the pack is always as close as possible to the theoretical maximum capacity of the pack.*

This advantage of True Balancing becomes significant when the cells are not well matched, as demonstrated in test 7. Cell capacities drift into unpredictable states as the battery is used. This is a particular problem in real world use, where you can't control the use environment and use patterns. As cell capacities drift into unpredictable states, True Balancing can always deliver the total capacity of the entire pack to the load, minus a small loss of between 2.5% and 5%.

(2) In test 7 we tested three different values of cut-off current (COC) at the end of the charge cycle. We are starting to gather data on how much additional energy True Balancing can get into the pack at different COC's. We tested values of 370mA, 200mA and 50mA for charge cycle COC. (We used a fixed value of 900mA for discharge cycle COC.)

During charging, True Balancing brings each cell up to FCV. After all of the cells have reached FCV, True Balancing will terminate charging when the primary charge current drops to COC.

COC is a parameter that can be set to any level. You can set COC to maximize battery capacity or to minimize stress on the cells or at any point in between those two extremes. And COC does not need to be a fixed parameter. It can be adjusted at any time to meet specific requirements. For example, the default setting for COC could be for low stress on the cells. But if the driver needs to make a long trip, COC could be temporarily adjusted to a lower value to provide longer driving range. This is another unique advantage of True Balancing.

Final Comments

The tests to date cover just a fraction of the benefits and advantages that True Balancing brings to battery systems. However these initial test results demonstrate three of the biggest advantages of True Balancing:

- Put more energy into the battery during charge cycles
- Get more energy out of the battery during discharge cycles
- At least 95% efficiency during balancing

These are just three benefits that True Balancing brings to batteries. There are almost 20 more.

However the test results to quantify just these three features demonstrate that a payback ratio of about 10:1 can be achieved by switching to True Balancing.

Additional Documents

The following documents are available:

- Illustration and explanation of the Gen 3 hardware and test system
- Detailed description of tests performed to date
- Full list of the features and benefits that True Balancing brings to battery systems
- Description of the range of tests that can be performed with the Gen 3 system
  - This last document will be helpful to review if you want to request a specific test

Contact Clint O’Conner to request any of these documents: clint@truebalancing.com