race-pack characterization.

soc curves + safety-fault testing.

vehicle: nimbus 2020/2021
race: ASC/FSGP 2021

How this note-book works:

This is a set of documentation on how to characterize the full-pack including state-of-charge (SoC) curves, determining currents to run SoC @, and accounting for impedance. We also reproduce the main battery faults to directly check safety conditions of the pack. This procedure can be used for the 2021 race-pack but can be adapted for future packs. **Please test responsibly, please practice proper HV safety.**

Table of contents:

characterization (past fault-testing).

data analysis + case study.

Battery Modes reference (errors):

```
0 NL - null
1 ST - startup
2 RN - run
3 E1 - error manual fault
4 E2 - error under voltage
5 E3 - error over voltage
6 E4 - error over current
7 E5 - error over temperature
8 E6 - error signal fault

ST -> RN, E?
RN -> E?
```

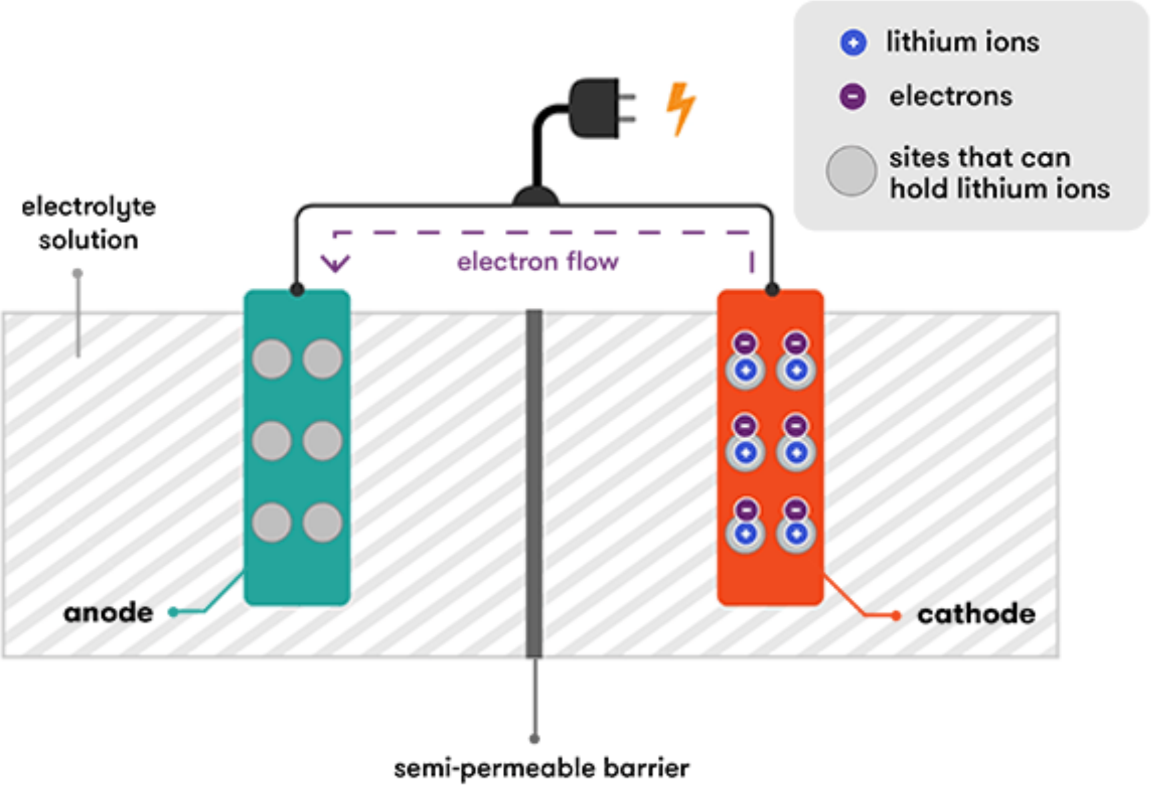
Battery state review:

A summary of the above modes,

NULL – an unknown battery mode it likely means the battery is not connected to the vehicle.
ST – battery is performing initial checks and will be ready soon.
RN – all system operation ready to drive.
E1 – the appropriate error for when the E-Stop of the vehicle is pressed.
E2 – appropriate error for MINIMUM cell voltage < 3.3 V/cell on the pack.
E3 – appropriate error for MAXIMUM cell voltage > 4.2 V/cell.
E4 – appropriate error for array/motor supplying too much current to pack *or* for systems drawing too much current from pack.
E5 – module thermistors monitoring battery temperature are too hot for safe operation.
E6 – likely means a cell-monitoring board is not connected or there is something wrong w/ the ISO-SPI communication between the modules themselves and the headboard.

SoC review:

So really quickly, what is battery State-of-Charge (SoC) and why do we care? To start, we need to know a little bit about battery chemistry…



The above image is from (https://www.science.org.au/curious/technology-future/lithium-ion-batteries) and essentially is a good picture of what's happening inside the battery cells. When charged, electrons sit on the anode (-) and as the battery discharges they flow to the cathode (+). Note the direction in the above diagram is current flowing + —> - which is CONVENTIONAL current—flow of protons—not actual current.

Essentially, as the battery discharges, the electrons build up on the cathode and the process of charging returns the electrons to the cathode. If we think of the anode as an electron bank that we can draw electrons from to power the circuit, the SoC of a battery is the amount of electron-charge left in this bank—in Coulombs—that we can use before the battery is considered empty.

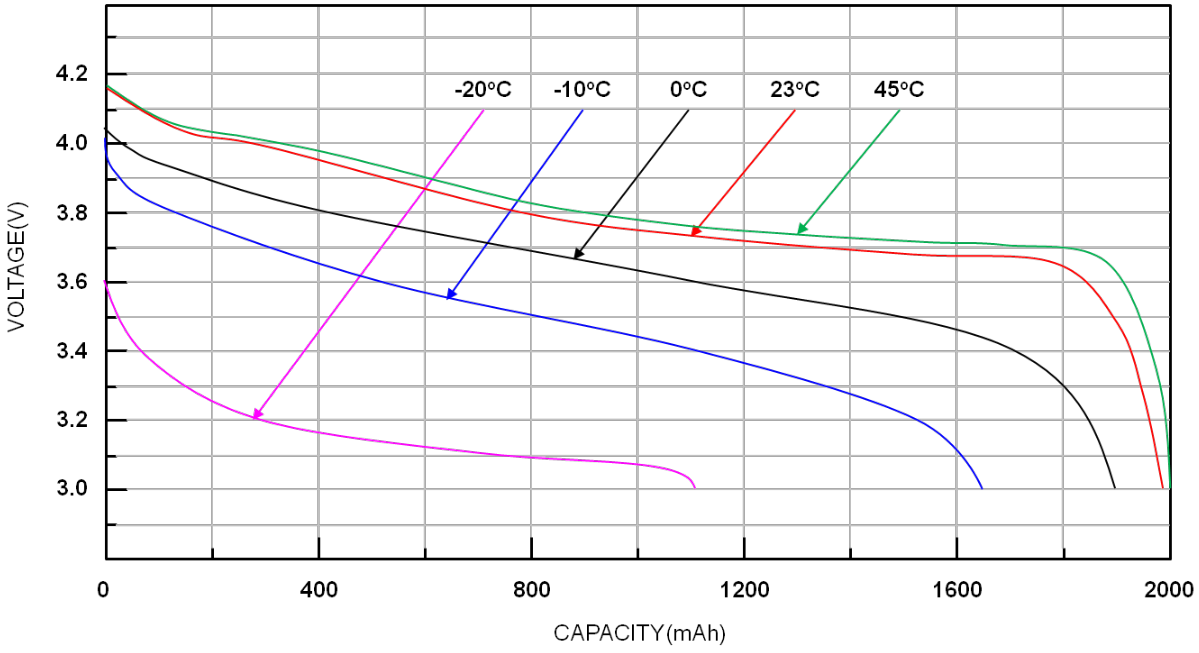
why not use cell voltage?:

So you might say well, I know Li-ion batteries as they discharge their cell voltage drops. So can't we just track the voltage and then we know how much is left in the pack?

Theoretically yes, but there's a few reasons we should not…

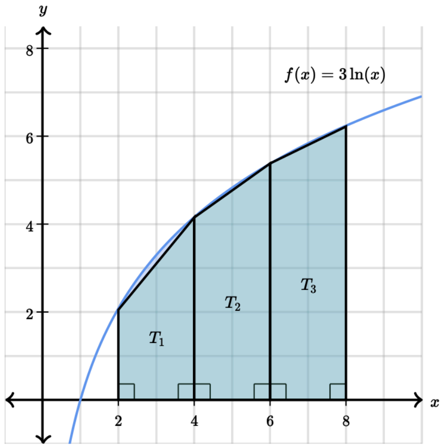
(1) a battery is not an ideal voltage source, you can think of it as an ideal voltage source in series with a small resistance and think about how as you start drawing current the voltage across this source + resistance will be less than the actual voltage of the battery, these are the impedance effects.
(2) many environmental factors including temperature, current draw, current spikes and peaking, age in #-of-cycles, affect the battery discharge curve. voltages can suddenly drop to unsafe values at the end of the curve or drop steeper in the middle based on environmental factors and age. this means voltage is not the best metric to tell us how much "juice" is left in the battery. the charge in the pack should stay roughly the same, however.
(3) utilizing charge allows us to use the unit of Watt-Hours (WH) and not Amp-Hours (AH). since WH are a unit of energy they're much more useful than AH—which are essentially useless since the amount of current we draw depends on the voltage of the system and the power requested.

typical battery discharge curve:



The above graph comes from (https://www.richtek.com/Design%20Support/Technical%20Document/AN024) and is a typical discharge curve for Li-Ion batteries. We can see the effect of temperature on the discharge curve above. The graph is a little misleading as it seems to suggest the hotter the cell the better the curve shape for us, but it’s important to note that after a certain temperature the cells can be chemically imbalanced or catch fire. Most of these cells are best for us ~ room temperature ~25°C.

Looking @ the graph in more detail we see two distinct axis. One axis is the voltage axis, the other axis is the capacity of the pack the *has been discharged up to that point in time*. The graph is parametric. V(t) and q(t) are plotted against each other. Notice that q(t) cannot be directly measured so we can say the x-axis—charge—is actually a Riemann-Sum of the current up to that point.



$$\int_{-2}^{5}\sqrt{x^2+1}\ \Delta x$$

Trapezoidal Rule:

$$\int_{a}^{b} f(x)\ \Delta x \approx \frac{b-a}{n}\left[\frac{f(a)+f(b)}{2}+\sum_{k=1}^{n-1} f\left(a+k\frac{b-a}{n}\right)\right]$$

The above graph is from (https://www.khanacademy.org/math/ap-calculus-ab/ab-integration-new/ab-6-2/a/understanding-the-trapezoid-rule) and the formulas from (https://vivadifferences.com/difference-between-trapezoidal-rule-and-simpsons-rule-in-surveying/). The trapezoidal sum is the most representative of the integral for a small time-step. We know that integrating current should give us a delta-charge.

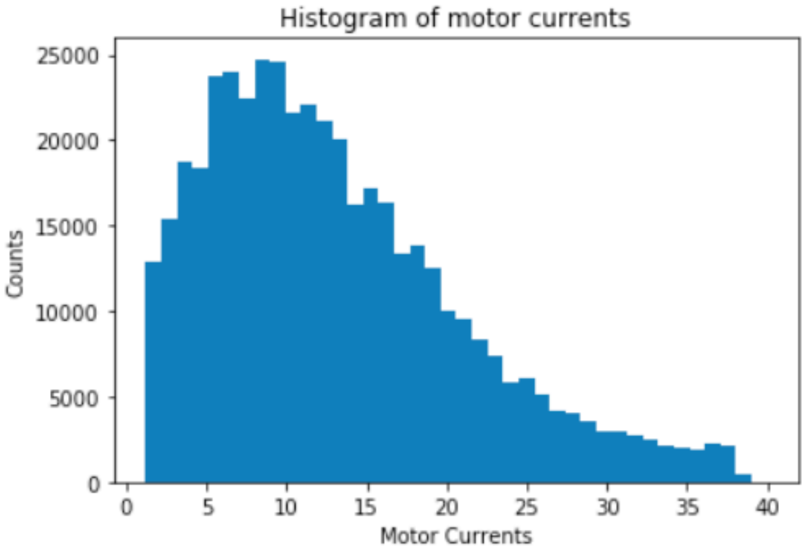
We want to create a discharge curve—really just an IV curve for the battery—so we may use this in strategy planning during the race. There are multiple plans to use information like this for strategy. We will discuss these in the next section.

What we’re interested in:

So really what curve do we want to get? Well, there’s two strategies to do this and we’ll list them here:

(1) take the most common and average vehicle current during the ASC 2018 race and come up with a representative current and temperature to perform battery discharge at.
(2) take a whole bunch of different readings at different currents and utilize computational tools to effectively predict battery SoC during the race.

We won't focus on strategy in this paper, but we will characterize the pack for both options (1) and (2) above—or we’ll try to. Let’s start by determining and appropriate current for (1).



```
Mean, Median Current: 13.12496132559471 , 11.600000000000001
```

Above is a histogram of motor current created by Yong-Hui Lim. The histogram shows the mean and median for current drawn during ASC 2018 was around 11-13A. Which means characterization somewhere in that range should take us a long way in race strategy. If time and materials permit, we will try to test at various other currents to get more accurate data. Impedance will be adjusted for at a later time.

Review of battery fault testing:

Before we get into any characterization, we want to ensure the battery safety systems are all fully operational and this means testing the fault conditions listed above. The procedures for this are as follows:

E1 – e-stop error, simply press the E-stop and observe the state change to E1 and the contactors disconnect. Probe appropriate HV connections.

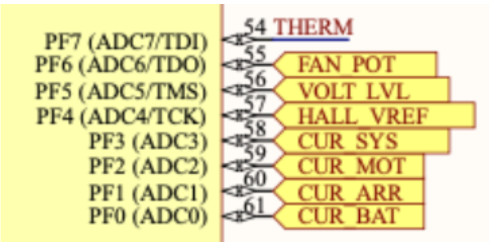
E6 – connection error, detach the ISO-SPI from cell-module 1 and verify E6 appears on the dash-display.

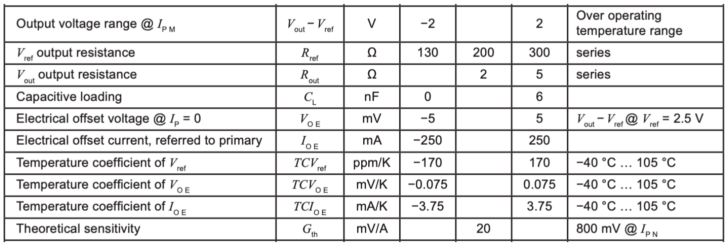
For the next two, detach the ISO-SPI from cell-module 1 and hook up a cell-board test setup w/ seven out of the eight cells in place. Hook a power supply to the eight cell slot and set the power supply to the SAME VOLTAGE as the rest of the cells.

E2 – under-voltage error, drop the attached power-supply voltage below ~3.4V until E2 is triggered, note the value @ which E2 was triggered and verify it matches the hard-coded value.

E3 – over-voltage error, raise the attached power-supply voltage above ~4.1V until E3 is triggered, note the value @ which E3 was triggered and verify it matches the hard-coded value.

For the next two, re-attache cell-module 1 and connect the power supply to "CUR_MOT", "CUR_ARR", and "CUR_BAT" in the diagram below on the ATCAN128 microcontroller. We will use the supply to "fake" the output of the HLSR-40-P current sensor.





Output voltage range @ I_{PM}	$V_{out} - V_{ref}$	V	−2		2	Over operating temperature range
V_{ref} output resistance	R_{ref}	Ω	130	200	300	series
V_{out} output resistance	R_{out}	Ω		2	5	series
Capacitive loading	C_L	nF	0		6	
Electrical offset voltage @ $I_P = 0$	V_{OE}	mV	−5		5	$V_{out} - V_{ref}$ @ $V_{ref} = 2.5$ V
Electrical offset current, referred to primary	I_{OE}	mA	−250		250	
Temperature coefficient of V_{ref}	TCV_{ref}	ppm/K	−170		170	−40 °C … 105 °C
Temperature coefficient of V_{OE}	TCV_{OE}	mV/K	−0.075		0.075	−40 °C … 105 °C
Temperature coefficient of I_{OE}	TCI_{OE}	mA/K	−3.75		3.75	−40 °C … 105 °C
Theoretical sensitivity	G_{th}	mV/A		20		800 mV @ I_{PN}

The above chart shows the sensitivity of the current sensors to be ~80mV/A. Let's say we have a 40A current limit set on the CUR_MOTOR. 40A*20mV/A is ~ 0.8V, let's say V_ref ~2.5V. We need to send a voltage signal to CUR_MOTOR pin of 2.5V+0.8V = 3.3V.

Note the following formula for current-voltage conversion:

CURRENT = SENSITIVITY*(CURR_[COMPONENT]-HALL_VREF)

We can use the above formula to both forward and back-solve for the voltage or the current. We will use the above procedure to test **E4**. Note that only "CUR_BAT" triggers a trip.

E5 – finally, to test over-temperature, we can remove a thermistor from the module and heat it w/ a heat gun until E5 is triggered and note the temperature @ which this happens.

Fault testing results:

error type:	test:	result:	pass/fail:
E6	removed module SPI	immediate E6	pass
E1	pressed e-stop	immediate E1, fixed on releasing e-stop + power cycle	pass
E2	turned power supply down slowly	E2 ~ 2.5V fix on power cycle after turning up supply	pass
E3	turned power supply up slowly	E3 ~ 4.1V fix on power cycle after turning supply back down	pass
E4	injected a 3.3V @ R21	trip @ +41.7A trip @ -49.1	warning ⚠
E5	used a heatgun to heat an attached thermistor	tripped @ 136°F	pass

results:

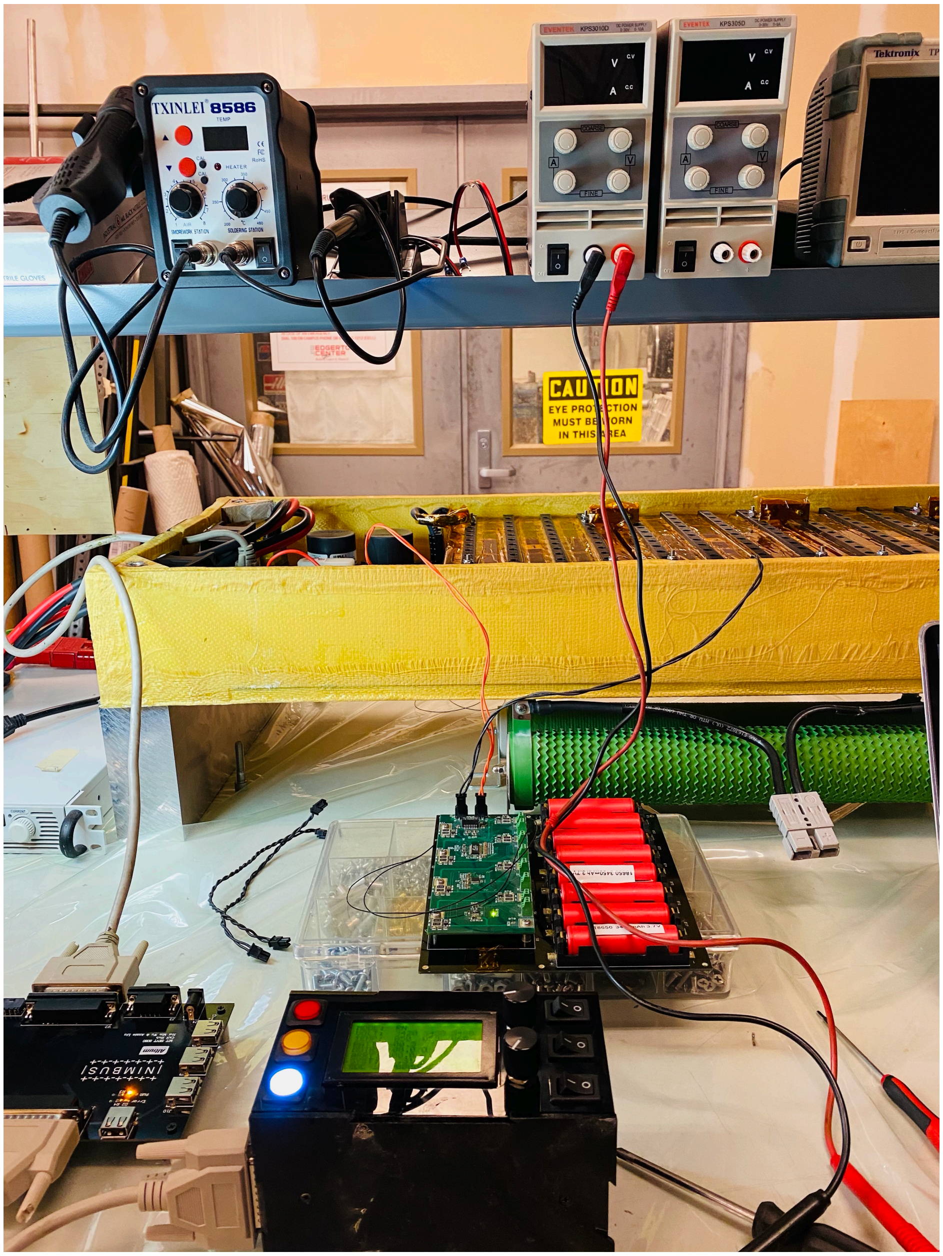
We passed all safety checks with the battery with the given test-setup but we have some points of concern we need to address.

(1) we want the over-current in the (-) direction to be LESS than the over-current in the forward direction—or at the very least the same.

(2) we are switching the current limit to 21A in firmware and will re-test afterwards. **—> passed**

Pictures of test setup:

The following is a set of pictures of the test-setup for future replication of this testing procedure.

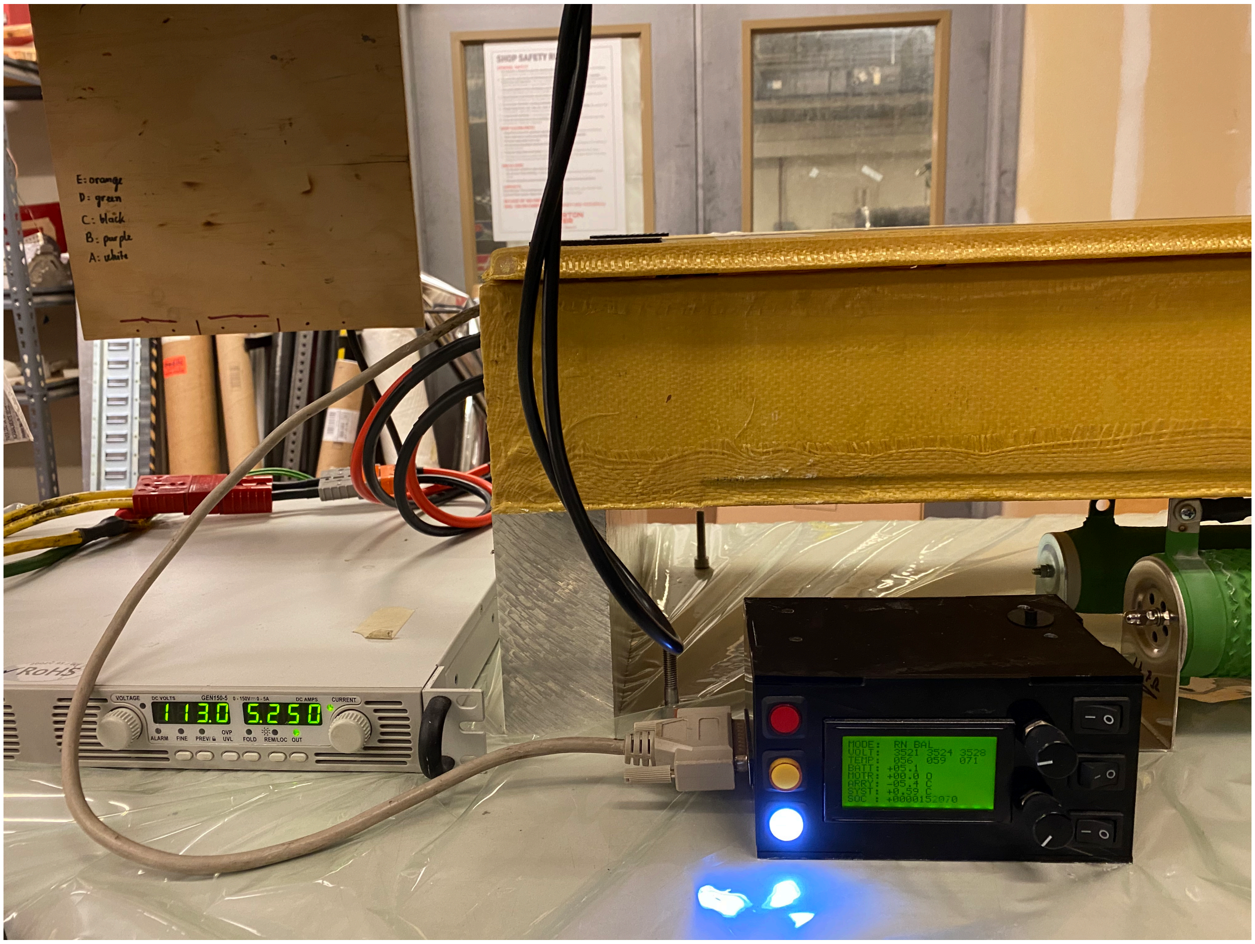


The power supply was hooked up to battery tap eight (BT-8) w/o a cell in place—in alligator clip configuration. And w/ multimeter probes to the -12V and R21 for current testing—see schematic for detailed hook-up.

Characterization procedure:

Now that the battery has passed safety checks we can move onto characterization. The procedure for this is fairly simple now that we've chosen the first discharge current (10A-15A).

step one: charge the battery to full-spec ~4.2V/Cell for our purposes



```
MODE:  RN BAL
VOLT:  3521 3524 3528
TEMP:  056  059  071
BATT: +05.1
MOTR: +00.0 D
ARRY: -05.4 C
SYST: +0.59 C
SOC : +0000152070
```

step two: connect the large resistor to the motor port, connect the dashboard to the battery, and insert the logging chip into the dashboard

***note, even a single pickle resistor cannot dissipate the power required to perform characterization, the setup involves (9x) 1-ohm resistors rated @ 1500W each, that means we will be discharging @ ~14.1A so each resistor will dissipate ~203.67W —> the 1500W rating is only for a time period of about 10s. We will also use fans to cool the setup.

Image 1: Dashboard plugged into batter and resistor cooling exhaust fan on an electrically insulated table.

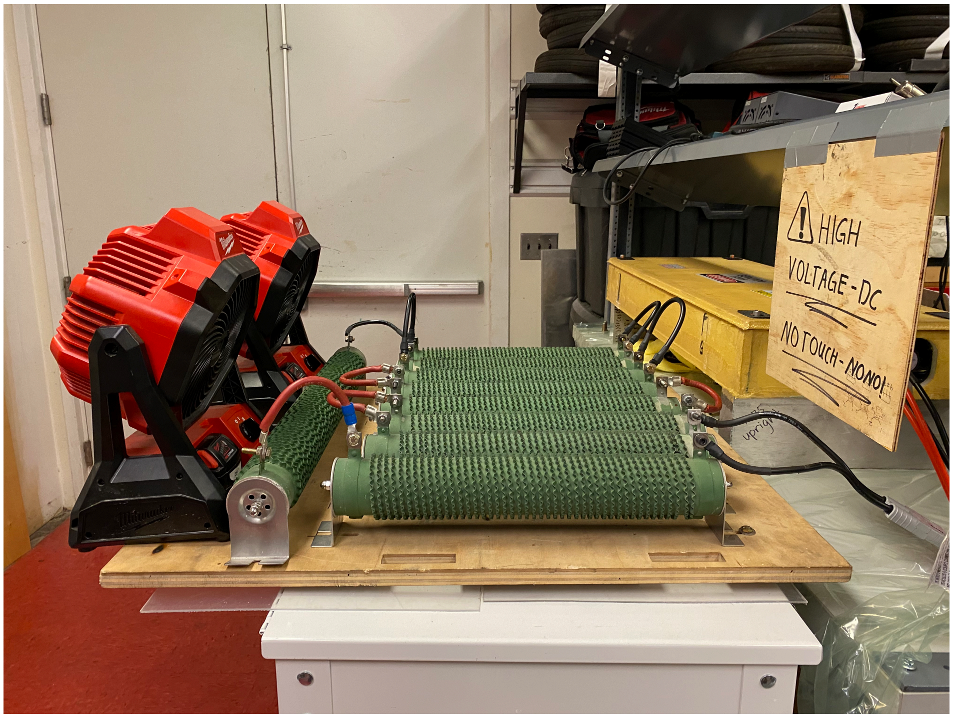


Image 1: (9x) 1500W 1-ohm resistors wired in series with two Milwaukee intake cooling fans on an electrically insulated table.

Since we are also testing the thermal management of the pack, we will let the BMS activate the fans as triggered by the software. This means we will not manually activate the fans for battery cooling unless the temperature reaches uncomfortable levels.

The Milwaukee fans should remain on during the duration of characterization to prevent the resistors from overheating.

actual characterization:

pack starting voltage— 4.111 4.115 4.121 (mi) (a) (ma)
logging rate— ~XHz (check decoded log itself)
discharge current— ~14.4—>14.7A
starting temp— ~~~58°F (cell-temp)~~ ~26.6°C (measured)
ambient air temp— ~26.8°C (ambient temp)
max resistor temp— ~98°C (surface-temp)
max electronics temp— ~38°C (surface-temp)
midpoint temp— ~~~78°F (cell-temp)~~ ~30.2°C (measured)
ending temp— ~~~87°F (cell-temp)~~ ~35.8°C (measured)
pack ending voltage— 2.841 2.887 2.921 (mi) (a) (ma)

estimated discharge time:

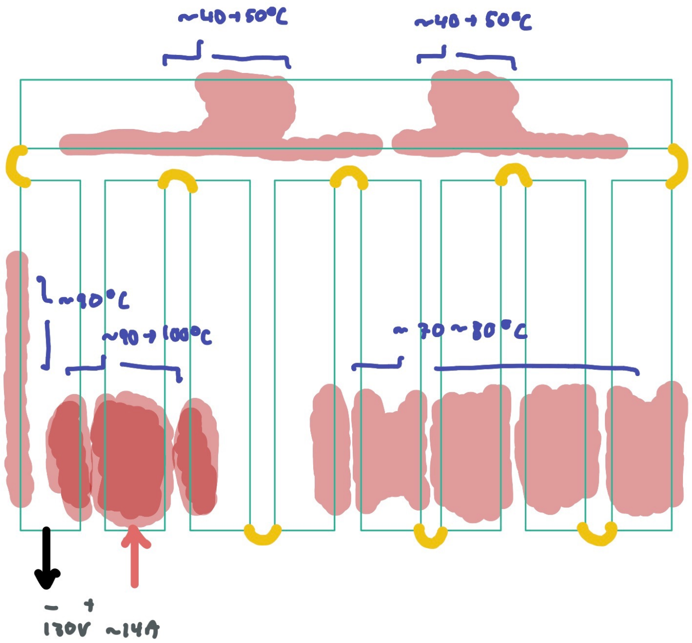
\-
32s13p pack, w/ 3450mah cells
discharge current ~14A
\-
13*3.450=44.85 Ah
44.85Ah/14A ~= 3.20h
actual discharge time: 3:12:50.75 (3.2 hours almost exactly)

notes:

**inaccurate battery temps being reported —> something to look into
**carried out thermal imaging of both the pack as well as the resistors
**we will get characterization time from the logs as the logs will have a dt
**we will integrate the charge ourselves and compare to the batt-calculated SoC in the logs
**logging was tested before we started characterizing the system
**note that the current will slightly decrease as the pack discharges
**electronics temp refers to temp of BMS components
**only parts of the resistor get up to high temperatures, rest are fine —> something to investigate (draw a diagram of which parts so we can inspect resistors?)
**as voltage in pack started dropping, current started dropping, and resistor temps dropped
**take a look at the kapton tape on the modules, some may be peeling off
**battery fans were not turned on at all, didn't need to turn them on, battery temp remained OK (note we're in an air-conditioned building w/ ambient maintained @ around 80°F/room temp)

Diagram of resistor temperatures:

drawing based on thermal imaging:



and for comparison a picture of the setup in the same orientation:

update: after re-looking @ the setup, we think the "spots" of heat come from places the fan was not cooling, better cooling can be attempted in the future.

Array characterization procedure:

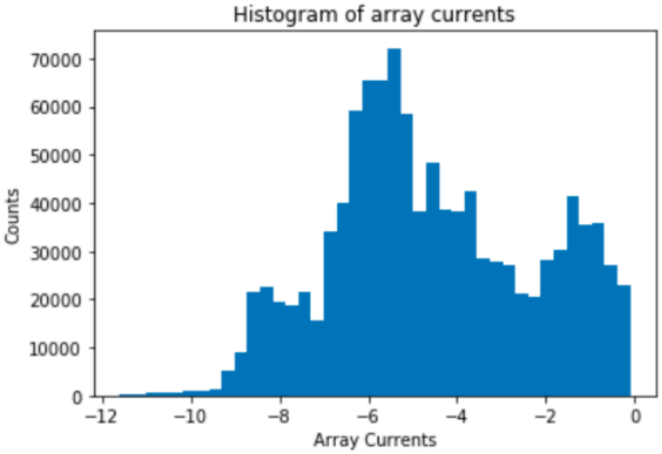
So the next step in the process is to characterize the array. It's important for us to know how much current we get out of the array at different insolation levels as this will help us plan for strategy. It's also important to know how fast the battery will charge up to full capacity at these current levels. Therefore, we can take a multi-part approach to array characterization.

(1) observe currents from the previous race to determine the typical current we got from the array during charging to select a representative current.
(2) utilize the same procedure as battery characterization—but this time for charging—to create a charge curve for the pack.
(3) place the array perpendicular to the sun for a day and keep it cool with water, measure the insolation we get from the sun, the open-circuit voltage (OCV) of the panel strings, and the short-circuit current (SCC) of the panel strings. we can also record other parameters like time of day and etc.
  (1) we can then adjust the currents to the MPPT voltage, to then create an insolation vs. current curve for the array.

determining a representative current:

```
filtered_data_df = data_df["array current"][data_df["array current"]<0]

plt.hist(filtered_data_df, 40)
plt.title("Histogram of array currents")
plt.xlabel("Array Currents")
plt.ylabel("Counts")
plt.show()
print("Mean, Median Current:", np.mean(filtered_data_df), ",", np.median(filtered_data_df))
```



```
Mean, Median Current: -4.557118937229569 , -4.9
```

According to the histogram of current from ASC-2018, the array averaged about 5A of current input to the battery. This means we want to do a battery charge characterization curve at around ~5A. The procedure for this is to simple charge the battery like normal from the power supply w/ the current limit @ 5A and log the data as it charges from empty to full.

array current vs. insolation test:

The procedure for testing the array is simple but first let's talk about how to measure insolation. In SI units, a Lumen is the measurement of total output of light from a source and it's absolute. A light-source has a lumen rating just light a lightbulb or similar. But all of the light from a source doesn't necessarily reach the panel location (in our case, not 100% of light from the sun reaches the Earth or where we are on the Earth). Therefore we need a different measure.

An "Irradiance Meter" measures insolation in the units of "Lux." A Lux is a Lumen/m^2 and is the SI unit that describes the amount of light that is actually hitting a surface. The meter that we chose for this is (https://www.amazon.com/dp/B08NCSZW4N/ref=cm_sw_r_oth_api_glc_fabc_RJMD5QCSRX7JWCBMMMD2).

Normally, when people characterize solar cells, they take an IV-curve tracer and trace the true IV curve of the solar cells and determine if the theoretical and actual peak power match (our theoretical peak is ~987W). We will take a slightly different procedure.

(1) first place the car in an open lot (like Albany lot).
(2) adjust the array on the array-stand to be as perpendicular to the sun as possible.
(3) spray the array with water to keep the cells cool.
(4) use the insolation meter to take a measurement. place the lux meter near the cells at the same angle to the sun.
(5) using a thermal camera, measure the cell temperatures.
(6) using a multimeter, measure the OCV and SCC of the two array strings.

***note that array characterization takes about 7 hours total. you want to start around 1PM when the sun is getting to it's highest point and go all the way to around 8PM when charging time would finish and the sun is fairly low. it's good to pick a day with good weather (we didn't, it rained, there were clouds towards the end so the data is a little skewed). nonetheless, this is super important to a proper characterization.*

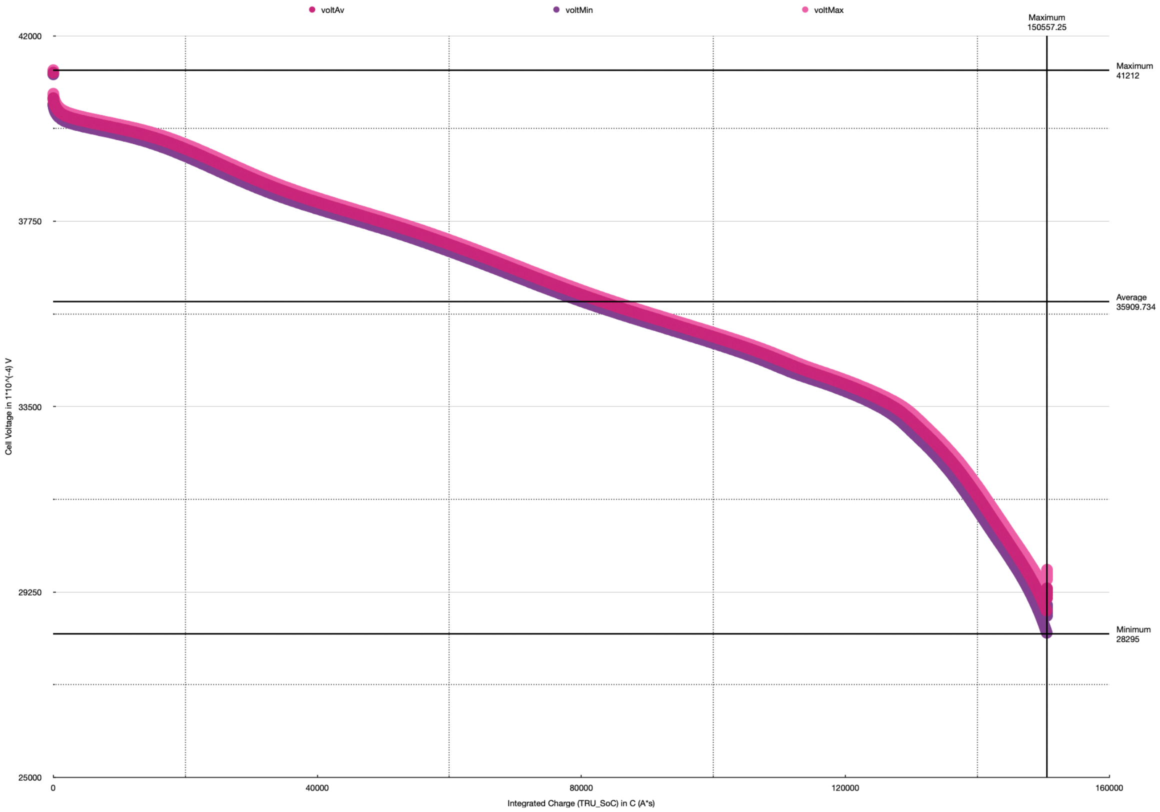
Data analysis:

Before we start let’s define some terms that will be important to discussion.

BC_SoC –> State-of-Charge (SoC) as calculated from battery/log
TRU_SoC -> integrated current from Tustin bilinear transform

There’s a few end-goals here. First, we want to graph the BC_SoC (or BAT_SoC) and compare that to the TRU_SoC in different areas to ensure the SoC as calculated from the battery is accurate compared to our “ground truth” of what we know is coming in and out of the pack.

The second goal is to create some battery curves that can be used for strategy and prediction. Note that the area under an SoC curve is the Wh power the battery has consumed.



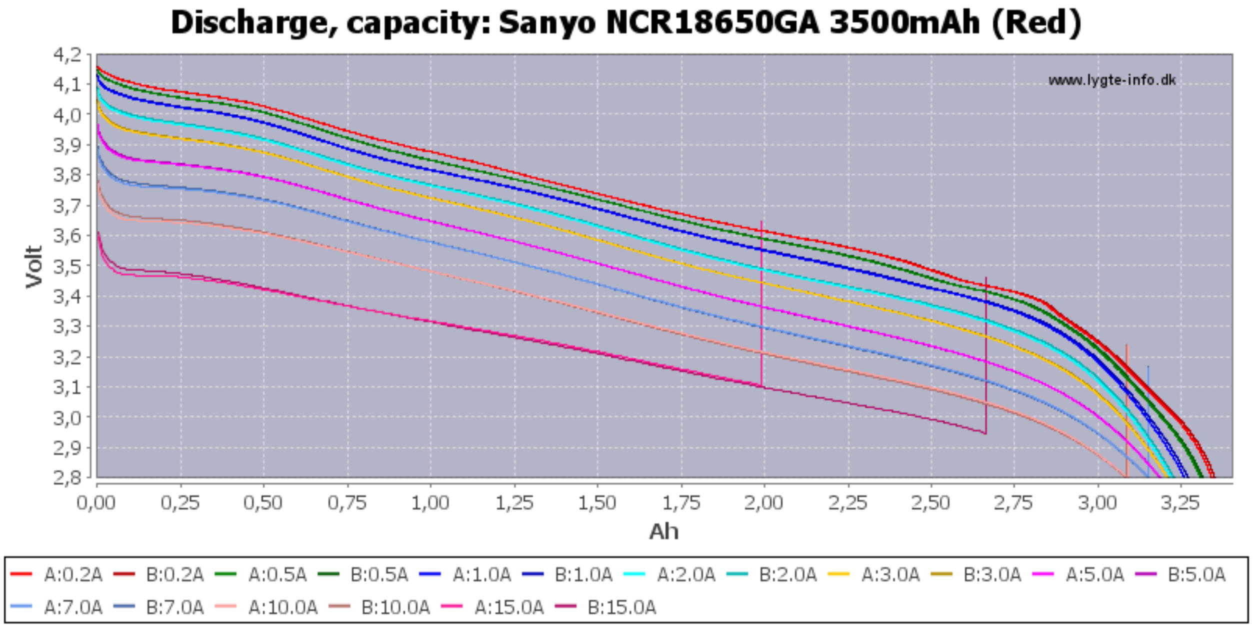
**above graph plots voltage against the tustin-bilinear-transform of the current. this is the battery voltage as compared to the TRU_SoC of the pack. note that this curve has no impedance adjustment so is not fully useful just yet.

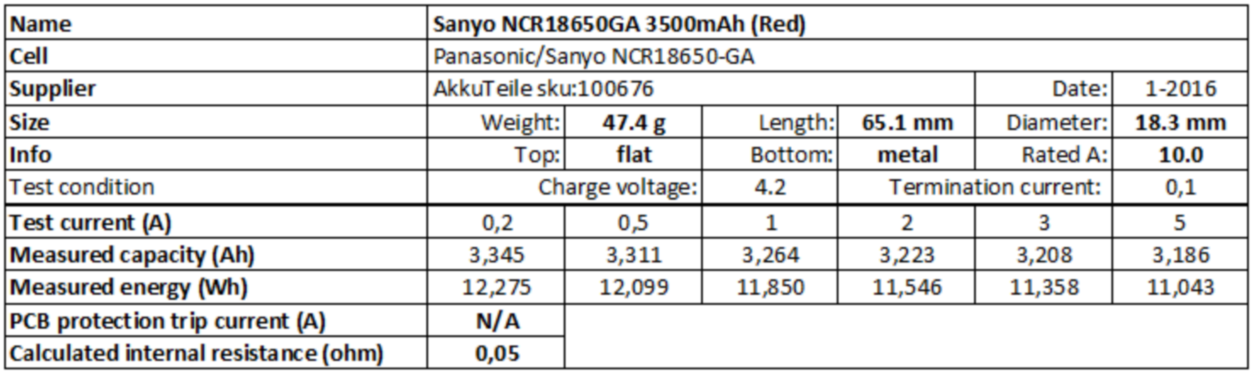
Based on the above, we can determine some basic numbers for the battery pack as a whole.

pack est. capacity: 44.85 (Ah)
pack meas. capacity: 41.82145 (Ah)
full-pack-capacity: V_avg * capacity ~= 4808.19 (Wh)
total charge in pack: ~150557.25 (C)

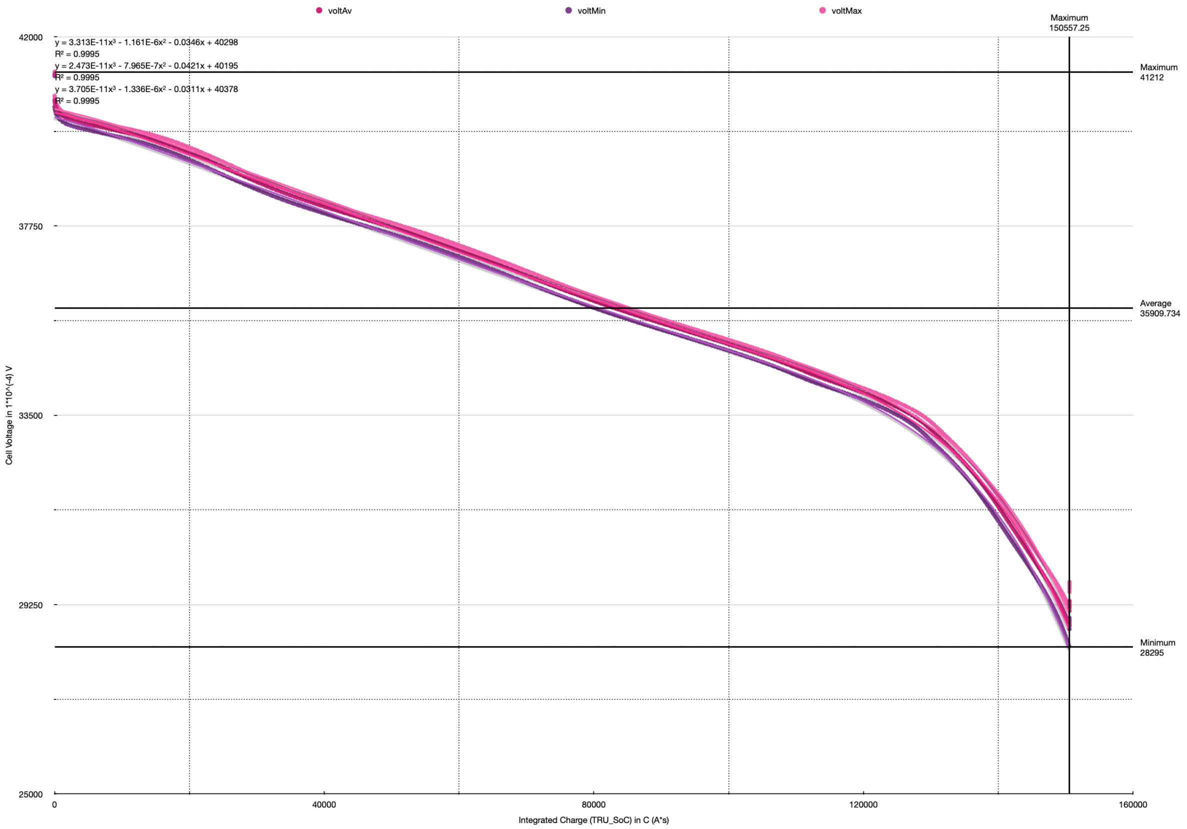
comparing w/ independent testing from online:

If we take a look at some testing of these batteries done by (https://lygte-info.dk/review/batteries2012/Sanyo%20NCR18650GA%203500mAh%20%28Red%29%20UK.html) to determine how close to expected our cells are operating at. Here is the data from that testing.





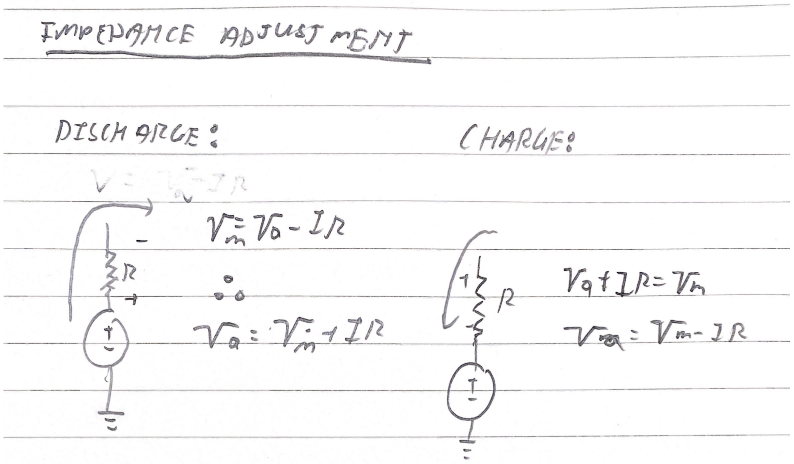
Name	**Sanyo NCR18650GA 3500mAh (Red)**					
Cell	Panasonic/Sanyo NCR18650-GA					
Supplier	AkkuTeile sku:100676				Date:	1-2016
Size	Weight:	**47.4 g**	Length:	**65.1 mm**	Diameter:	**18.3 mm**
Info	Top:	**flat**	Bottom:	**metal**	Rated A:	**10.0**
Test condition	Charge voltage:		4.2	Termination current:		0,1
Test current (A)	0,2	0,5	1	2	3	5
Measured capacity (Ah)	3,345	3,311	3,264	3,223	3,208	3,186
Measured energy (Wh)	12,275	12,099	11,850	11,546	11,358	11,043
PCB protection trip current (A)	**N/A**					
Calculated internal resistance (ohm)	**0,05**					



**the above is our non-adjusted discharge graph, we will compare this to the 1.0A discharge curve from the online characterization because if the pack is discharging at 10-15A and we have a 13p configuration, we can estimate an average cell current of around 1.0A.

We can see that the curves match pretty well! So we are pretty sure we can say our cells are fairly healthy. Now we want to go onto impedance adjustment

math for impedance adjustment: **R=0.05 OHM (according to above)**


IMPEDANCE ADJUSTMENT

DISCHARGE:

$V = V_a - IR$

$V_m = V_a - IR$

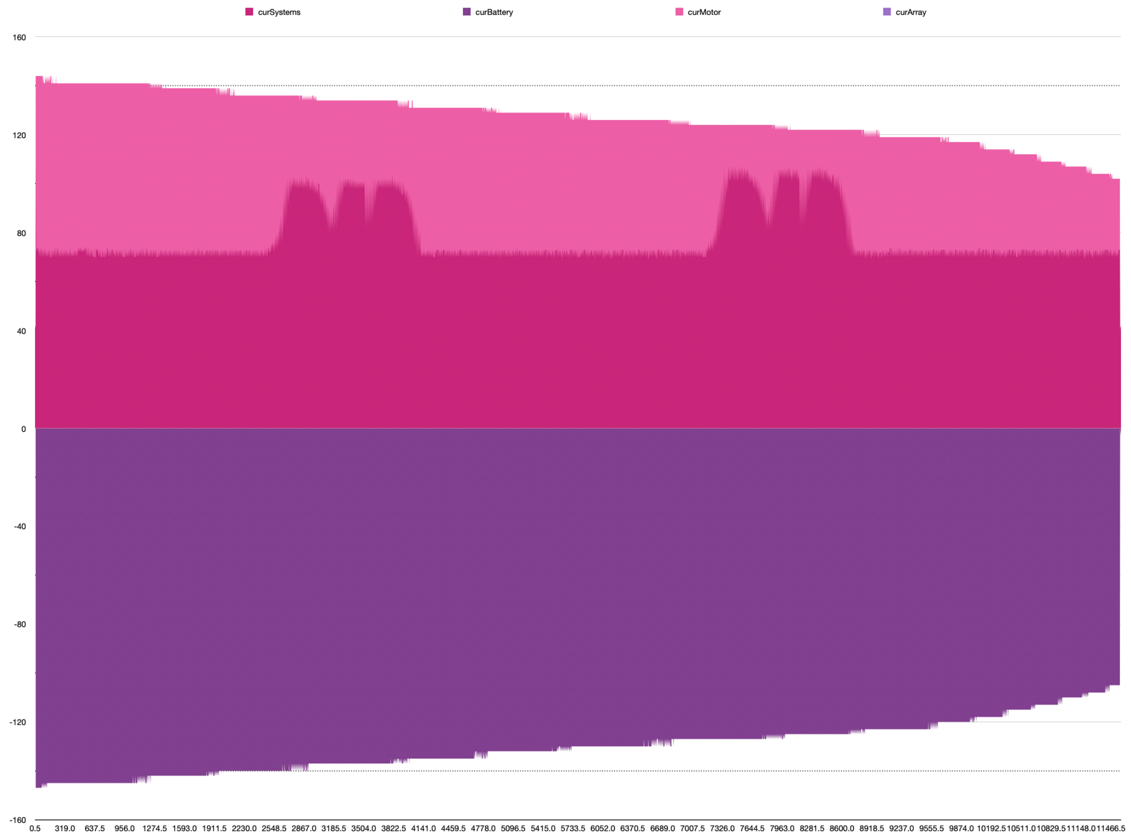
$\therefore$

$V_a = V_m + IR$

CHARGE:

$V_a + IR = V_m$

$V_a = V_m - IR$



***above graph simply shows the areas of each of the currents, the area of -curBattery is the total charge that exited the pack.*

For impedance adjustment, consider the model of a battery cell. A battery cell can be modeled as a voltage source in series with a resistance. The voltage across the terminals is the true chemical voltage of the cell minus the current exiting the pack times the internal resistance of the cell (R=0.05ohm according to the data sheet + above characterization).

so here's some basic math:

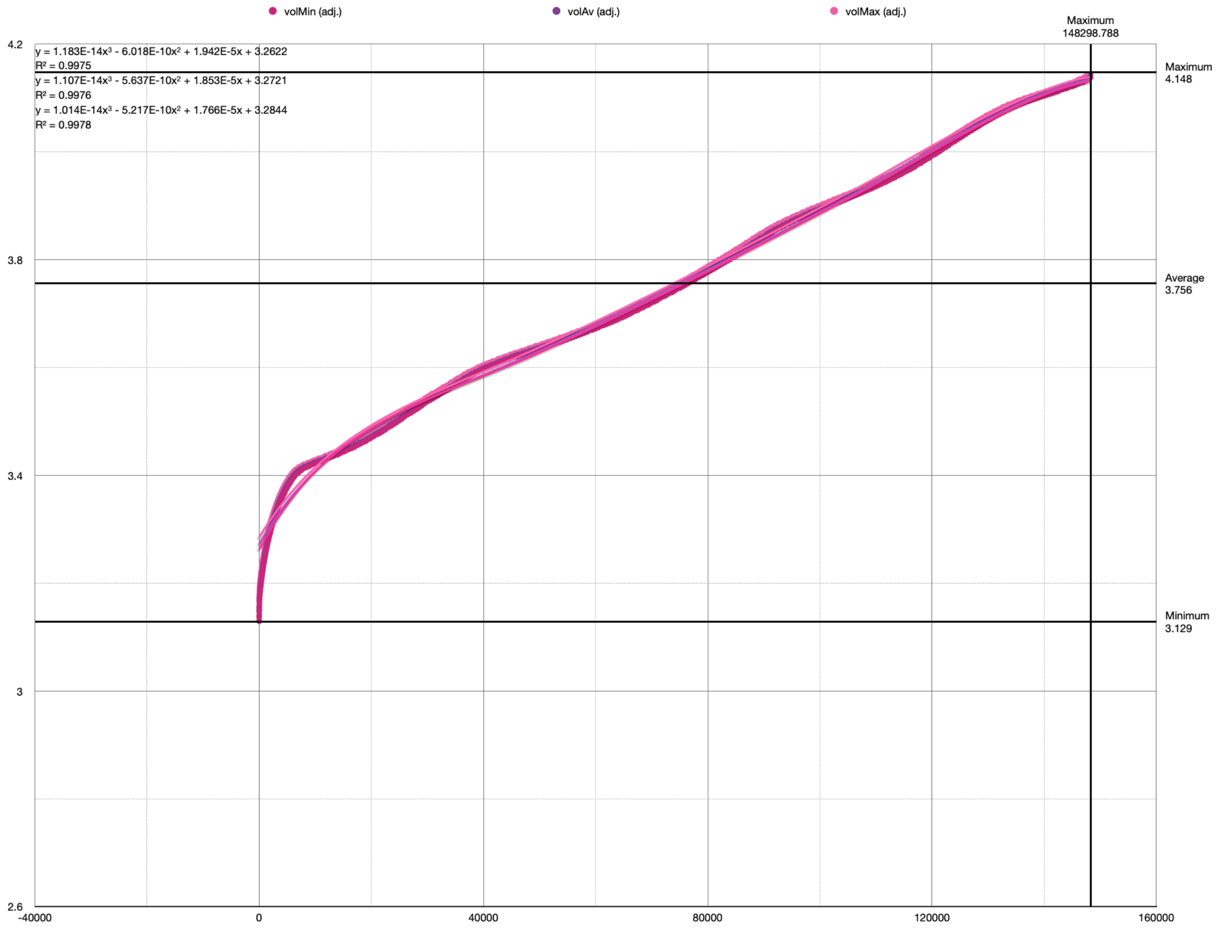
***if we discharge at X (A) of current, then in 13p configuration each cell will be discharging at around x/13 (A) of current. this assumes that the cells all have similar resistances and are at similar voltages which is a valid assumption for our pack.*
***when we are discharging the battery, the battery terminals will see V-iR voltage across them as seen on the drawing on the previous page. therefore, our impedance adjustment is as follows…*

$$V\_adj = V\_cell+|i\_batt|/13*R\_cell$$

***note the absolute value of current as well as the units of the expression. do not blindly plug in the logs to this formula. for charging it will be the opposite…*

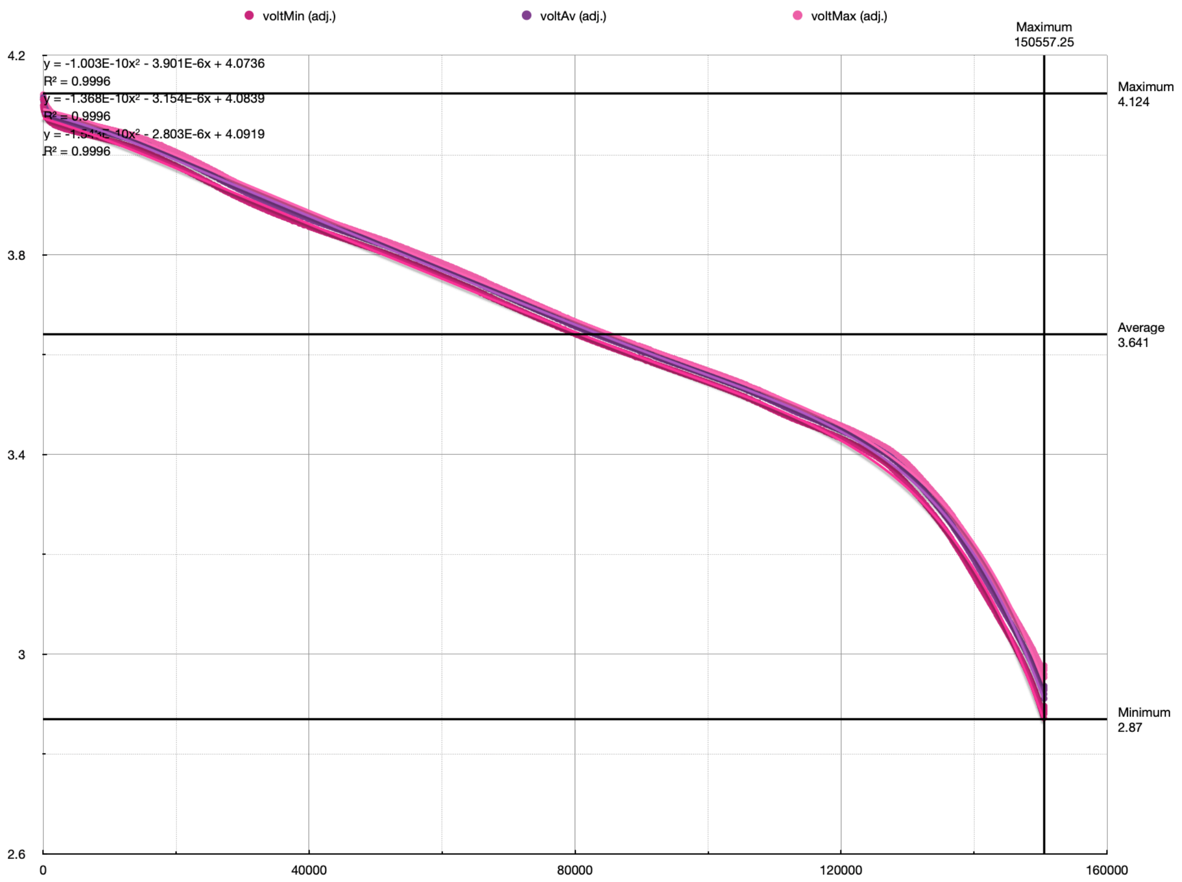
$$V\_adj = V\_cell-|i\_batt|/13*R\_cell$$

impedance-adjusted charge graph @ 5A:



***the above graph is an impedance-adjusted charge graph for the current of around 5A. we have also produced a line of best fit that slightly matches the data. the equations for line of best fit were calculated with a polynomial approximation in Apple Numbers but we recommend using the actual raw data - email adim@mit.edu for this data (the equations don't fit the curve well).*

impedance-adjusted discharge graph @ 10A:



***the above graph is an impedance-adjusted discharge graph for the current of around 10A. we have also produced a line of best fit that slightly matches the data. the equations for line of best fit were calculated with a polynomial approximation in Apple Numbers but we recommend using the actual raw data - email adim@mit.edu for this data (the equations don't fit the curve well).*

comparing charge + discharge:

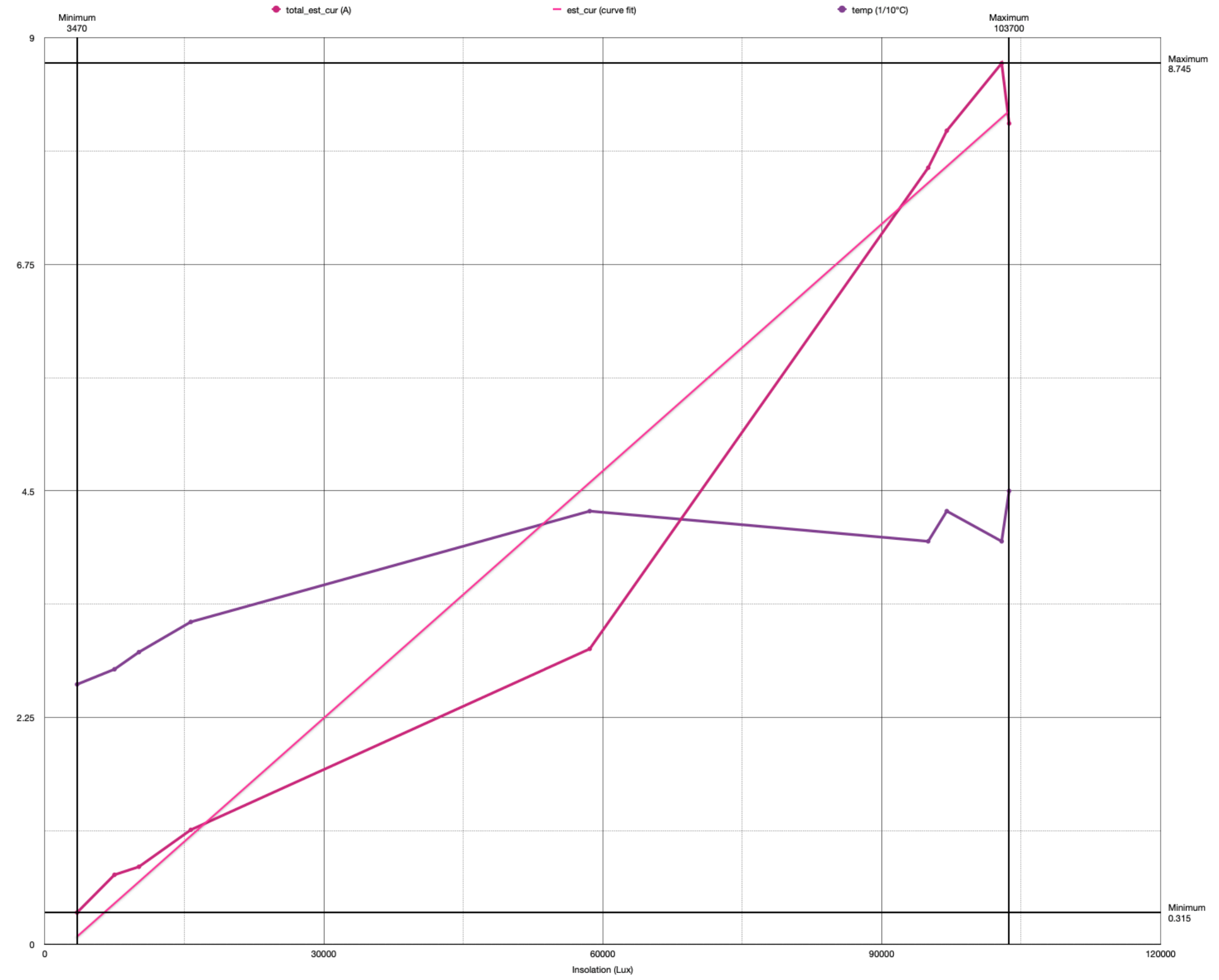
For a real quick sanity check, let's see that the state-of-charge calculated from both charge and discharge roughly match. These numbers can be read straight off the graph.

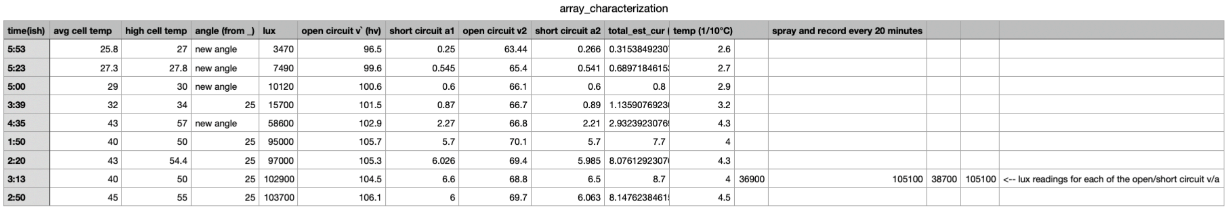
total charge from discharging the pack: 150557.25 (C)
total charge from charging the pack: 148298.788 (C)

We can see from the above, that the charge and discharge from the pack produce relatively the same numbers. We can say the difference is probably related to different start and just other uncontrolled factors of the experiment.

array characterization curve-fit data:

****for all of the below data, assume that the array is always perpendicular to the sun as—visually speaking—during testing we attempted to keep it this way. therefore any cos(theta) term in panel efficiency goes to "1," and we can assume the panels are operating at their stated efficiency according to the data-sheet.**

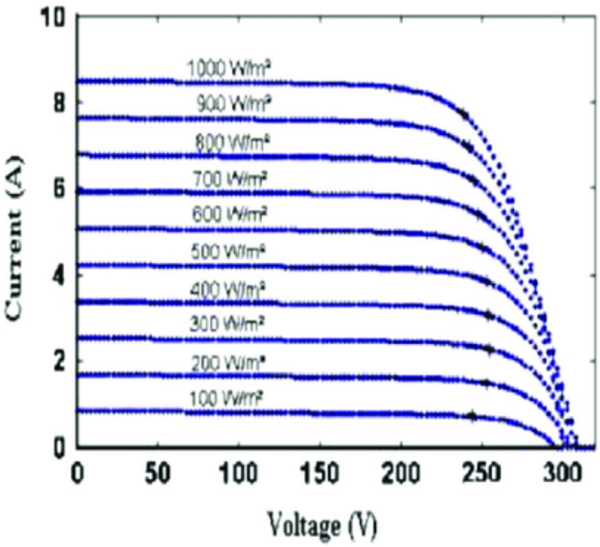


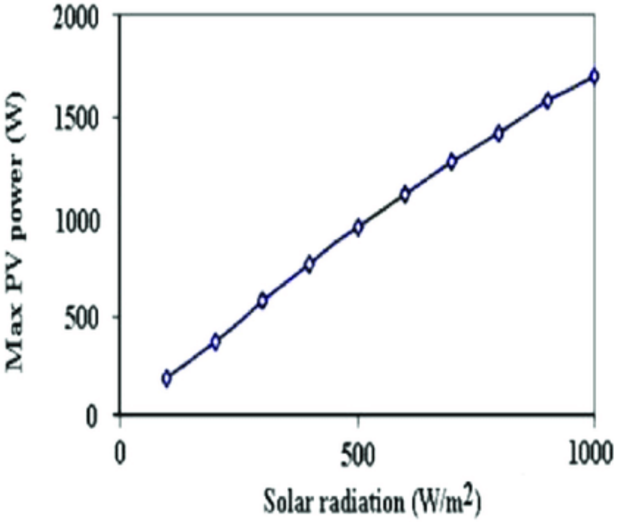

array_characterization

time(ish)	avg cell temp	high cell temp	angle (from _)	lux	open circuit v` (hv)	short circuit a1	open circuit v2	short circuit a2	total_est_cur (	temp (1/10°C)		spray and record every 20 minutes			
5:53	25.8	27	new angle	3470	96.5	0.25	63.44	0.266	0.31538492307	2.6					
5:23	27.3	27.8	new angle	7490	99.6	0.545	65.4	0.541	0.6897184615	2.7					
5:00	29	30	new angle	10120	100.6	0.6	66.1	0.6	0.8	2.9					
3:39	32	34	25	15700	101.5	0.87	66.7	0.89	1.1359076923	3.2					
4:35	43	57	new angle	58600	102.9	2.27	66.8	2.21	2.932392307	4.3					
1:50	40	50	25	95000	105.7	5.7	70.1	5.7	7.7	4					
2:20	43	54.4	25	97000	105.3	6.026	69.4	5.985	8.0761292307	4.3					
3:13	40	50	25	102900	104.5	6.6	68.8	6.5	8.7	4	36900	105100	38700	105100	<-- lux readings for each of the open/short circuit v/a
2:50	45	55	25	103700	106.1	6	69.7	6.063	8.147623846	4.5					

*****the above graph and raw data shows the data-points we collected during array characterization. the pink line is the linear fit of the data.***

An important note here on the linear fit, it's honestly not the best representation of how a solar cell should reach to changes in insolation. The graph really should rise and then slowly plateau. It should look similar to the graph below from (https://www.researchgate.net/figure/Effect-of-varying-the-solar-irradiance-on-V-I-PV-characteristics-and-maximum-generated_fig2_289600570).





We decided to go with the linear fit for a few reasons. First, we really only had a few datapoint so there wasn't enough to curve-fit properly. Data could be collected more frequently but also more precisely over the range of light-levels for better characterization. Second, we really just want an estimate of current based on insolation so the scout vehicle can report back insolation for strategy's planning.

***a few more notes on the above data. you'll notice that the current we plotted is the adjusted current. this current comes from calculating based on the array OCV and SCC and the MPPT output voltage what the estimated current into the battery pack would be from power conservation. the formula is simple:*

*SUM ((string_1 OCV) / (MPPT output_voltage) * (string_1 SCC) +*
*(string_2 OCV) / (MPPT output_voltage) * (string_1 SCC)) = I_batt_est*

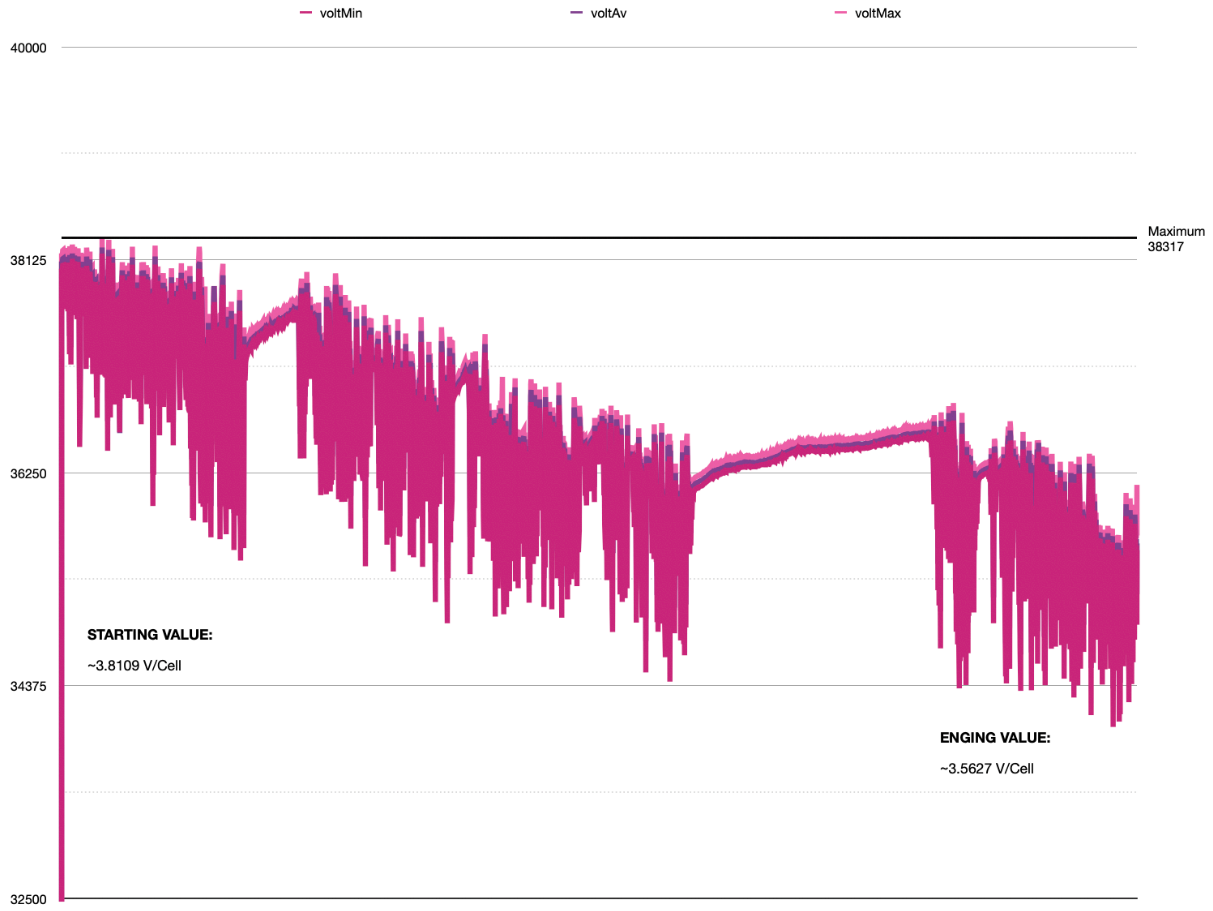
***we assumed an MPPT output voltage of 130V for this test which is a typical charging voltage for the battery pack. this voltage changes with pack voltage as the MPPT automatically adjusts for max-peak-power, but we can assume it is somewhere in that area.*

Case study—a trip to Sandwich, MA 7-10-2021:

We took a trip to Sandwich, MA, and we had sandwiches but we drove the solar car there and got some data so we will now analyze this data while also eating a sandwich (it's the mozzarella one from Flour, very good, yum). The purpose of this case-study is multi-fold.

(1) we want to to be able to determine if the TRU_SOC of the battery and the BAT_SOC match, that's the integrated charge vs the battery-calculated SoC.
(2) we want to be able to reconcile the SoC curve we got, the SoC from the battery, and the voltage plot we get from the battery during the run.
(3) we want to note any trends in the data.

initial curves and data:

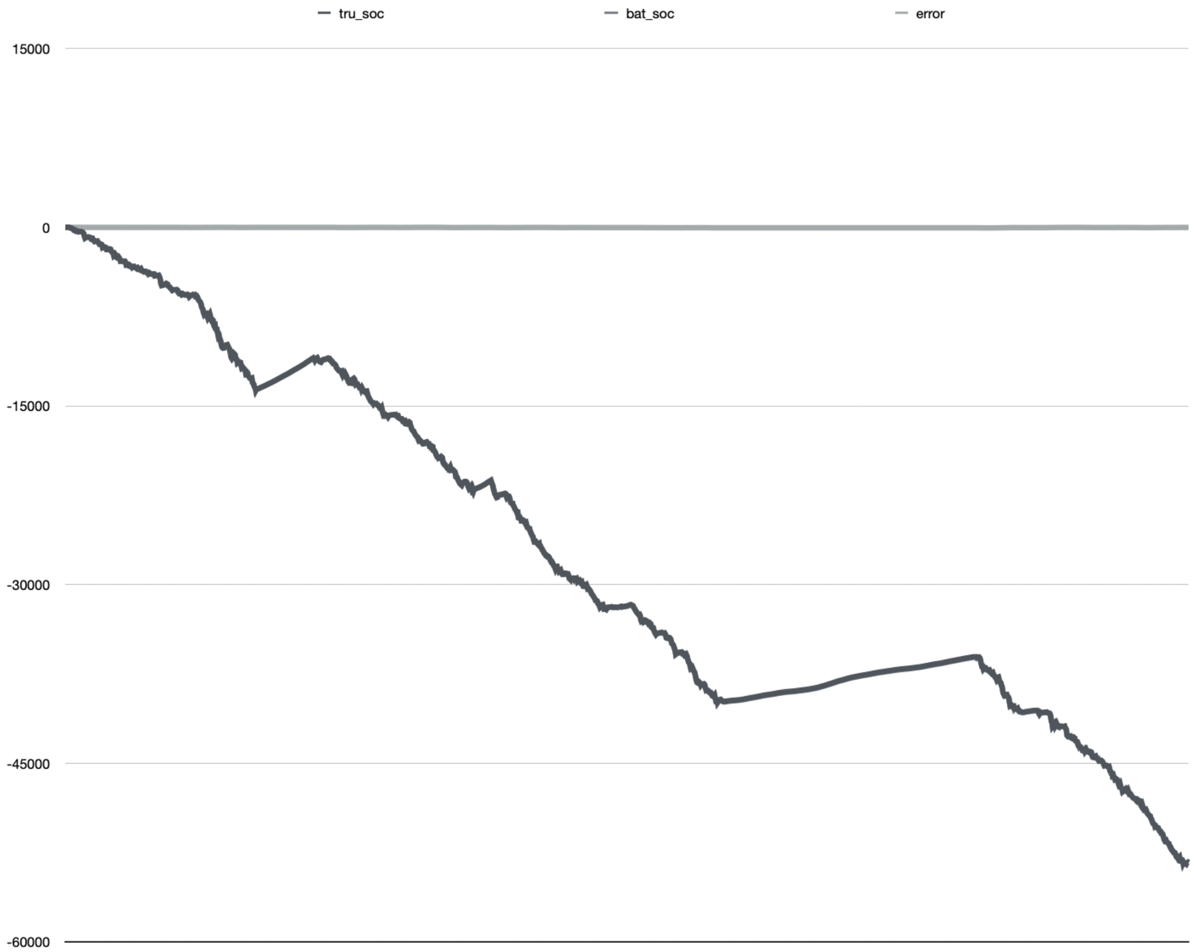


****the above is a plot of voltages of the battery over the course of the drive which, based on the above log, was about 5 hours.*

****the above is a plot for currents in the battery. the linear regions of positive current indicate times where we stopped for while the array was on (periods of charging).*

The data lines up fairly well. The SoC curve shows long periods of discharge followed by short periods of increase. The line up very well with the driving as we stopped two short times and one long time for repairs, or lunch. During these times we never turned the car off and allowed it to charge on solar power. All other times battery current varied wildly but SoC steadily decreased as we were driving for the rest of the sections.

We now want to take this data and do the following. We want to start with the original battery SoC discharge curve, we want to use that to determine the initial SoC of the pack and the final SoC of the pack based purely on cell voltages. We then want to subtract these two and compare the change in the SoC actually with the predicted SoC change calculated by the battery pack.



****and finally, a plot of the TRU_SOC vs. the BAT_SOC which shows minimal errors. we can chalk any errors up to differences in integration schemes and sampling-frequency for integration. can't even really see the difference between these two curves for the most part.*

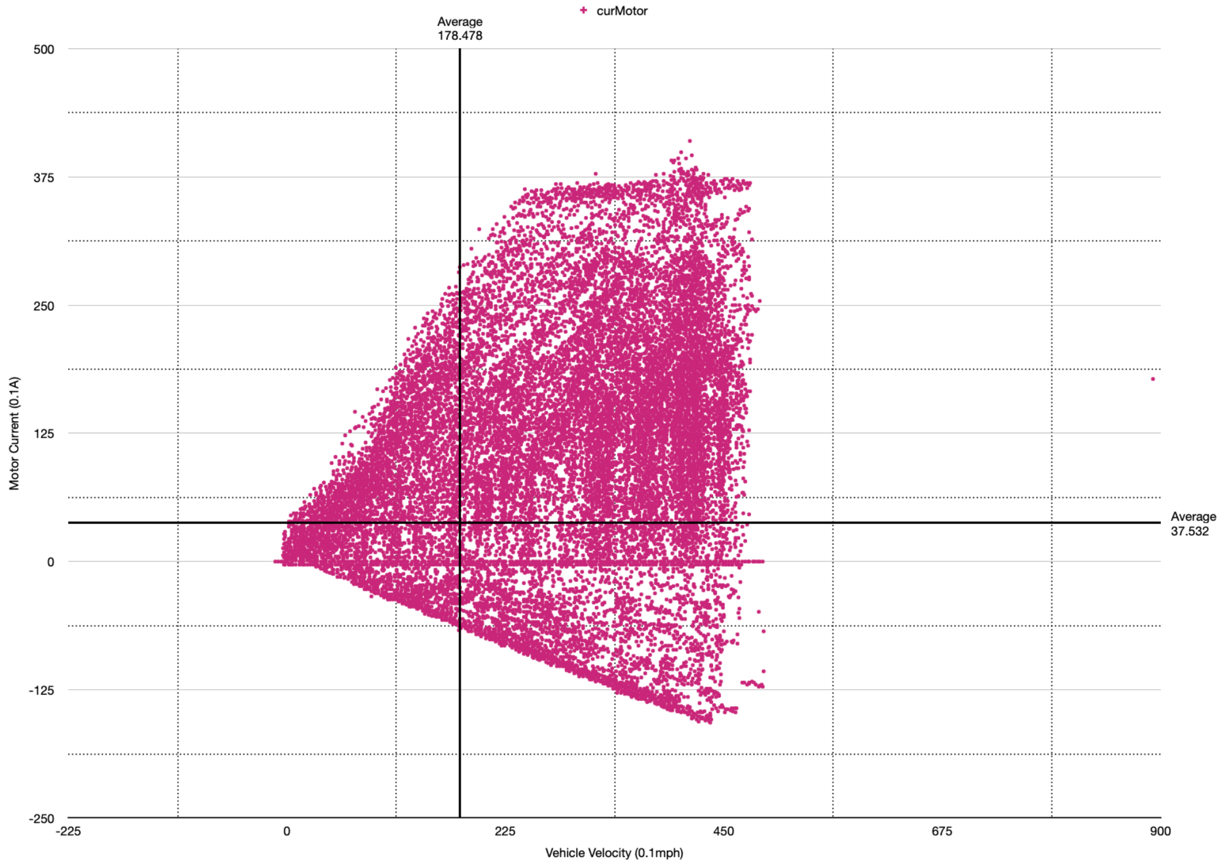
reconciling battery SoC numbers:

starting voltage— ~3.8 (V/Cell)
ending voltage— ~3.56 (V/Cell)
BAT_SOC ending charge— -53376.2244 (C)

***now based on the SoC curve we gathered before, 3.8 V/Cell is ~= 38000 (C) exited the pack, and 3.56 V/Cell is ~= 86000 (C) exited the pack. That's about 48000(C) change, which is within estimation error for SoC. Note the curve we are reading is also not impedance-adjusted so the error could result from this as well.*

NEXT STEPS: We want to be able to impedance adjust the graphs and make a more useful SoC graph with more tick-marks on the axis so it's easier to read quickly. We also want to be able to predict the current we're going to draw at various speeds and at various inclines on the road (if a road is severely uphill/etc). These are things we can do from plotting testing logs in ArcGIS, and while on the race as well. This is an issue for later analysis and not this notebook.

plotting velocity vs. current for the trip:



We also want to see is there any trend in how much current we draw at different velocities and is there any approximations we can use based on this to better our strategy.

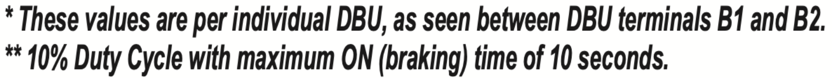
This graph above is utterly meaningless, why? Look at it and try to find a relation… too many confounding variables. A more accurate test would be to use a dynamometer and get data that way. For now we will ignore this aspect as it goes into motor characterization not array or pack characterization and that would be too much for this notebook.

Lessons learned:

A few notes for future characterization peoples. We made a few of these mistakes multiple times so they are worth mentioning.

(1)note about the power resistors—so we started w/ this resistor[1] which is a 1500W braking resistor @ 13ohms. We calculated 130V/13ohm*130V ~ 1300W of power for the resistor to dissipate and we assumed since 1300W < 1500W it would be OK. This was an incorrect assumption.

  (1)(1)to understand why, it's very important to look at the data-sheet[2] for such a resistor.
  (1)(2)first, the data-sheet states these ratings are for the following situation, that's ~10s for thermal reasons:



**** These values are per individual DBU, as seen between DBU terminals B1 and B2.***
***** 10% Duty Cycle with maximum ON (braking) time of 10 seconds.***

  (1)(3)They are also rated for AC current which actually helps increase the power rating as the DC current is more taxing from a thermal standpoint as the electrons flow and cause friction constantly in a single direction. AC current peaks, subsides, and moves back and forth so less heat is generated.
  (1)(4)all-in-all, we cannot use a single resistor to discharge the pack.

(2)the solution to this problem is to take 10x 1-ohm pickle-style braking resistors rated to ~1500-2000W so each only needs to dissipate 1/10 of the total power. We can also cool these resistors with fans to ensure they stay within safe operating temperatures.

notes on a specific battery fault we kept receiving:

(1)when we first plugged in the array on a sunny day and started running the car with it we kept getting an E4 "overcurrent" error on the battery pack.
  (1)confusion… so much confusion

(2)so this was a while to debug and fix but the main idea is that when the array is plugged in, everything is pre-charging

---

[1] (https://www.automationdirect.com/adc/shopping/catalog/drives_-a-_soft_starters/ac_variable_frequency_drives_(vfd)/vfd_accessories/braking_units_-a-_resistors/gs-br-1k5w013) — Automation Direct Braking Resistor

[2] (https://cdn.automationdirect.com/static/specs/gs4accbrake.pdf) — Braking Resistor Datasheet

and the contactors are switching on—there’s a whole lot of magnetic interference and other nonsense going on.

- (1)the current sensors are hall-effect sensors (magnetic field current sensors) and the contactors are big relays which use magnetism to switch large “contacts” on and off. what was happening is b/c there was so much EMI, the current sensor was detecting a fake spike in current and sending an over-current error to the battery (can figure this out with an oscilloscope probing of the sensor output).
- (2)the fix to this is to perform a software low-pass on the current sensor output (or develop a better hardware low-pass filter on the headboard itself for future headboards). this is OK for safety considering that currents that are properly dangerous for the cell needs to last > just a small pulse to do any significant damage or cause any thermal issues. a properly spec-ed low-pass is really there to remove any noise in measurement.

(3)we also had a weird issue w/ a sticky array contactor, we were using a Gigavac P125BDA. we still aren’t sure why this contactor was sticky but something to think about in the future.

- (1)we might recommend replacing these small contactors with the larger Gigavac contactors we usually use as they don’t seem to have this problem, or we recommend isolating the problem with these small contactors.

Written for the 2021 American Solar Challenge
Nimbus 2020/2021

BORN. BY. FIRE.