



The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any reuse of this report or its findings, conclusions, or recommendations is at the sole risk of the user.

SES Cell Electrical Test

Binghong (Alex) Han, Ph.D., P.E.

Jonathon Harding, Ph.D., P.E.

Zhuhua Cai, Ph.D., P.E.

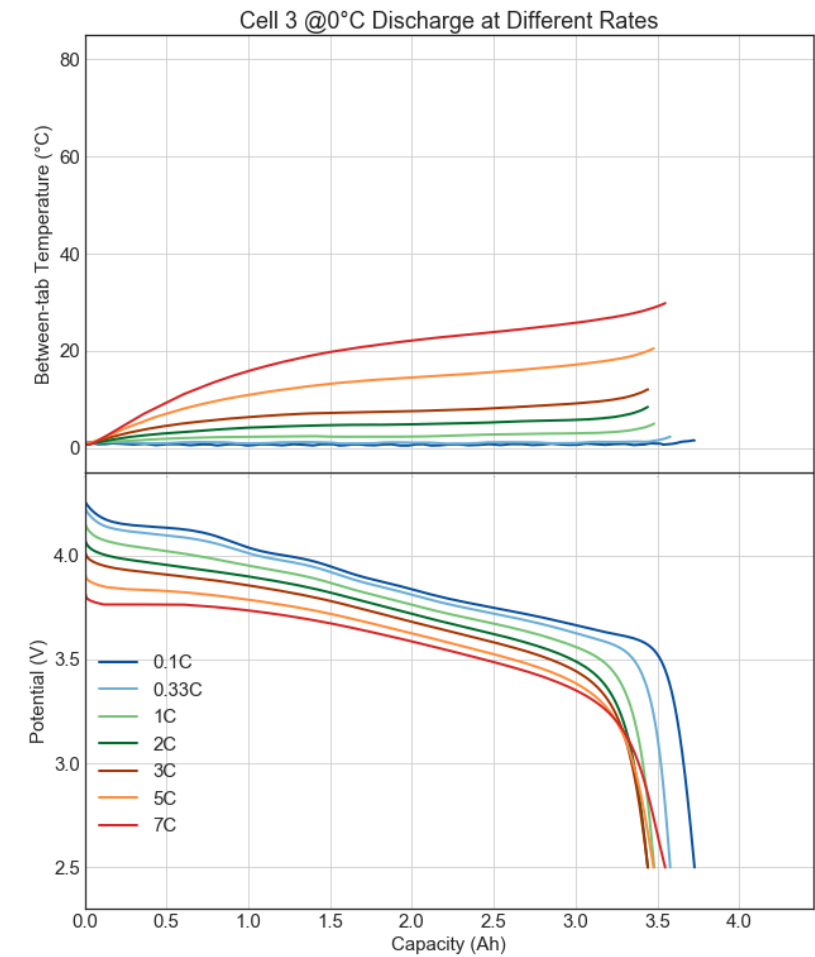
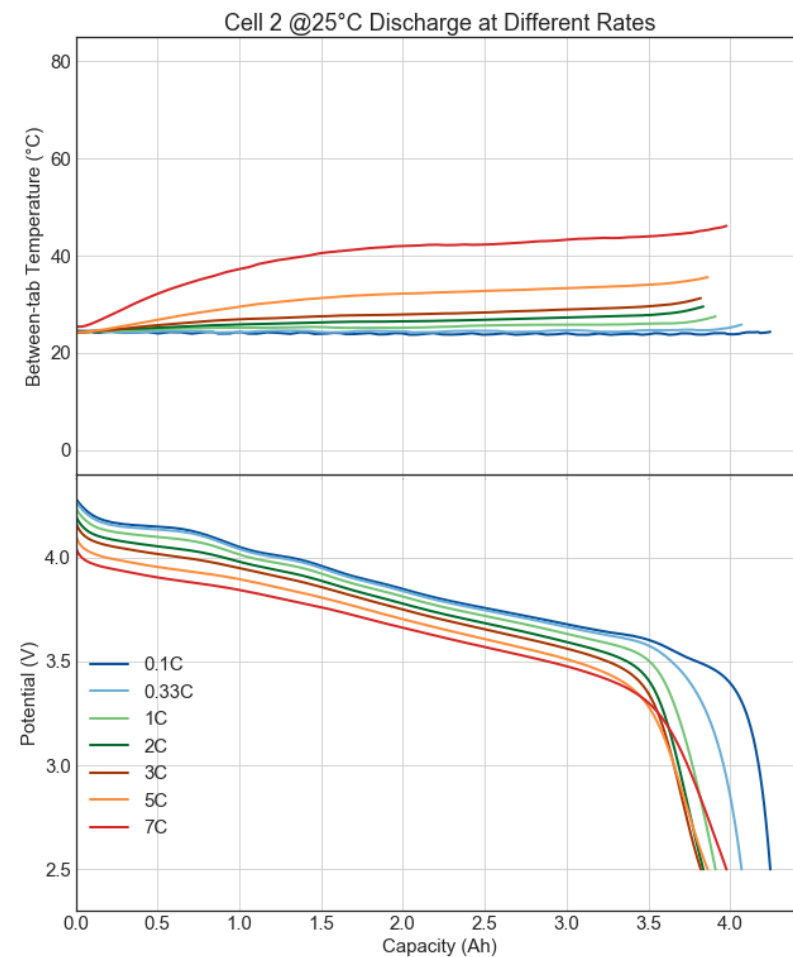
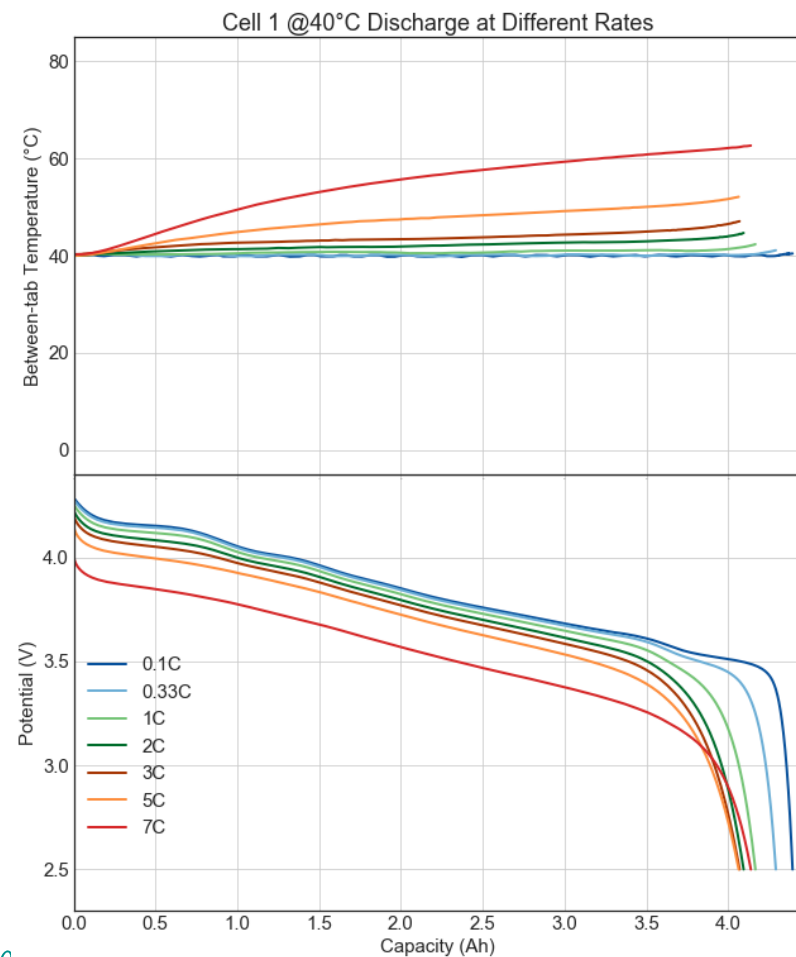
May 07, 2021

- Exponent was retained to assist in evaluating the performance of secondary lithium-metal cells produced by SES when discharged at various rates
- Exponent received three (3) cells from SES for testing
- Exponent performed the following analyses:
 - Open circuit voltage (OCV), AC impedance, weight, and energy density measurement on the as-received cells
 - Visual inspection and photo documentation for the as-received cells
 - Cycling tests using the protocol provided by SES under 40 °C, 25 °C, and 0 °C (1 cell for each temperature)
 - Fast-charging test on one cell using the protocol provided by SES at 25 °C

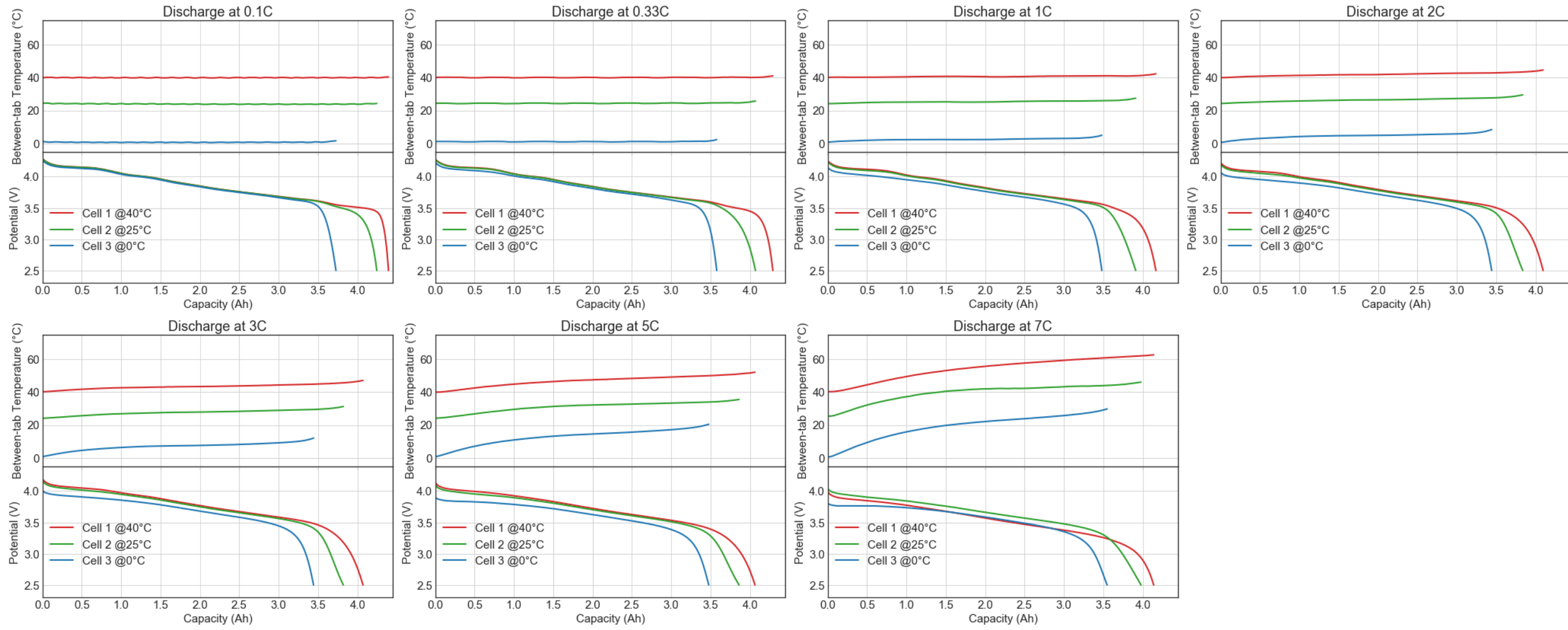
Cycling Test Summary (1/2)- Discharge at Different Rates



- All three cells finished the capacity check cycle and discharge cycles up to 7C
- The highest measured cell temperatures during the 7C high-rate discharge in the 40 °C, 25 °C, and 0 °C tests are 81.8 °C, 78.5 °C, and 45.7 °C, respectively
 - The maximum recorded temperature was always on the positive tab
- The discharge capacity during the 7C high-rate discharge in the 40 °C, 25 °C, and 0 °C tests are 4.14 Ah, 3.98 Ah, and 3.55 Ah, respectively
- The discharge energy during the 7C high-rate discharge in the 40 °C, 25 °C, and 0 °C tests are 14.6 Wh, 14.4 Wh, and 12.6 Wh, respectively
- An increase in capacity was observed at 7C (relative to 5C) for all three cells, which is attributed to the substantial increase in cell temperature during high-rate discharge



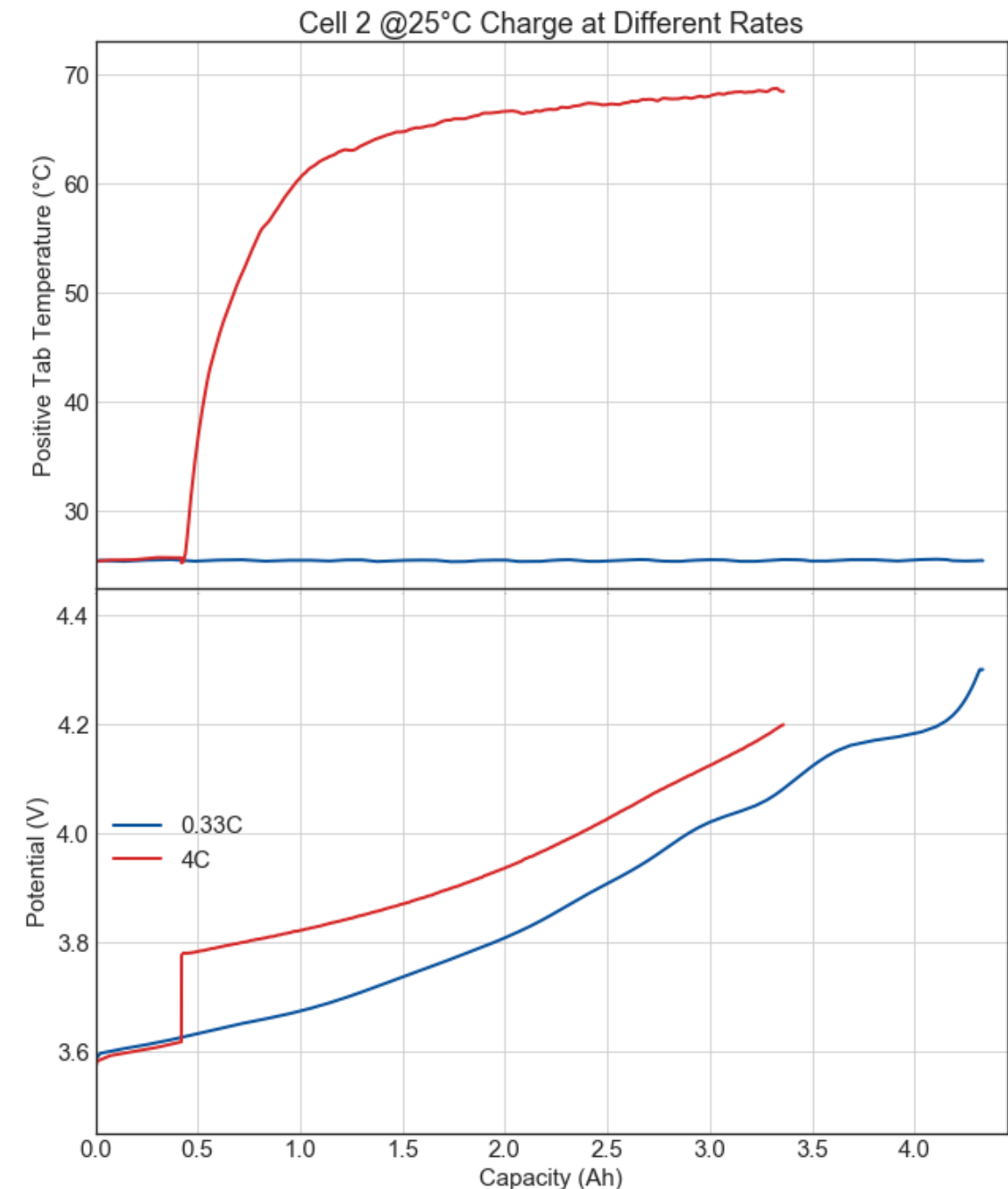
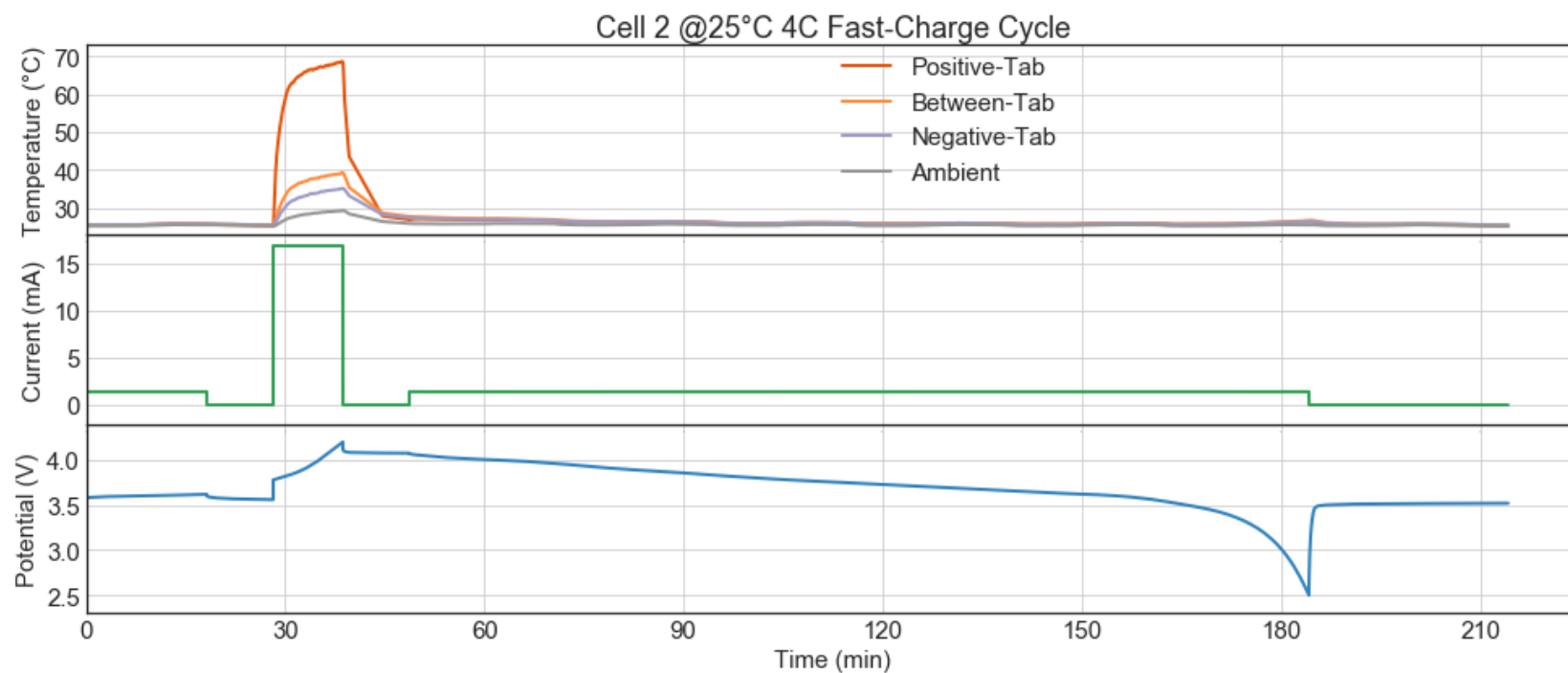
Cycling Test Summary (2/2)- Discharge Profile Comparison



Fast-charging Test Summary



- The cell successfully completed the capacity check cycle and the 4C fast-charge cycle
 - Charging from 10% to 80% of the nominal capacity at 4C took 10.5 minutes
 - The maximum voltage reached during fast charging was 4.20 V
- The highest measured cell temperature during the 4C high-rate charge was 68.7 °C
 - The maximum recorded temperature was on the positive tab



Cell Intake Visual Inspection



- Exponent received 3 SES pouch cells (identified here as “Cell 1” to “Cell 3”)
- No notable exterior defect was observed after visual inspection of all three cells

Cell 1



Cell 2



Cell 3



Cell Intake Measurements



- Exponent measured 1 kHz AC Impedance (ACImp), open-circuit voltage (OCV), thickness, and mass for each cell at intake, and the results are shown below
 - The 0.1C discharge capacity and energy reported here is based on the discharge during the capacity check cycle (described in later slides)
 - The energy density here is calculated based on the discharge energy in the capacity check cycle shown in the later slide measured at different temperatures, the cell mass and thickness shown in the table below, and the cell length (71.5 mm) and width (48.5 mm) in the specification sheet provided by SES

Cell #	Label	Mass (g)	Thickness (mm)	OCV (V)	Test Temperature (°C)	0.1C Discharge Capacity (Ah)	0.1C Discharge Energy (Wh)	Energy Density (Wh/kg)	Energy Density (Wh/L)
1	S06L45001	43.6	6.59	3.52	40	4.39	16.8	385	734
2	S06L45002	43.6	6.58	3.52	25	4.24	16.2	372	710
3	S06L45003	43.5	6.59	3.52	0	3.72	14.3	329	627

Electrical Test Setup



- Cells were clamped into test fixtures provided by SES, following the instructions provided by SES
 - The cells were centered and sandwiched between the plates. The bolts were tightened using a torque wrench to apply 5 pound-force-inches to secure the cell inside the fixture
 - Thermocouples were put at the positive tab, between tabs, and negative tab locations (red arrows & dots) to log the cell temperature change during the tests
- Cells 1, 2, and 3 were tested at 40 °C, 25 °C, and 0 °C, respectively, using the electrical test protocol provided by SES (slide 10)
- Cell 2 was further tested at 25 °C using the fast-charging electrical test protocol provided by SES (slide 21)



Cycling Test Results

Ex

Cycling Test Protocol

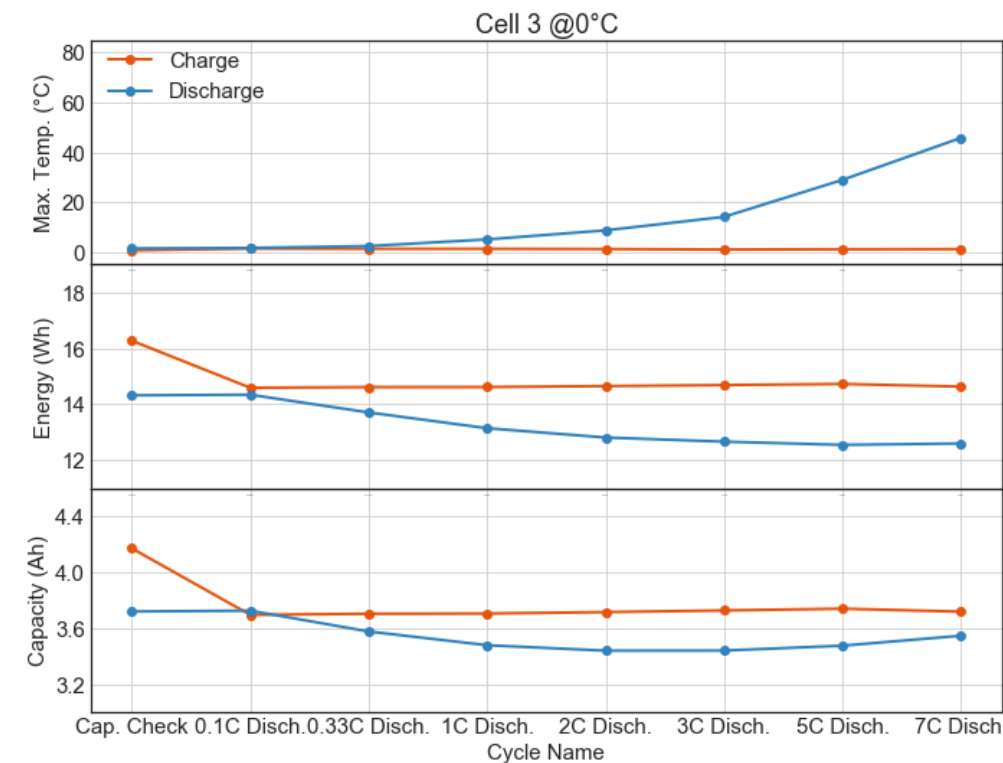
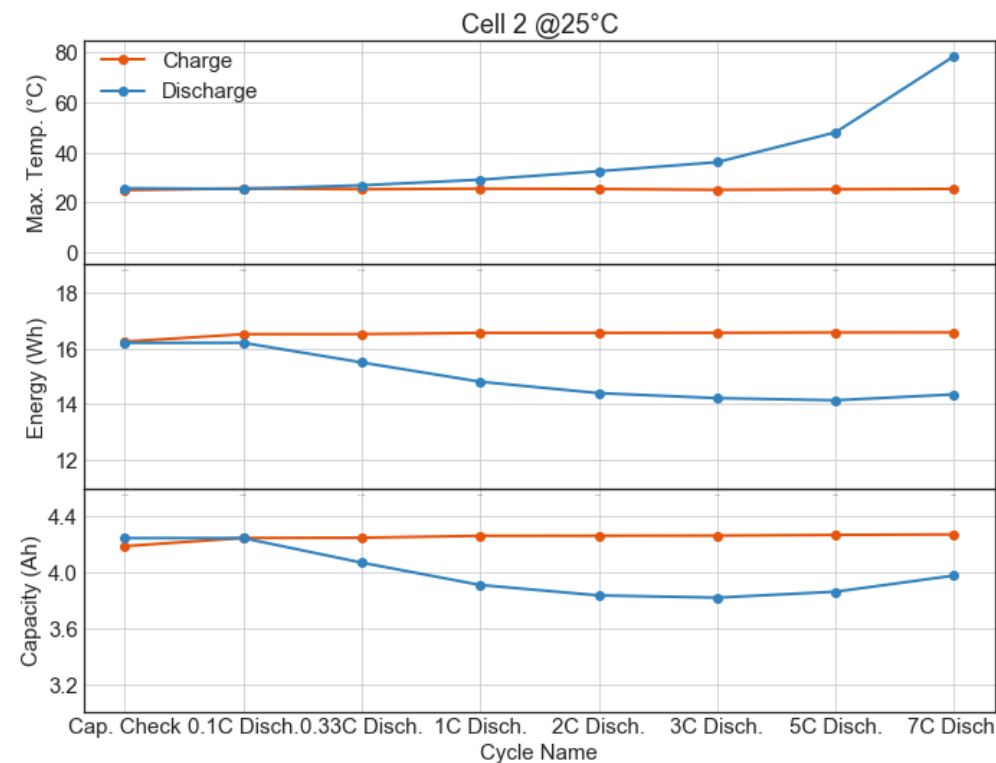
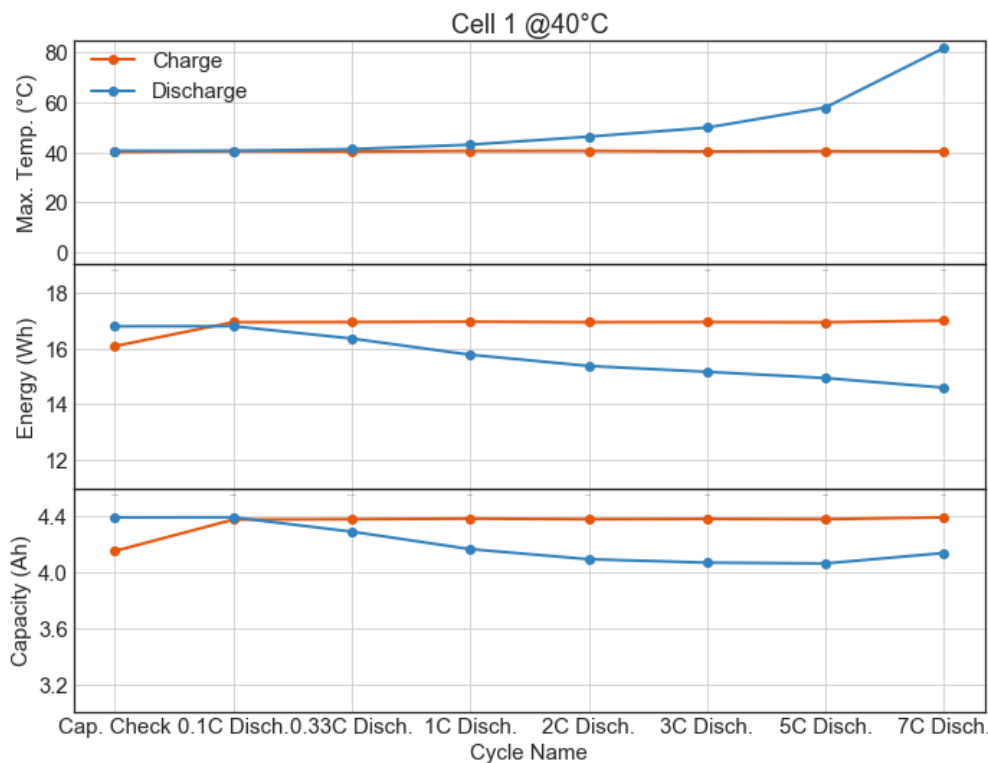
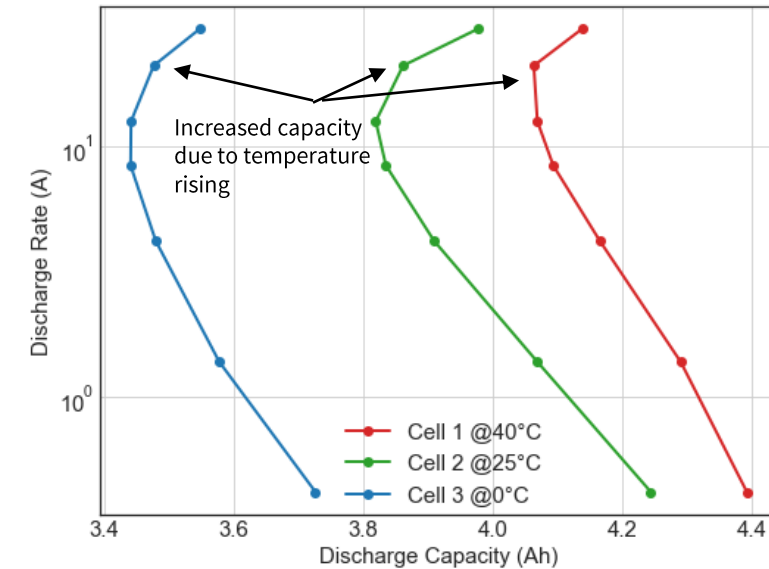


- Capacity check cycle
 - Rest for 2hr in each different temperature chamber (0 °C, 25 °C, or 40 °C)
 - Constant Current Charge at 0.1C (0.42A) until Voltage = 4.30V
 - Constant Voltage Hold at 4.30V until Current < 0.05C (0.21A)
 - Rest for 20 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 20 mins
- Rate capability test (0.1C)
 - Constant Current Charge at 0.33C (1.4A) until Voltage = 4.3V
 - Constant Voltage Hold at 4.3V until Current < 0.05C (0.21A)
 - Rest for 10 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 30 mins
- Rate capability test (0.33C)
 - Constant Current Charge at 0.33C (1.4A) until Voltage = 4.3V
 - Constant Voltage Hold at 4.3V until Current < 0.05C (0.21A)
 - Rest for 10 mins
 - Constant Current Discharge at 0.33C (1.4A) until Voltage = 2.5V
 - Rest for 30 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 10 mins
- Rate capability test (1C)
 - Constant Current Charge at 0.33C (1.4A) until Voltage = 4.3V
 - Constant Voltage Hold at 4.3V until Current < 0.05C (0.21A)
 - Rest for 10 mins
 - Constant Current Discharge at 1C (4.2A) until Voltage = 2.5V
 - Rest for 30 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 10 mins
- Rate capability test (2C)
 - Constant Current Charge at 0.33C (1.4A) until Voltage = 4.3V
 - Constant Voltage Hold at 4.3V until Current < 0.05C (0.21A)
 - Rest for 10 mins
 - Constant Current Discharge at 2C (8.4A) until Voltage = 2.5V
 - Rest for 30 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 10 mins
- Rate capability test (3C)
 - Constant Current Charge at 0.33C (1.4A) until Voltage = 4.3V
 - Constant Voltage Hold at 4.3V until Current < 0.05C (0.21A)
 - Rest for 10 mins
 - Constant Current Discharge at 3C (12.6A) until Voltage = 2.5V
 - Rest for 30 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 10 mins
- Rate capability test (5C)
 - Constant Current Charge at 0.33C (1.4A) until Voltage = 4.3V
 - Constant Voltage Hold at 4.3V until Current < 0.05C (0.21A)
 - Rest for 10 mins
 - Constant Current Discharge at 5C (21A) until Voltage = 2.5V
 - Rest for 30 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 10 mins
- Rate capability test (7C)
 - Constant Current Charge at 0.33C (1.4A) until Voltage = 4.3V
 - Constant Voltage Hold at 4.3V until Current < 0.05C (0.21A)
 - Rest for 10 mins
 - Constant Current Discharge at 7C (29.4A) until Voltage = 2.5V
 - Rest for 30 mins
 - Constant Current Discharge at 0.1C (0.42A) until Voltage = 2.5V
 - Rest for 10 mins

Cycling Test Summary



- The highest measured cell temperatures during the 7C high-rate discharge in the 40 °C, 25 °C, and 0 °C tests are 81.8 °C, 78.5 °C, and 45.7 °C, respectively
 - The maximum recorded temperature was always on the positive tab
- The discharge capacity during the 7C high-rate discharge in the 40 °C, 25 °C, and 0 °C tests are 4.14 Ah, 3.98 Ah, and 3.55 Ah, respectively
- The discharge energy during the 7C high-rate discharge in the 40 °C, 25 °C, and 0 °C tests are 14.6 Wh, 14.4 Wh, and 12.6 Wh, respectively
- An increase in capacity was observed at 7C (relative to 5C) for all three cells, which is attributed to the substantial increase in cell temperature during high-rate discharge



Result Table



- A summary of the cycling test results on all three cells is shown below

Cycle Name	Max. Ch. Rate	Max. Disch. Rate	Cell 1 @ 40 °C						Cell 2 @ 25 °C						Cell 3 @ 0 °C					
			Charge			Discharge			Charge			Discharge			Charge			Discharge		
			Cap. (Ah)	Energy (Wh)	Max. T. (°C)	Cap. (Ah)	Energy (Wh)	Max. T. (°C)	Cap. (Ah)	Energy (Wh)	Max. T. (°C)	Cap. (Ah)	Energy (Wh)	Max. T. (°C)	Cap. (Ah)	Energy (Wh)	Max. T. (°C)	Cap. (Ah)	Energy (Wh)	Max. T. (°C)
Capacity Check *	0.1C	0.1C	4.15	16.08	40.1	4.39	16.78	40.6	4.19	16.24	24.7	4.24	16.19	25.5	4.17	16.27	0.6	3.72	14.32	1.4
0.1C Discharge	0.33C	0.1C	4.38	16.93	40.4	4.39	16.79	40.5	4.25	16.50	25.5	4.24	16.20	25.2	3.70	14.59	1.3	3.73	14.34	1.5
0.33C** Discharge	0.33C	0.33C	4.38	16.94	40.2	4.29	16.35	41.2	4.25	16.51	25.1	4.07	15.49	26.7	3.70	14.61	1.2	3.58	13.71	2.3
1C** Discharge	0.33C	1C	4.38	16.95	40.5	4.17	15.77	43.0	4.26	16.55	25.3	3.91	14.81	28.9	3.71	14.62	1.2	3.48	13.15	5.0
2C** Discharge	0.33C	2C	4.38	16.93	40.5	4.09	15.37	46.2	4.26	16.55	25.2	3.84	14.40	32.3	3.72	14.65	1.1	3.44	12.81	8.6
3C** Discharge	0.33C	3C	4.38	16.94	40.3	4.07	15.16	49.9	4.26	16.55	24.9	3.82	14.22	36.0	3.73	14.69	0.9	3.44	12.67	14.0
5C** Discharge	0.33C	5C	4.38	16.93	40.4	4.06	14.94	57.9	4.27	16.57	25.1	3.86	14.14	47.9	3.74	14.73	1.0	3.48	12.55	28.9
7C** Discharge	0.33C	7C	4.39	16.99	40.3	4.14	14.59	81.8	4.27	16.57	25.3	3.98	14.35	78.5	3.72	14.63	1.1	3.55	12.60	45.7

*The cell started charging from the as-received state-of-charge

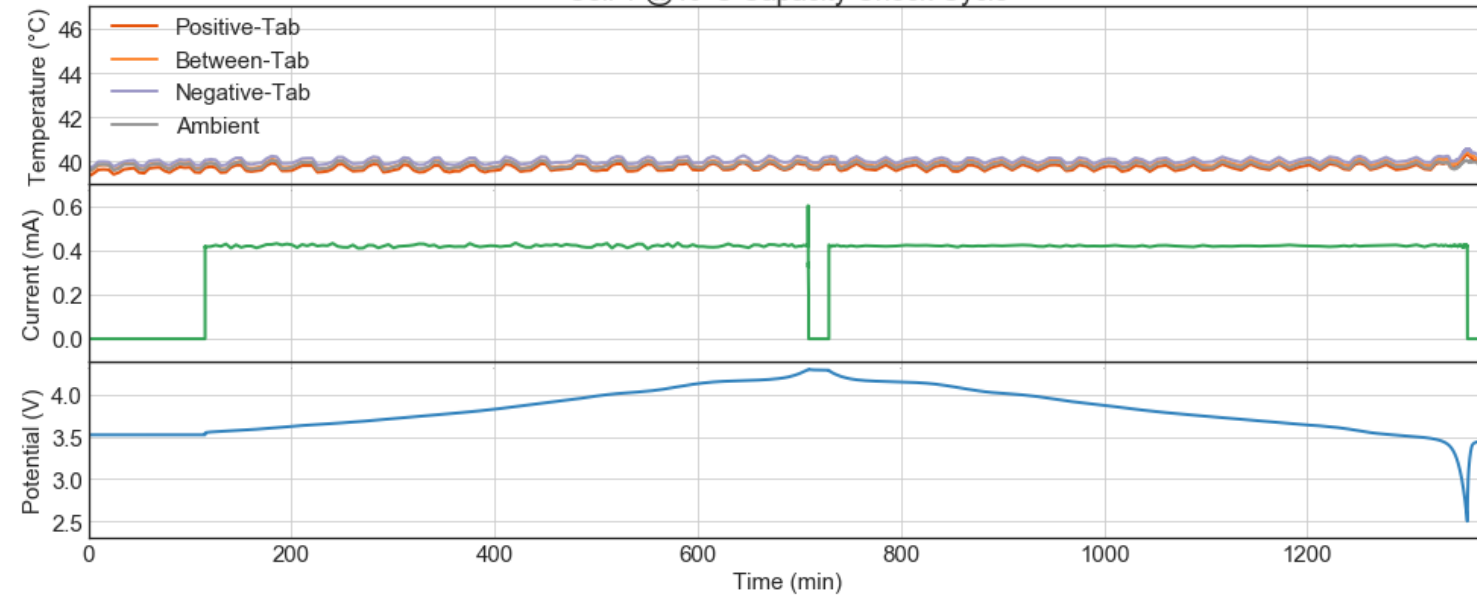
** The discharge values here are from the discharge process at the corresponding max. discharge rates (not including the slow-rate discharge at the end)

Charge and Discharge Profiles for Cell 1 @ 40 °C (1/2)

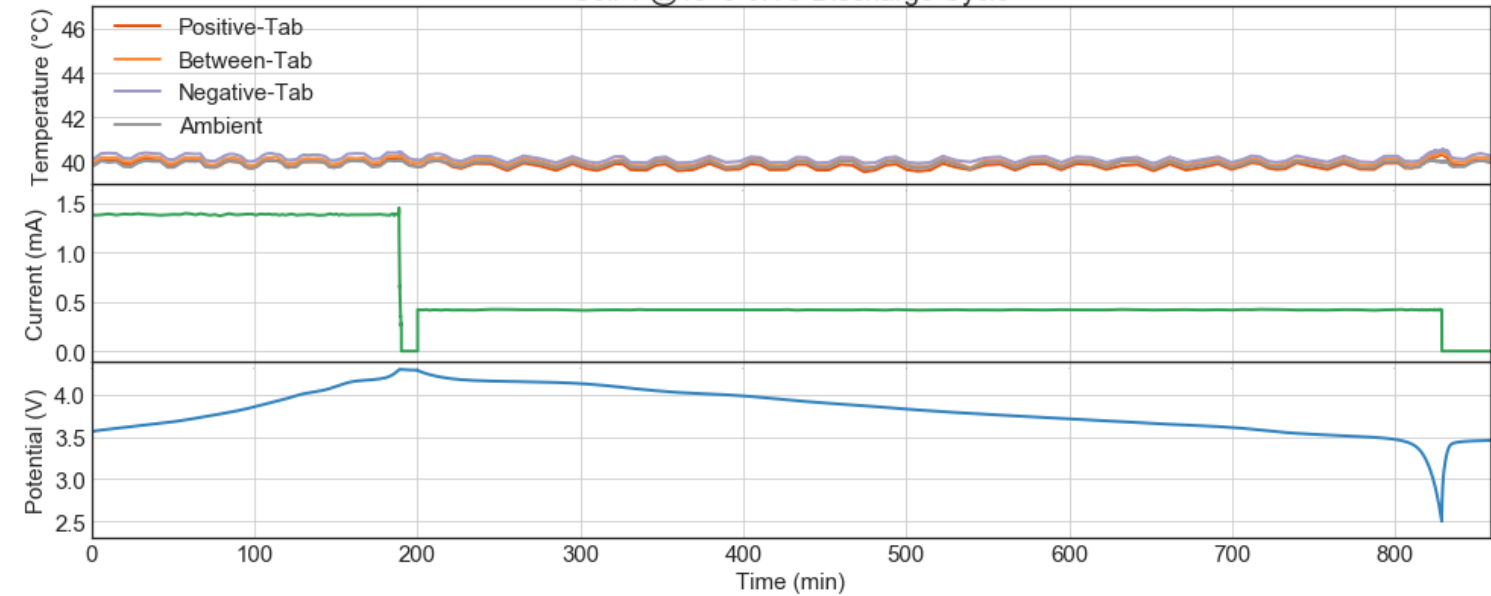


- The capacity check cycle and the 0.1C, 0.33C, and 1C discharge cycles of Cell 1 at 40 °C are shown below

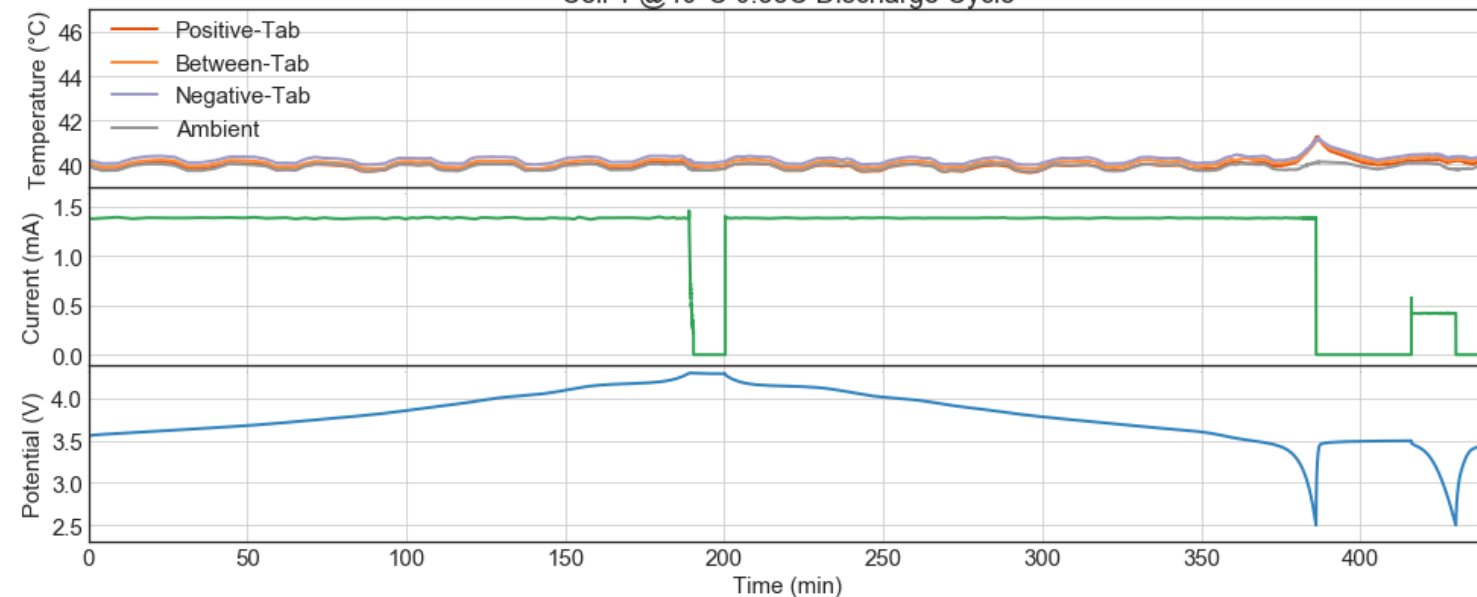
Cell 1 @40°C Capacity Check Cycle



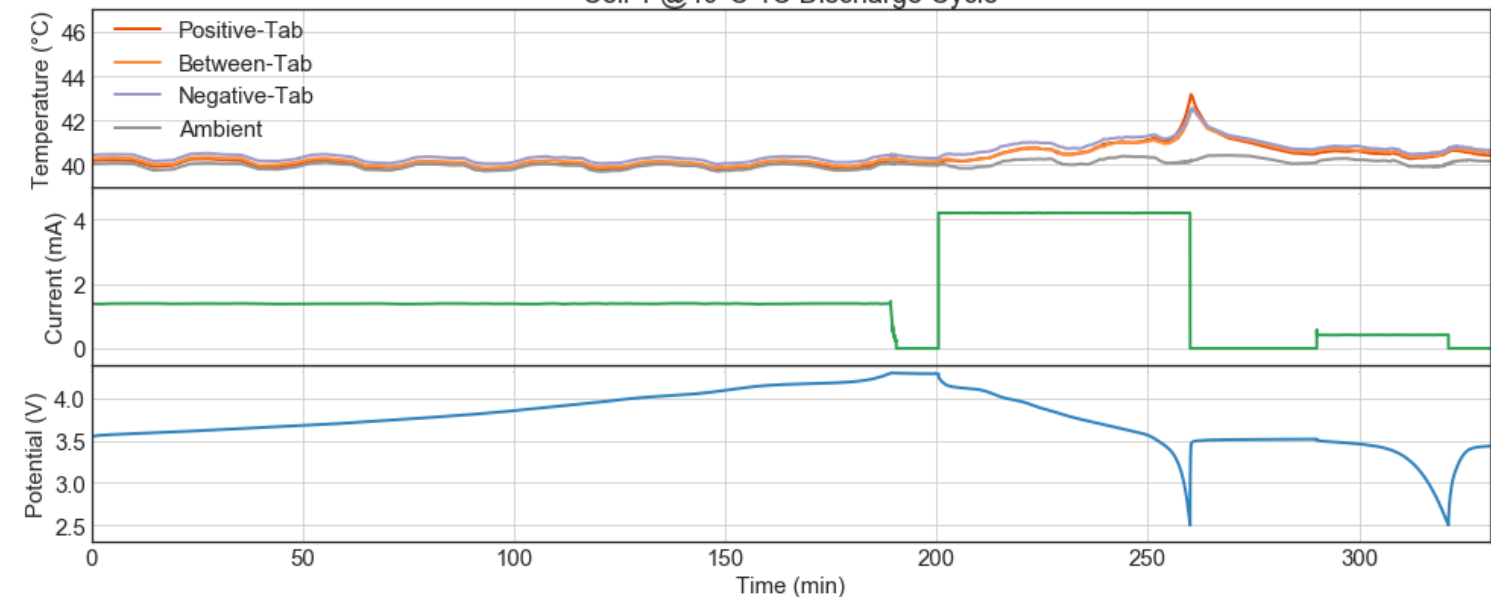
Cell 1 @40°C 0.1C Discharge Cycle



Cell 1 @40°C 0.33C Discharge Cycle



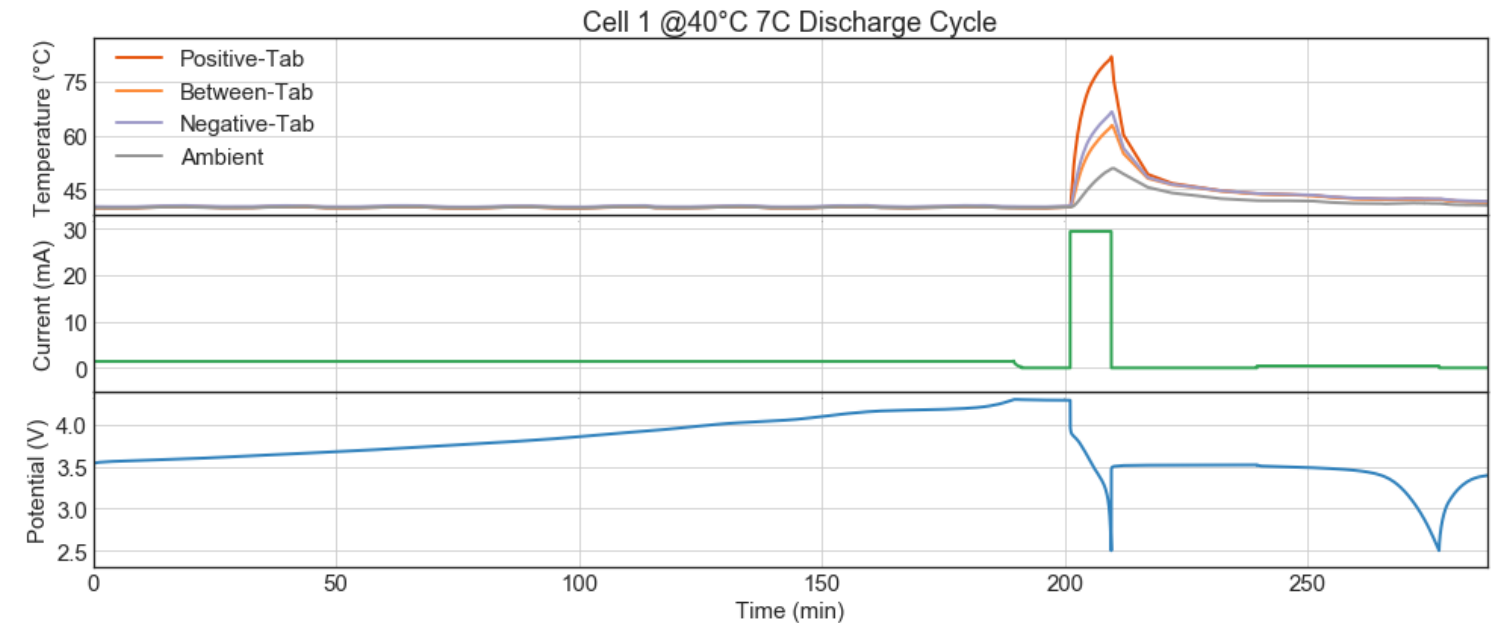
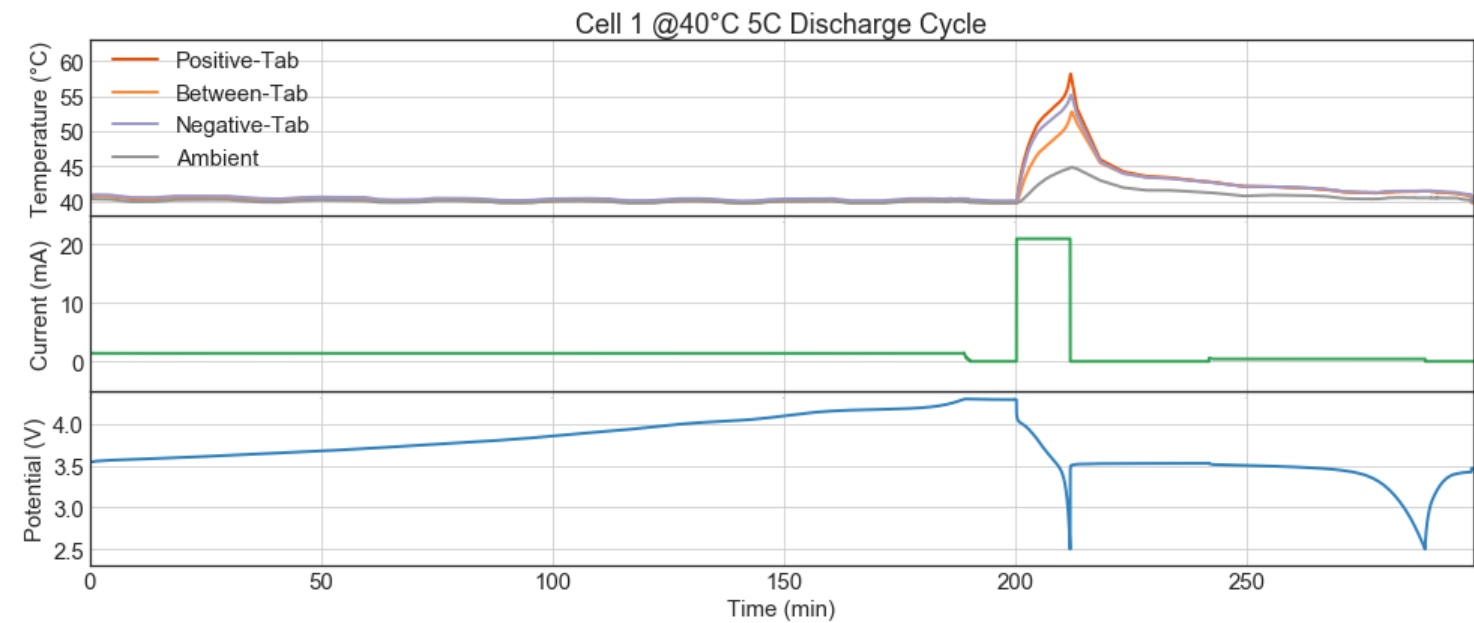
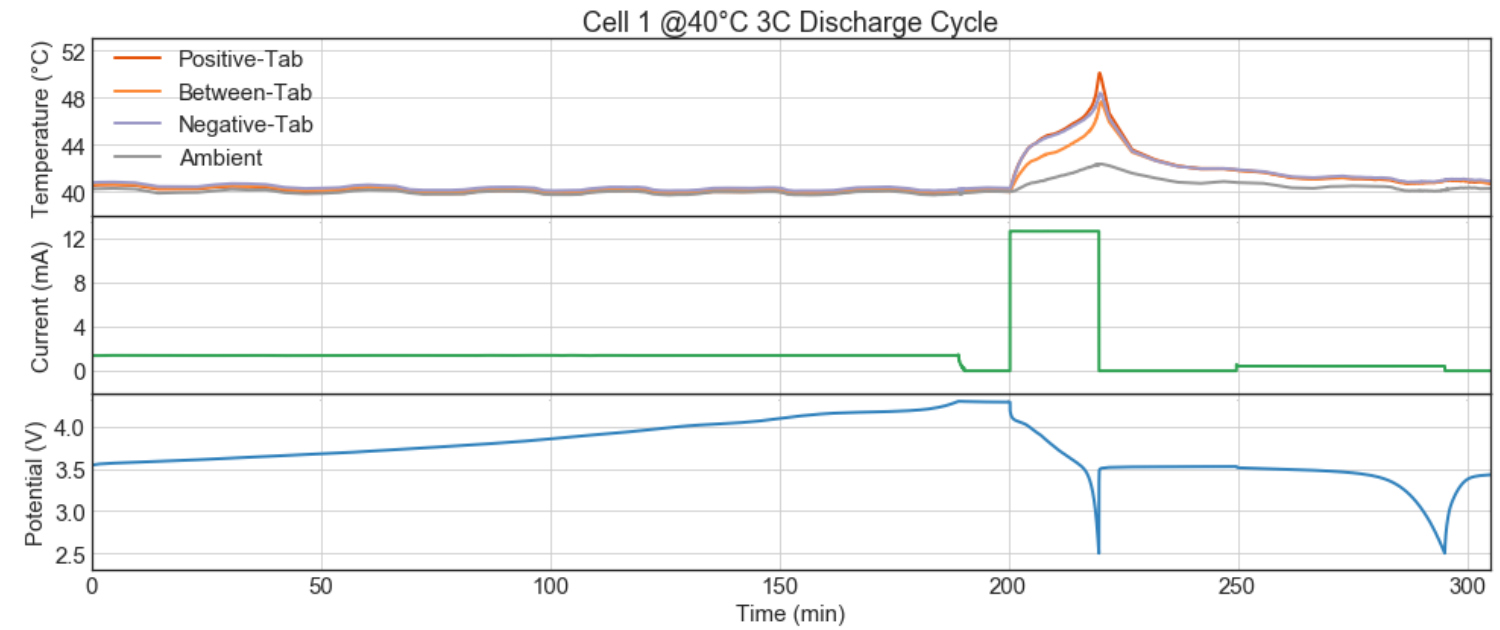
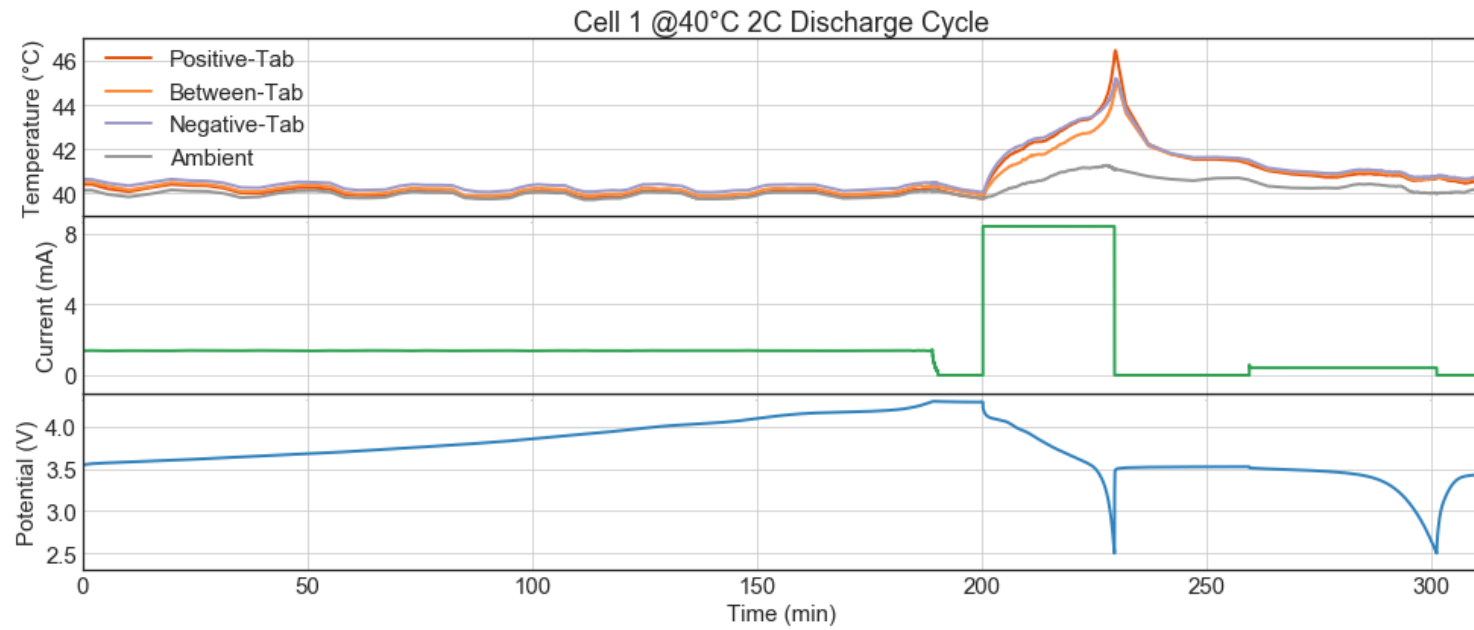
Cell 1 @40°C 1C Discharge Cycle



Charge and Discharge Profiles for Cell 1 @ 40 °C (2/2)



- The 2C, 3C, 5C, and 7C discharge cycles of Cell 1 at 40 °C are shown below

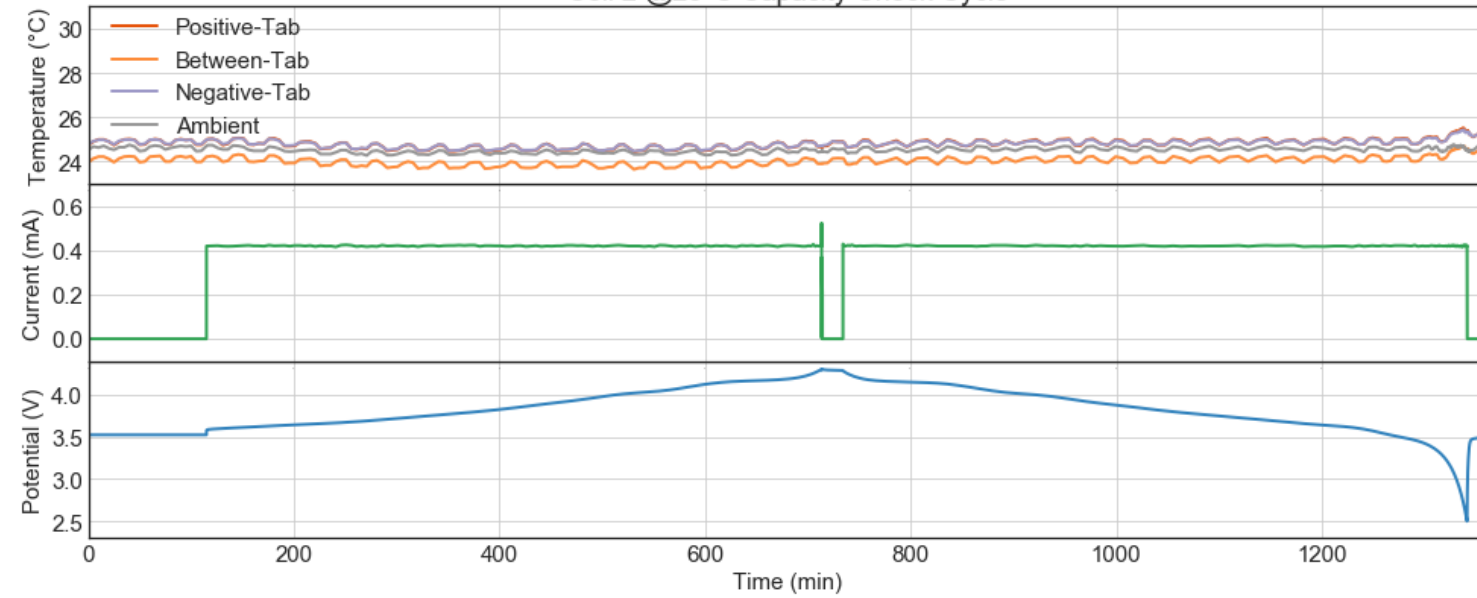


Charge and Discharge Profiles for Cell 2 @ 25 °C (1/2)

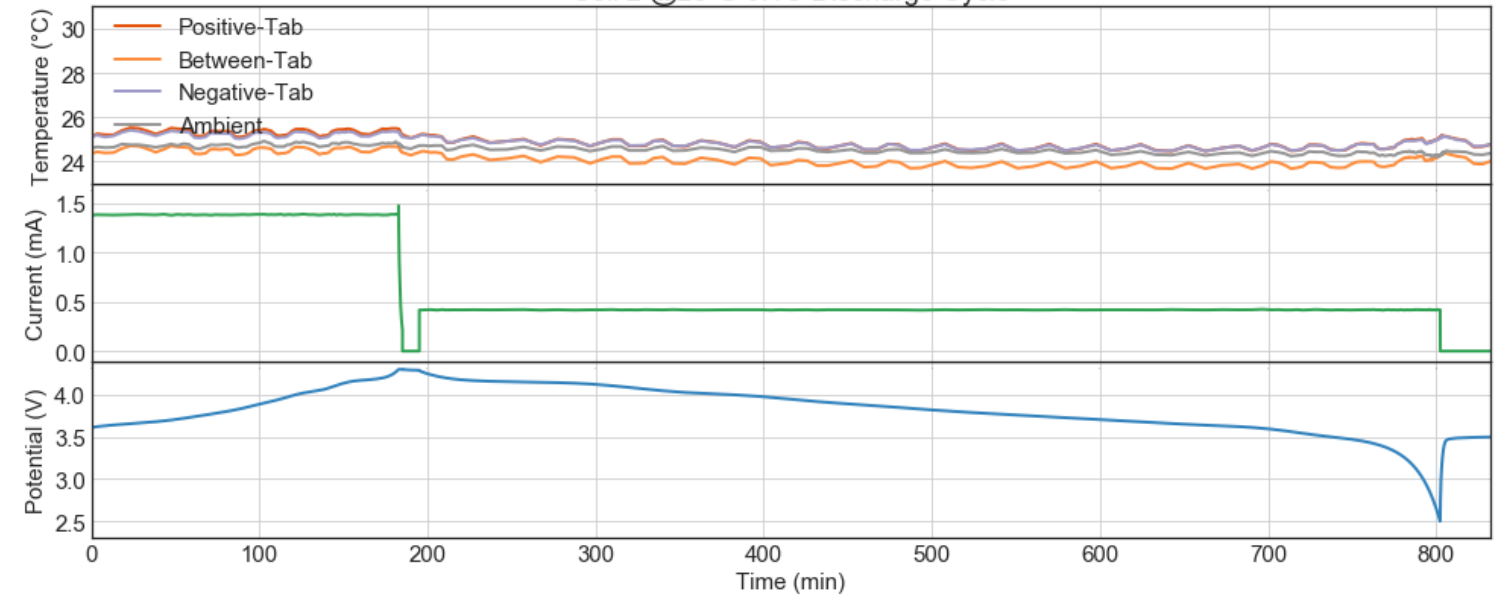


- The capacity check cycle and the 0.1C, 0.33C, and 1C discharge cycles of Cell 2 at 25 °C are shown below

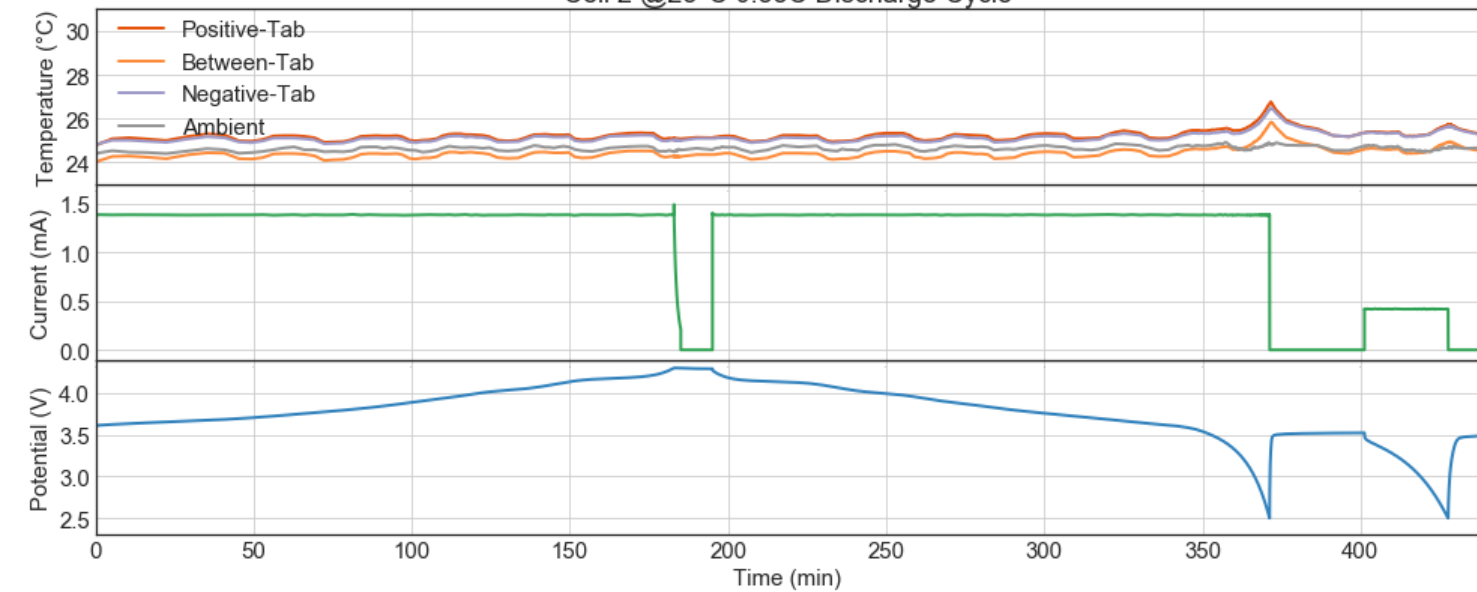
Cell 2 @25°C Capacity Check Cycle



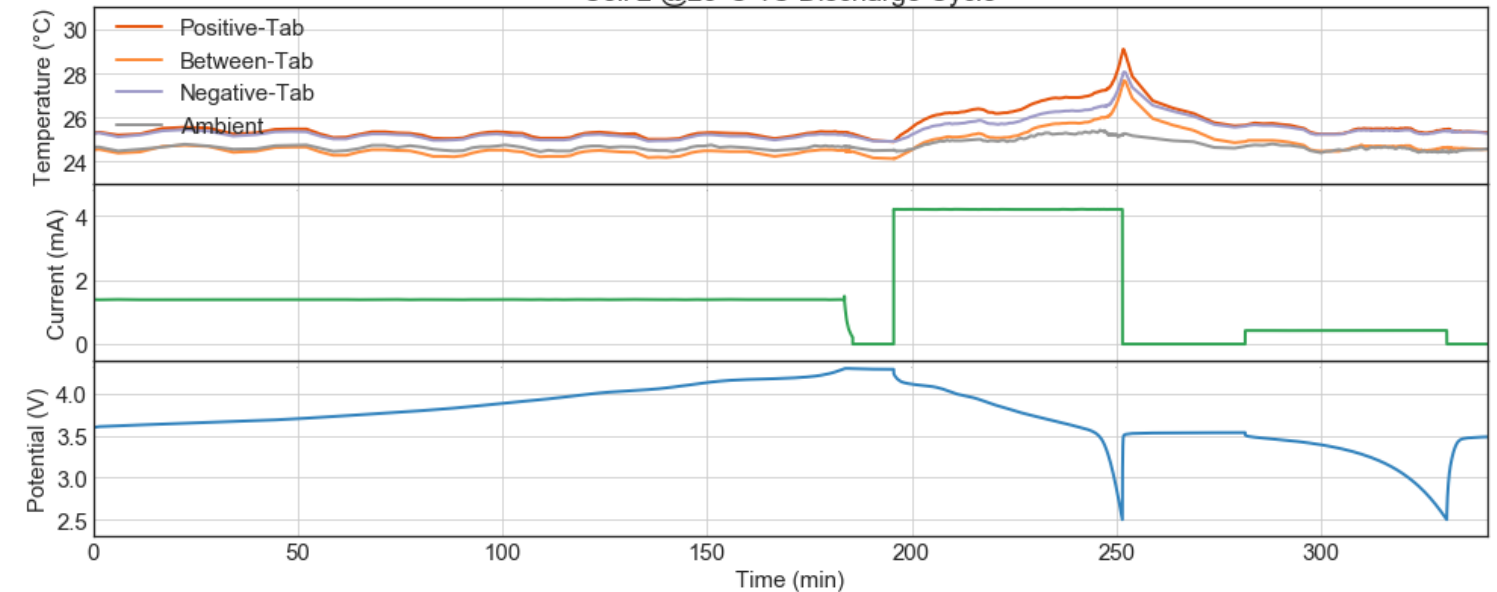
Cell 2 @25°C 0.1C Discharge Cycle



Cell 2 @25°C 0.33C Discharge Cycle



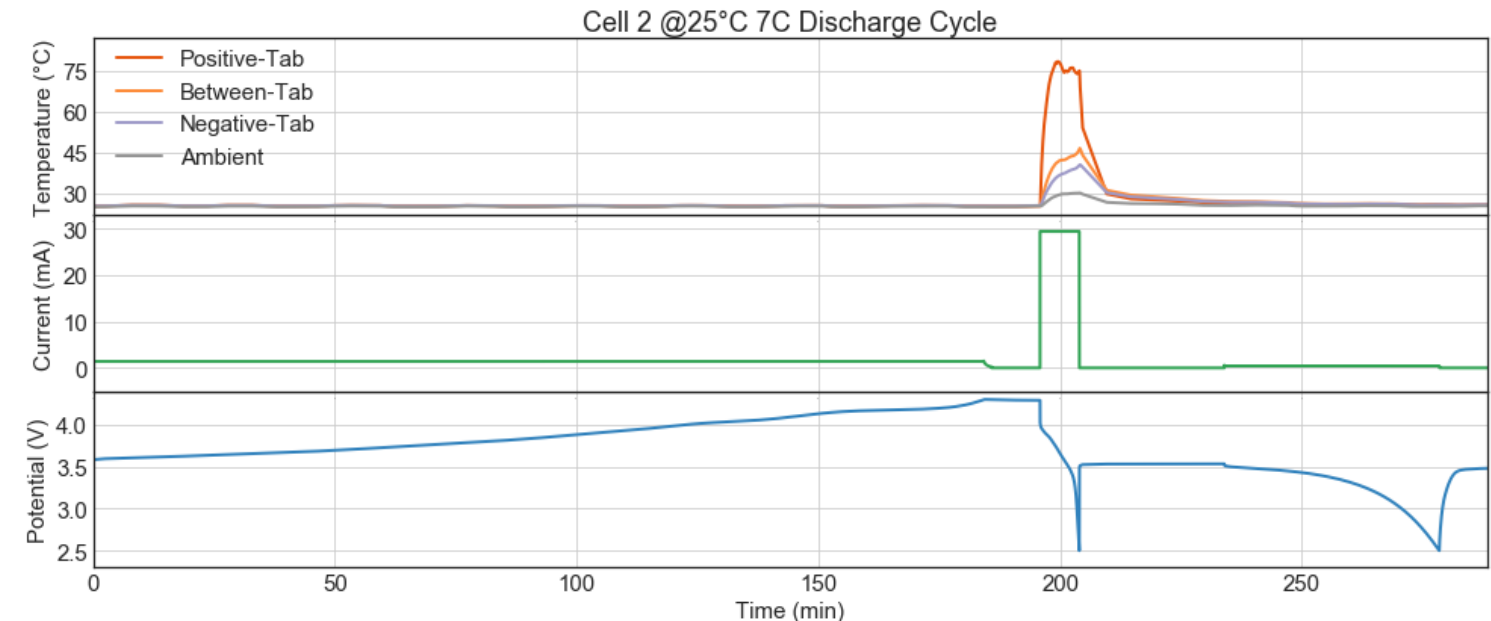
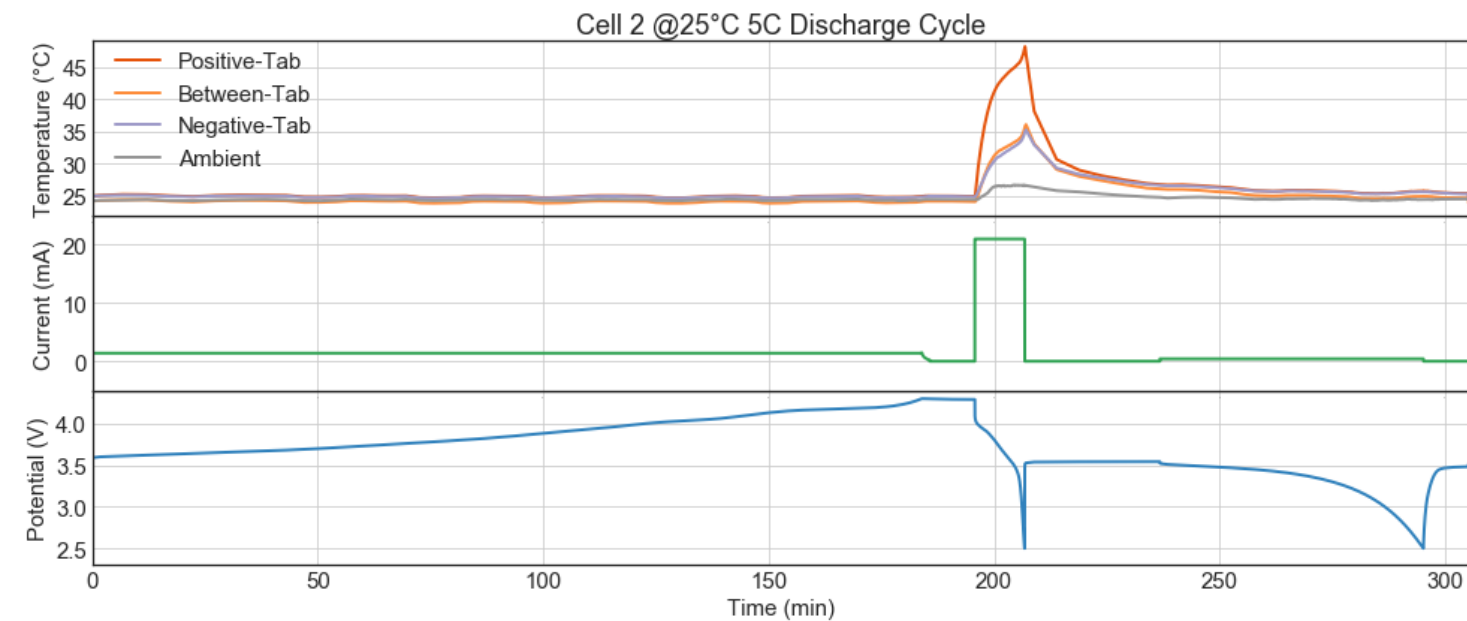
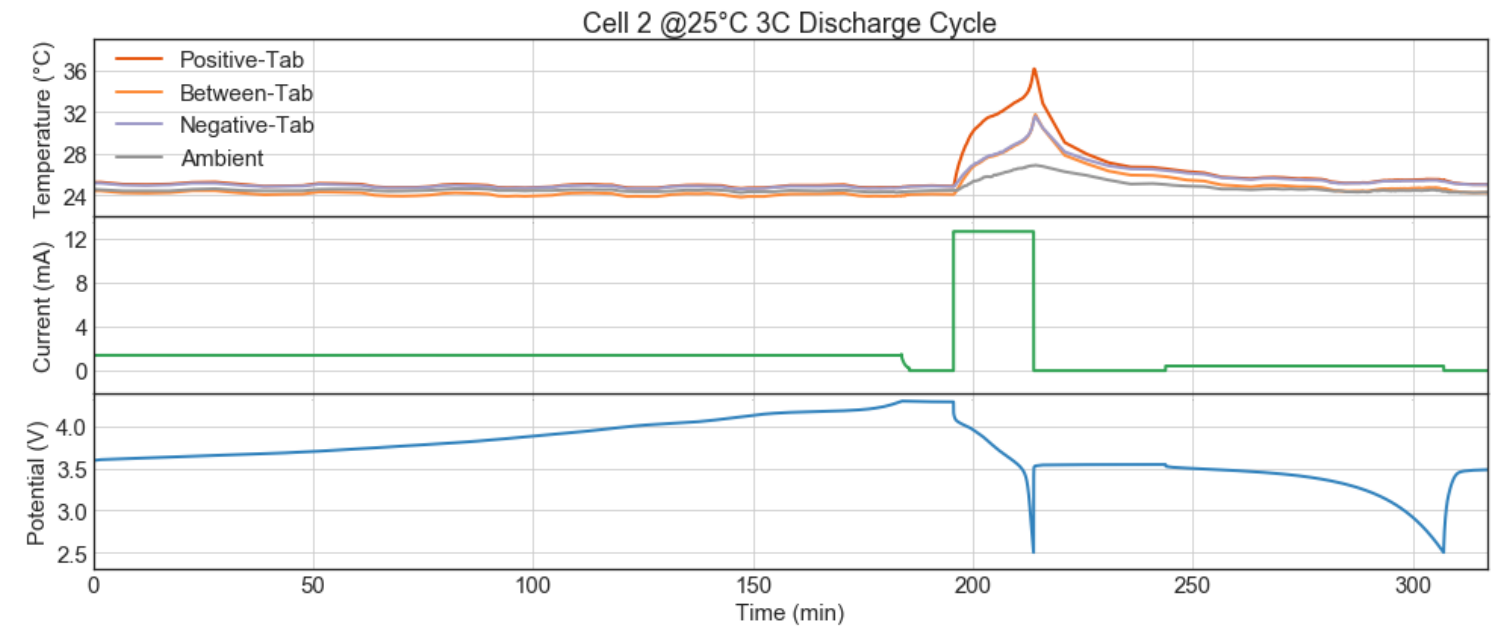
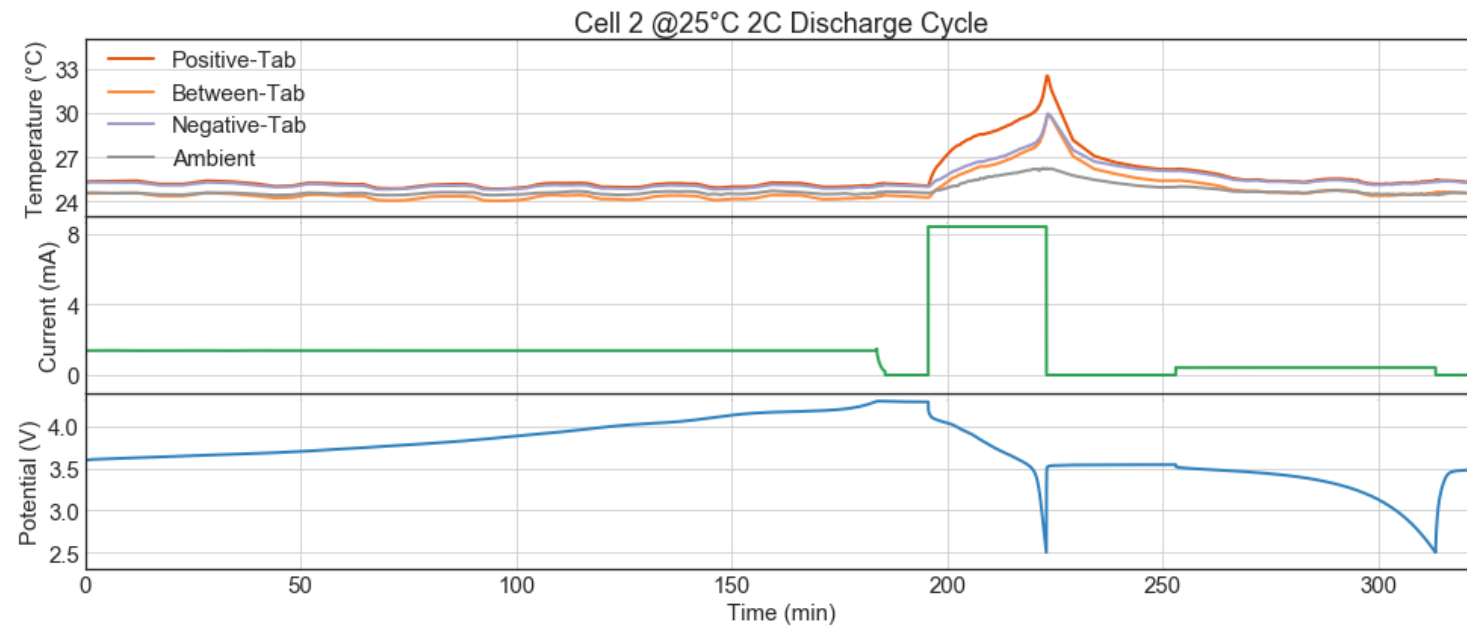
Cell 2 @25°C 1C Discharge Cycle



Charge and Discharge Profiles for Cell 2 @ 25 °C (2/2)



- The 2C, 3C, 5C, and 7C discharge cycles of Cell 2 at 25 °C are shown below

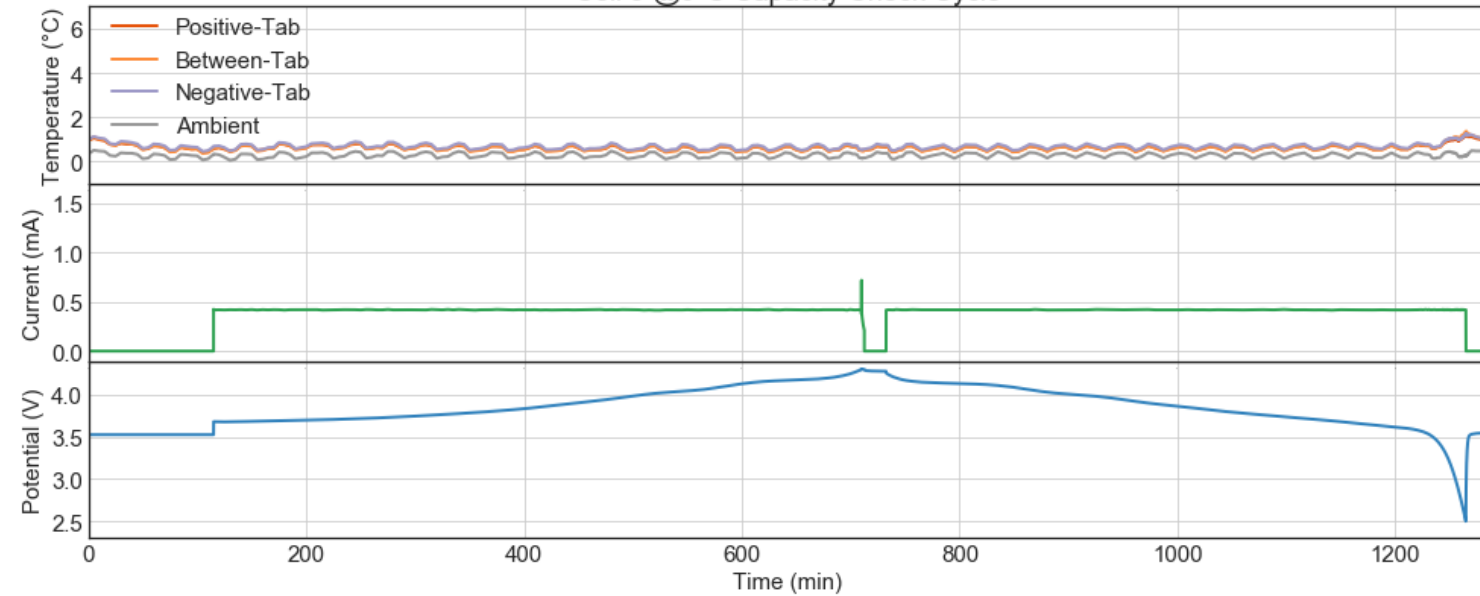


Charge and Discharge Profiles for Cell 3 @ 0 °C (1/2)

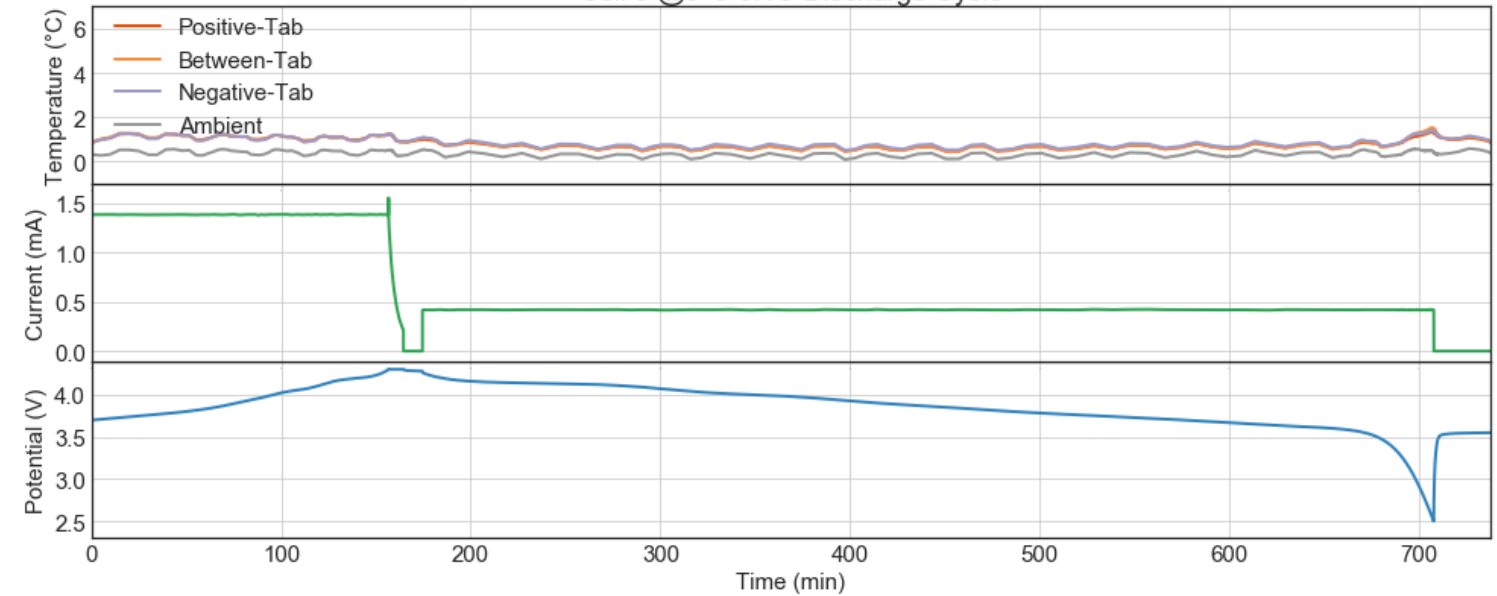


- The capacity check cycle and the 0.1C, 0.33C, and 1C discharge cycles of Cell 3 at 0 °C are shown below

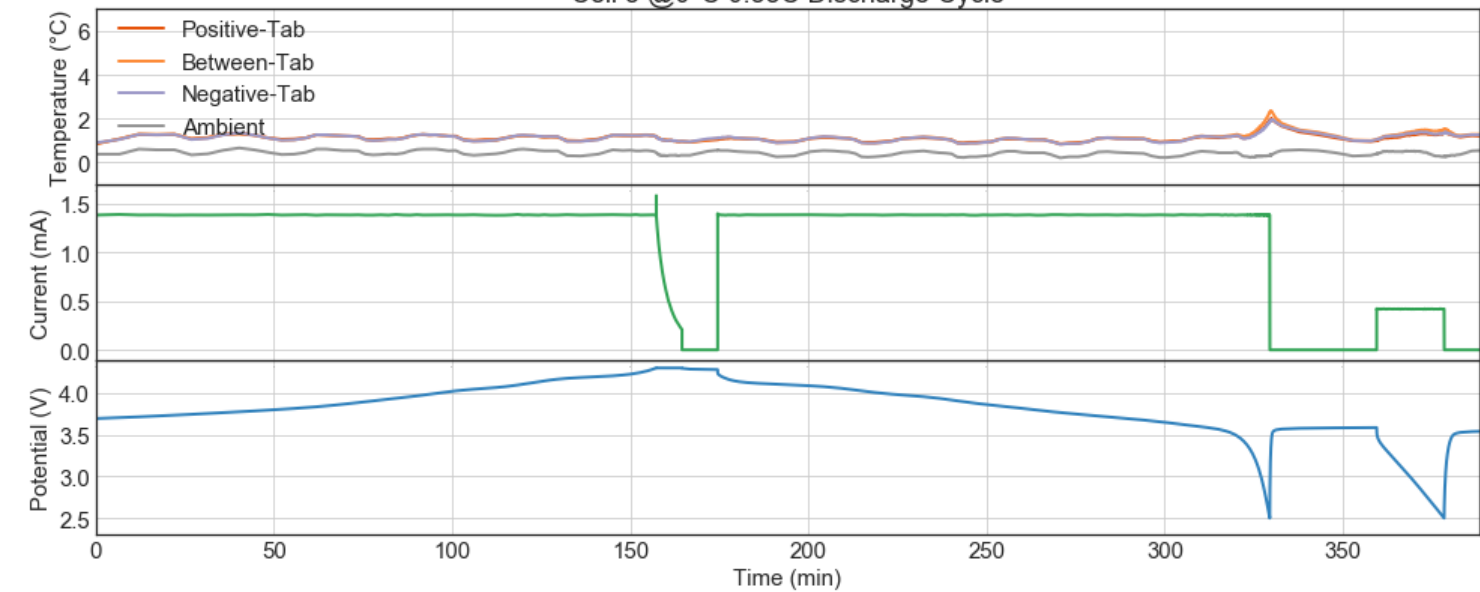
Cell 3 @0°C Capacity Check Cycle



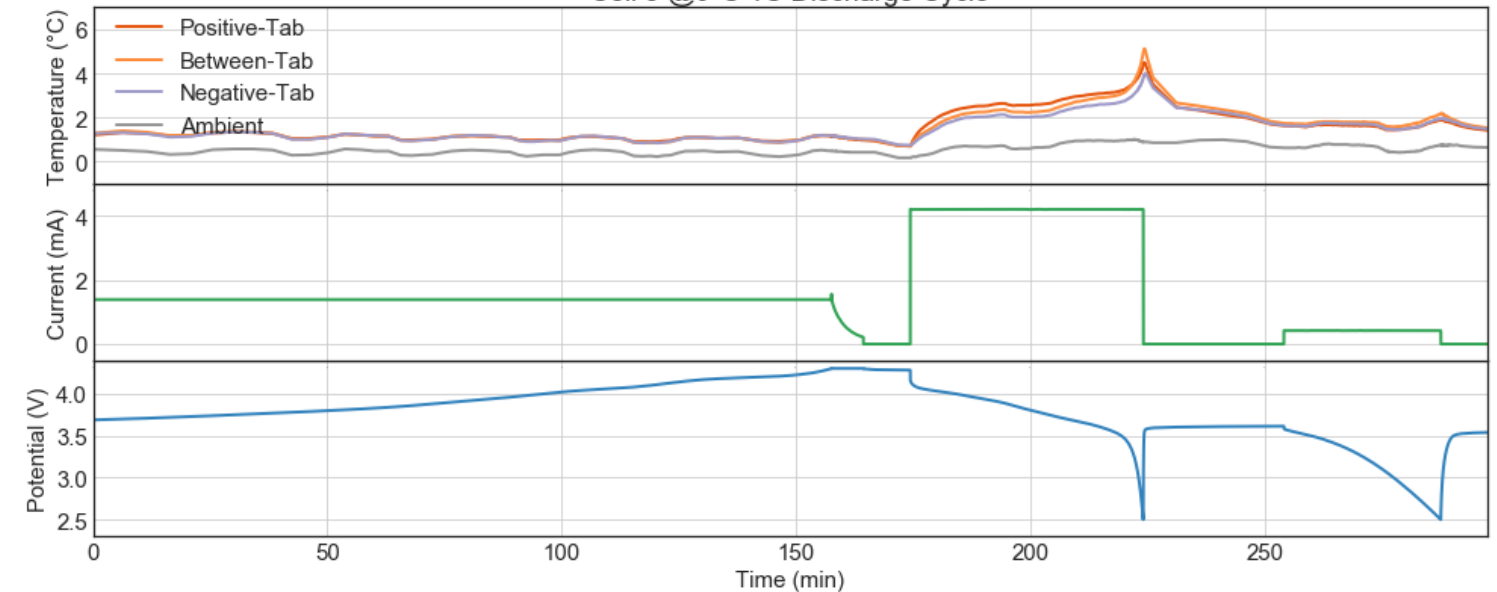
Cell 3 @0°C 0.1C Discharge Cycle



Cell 3 @0°C 0.33C Discharge Cycle



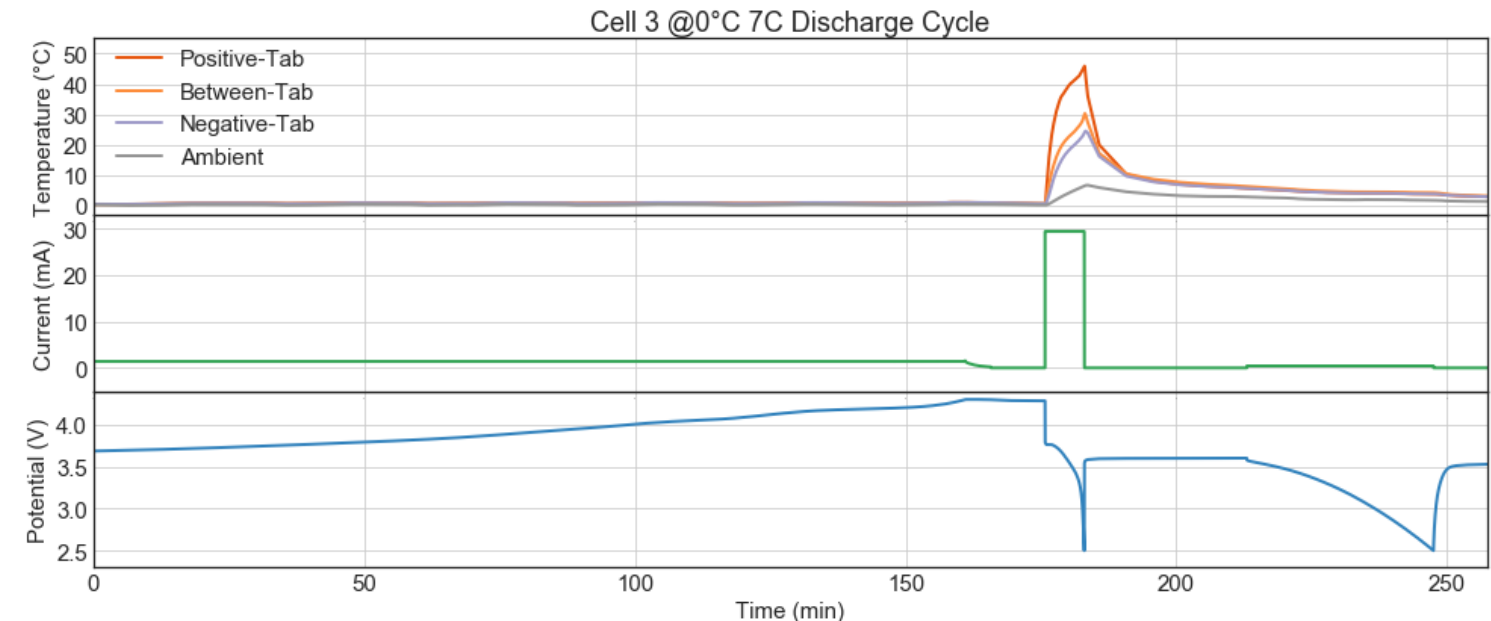
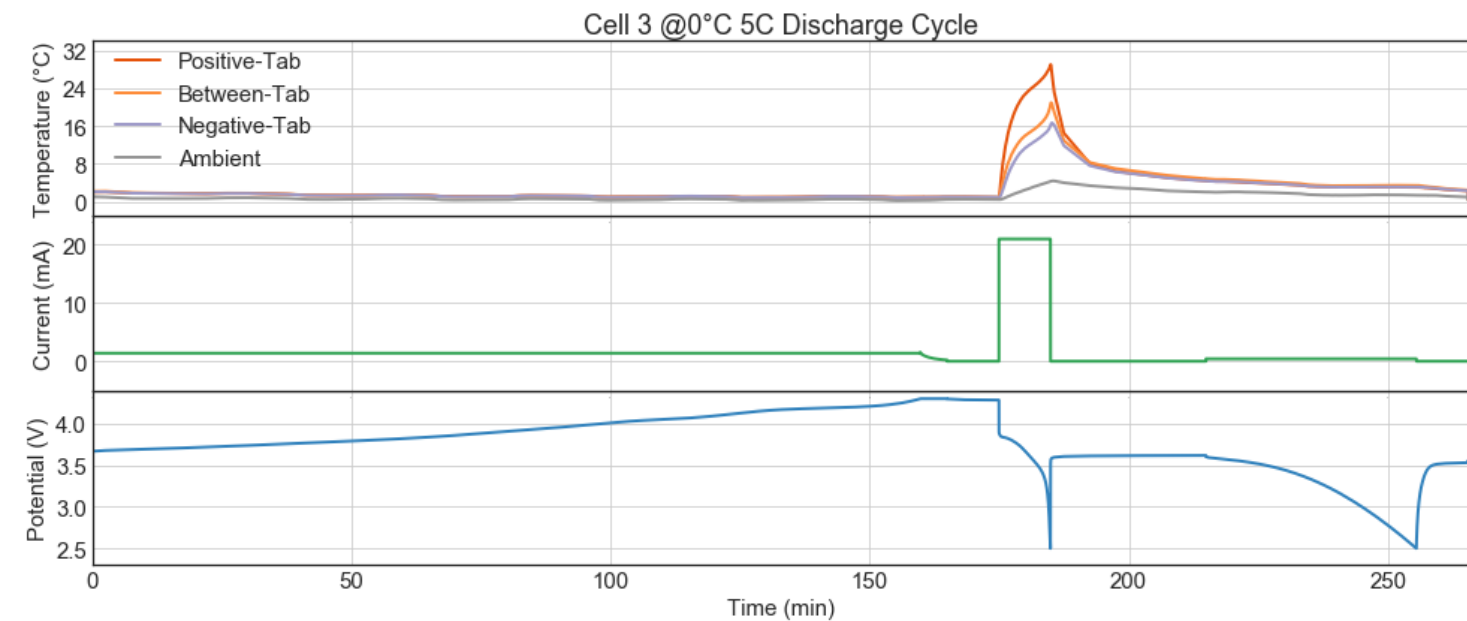
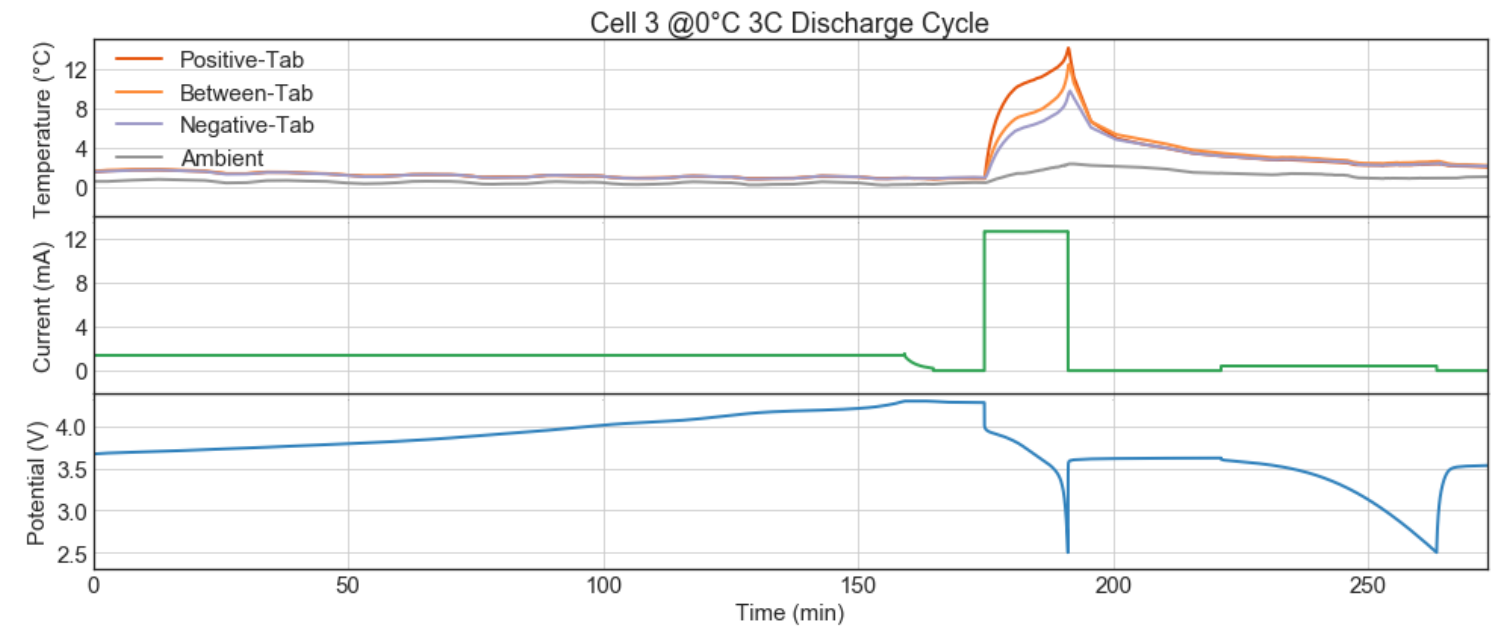
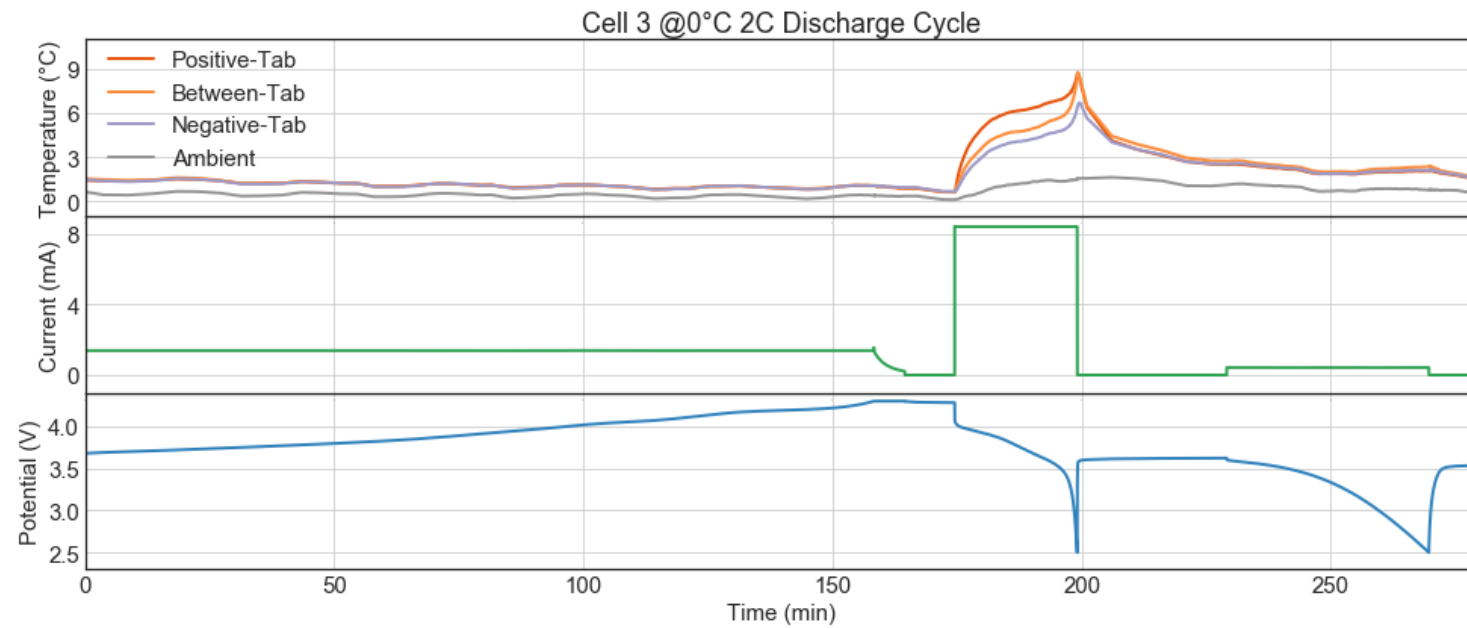
Cell 3 @0°C 1C Discharge Cycle



Charge and Discharge Profiles for Cell 3 @ 0 °C (2/2)



- The 2C, 3C, 5C, and 7C discharge cycles of Cell 3 at 0 °C are shown below



Fast-charging Test Results

Ex

Fast-charging Test Protocol

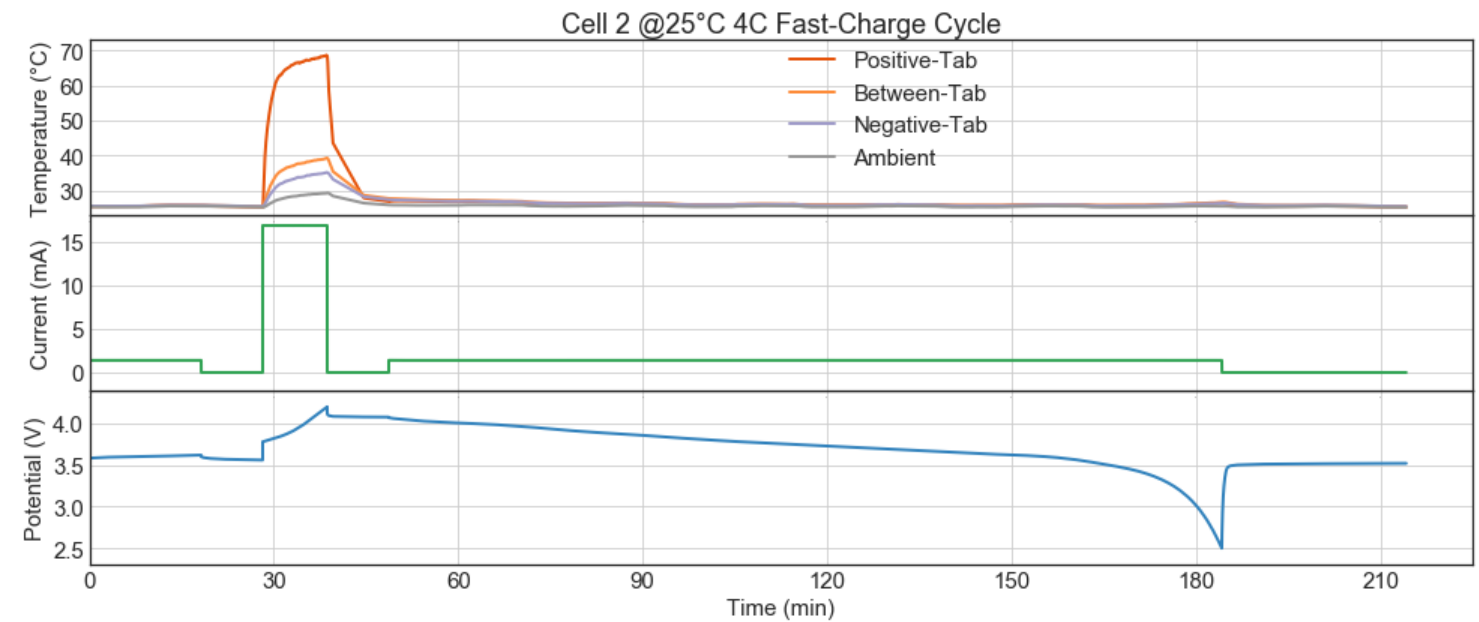
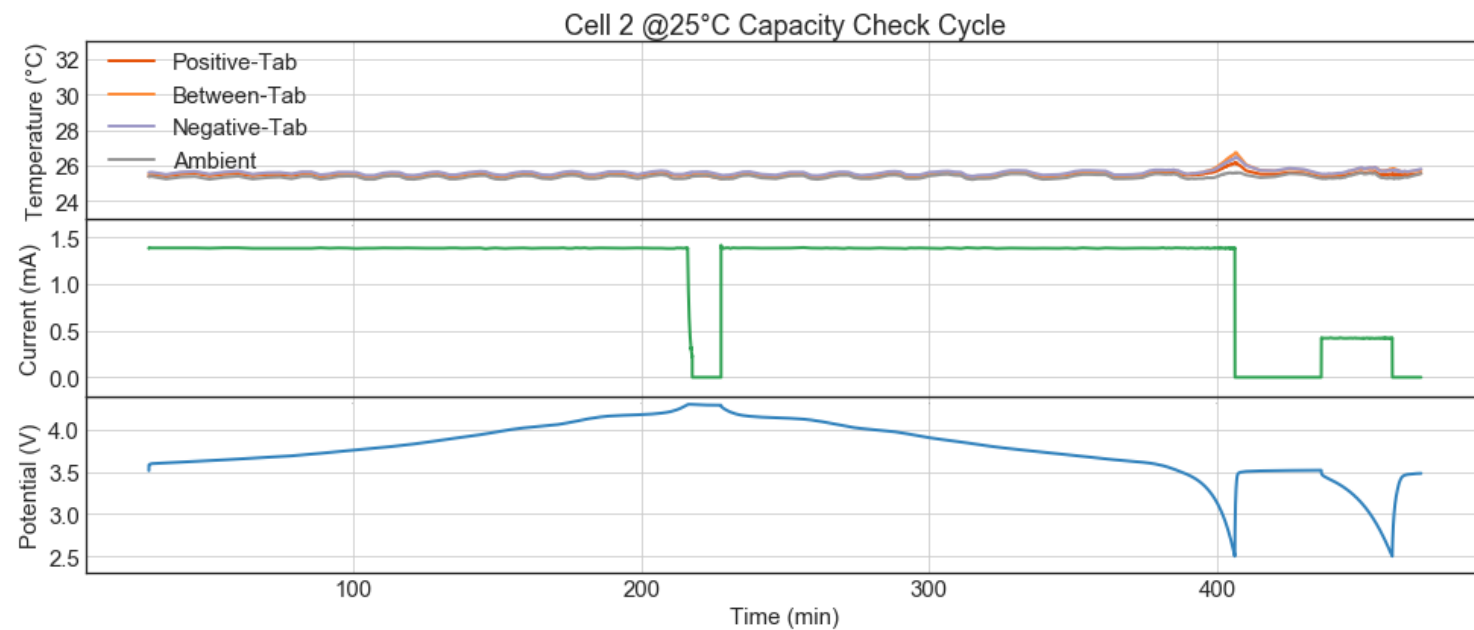


- Initial discharge
 - Constant current discharge at 0.1C (0.42 A) until voltage = 2.5 V for conditioning
 - Rest for 10 mins
- Capacity check cycle
 - Constant Current Charge at 0.33C (1.4 A) until Voltage = 4.3 V
 - Constant Voltage Hold at 4.3 V until Current < 0.05C (0.21 A)
 - Rest for 10 mins
 - Constant Current Discharge at 0.33C (1.4 A) until Voltage = 2.5 V
 - Rest for 30 mins
 - Constant Current Discharge at 0.1C (0.42 A) until Voltage = 2.5 V for conditioning
 - Rest for 10 mins
- 4C Fast-charge
 - Constant Current Charge at 0.33C (1.4 A) until charge capacity = 0.42 Ah (SoC 10% of 4.2 Ah)
 - Rest for 10 mins
 - Constant Current Charge at 4C (16.8 A) until Voltage = 4.3 V
 - Constant Voltage Hold at 4.3 V until charge capacity = 3.36 Ah (SoC 80% of 4.2 Ah, total fast-rate charge capacity of 2.94 Ah)
 - Rest for 10 mins
 - Constant Current Discharge at 0.33C (1.4 A) until Voltage = 2.5 V
 - Rest for 10 mins

Fast-charging Test Results



- The capacity check cycle and the 4C fast-charge cycle of Cell 2 at 25 °C are shown below, as well as a summary table of the electrical test results



Cycle Name	Max. Charge Rate	Max. Discharge Rate	Cell 2 @ 25 °C					
			Charge			Discharge		
			Capacity (Ah)	Energy (Wh)	Max. Temp. (°C)	Capacity (Ah)	Energy (Wh)	Max. Temp. (°C)
Capacity Check	0.33C	0.33C	4.33	16.80	25.7	4.12*	15.68*	26.7*
4C Fast-Charge	4C	0.33C	3.36	13.12	68.7	3.13	11.62	27.7

* The discharge values here are from the 0.33C discharge process (not including the 0.1C discharge)

- The purpose of this report was to communicate Exponent's findings in cell performance examination results on Cells provided by SES.
- In the analysis, we have relied on material samples and information provided by SES. We cannot verify the correctness of this input, and rely on SES for accuracy.
- Although Exponent has exercised usual and customary care in the conduct of this analysis, the responsibility for the design, manufacture and quality of the product remains fully with SES.