

Thermal Runaway Propagation Testing of Lithium Battery Shipments for Safe Transportation



**J. Jeevarajan, Ph.D.,
Underwriters Laboratories Inc.**

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Introduction and Background

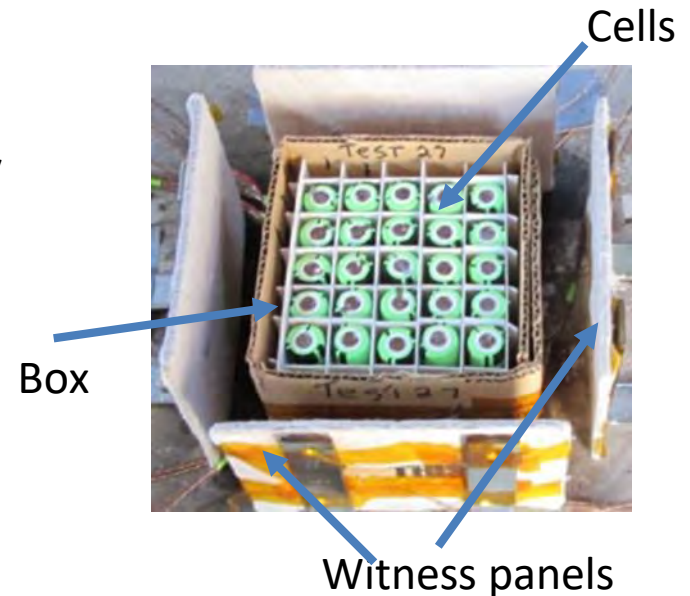
- Lithium-ion batteries are being used in ground, aviation, space, sea, etc. applications in various sizes
- Introduced in recent years into the utility/stationary energy storage industry
- Tens of thousands to billions of cells manufactured for different types of applications from portable equipment to large ESS.
- Challenge is to **screen and match** every individual cell.
 - Typical COTS and some custom battery manufacturing process does not include cell screening and matching (aerospace may be a small exception)
 - Cells are assembled into batteries in the ‘as received’ condition at lower SOC (typically 40%)
- Are assembled batteries **tested under relevant stringent** conditions before they are sent out into the field?
- Shipping/Transportation industry is facing major challenges in shipping lithium (primary and rechargeable) cells and batteries.

Extract from FAA presentation:

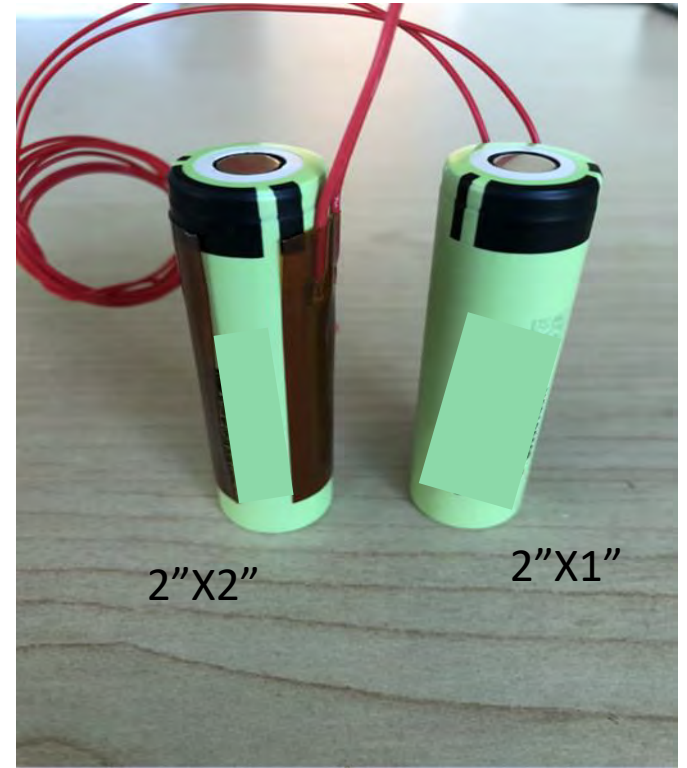
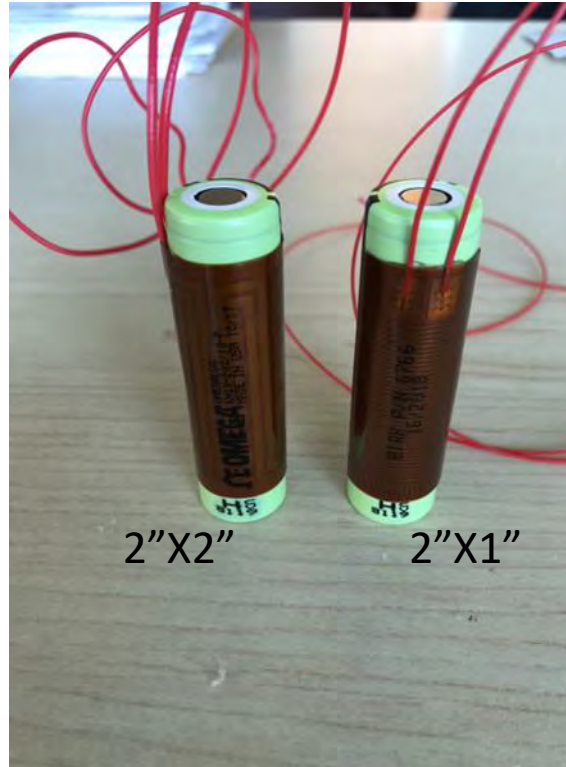
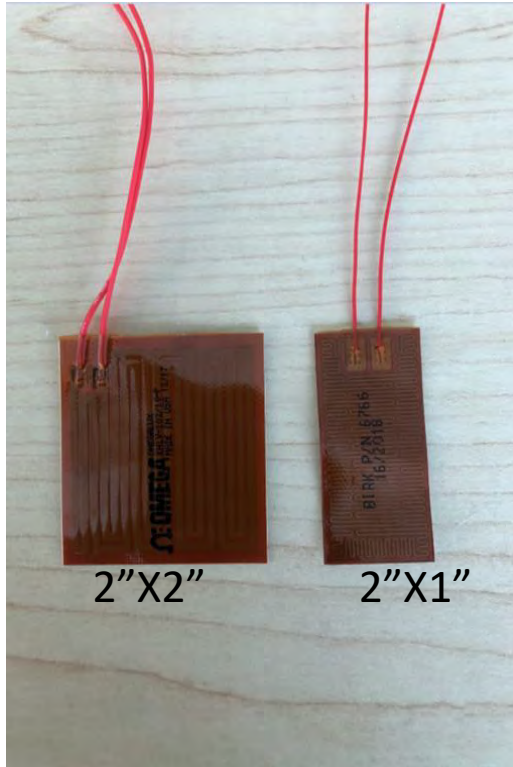
- **Aviation Cargo and Passenger Baggage Incidents Involving Smoke, Fire, Extreme Heat or Explosion**
 - *As of June 30, 2015, 158 air/airport incidents involving batteries carried as cargo or baggage that have been recorded since March 20, 1991*
- *Note: These are recent cargo and baggage incidents that the FAA is aware of. This should not be considered as a complete listing of all such incidents. The incident summaries included here are intended to be brief and objective. They do not represent all information the FAA has collected, nor do they include all investigative or enforcement actions taken. This list does not include three major aircraft accidents where lithium battery cargo shipments were implicated but not proven to be the source of the fire: An Asiana Airlines 747 near South Korea on July 28, 2011, a UPS 747 in Dubai, UAE on September 3, 2010 and a UPS DC-8 in Philadelphia, PA on February 7, 2006*

Current Study

- Tested single (3.4 Ah 18650) Li-ion cells in 25 cell (5X5) arrangement with the following variables
 - SOC: 100 % SOC; 3 % SOC
 - Heater dimensions: 2"X2"; 1"X2"
 - Heater thickness: Thick heater (0.014"); Thin heater (0.012")
 - Location of trigger cell – Center, corner and side wall (edge)
 - Temperature:
 - Max temp. 392 °F
 - Temperature held at 392 °F for one hour
 - Temperature increased until thermal runaway
 - Heating Rate
 - 19 - 20 °F / min rate of heating
 - 7 - 8 °F / min rate of heating
 - 3 - 4 °F / min rate of heating
 - Package/Box Configuration
 - Lid Open and Closed Box
- Witness panels were made of cardboard covered with cheesecloth placed 1 inch away from each side of the box.
- Total of 35 tests (33 on 3.4 Ah 18650 and 2 on 3.4 Ah pouch format li-ion cells) performed to date.



Heater Info

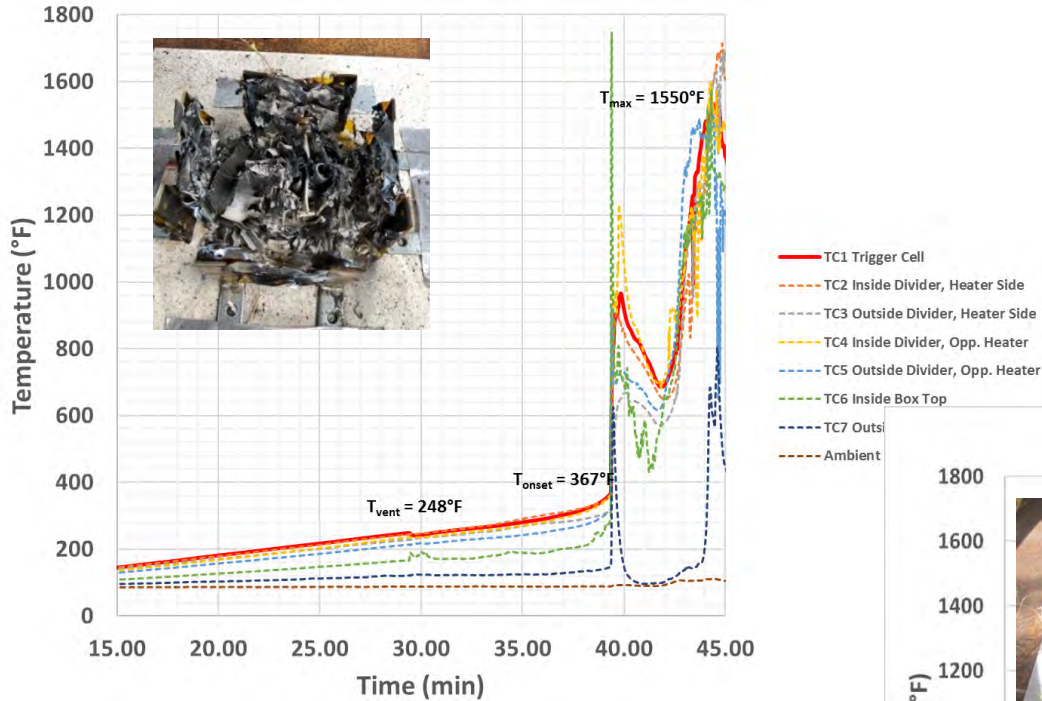


2"x 2" (Omega) & 2"x 1" (Birk Engineering)

Thermal Runaway Propagation Test

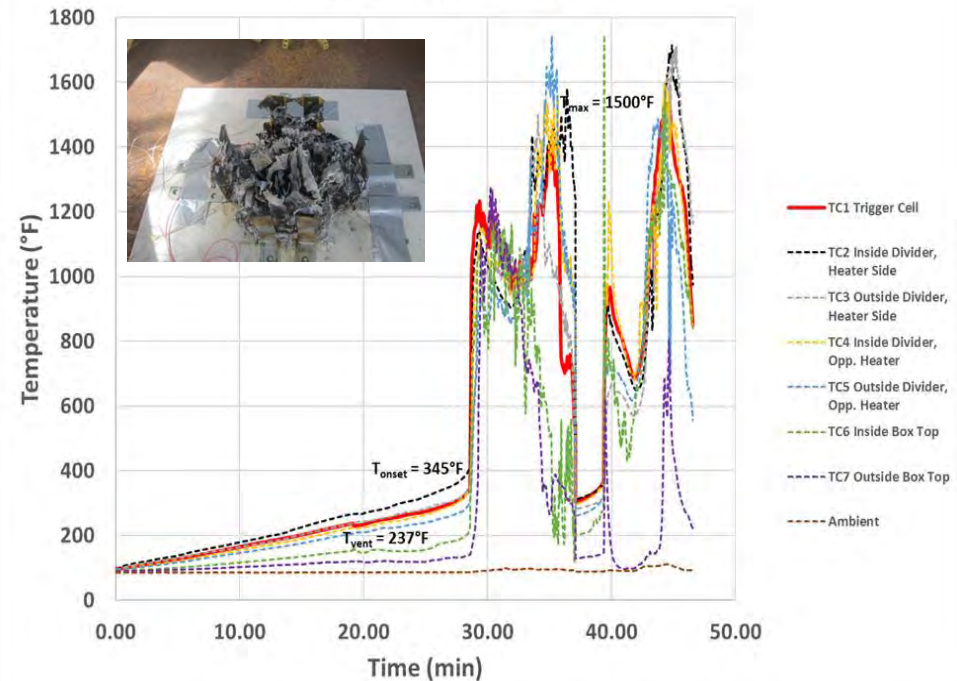
Single Cell (3.4 Ah) at 100 % SOC and Thick and Thin Heater

Test14_SingleCell_100%SOC_ThickHeater

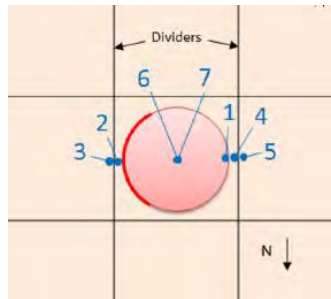


No significant changes in the use of either heater. Thin heater did not have adhesive and required additional tape to hold it in place. Decision made to go with thick heater for all tests

Test15_SingleCell_100%SOC_ThinHeater

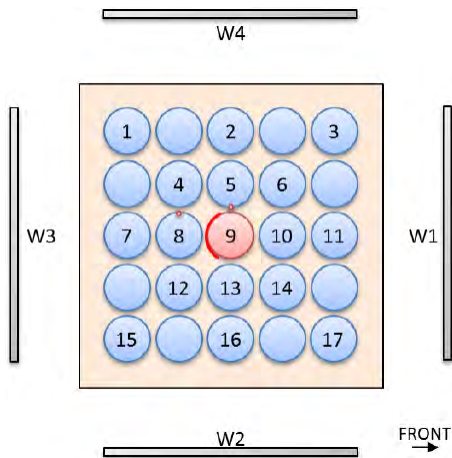


Pre-Test



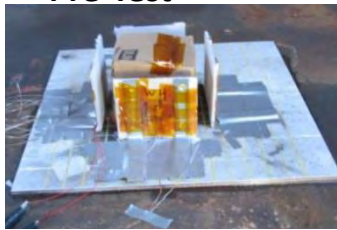
Thermal Runaway Propagation Test

25 Cell (3.4 Ah) at 100 % SOC and Center Cell Trigger

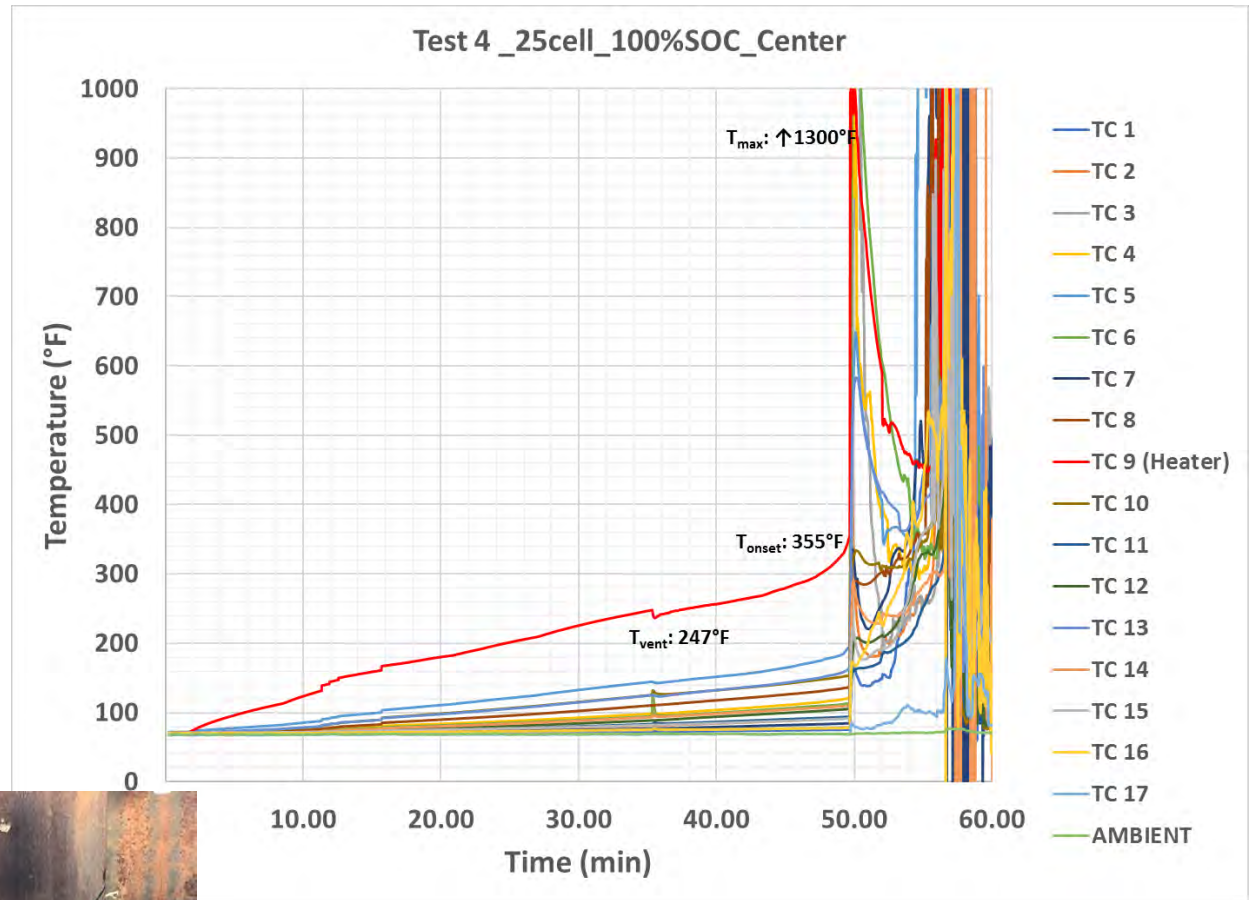


Cells not electrically connected
W: Witness panels – cardboard covered with cheesecloth

Pre-Test



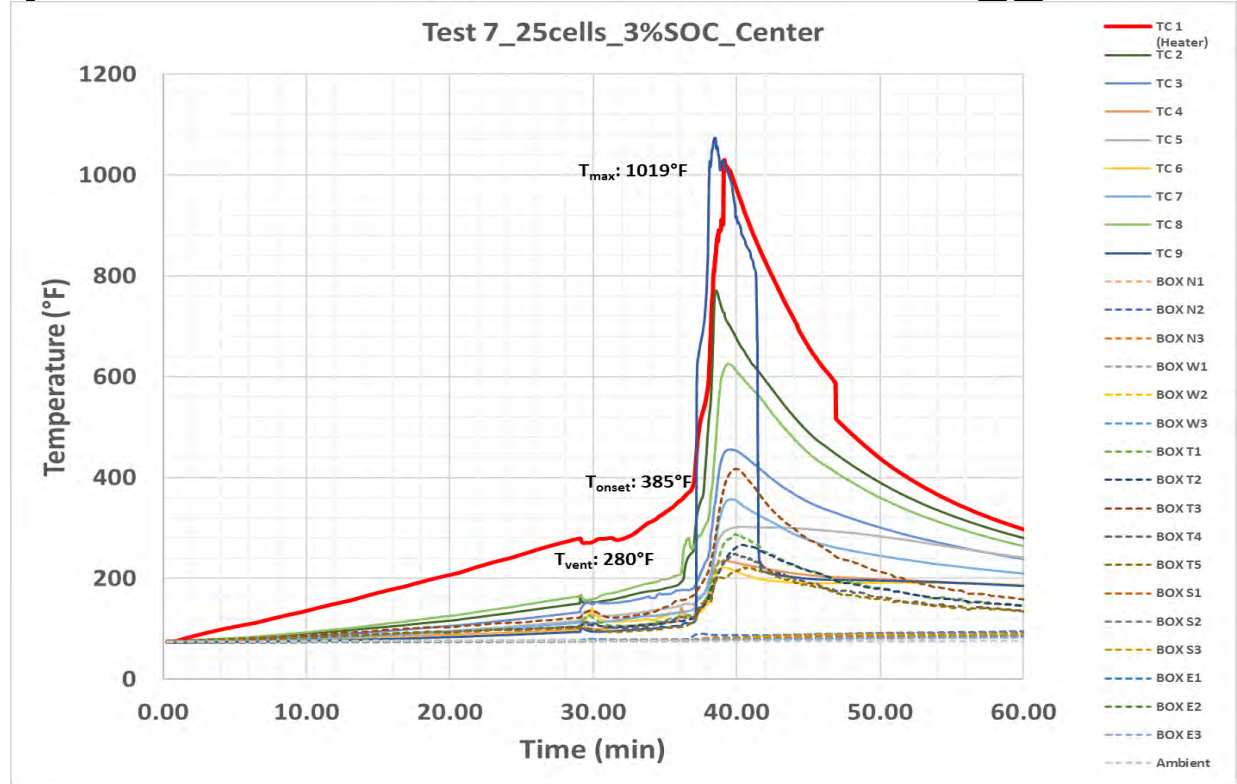
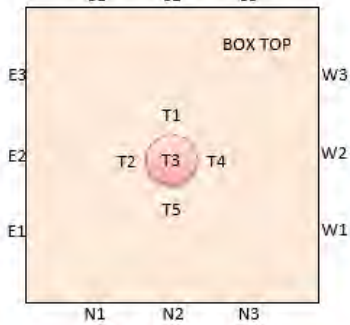
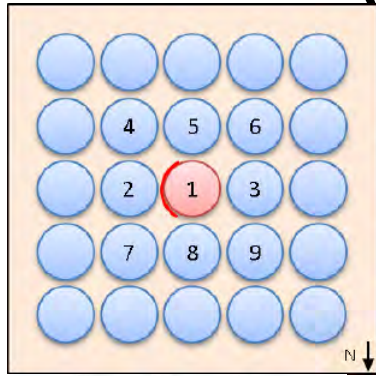
Post-Test



Observations: Trigger cell vented, later went into thermal runaway with fire and propagated, all cells went into thermal runaway; No smoke was observed outside the box until thermal runaway

Thermal Runaway Propagation Test

25 Cell (3.4 Ah) at 3 % SOC and Center Cell Trigger



Pre-Test



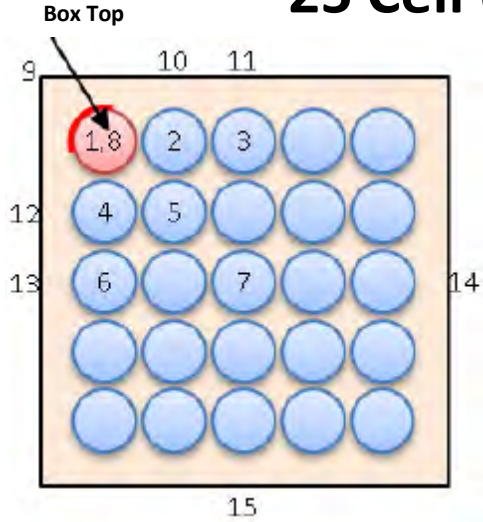
Post-Test



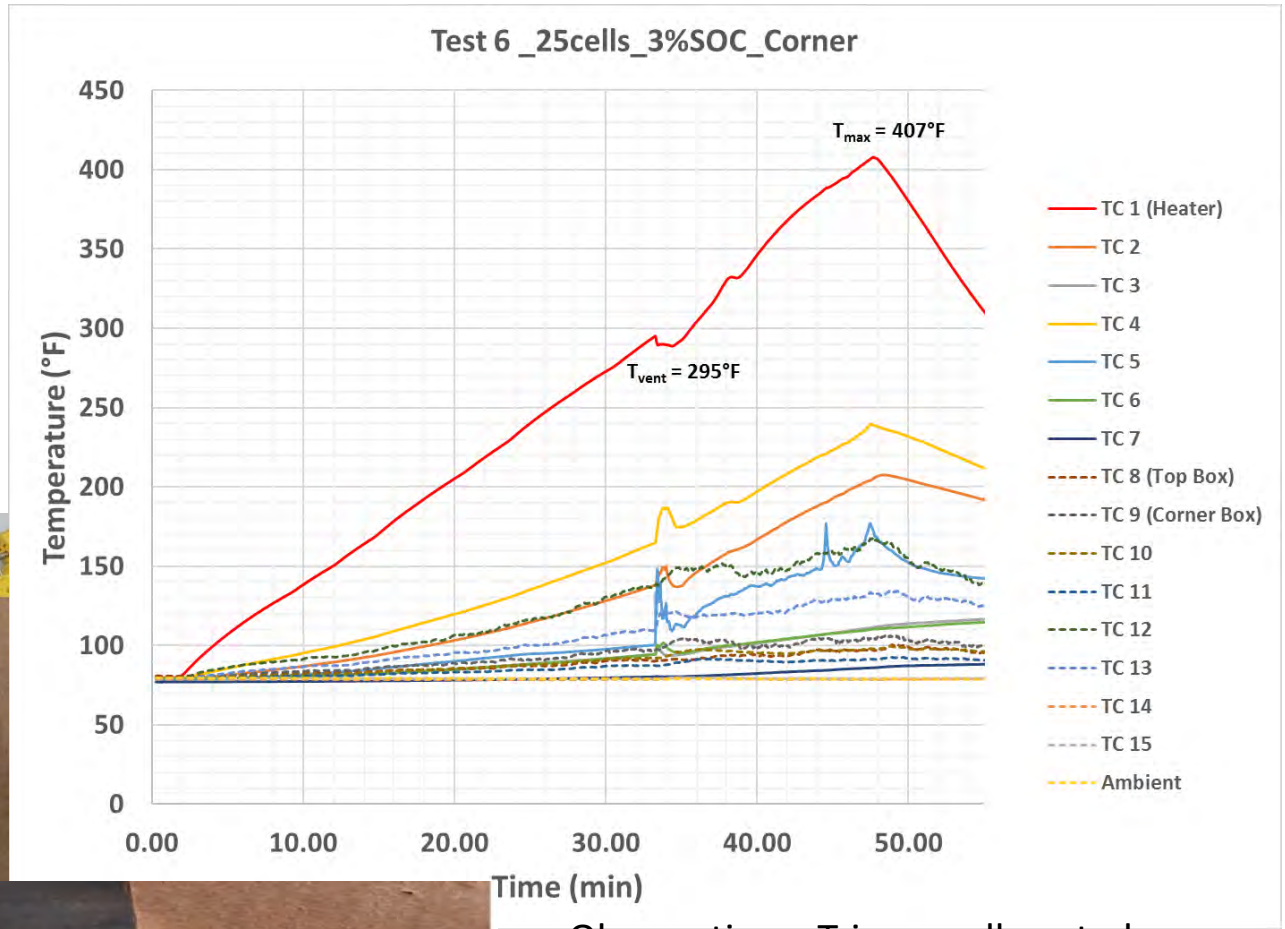
Observations: Trigger cell vented and later underwent thermal runaway, no propagation, moderate damage. Trigger cell voltage: 0V, adjacent damaged cell: 0.737V, rest of the cell voltages: 3.36V. A lot of smoke was observed outside the box, but no fire.

Thermal Runaway Propagation Test

25 Cell (3.4 Ah) at 3 % SOC and Corner Cell Trigger



Pre-Test



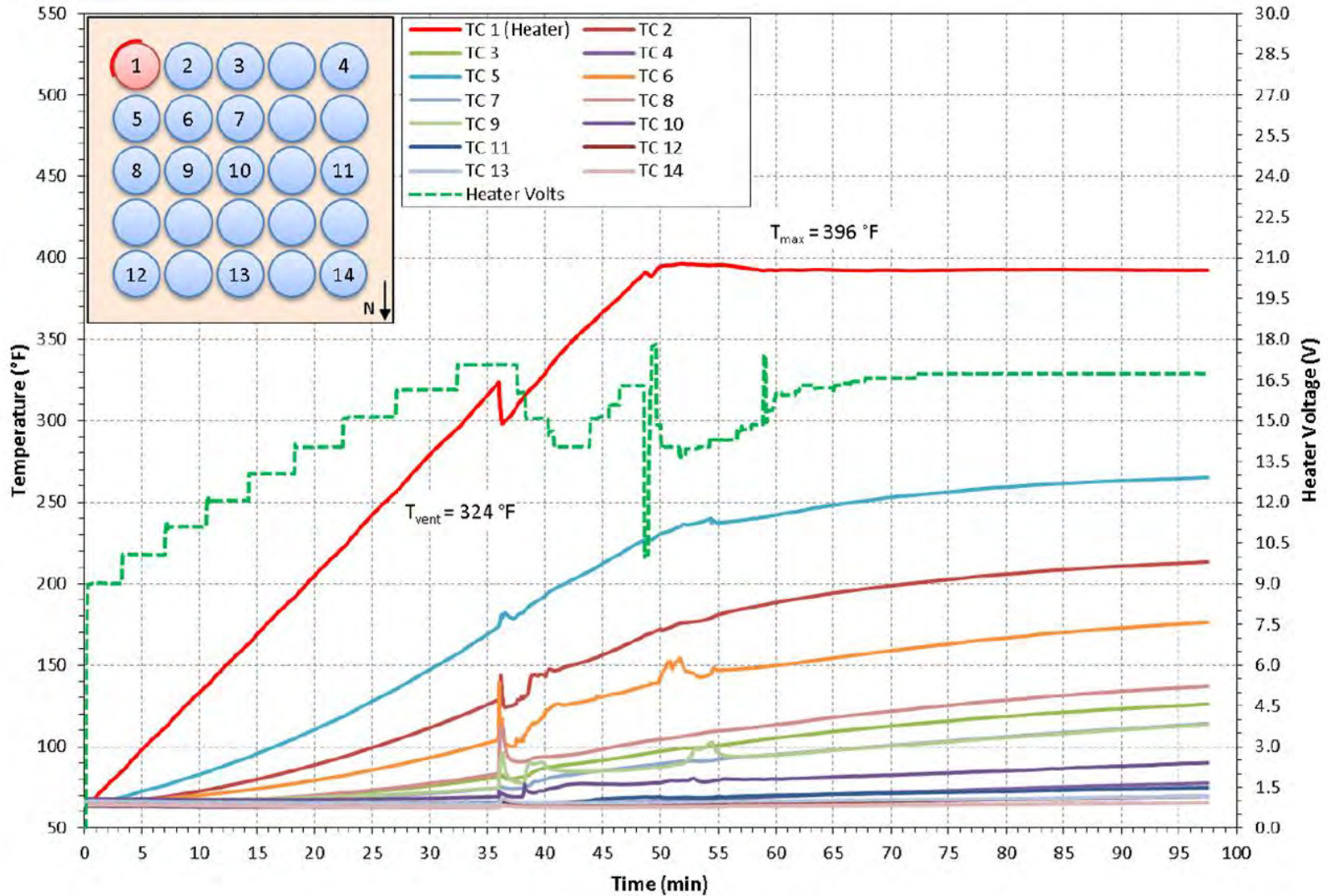
Post-Test

Observations: Trigger cell vented, no thermal runaway (test stopped when temperature was uncontrollable >392 °F, little damage. Voltage for all cells, except trigger cell: ~3.36V. No smoke or flame was observed outside the

Thermal Runaway Propagation Test

25 Cell (3.4 Ah) at 3 % SOC and Corner Cell Trigger

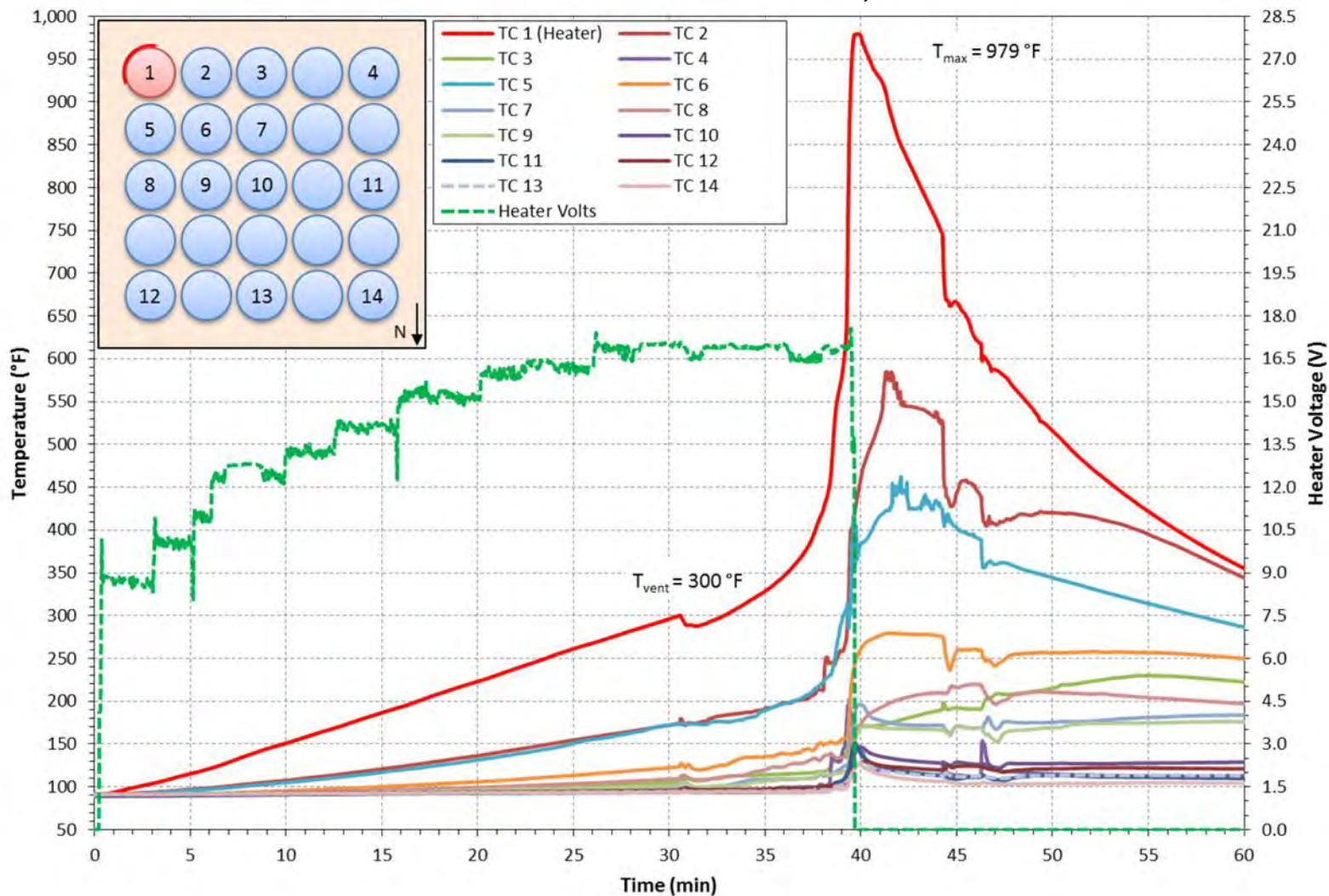
Hold at ~200 deg C for one hour



Thermal Runaway Propagation Test

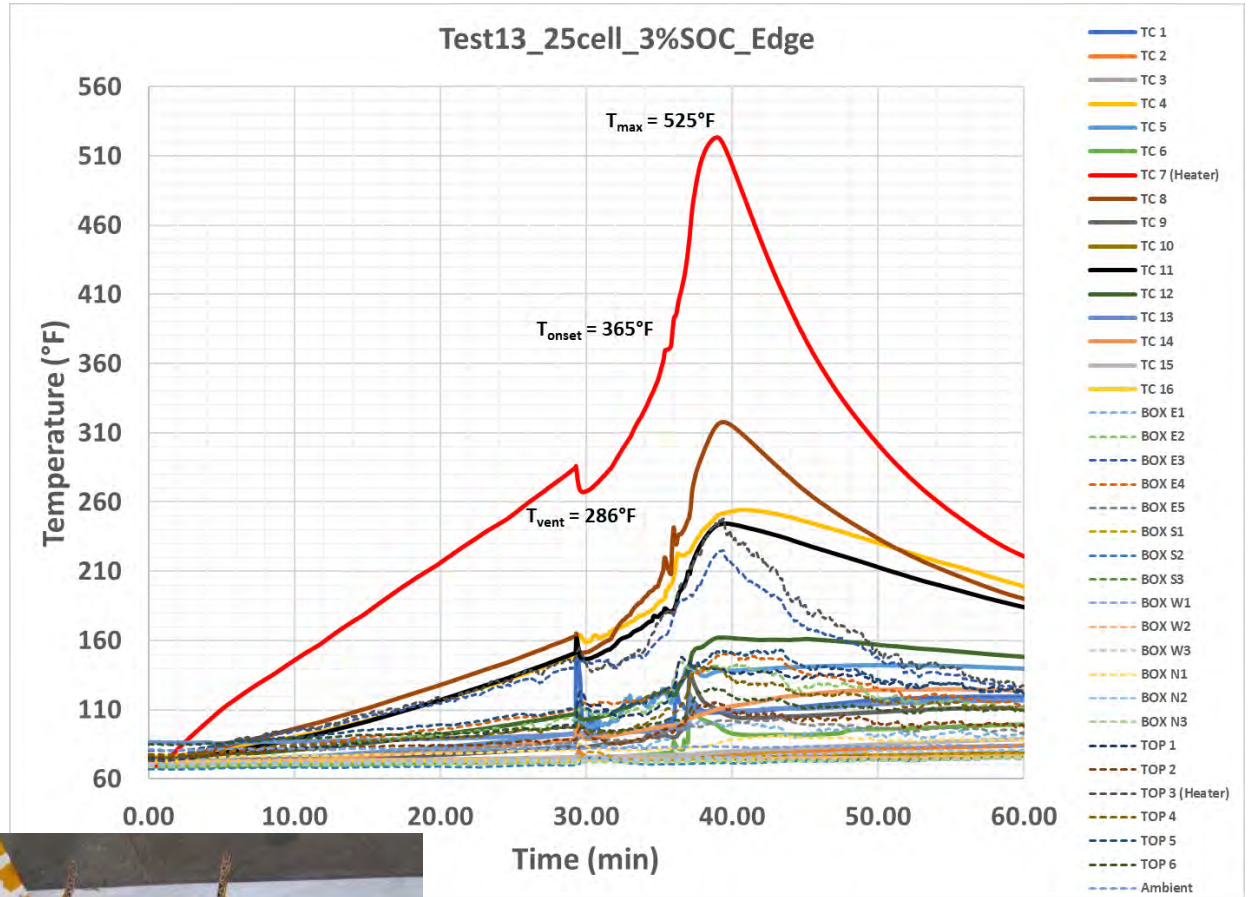
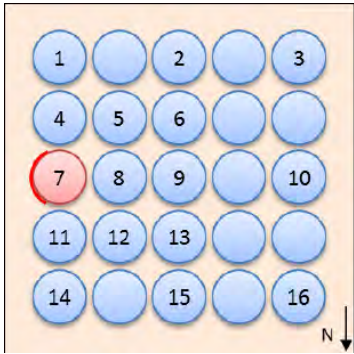
25 Cell (3.4 Ah) at 3 % SOC and Corner Cell Trigger

No hold; heated until thermal runaway

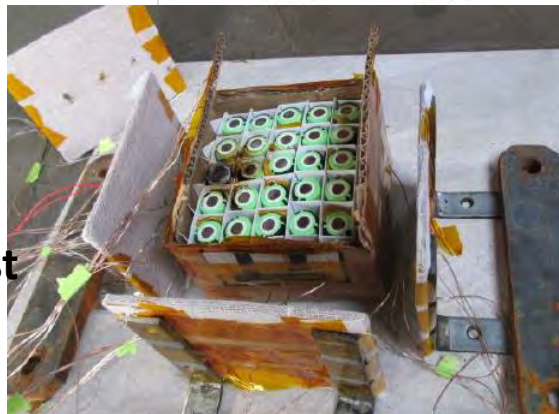


Thermal Runaway Propagation Test

25 Cell (3.4 Ah) at 3 % SOC and Side Wall (Edge) Cell Trigger



Pre-Test



Post-Test

Observations: Trigger cell vented, underwent thermal runaway, but no propagation. All cells except of trigger cell, held voltage at $\sim 3.35V$. Light smoke was observed outside the box, but no flame.

Summary

- No difference in performance of thick or thin heaters; thick heater did not require additional tape to hold it in place, hence all tests were carried out with thick heater.
- The 2"X1" heater not different from the 2"X2" heater tape but the 2"X1" heater simulated local heating better. Questions arose as to whether the larger heater caused additional heating of adjacent cells. The smaller heater allows for cell heat to radiate to adjacent cells in a more consistent manner.
- 7-8 °F / min heating rate was found to be optimal for consistent test results.

Acknowledgments

- **Stress Engineering Services Inc.**
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- **NASA – Johnson Space Center**
 - Dereck Lenoir, Tony Parish
- **UL Team**
 - Saad Azam, Dennis Avelar



THANK YOU.

Back Up Charts



Summary of Tests

Phase	Test No.	Date	SOC	Heater Location	Heater Type	Heating Protocol	Sample Configuration	Vent Temp [°F]	TR Temp [°F]	Max Temp [°F]	TR Behavior
1	1	1/18/2018	100%	Center	2x2"	7-8°F/min to TR	No Box	243	302	633	Vented, ejected contents, no propagation, 24 cells rem.
1	2	1/18/2018	100%	Corner	2x2"	7-8°F/min to TR	No Box	246	339	1512	Vented, sustained fire, then propagation, 10 cells rem.
1	3	1/29/2018	100%	Single	1x2"	7-8°F/min to TR	No Box	~248	335	919	Vented, sustained fire
1	4	1/29/2018	100%	Center	1x2"	7-8°F/min to TR	In Cardboard Box, with Lid	248	355	1335	Vented, sustained fire, then propagation, 0 cells rem.
1	5	1/29/2018	100%	Corner	1x2"	7-8°F/min to TR	In Cardboard Box, with Lid	250	350	1316	Vented, sustained fire, then propagation, 1 cell rem.
1	6	2/15/2018	3%	Corner	1x2"	7-8°F/min to TR or 400°F	In Cardboard Box, with Lid	295	-	408	Vented, no thermal runaway, little damage
1	7	2/16/2018	3%	Center	1x2"	7-8°F/min to TR or 400°F	In Cardboard Box, with Lid	280	392	1030	Vented, thermal runaway, no propagation, moderate damage
1	8	2/19/2018	100%	Center	1x2"	7-8°F/min to TR	In Cardboard Box, without Lid	255	338	2382	Vented, sustained fire, then propagation, 0 cells rem.
1	9	2/19/2018	100%	-	1x2"	20°F/min to 800°F	Single Layer Cardboard	-	-	-	-
1	10	2/19/2018	100%	-	1x2"	20°F/min to 800°F	Double Layer Cardboard	-	-	-	-
1	11	2/22/2018	100%	Center	1x2"	7-8°F/min to TR or 400°F	CellBlock with Loose Fill, Cardboard Box w/ Lid	225	326	787	Vented, ejected contents, loose fill activated, no propagation, 24 cells rem.
1	12	2/22/2018	100%	Center	1x2"	7-8°F/min to TR or 400°F	CellBlock without Loose Fill, Cardboard Box w/ Lid	275	369	703	Vented, ejected contents, no propagation, 24 cells rem.
1	13	3/20/2018	3%	Edge	1x2"	7-8°F/min to TR	In Cardboard Box, with Lid	286	363	523	Vented, thermal runaway, no propagation

Summary of Tests

2	14	7/9/2018	100%	Single	1x2"	7-8°F/min to TR	In Cardboard Box, with Lid	249	367	966	Vented, thermal runaway
2	15	7/11/2018	100%	Single	1x2" Thin	7-8°F/min to TR	In Cardboard Box, with Lid	237	346	1532	Vented, thermal runaway
2	16	7/13/2018	3%	Corner	1x2"	7-8°F/min to TR or Tmax	In Cardboard Box, with Lid	325	~445	608	Vented, thermal runaway, no propagation, moderate damage
2	17	7/13/2018	3%	Center	1x2"	7-8°F/min to TR or Tmax	In Cardboard Box, with Lid	295	~445	642	Vented, thermal runaway, no propagation, little damage
2	18	7/18/2018	3%	Corner	1x2"	7-8°F/min to TR or Tmax	In Cardboard Box, with Lid	316	~416	973	Vented, thermal runaway, no propagation, significant damage, drop in cell voltage
2	19	7/18/2018	3%	Center	1x2"	7-8°F/min to TR or Tmax	In Cardboard Box, with Lid	293	~434	575	Vented, thermal runaway, no propagation, little damage, no drop in cell voltage
2	20	7/20/2018	3%	Corner	1x2"	7-8°F/min to TR or Tmax	In Cardboard Box, with Lid	300	~422	979	Vented, thermal runaway, no propagation, significant damage, drop in cell voltage
2	21	7/27/2018	3%	Corner	1x2"	7-8°F/min to TR or Tmax	In Cardboard Box, with Lid	302	~394	1111	Vented, thermal runaway and fire, full propagation
2	22	8/15/2018	3%	Edge	1x2"	7-8°F/min to TR or 392°F and hold for 1hr	In Cardboard Box, with Lid	305	392*	633	Vented, thermal runaway, no propagation, little damage, no drop in adj. cell voltage
2	23	8/15/2018	3%	Edge	1x2"	7-8°F/min to TR or 392°F and hold for 1hr	In Cardboard Box, with Lid	306	387	1004	Vented, thermal runaway and fire, full propagation
2	24	8/29/2018	3%	Corner	1x2"	7-8°F/min to TR or 392°F and hold for 1hr	In Cardboard Box, w/o Lid	293	390	923	Vented, thermal runaway and fire, full propagation
2	25	8/29/2018	3%	Corner	1x2"	7-8°F/min to TR or 392°F and hold for 1hr	In Cardboard Box, w/o Lid	308	-	399	Vented, no thermal runaway, no damage to adj cell, no drop in adj. cell voltage
2	26	8/30/2018	100%	Corner	1x2"	7-8°F/min to TR	In Cardboard Box, w/o Lid	249	346	1556	Vented, thermal runaway and fire, full propagation
2	27	8/31/2018	3%	Corner	1x2"	7-8°F/min and maintain to TR/392°F, hold for 1hr	In Cardboard Box, w/o Lid	293	-	396	Vented, no thermal runaway, no damage to adj cell, no drop in adj. cell voltage
2	28	9/5/2018	100%	Single	1x2"	19-20°F/min and maintain to TR	In Cardboard Box, with Lid	226	362	1233	Vented, thermal runaway
2	29	9/5/2018	100%	Single	1x2"	7-8°F/min and maintain to TR	In Cardboard Box, with Lid	254	375	1054	Vented, thermal runaway
2	30	9/5/2018	100%	Single	1x2"	3-4°F/min and maintain to TR	In Cardboard Box, with Lid	268	358	1178	Vented, thermal runaway
2	31	9/5/2018	3%	Single	2x2"	7-8°F/min and maintain to TR/392°F, hold for 10 min, then heat again at 7-8°F/min and maintain to TR/Tmax	In Cardboard Box, with Lid	296	-	812	Vented, thermal runaway

Summary of Tests

2	34	10/12/2018	100%	Corner	1x2"	7-8°F/min and maintain to TR/392°F, hold for 1hr	In Cardboard Box, with Lid	no data	no data	no data	Vented, Thermal Runaway
2	35	10/12/2018	3%	Corner	1x2"	7-8°F/min and maintain to TR/392°F, hold for 1hr	In Cardboard Box, with Lid	no data	no data	no data	Vented, no thermal runaway, no damage to adj cell, no drop in adj. cell voltage