Measurement of Energy Distributed Between Cell Mass and Hot Ejecta during Thermal Runaway of Lithium Ion Cells at Varying State of Charge

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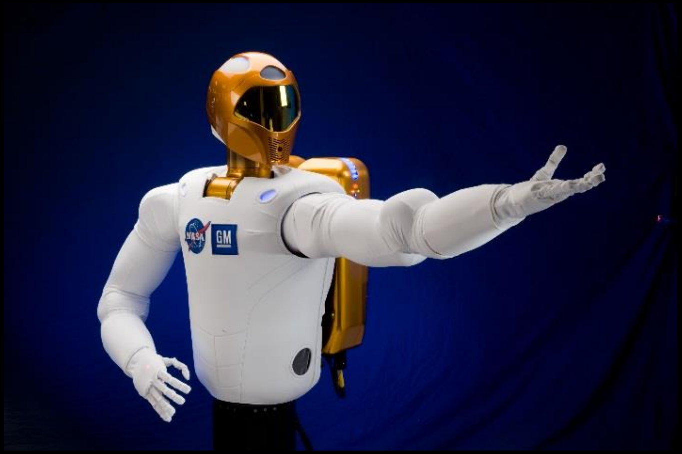
A04: Battery Safety
10/14/2015



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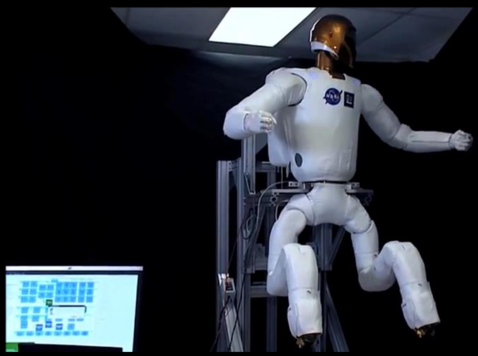
NASA Battery Safety

- NASA Human Space Flight Battery Safety
  - NASA follows a two fault tolerant strategy to protect lithium-ion battery systems.
  - Three levels of control or design for minimum risk for all catastrophic hazards
    - Overcharge, Over temperature, Overcurrent
  - 100% of cells in batteries are screened for detectable faults

- Internal Short Circuit Risk
  - Internal short circuits had been an accepted risk. Measures such as manufacturer audits and cell screening were previously employed to reduce this risk
  - Internal short circuit failure has been highlighted by the Boeing 787 battery fire, which demonstrated the severity of thermal runaway propagation
  - Cascading failure of cells became a major focus of severity reduction work at NASA
  - <u>NASA revised its requirements (20793 RevC) to include evaluation of thermal runaway severity and potential mitigation measures</u>

Lithium-ion Battery Projects



Robonaut 2 Humanoid Battery

- 5.8kWh, 300 Cells: 12P25S config
- Boston Power Swing 5300
    - 5.3Ah Prismatic Cell
- Investigating Severity Reduction

LREBA Space Suit Battery

- 400Wh, 45 Cells: 9P5S config
- Samsung ICR18650-26F
    - 2.6Ah 18650 Cell
- Redesigned to prevent propagation of thermal runaway

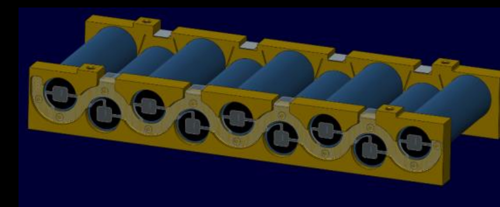
Initial Evaluation

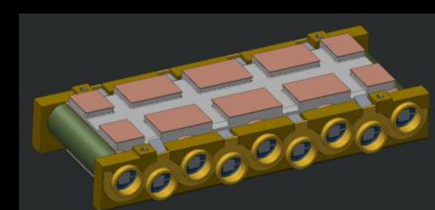
With severity reduction measures

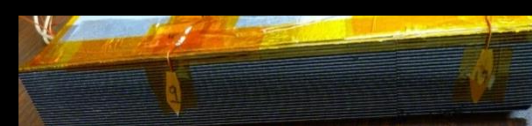
LLB Space Suit Battery

- 650Wh, 80 Cells: 16P5S config
- Moli 18650J
    - 2.37Ah 18650 Cell
- Currently on ISS
- Investigating Severity Reduction

LREBA Thermal Runaway Severity Reduction







- Results of NESC LREBA Severity Reduction assessment
  - Testing indicates that prevention of thermal runaway after the first cell propagates is unlikely
  - Three major contributors were identified
    - Direct cell-to-cell heat conduction
    - Electrical short circuits causing cell heating in adjacent cells
    - Violent release of hot gases and other effluents
  - This work was presented in detail at the 2014 NASA Battery Workshop
    - Thermal Runaway Severity Reduction Assessment & Implementation: On LREBA

https://batteryworkshop.msfc.nasa.gov/presentations/TR%20Severity%20Reduction%20Assessment%20&%20Implementation%20on%20LREBA%20-%20Final%20for%20Workshop.pdf

Design to Prevent Cascading Failure

- Developing battery pack thermal models for thermal runaway can allow designers to develop designs that reduce the risk of cascading failure

- Energy released during thermal runaway by an individual cell needs to be properly characterized to build and validate a model

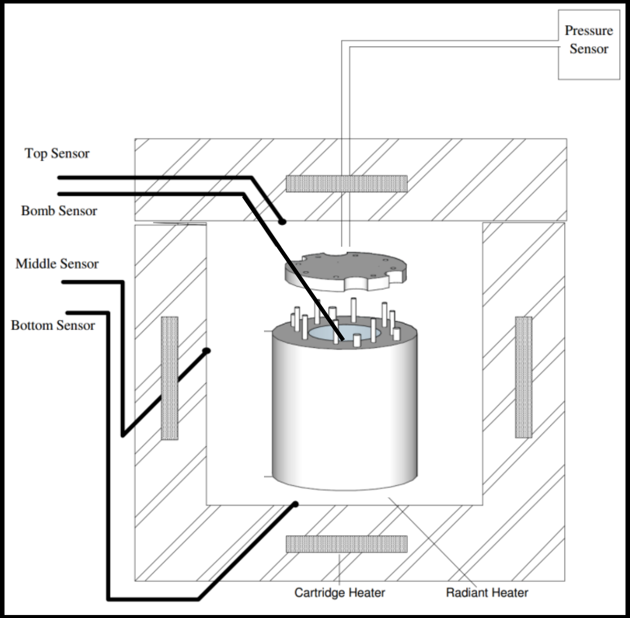
- The approach used in this work seeks to measure the exothermic energy cells deposit to their environment during thermal runaway
  - Assess distribution of energy between cell mass and ejected effluents
  - Measure cell onset temperature for thermal runaway
  - Assess effects of state of charge upon thermal runaway

Accelerating Rate Calorimetry

- This method has been used previously to characterize onset temperature of thermal runaway in lithium ion cells as well as attempt to capture the exothermic energy of the cell

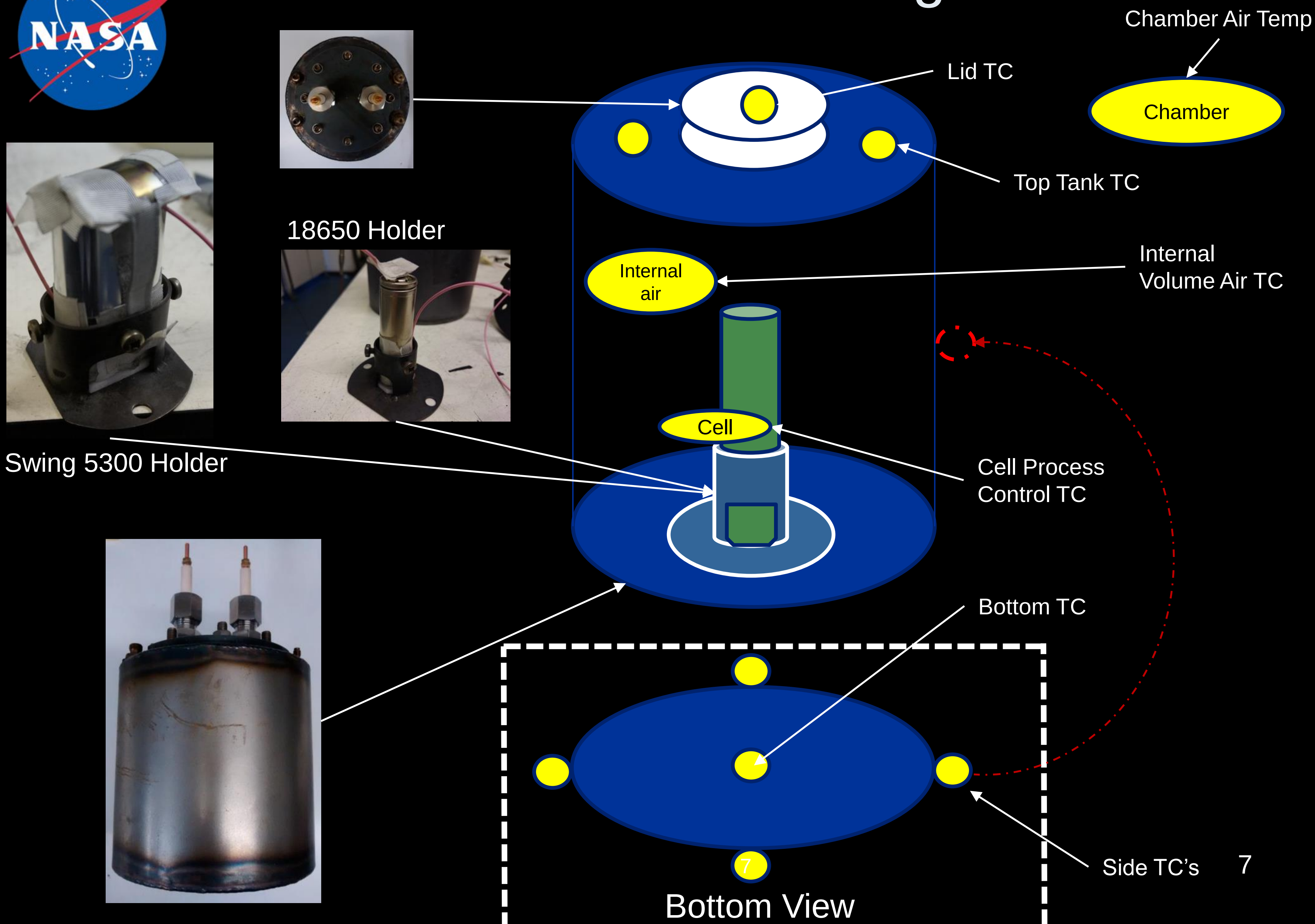
- A new “tank” based approach was taken here to help capture the significant additional energy released through ejecta and gas from the cell during the event

- A pressure vessel or “battery tank” was designed to enclose the cell under test and the entire assembly was placed in the Calorimeter for test.

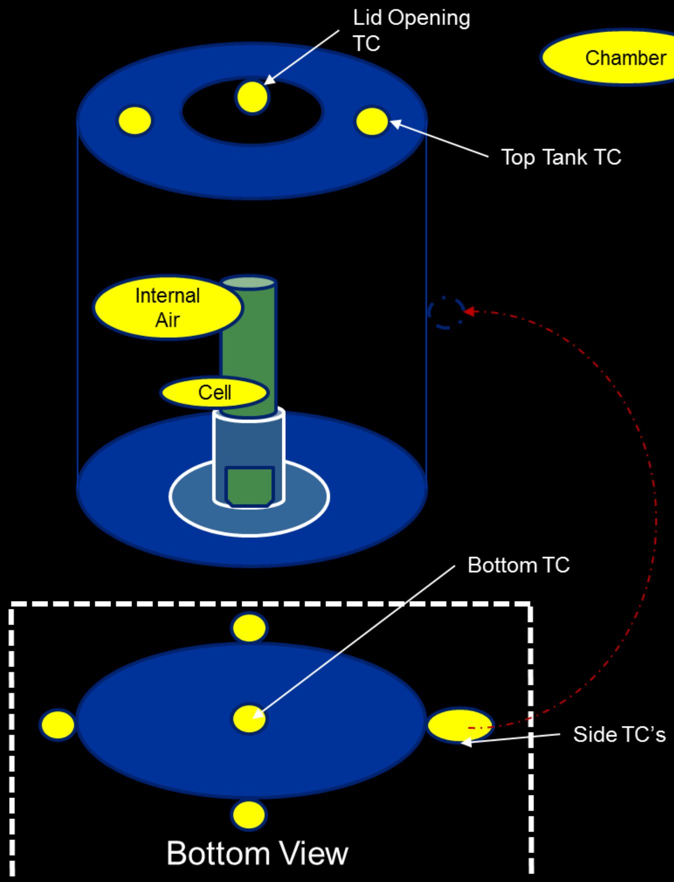


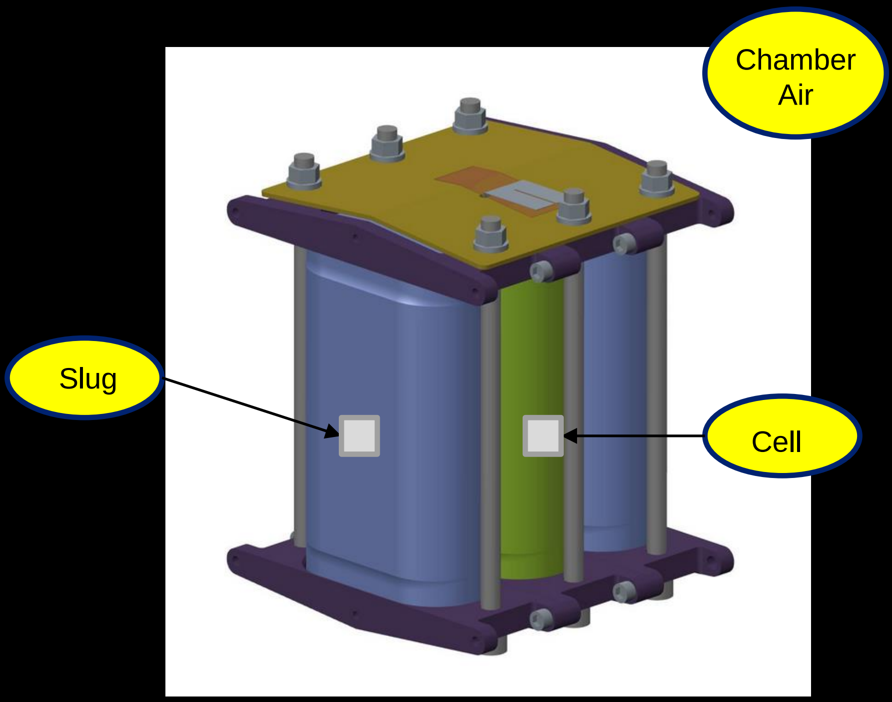
http://www.thermalhazardtechnology.com/uploaded_images/files/TI%20Sheets/TIN002%20-%20An%20Introduction%20to%20Accelerating%20Rate%20Calorimeter.pdf

Closed Tank Testing



Open Tank Testing





Swing 5300 Open Configuration

- Mimics battery assembly cell constraints
- Important due to cell side vents and expansion behavior during runaway

18650 Open Configuration

- Matches closed tank configuration with the lid open
- Allows a clear path away from the tank for material ejected from the cell vent

Test Matrix

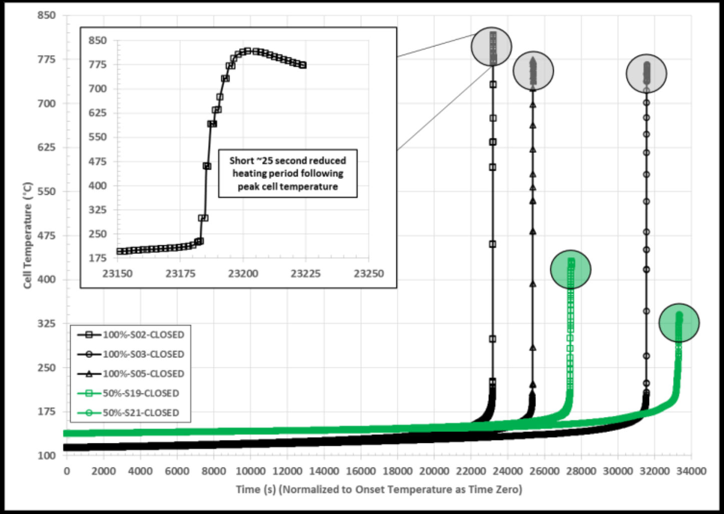
- The ARC experiments were run in triplicate for each cell type in both Open and Closed Tank configurations
- In addition all of these tests were repeated for both 100% and 50% State of Charge
- Energy calculations begin at the onset of thermal runaway
  - The ARC turns off its heaters after onset (These are used to maintain the isothermal environment during heat-wait-seek)
- The energy calculations end when a sharp decline in heating rate is detected
  - At this point the cell reaction has stopped or significantly slowed

Closed Tank Test Data

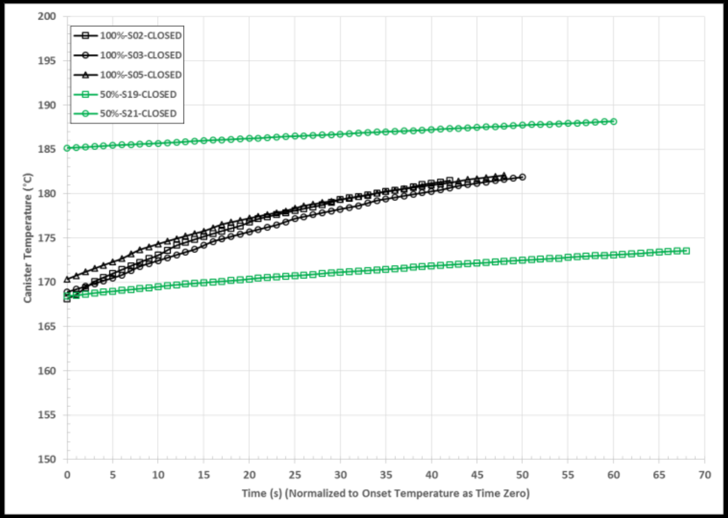
(Preliminary Results)

Closed Tank Results: Samsung 18650-26F

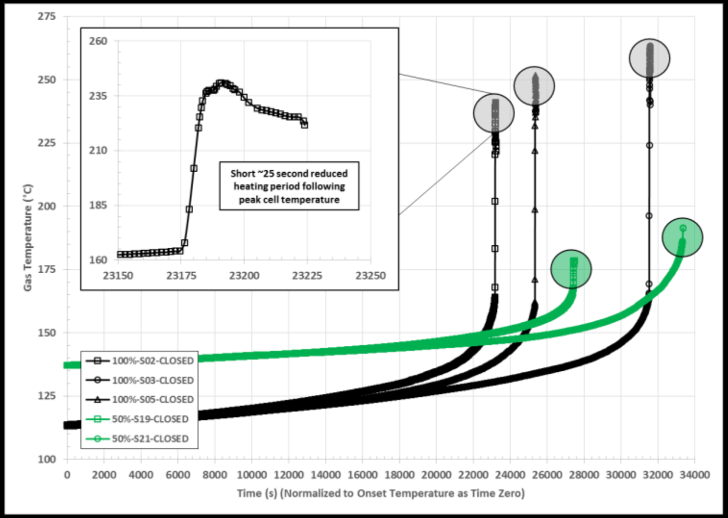
CELL TEMPERATURES (100%SOC and 50%SOC CLOSED)



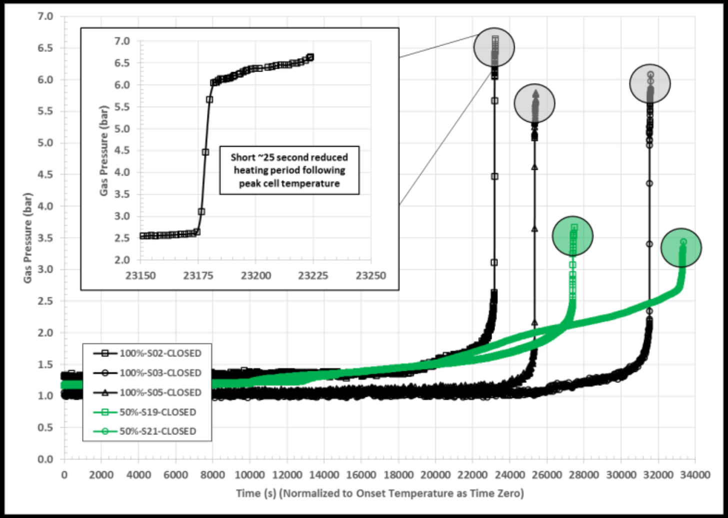
CANISTER TEMPERATURES (100%SOC and 50%SOC CLOSED)



GAS TEMPERATURES (100%SOC and 50%SOC CLOSED)



GAS PRESSURE (100%SOC and 50%SOC CLOSED)



Closed Tank Results: Samsung 18650-26F

Cell	State of Charge	Nominal Capacity (Ah)	Nominal Electrical Energy(kJ)
Samsung SDI ICR18650-26F	100%	2.600	34.6
Samsung SDI ICR18650-26F	50%	1.300	17.3

Test ID	S.O.C	Cell Mass Before/After (gm)	Post Charge Voltage (V)	Start/End Pressure (bar)
S02	100%	44.7 / 36.3	4.08	2.0 / 6.4
S03	100%	44.7 / 36.6	4.15	1.6 / 5.7
S05	100%	44.8 / 35.9	4.16	1.4 / 5.6
S19	50%	44.7 / 40.1	3.79	1.2 / 3.7
S21	50%	44.7 / 41.0	3.79	1.2 / 3.4

Test ID	S.O.C	Cell Onset Temperature (°C)	Cell Max Temperature (°C)	Cell Energy (kJ)	Canister Energy (kJ)	Gas Energy (kJ)	Total Energy (kJ)
S02	100%	114.5	816.9	30.5	12.8	0.6	43.9
S03	100%	114.2	766.6	27.3	12.6	0.5	39.0
S05	100%	113.7	775.0	27.8	11.3	0.4	39.5
S19	50%	138.1	431.8	12.9	5.0	0.06	17.9
S21	50%	138.2	340.9	11.5	2.9	0.09	14.4

Closed Tank Results: Moli 18650J

Cell	State of Charge	Nominal Capacity (Ah)	Nominal Electrical Energy(kJ)
Moli 18650J	100%	2.37	32.0
Moli 18650J	50%	1.635	16.0

Test ID	S.O.C	Cell Mass Before/After (gm)	Post Charge Voltage (V)	Start/End Pressure (bar)
M13	100%	47.0 / 39.1	4.18	2.3 / 6.7
M15	100%	47.1 / 38.8	4.18	2.6 / 6.7
M16	100%	47.2 / 39.1	4.16	2.5 / 7.8
M#	50%			
M#	50%			
M#	50%			

Test ID	S.O.C	Cell Onset Temperature (°C)	Cell Max Temperature (°C)	Cell Energy (kJ)	Canister Energy (kJ)	Gas Energy (kJ)	Total Energy (kJ)
M13	100%	118.6	666.1	23.5	14.5	0.4	38.4
M15	100%	118.6	673.2	23.1	8.1	0.4	31.6
M16	100%	119.1	696.4	24.1	8.4	0.4	32.9
M#	50%						
M#	50%						
M#	50%						

Closed Tank Results: BP Swing 5300

Cell	State of Charge	Nominal Capacity (Ah)	Nominal Electrical Energy(kJ)
Boston Power Swing 5300	100%	5.300	19.3
Boston Power Swing 5300	50%	2.65	9.65

Test ID	S.O.C	Cell Mass Before/After (gm)	Post Charge Voltage (V)	Start/End Pressure (bar)
BP01	100%	93.1 / 73.3	4.18	3.0 / 15.7
BP06	100%	93.0 / 71.6	4.18	2.6 / 12.6
BP28	100%	93.2 / 72.3	4.19	2.3 / 17.8
BP#	50%			
BP#	50%			
BP#	50%			

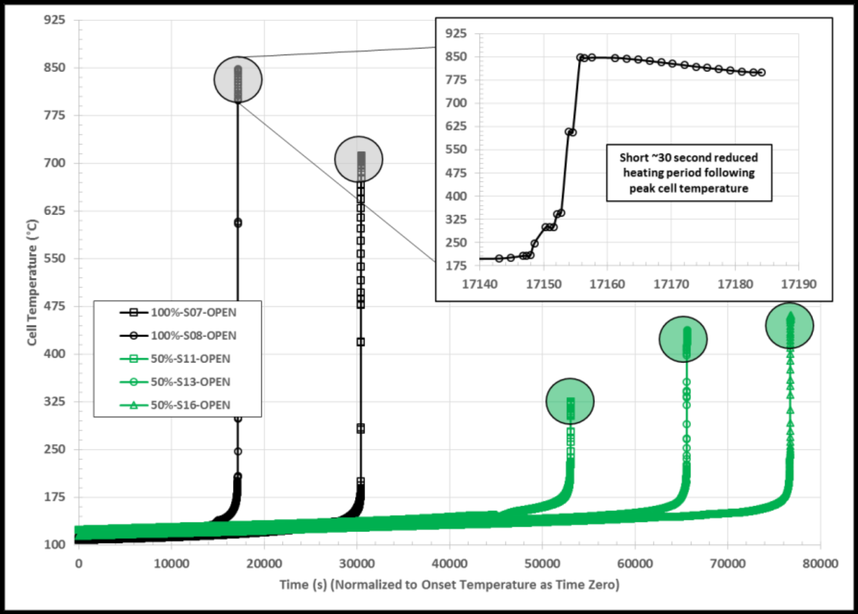
Test ID	S.O.C	Cell Onset Temperature (°C)	Cell Max Temperature (°C)	Cell Energy (kJ)	Canister Energy (kJ)	Gas Energy (kJ)	Total Energy (kJ)
BP01	100%	108.3	644.7				
BP06	100%	93.9	548.6				
BP28	100%	93.9	704.0				
BP#	50%						
BP#	50%						
BP#	50%						

Open Tank Data

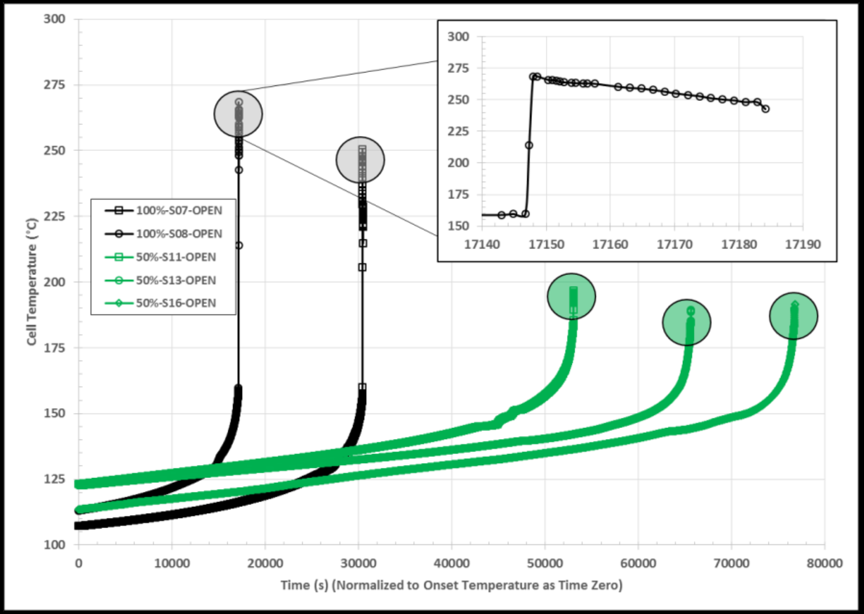
(Preliminary Results)

Open Tank Results: Samsung 18650-26F

CELL TEMPERATURES (100%SOC and 50%SOC OPEN)



GAS TEMPERATURES (100%SOC and 50%SOC OPEN)



Open Tank Results: Samsung 18650-26F

Cell	State of Charge	Nominal Capacity (Ah)	Nominal Electrical Energy(kJ)
Samsung SDI ICR18650-26F	100%	2.600	34.6
Samsung SDI ICR18650-26F	50%	1.300	17.3

Test ID	S.O.C	Cell Mass Before/After (gm)	Post Charge Voltage (V)
S07	100%	44.7 / 33.4	4.16
S08	100%	44.8 / 33.3	4.16
S11	50%	44.7 / 39.3	3.79
S13	50%	44.7 / 39.6	3.79
S16	50%	44.6 / 39.6	3.79

Test ID	S.O.C	Cell Onset Temperature (°C)	Cell Max Temperature (°C)	Cell Energy (kJ)	Canister Energy (kJ)	Gas Energy (kJ)	Total Energy (kJ)
S07	100%	107.7	711.9	22.2	15.8	N/A	38
S08	100%	114.1	847.2	25	8.9	N/A	33.9
S11	50%	124	325.7	9.2		N/A	9.2*
S13	50%	123.4	437.3	15.3		N/A	15.3*
S16	50%	114.3	461	13.9		N/A	13.9*

*Missing canister energy in total energy calculation

Open Tank Results: Moli 18650J

Cell	State of Charge	Nominal Capacity (Ah)	Nominal Electrical Energy(kJ)
Moli 18650J	100%	2.37	32.0
Moli 18650J	50%	1.635	16.0

Test ID	S.O.C	Cell Mass Before/After (gm)	Post Charge Voltage (V)
M05	100%	47.1 / 38.6	4.16
M09	100%	47.3 / 38.2	4.175
M#	100%		
M17	50%	47.0 / 43.0	3.80
M20	50%	47.1 / 42.2	3.835
M#	50%		

Test ID	S.O.C	Cell Onset Temperature (°C)	Cell Max Temperature (°C)	Cell Energy (kJ)	Canister Energy (kJ)	Gas Energy (kJ)	Total Energy (kJ)
M05	100%	113.4	794.2	29.1		N/A	29.1*
M09	100%	118.9	804.1	31.0		N/A	31.0*
M#	100%					N/A	
M17	50%	123.2	388.2	12.8		N/A	12.8*
M20	50%	124.1	447.5	14.1		N/A	14.1*
M#	50%					N/A	

*Missing canister energy in total energy calculation

Comparisons

Samsung
100% SOC vs 50% SOC

- Energy produced is lower at a lower state of charge
  - 50% SOC yielded 40% of the energy measured at 100% SOC
  - Electrode material's are at their highest level of reactivity when fully charged and there for it tracks that lower energies are produced at a lower state of charge
  - In addition the electrochemical energy reduction may result in lower heating currents when internal short circuits are formed
- Cell maximum temperatures also were reduced at lower states of charge
- Onset temperature was affected inversely with state of charge
  - Reduced onset temperature and lower overall energy release results in larger thermal margins at lower state of charge. This shows that risk of cascading failure will be reduced as state of charge is reduced.

Samsung SDI ICR18650-26F: Closed Tank Test							
State of Charge	**Samples**	**MEAN: Onset Temperature (°C)**	**STDEV: Onset Temperature**	**MEAN: Cell Max Temperature (°C)**	**STDEV: Cell Max Temperature**	**MEAN: Total Energy (kJ)**	**STDEV: Total Energy**
100% SOC	3	**114.1**	0.330	**786.2**	22.0	**40.8**	2.20
50% SOC	2	**138.2**	0.05	**386.4**	45.5	**16.2**	1.75

Samsung Open vs Closed

- Open tests were slightly less energetic
  - Onset temperature and cell maximum temperatures were reduced slightly
  - Total energy calculated was also less in the open configuration
- Gas Energy
  - It is expected that we would lose the energy computed from the gas in this configuration but the ~0.5 kJ doesn't make up for the ~5 kJ gap in energy
  - This demonstrates that ~11% of the remaining energy can be attributed to the cell effluents during thermal runaway AND to conducted energy from the cell to the canister.
  - Computation of the canister energy will yield the % of energy in the effluents assuming all ejected material left the canister in the open configuration

Samsung SDI ICR18650-26F: Closed Tank Test							
Test Configuration	**Samples**	**MEAN: Onset Temperature (°C)**	**STDEV: Onset Temperature**	**MEAN: Cell Max Temperature (°C)**	**STDEV: Cell Max Temperature**	**MEAN: Total Energy (kJ)**	**STDEV: Total Energy**
100% SOC Closed Test	3	**114.1**	0.330	**786.2**	22.0	**40.8**	2.20
100% SOC Open Test	2	**110.9**	3.2	**779.6**	67.7	**35.95**	2.05

Moli Open vs Closed

- Moli cell results trend similarly with the Samsung cell results
- Gas contribution was ~0.4kJ in closed testing
- Leaves 3.8kJ attributed to effluents or cell energy conducted to the canister
- This energy also makes up about ~11% of the energy release computed for the Moli cell.

Moli 18650J: 100% SOC Test							
Test Configuration	Samples	MEAN: Onset Temperature (°C)	STDEV: Onset Temperature	MEAN: Cell Max Temperature (°C)	STDEV: Cell Max Temperature	MEAN: Total Energy (kJ)	STDEV: Total Energy
100% SOC Closed Test	3	118.8	0.24	678.6	12.94	34.3	2.95
100% SOC Open Test	2	116.2	2.75	799.2	4.95	30.1	0.95

Final Notes

- Improvements to thermal runaway cell characterization testing is important for future model development
  - Safe design influenced by models early in the design phase can substantially reduce safety, budget, and schedule risk
- Better understanding of the energy release pathways will help inform battery thermal design at the early stages.
  - This will help engineers balance thermal management of the cell body with management of ejected material and gas
- State of charge has a clear correlation to onset temperature and over all energy release from lithium ion cells
  - This could be exploited to reduce over all risk of cascading failure during periods of inactivity

Acknowledgements

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Thank you!

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