Enhancing Thermal Stability and Performance of Lithium-Ion Batteries Using Latent Heat Storage Materials

Battery Power 2016

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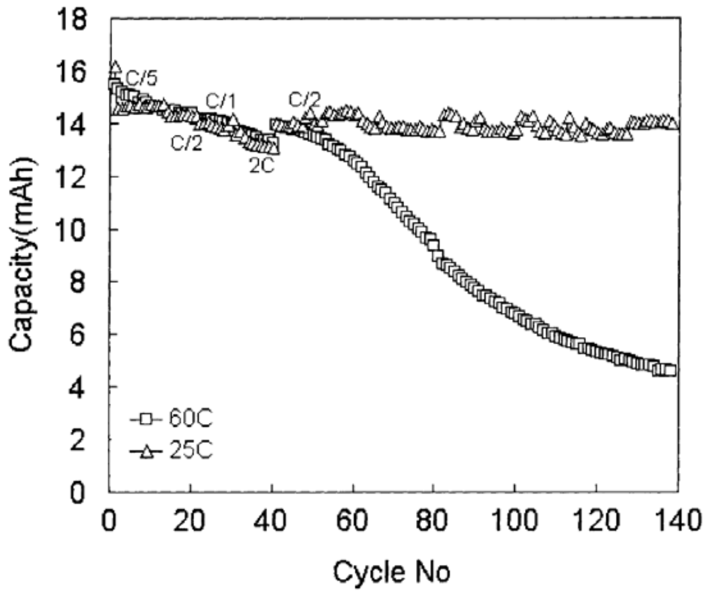
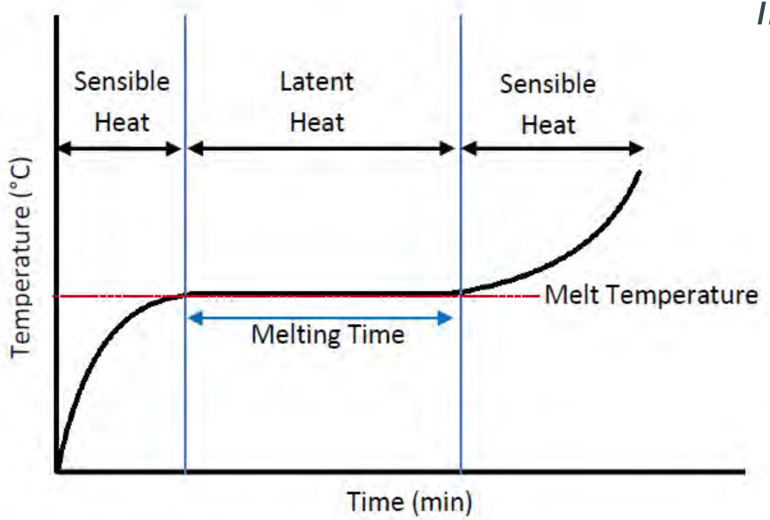
Temperature Dependent Li-ion Battery Performance

Thermal management for lithium-ion cells is critical in meeting high performance and stringent safety demands.



- **Potential Heat Sources**
  - Joule Heating/Self heating
  - Environmental
- **Electrochemical/Mechanical Degradation**
  - Degradation can occurs at 50°C or higher
  - Susceptible to cycle life loss at higher operating temperatures.
  - Capacity loss translates to shorter operating times.
  - Reduction in power capabilities
  - Electrical imbalance in packs
- **Safety Issues**
  - Thermal runaway probability is greatly enhanced
  - Pack electronics/packaging can become damaged before safety cutoffs are triggered.
  - If thermal runaway occurs, catastrophic and potentially lethal failure of pack and devices is possible.

Outlast's Latent Heat Storage (LHS) materials are a broad range of specifically engineered products based on *changing states of matter or phase* in order to absorb and release heat in a controlled manner for effective thermal control.



Ideal time vs. temperature curve for LHS materials.

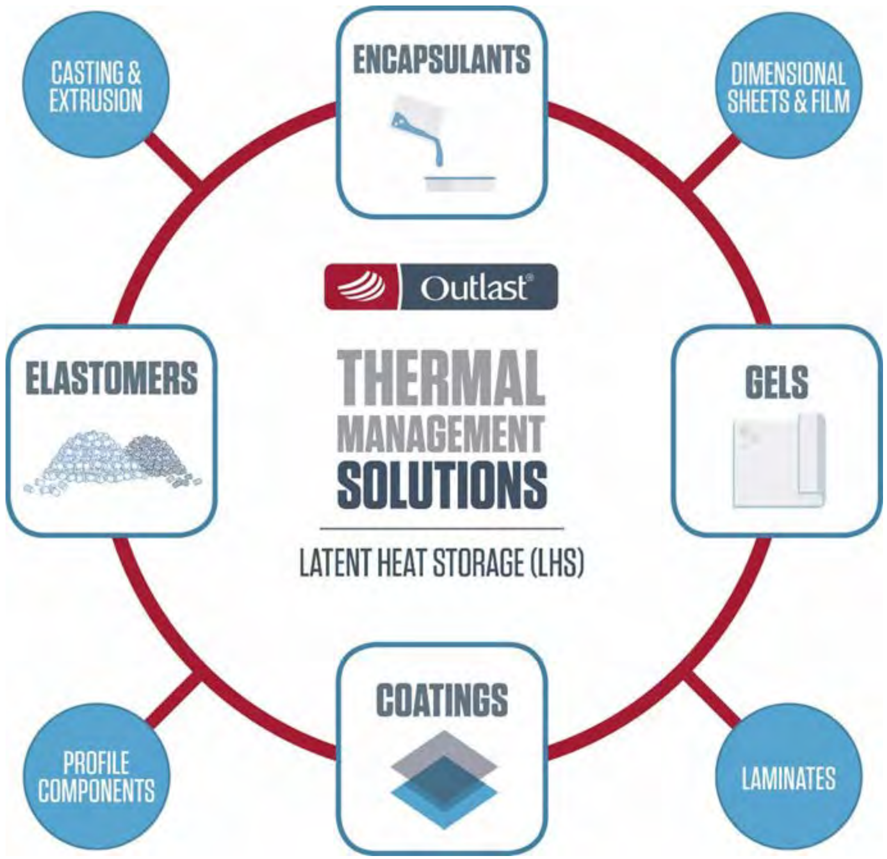
Outlast LHS materials rely on a number of inherent physical properties for effective thermal control:

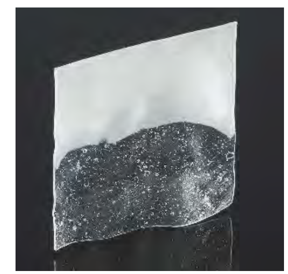
- Phase change temperatures: can be "tuned" to a wide range of temperatures (-5 to 190°C).
- Reversible phase transitions: The material is able to go through repeated changes of phase without loss of thermal absorption properties.
- Latent Heat: defined as the amount of thermal energy required for a certain mass of material to undergo a change in phase, is typically quantified as joules per gram (J/g).

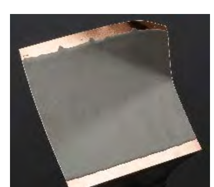
Outlast Latent Heat Storage (LHS) materials derived from PCMs can offer enhance passive thermal management performance through enhanced thermal energy storage properties.

Commercial LHS Products for Electronic and Industrial Applications

LHS materials are provided in a number of different formats from compounded product to finished components:



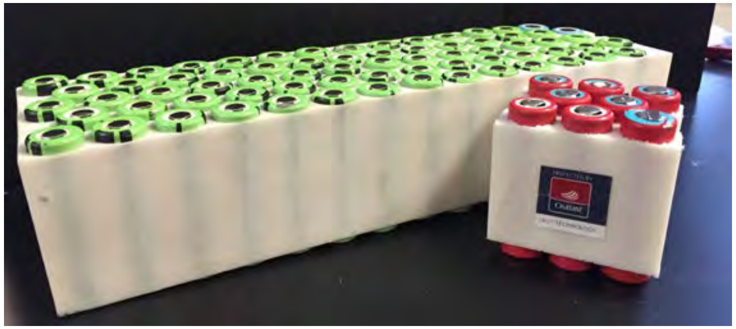




LHS Products for Li-ion Battery Thermal Management

LHS-based materials offer an integrated approach to maintaining optimal thermal parameters for peak performance and improved safety.

LHS Li-ion Cell Sleeve

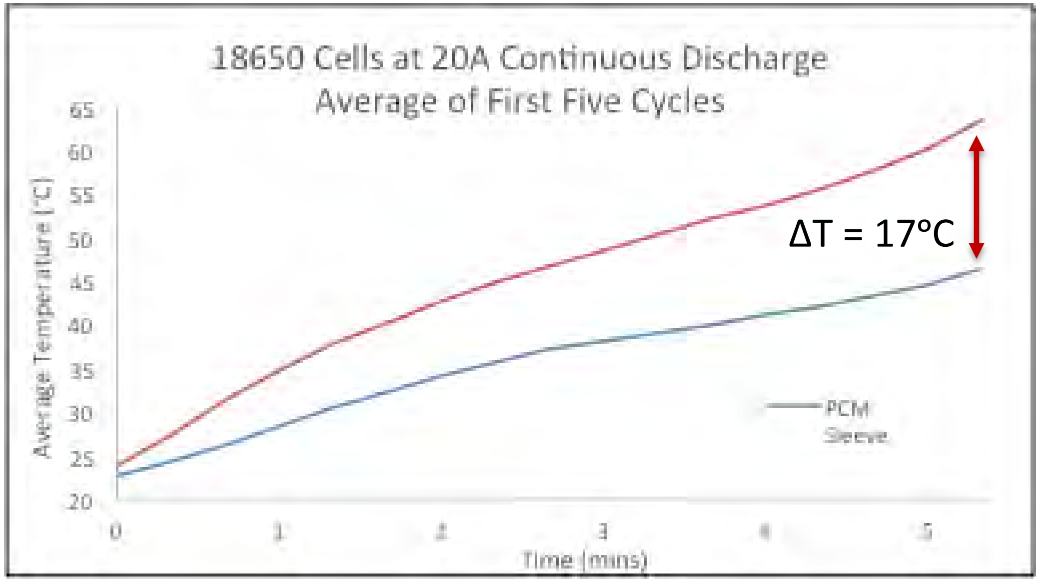


LHS Li-ion Battery Matrix

- Designed to maintain acceptable cell and pack temperatures that minimize degradation and maximize performance.
- Can be applied to many different cell sized, formats, and capacities.
- UL94-V0 flame retardant.
- Robust in a multitude of hot and cold environments without any pump-out/leaking of material.
- Highly electrically resistive

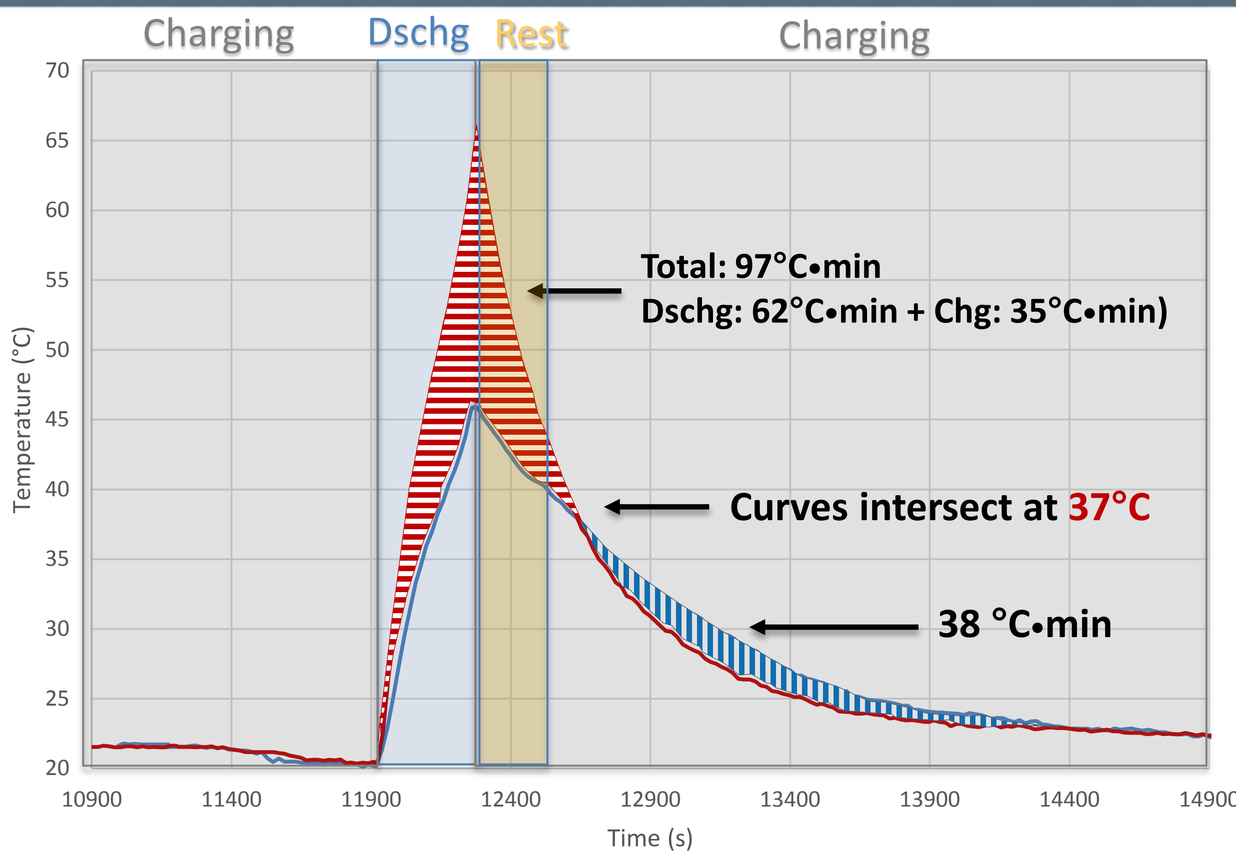
LHS Li-ion Cell Sleeve

LHS materials are designed to absorb heat off of cell surfaces during energy intensive operations and dissipating it during rest and low rate charge/discharge cycles.



- Simultaneously tested control and LHS sleeved 18650 cells at 20A discharges showed an averaged end of discharge cell surface temperatures of 63°C and 46°C respectively.
  - 17°C difference compared to 26°C difference for the 10A discharge case.
  - Balance of LHS properties with application requirements and cell/pack ratings for optimized performance.

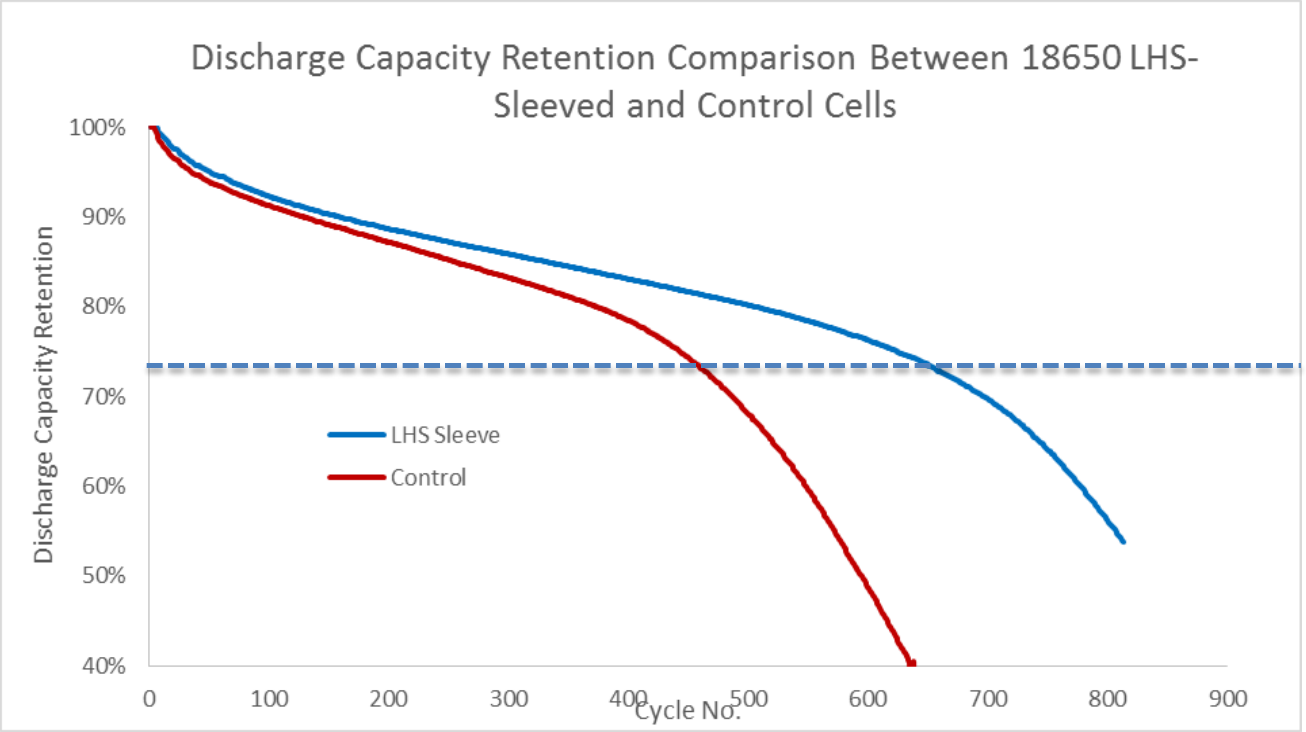
Thermal History Comparison



Total Thermal History Reduction from LHS Sleeve: 59°C•min

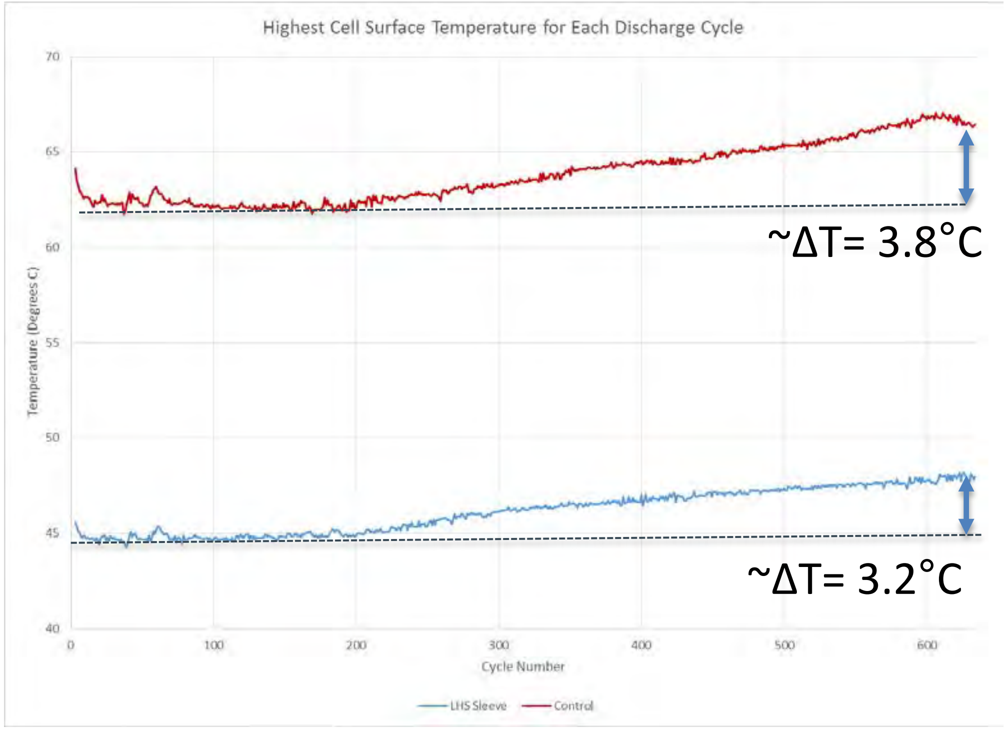
- Numerical integration of thermal curves show that control cells have an higher thermal history of 97°C/min during cycling until reaching 37ºC during the cool-down/charge phase.
- Below 37°C LHS sleeved cells had a higher thermal history than that of control batteries until ambient reached due to thermal dissipation of stored energy.
- Approx. 60% of total thermal history of control occurs above maximum cell surface temps (47°C) of LHS sleeved cells.
- This higher thermal history for the control cells is compounded upon each subsequent cycle

Larger thermal stress on the non-LHS cells leads to loss in electrochemical capacity retention across operation lifetime of the cell or battery pack.



LHS cells remained above 75% capacity retention for 40% overall increase in cycle life.

LHS Thermal Cycling Behavior

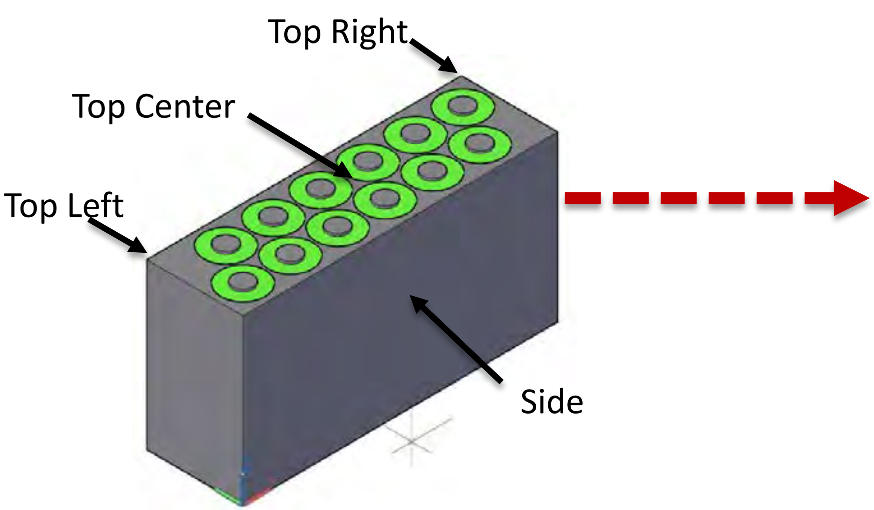


- Temperature deviation after 650 cycles (taking into account surrounding environment fluctuations/cell conditioning) was less than 3.5°C for the LHS sleeve.
  - *No significant temperature deviation between LHS Sleeve vs. Control cells for 650 cycles.*
    - *LHS sleeve maintained its effective thermal absorption properties over the lifetime of the battery.*

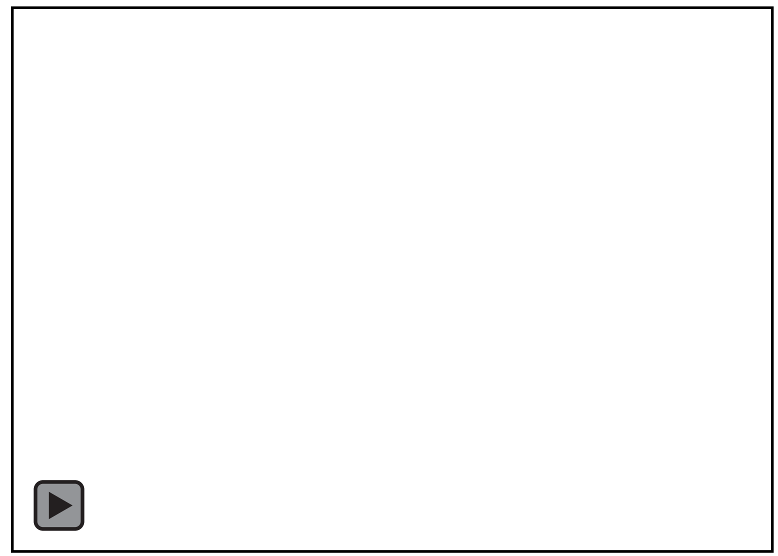
LHS Li-ion Battery Matrix

LHS Battery Matrix:

- Maintain optimal cell surface temperature through thermal absorption from self-heating.
- Limit thermal interactions/transfer between cells
- Better ***thermal homogeneity*** across pack, i.e. limiting hot spots/disproportionate cell heating.



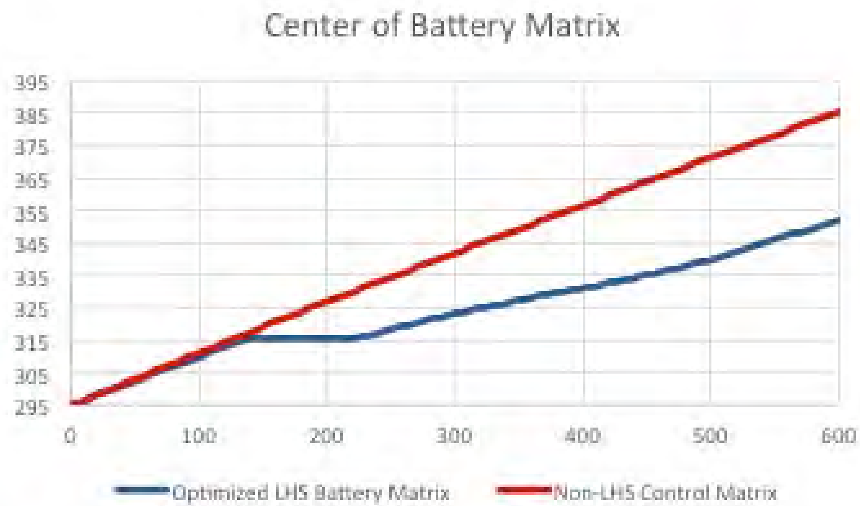
Li-ion LHS Battery Matrix



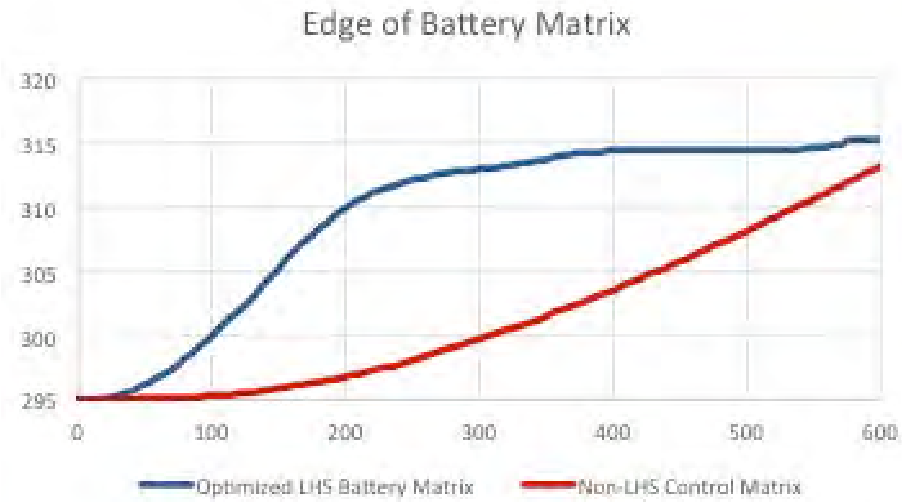
Thermal Model of LHS Matrix with 12 18650s Li-ion cells dissipating 12W.

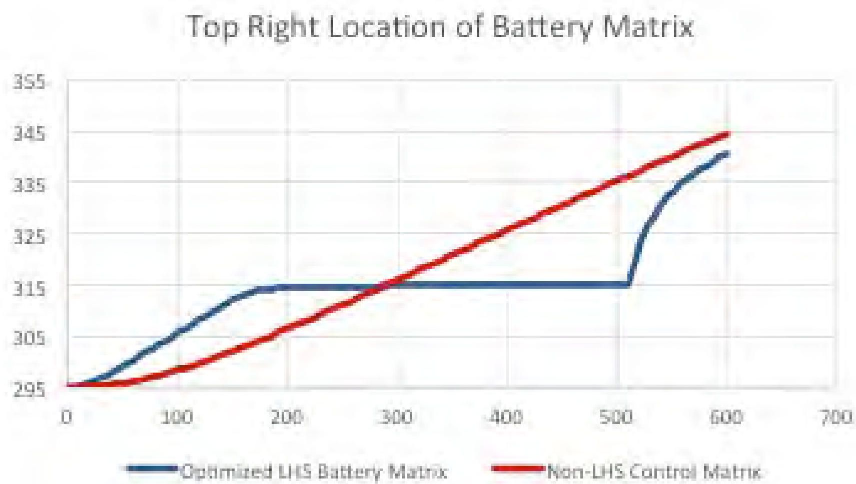
Homogeneity of Li-Ion Battery Pack with LHS Pack

Center of pack cooler with LHS



LHS moves heat away from center, and out to edge.



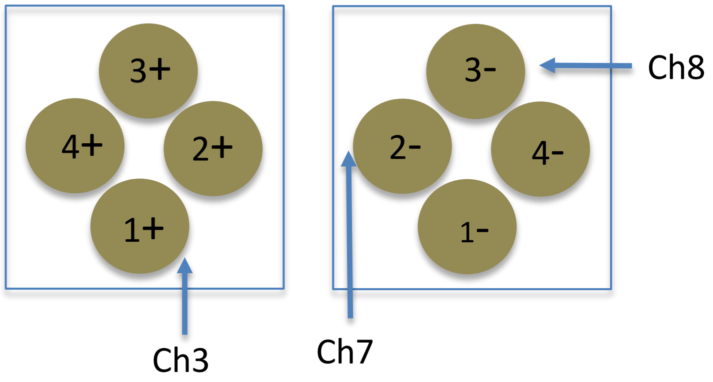


Effective utilization of LHS Matrix Volume.

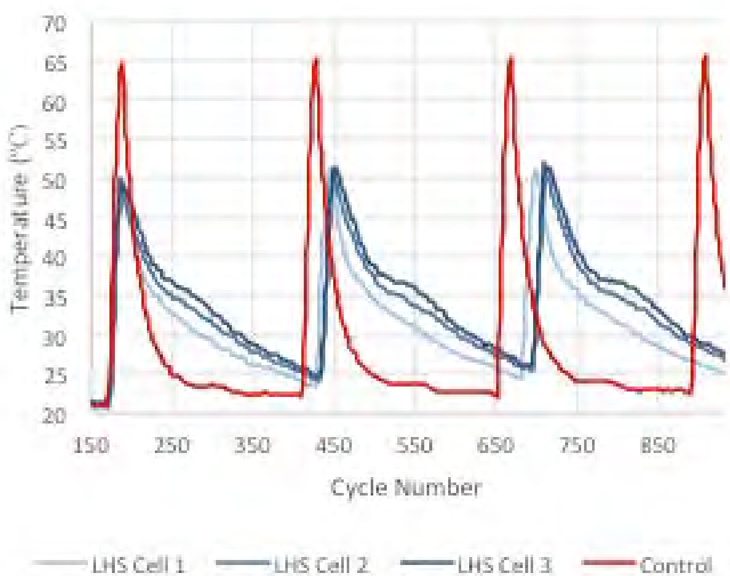
Four LGDAHB41865 1.5Ah Li-ion cells connected in parallel and placed in LHS Battery Matrix

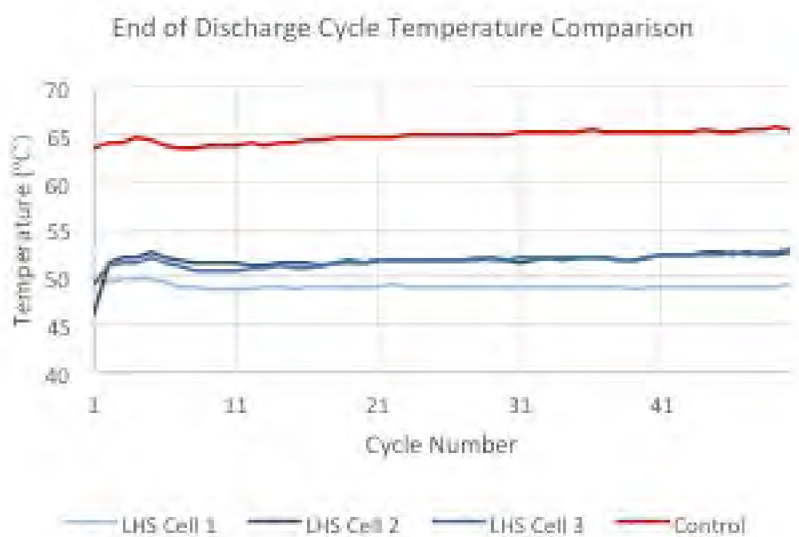
Testing Program:

- The cells rest for 1 minute before charging at 6A till voltage reaches 4.2V, then trickle charges until current drops to 0.25A.
- Cells rest for 30 seconds before discharging at 80A until voltage of 2.5V is achieved.
- The cells rest for 10 minutes before looping back to the charge cycle. This repeats for 1000 cycles.



All thermocouples placed midway between positive and negative ends of cells



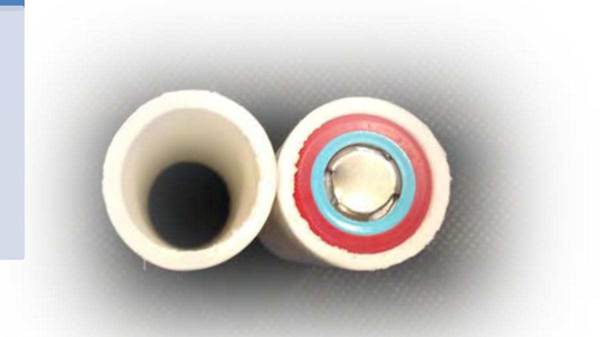


Fast Charge Testing Parameters

Objective: Characterize effects of fast charging on commercial Li-ion cells and determine ability of LHS to mitigate reduction in performance.

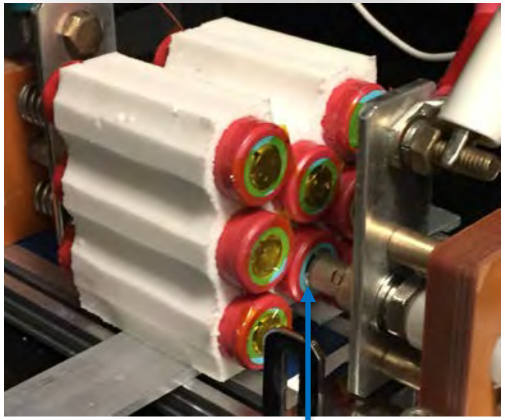
Mitigate thermal effects from fast charging that:

- Reduce capacity and power
- Promote poor charge transfer→ time to desired SOC
- Damage cell components, i.e. separators that can lead to short circuit and thermal runaway.



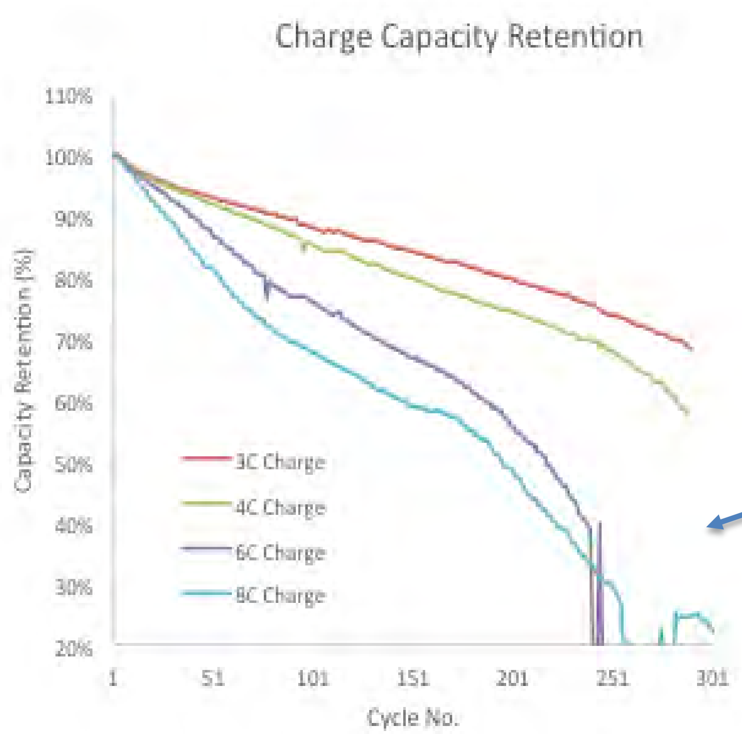
Testing Setup: Compared cells with LHS sleeves and in 8-cell LHS battery matrix with control cells.

- Each cell underwent the same testing program while temperature, voltage, and current were measured in real-time.
- Charge rates from 2C up to 8C tested (CC up to 4.2V then held at voltage till current dropped to 60mA).
- Discharge rate held at 10C
- Cells cooled to 25C after charge before discharge; Cells cooled to 30C after discharge before charge.

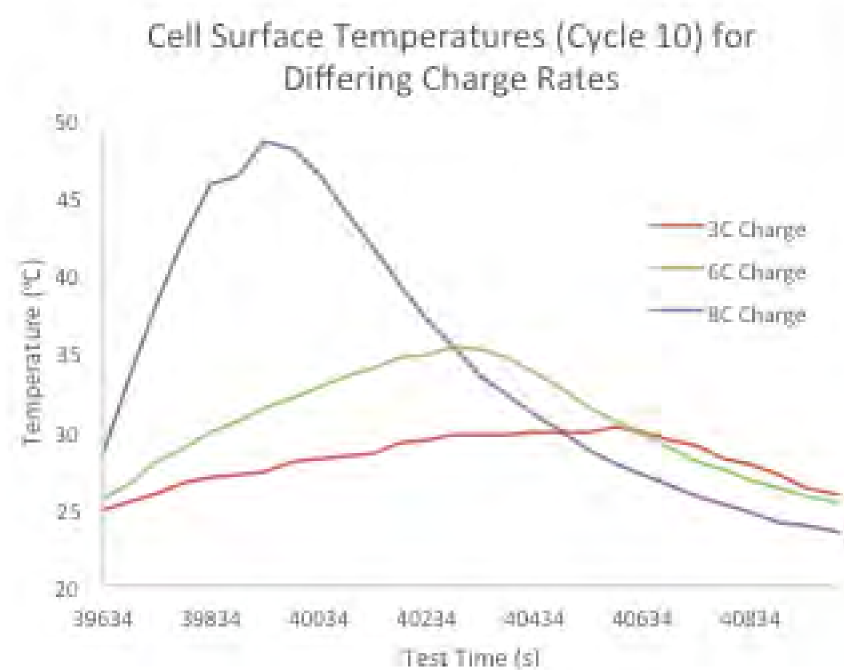


Only center cell tested

Effect of C-rate on Charge Capacity Retention and Temperature



Cell failure

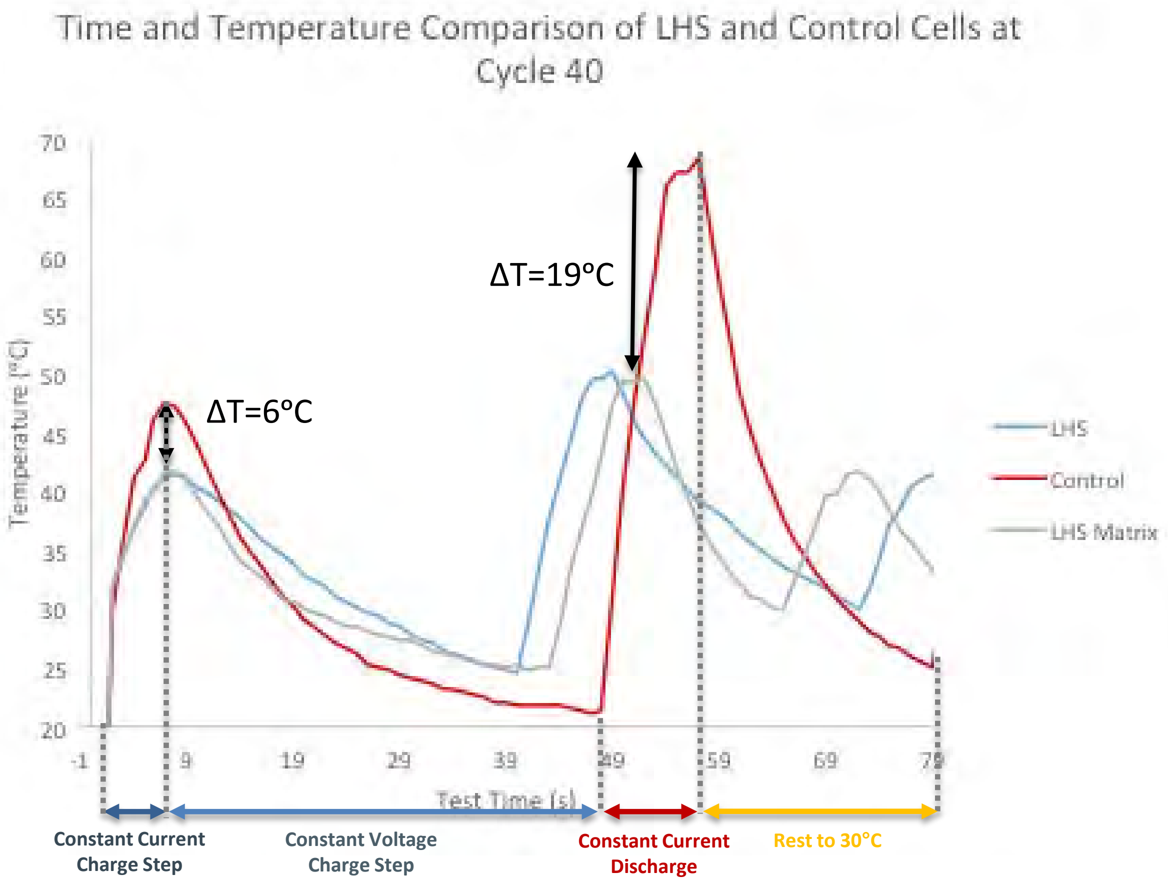


As charge rate increase, the capacity retention/cycle life of the cell drastically decreases and cell temperature increases.

Significant increase in cell surface temperatures were observed when charged at 8C, approaching 50°C by end of constant current charging step.

Time and Temperature Comparison

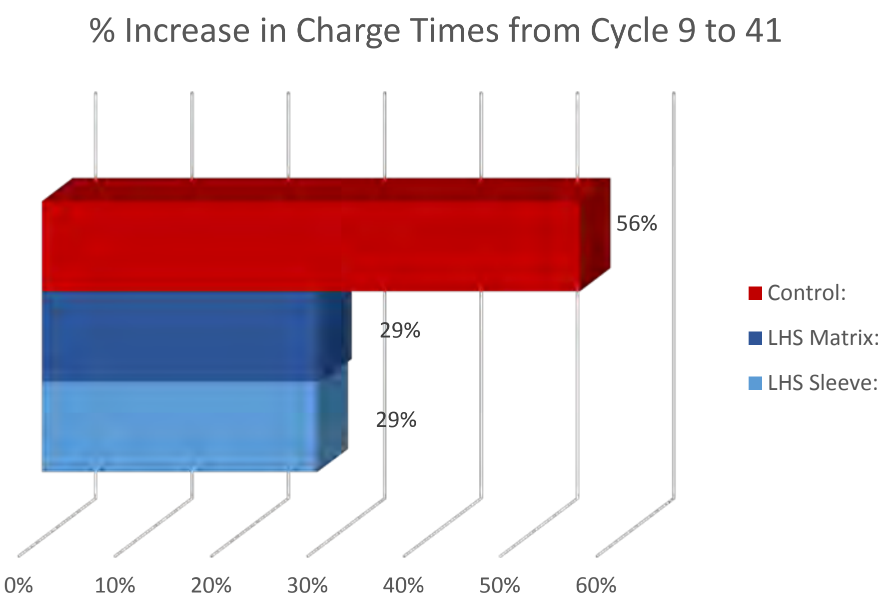
Compared UR18650RX cells using Outlast LHS™ ENH60-90 battery sleeves (6.82g) and an 8-cell LHS battery Matrix to control cells using 8C test protocol.

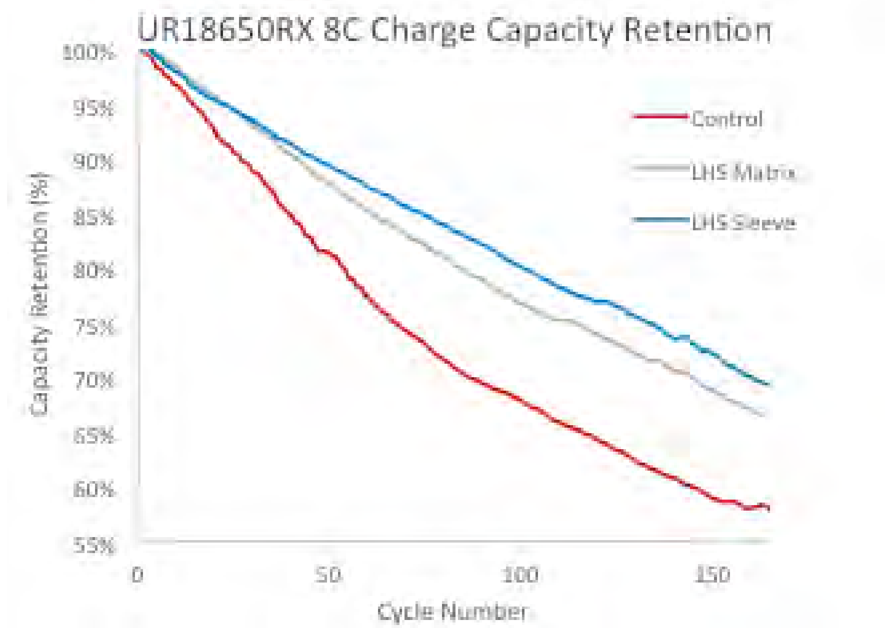


Fast Charging Benefits with LHS

Test Result Highlights:

- Up to 15% better charge and discharge capacity retention using LHS sleeve compared to control cell
- *56%* increase in charge time of control cell vs 29% increase in LHS cell from cycle 9 to 41. Thermal degradation that limits fast charging ability of cell minimized by maintaining shorter charge durations.
- Cell surface temperatures using LHS sleeve were reduced by 6°C at 8C charge and 19°C at 10C discharge.





While 8C charge rates are unrealistic, this case demonstrates that LHS ability to operate effectively beyond recommend manufacturer specs (typically 3C) for single cells.

Lithium-Ion Safety

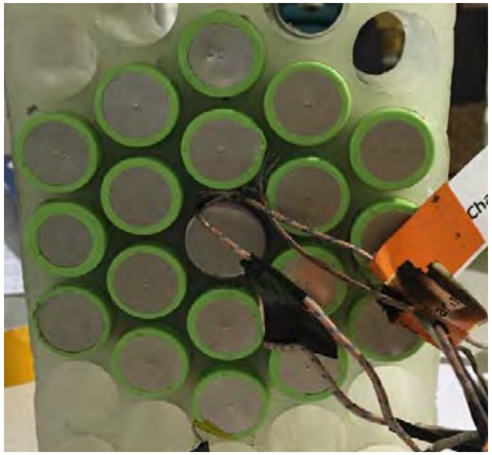
- **Failure Modes**
  - *Thermal abuse*
    - Elevated environmental temperatures
    - Self-heating from adjacent cells
  - *Physical Damage*
    - Shock, puncture, crush, or vibrations that can cause internal cell shorts
  - *Overcharge/discharge*
    - Some chemistries can generate significant heat if overcharge/discharge event occurs and less tolerant to its effects.
- **Thermal Abuse Event**
  - *Stage 1:* An onset temperature (self heating rate) is reached due to internal and/or external heat sources. Heat needs to be dissipated from cell and pack effectively in order to avoid reaching stage 2.
  - *Stage 2:* Acceleration of heat being released from cell and pack. Heating rate begins to exceed dissipation rate.
  - *Stage 3:* Runaway occurs, rapid rise in heat generation that leads to cell failure. Flame and loss of cell integrity likely.

Mitigation of abuse event with LHS

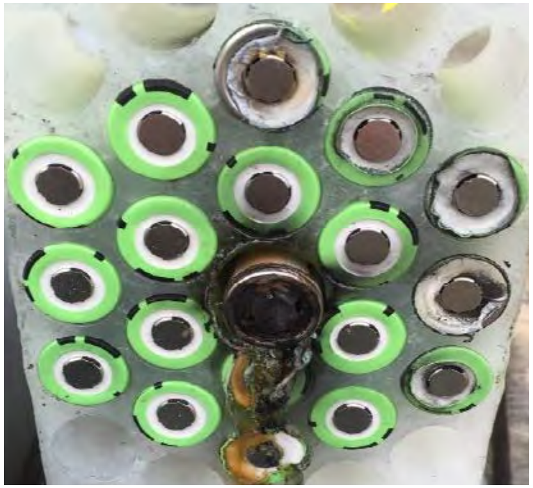
- High heat absorption properties allow LHS to prevent stage 1 and stage 2 events from occurring.
- Inherent flame retardancy of material (UL94-V0) inhibits propagation of thermal runway during stage 3 event. Surrounding cells unaffected physically and thermally from event.

Thermal Runaway Testing with LHS

Center cell short circuited to trigger thermal runaway



Positive side after thermal runaway event



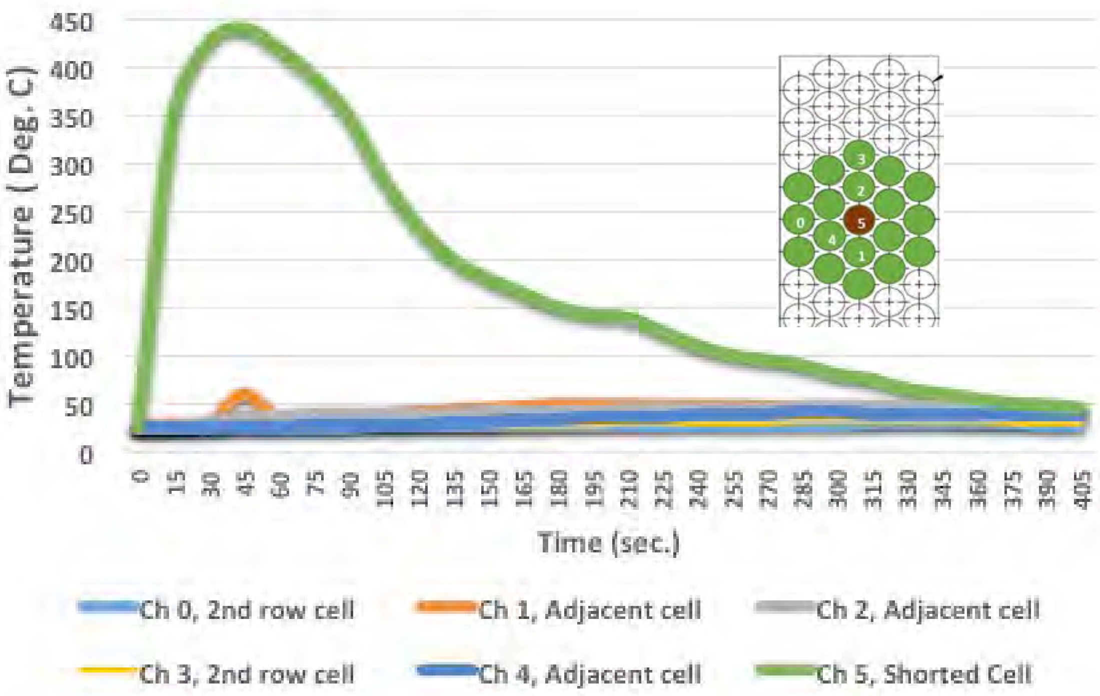
Negative side after thermal runaway event

Flame retardant LHS contains stage 3 event to single trigger cell

Heat absorption properties keeping surrounding cells below damaging temperatures

No propagation of thermal event

Thermal Runaway Testing with LHS



Test Results	
Maximum temperature at trigger cell	427°C
Maximum temp of cell# 2	52°C
Maximum temp of cell# 1	48°C
Time to reach the max temp in cell #2	160 s
Time to reach the max temp in cell #1	220 s

-Thermal runaway propagation was limited to trigger cell. Average ΔT between trigger cell (#5) and radial cells (#2,3,4) was approximately 360° C

-A maximum temperature of 52° C was observed for radial cell 2 during stage 3 runaway.

-Surrounding cells maintained same voltage during testing. No indication of thermal effects to surrounding cells.

Concluding Remarks

- **Outlast's latent heat storage materials offer a robust, integrated passive thermal management system that absorbs and dissipates thermal energy during certain thermal abuse events in order to:**
  - Maintain optimal cell and pack temperatures during operations, enhancing electrochemical function.
    - Limit capacity/power fade during fast charge/ high discharge operations
  - Provide thermal homogenity and effective dissipation in compact, high energy density pack designs.
  - Limit possible thermal abuse situations that can cause thermal runaway
  - Inhibit propagation in packs utilizing both energy absorption and inherent flame retardant properties.

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