UNDERSTANDING THERMAL RUNAWAY RESPONSE VARIABILITY

UTILIZING THE BATTERY FAILURE DATABANK TO INFORM THERMAL MODEL DRIVEN DESIGNS

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WEBINAR | REDUCING BATTERY THERMAL RUNAWAY RISKS THROUGH TESTING AND SIMULATION

JUNE 29TH, 2021

DESIGNING SAFE BATTERIES

- **It is the responsibility of the lithium-ion (Li-ion) battery pack designers to ensure that a safe battery design is achieved prior to final production.**
- **To do so, designers should consider the following [1]:**
  - Always assume that thermal runaway will eventually happen and design such that a single cell thermal runaway event is not catastrophic.
  - Design such that cell to cell propagation will not occur.
- **Thermal management systems designed to minimize the effects of thermal runaway and prevent cell-to-cell propagation should take into consideration the impacts of the following:**
  - No two thermal runaway events are the same, even for the same manufacturer, cell type, and state-of-charge; there is a range of possible outcomes.
  - Cell failure type (e.g. top vent, bottom vent, bottom or side wall rupture, spin groove breach, et…).
  - Thermal runaway behavior as a function of trigger mechanism and cell format.

[1] *Crewed Space Vehicle Battery Safety Requirements. JSC-20793 Rev D. JSC Engineering Directorate, Power and Propulsion Division*

DESIGNING SAFE BATTERIES

- **A fundamental first step in designing a safe battery is to conduct specialized cell level abuse testing:**
  - This testing can reveal unique insights into how the cell fails and how those failure modes could impact the overall safety of the battery design.
  - One such insight might be if the cell tends to fail nominally through a top or bottom vent, or if the cell has a propensity to fail off-nominally in the form of side wall ruptures, bottom ruptures, and spin groove breaches.
- **Various forms of calorimetry are often used to characterize cell level thermal runaway response:**
  - Total energy release range and fractional energy release.
  - Composition, mass, and volume of the ejected solids, liquids, and gases.
  - Combustion effects and burning behavior.
  - Onset temperature of decomposition, acceleration temperature, and trigger temperature.
- **This information is important because, if obtained early in the design process, it can aid designers in making well educated decisions on the design of their battery and thermal management system.**

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **Fractional Thermal Runaway Calorimetry (FTRC) is used to characterize (1) the total heat output and (2) fraction of heat released through the cell casing vs. through the ejected materials:**
  - Symmetric design supports characterization of heating as a result of venting or rupture in any direction.
  - The energy fractions are determined by post-processing the temperature vs. time data for each calorimeter component (i.e. $dE_{Component,i} = m_i C_{p_i} dT_i$) and then adding together based on sub-assembly.

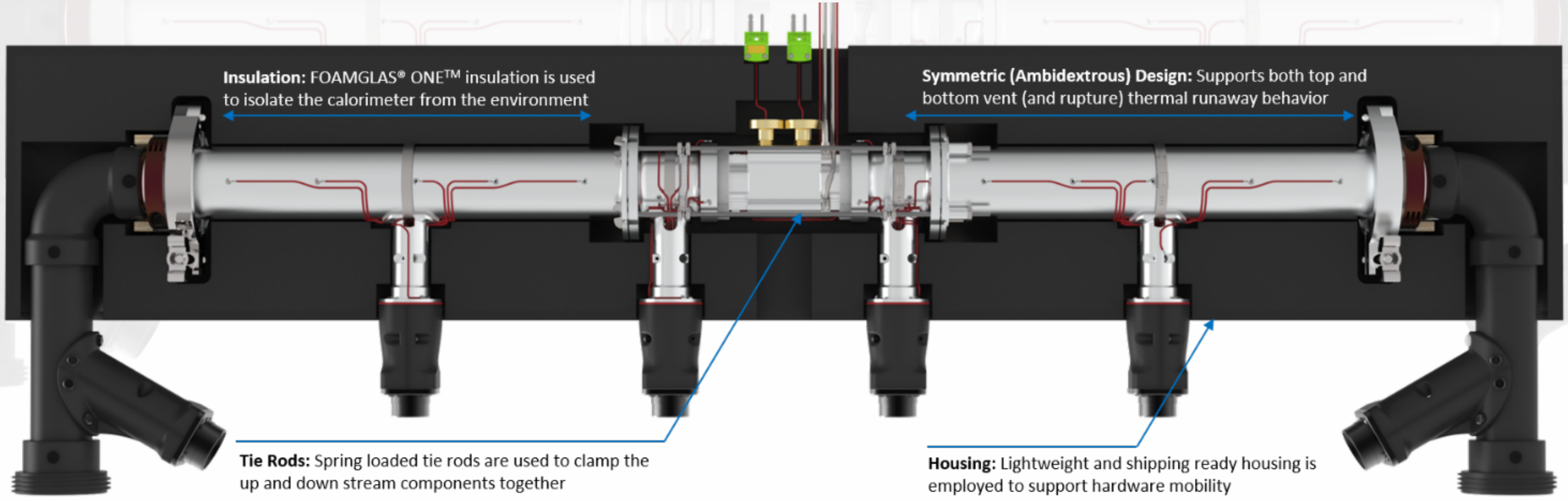


Image submitted to Journal of Power Sources, June 2021.

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **The FTRC is designed to help characterize directional/fractional thermal runaway heat output:**
  - The cell chamber assembly is isolated from the remainder of the up and downstream calorimeter components with low conductivity ceramic bushings.
  - Maintaining thermal isolation is critical to our team's ability to discern the fraction of energy released through the cell casing vs. through the ejected material.
  - The ejecta mating segment is designed to capture and stop complete jellyroll ejections.

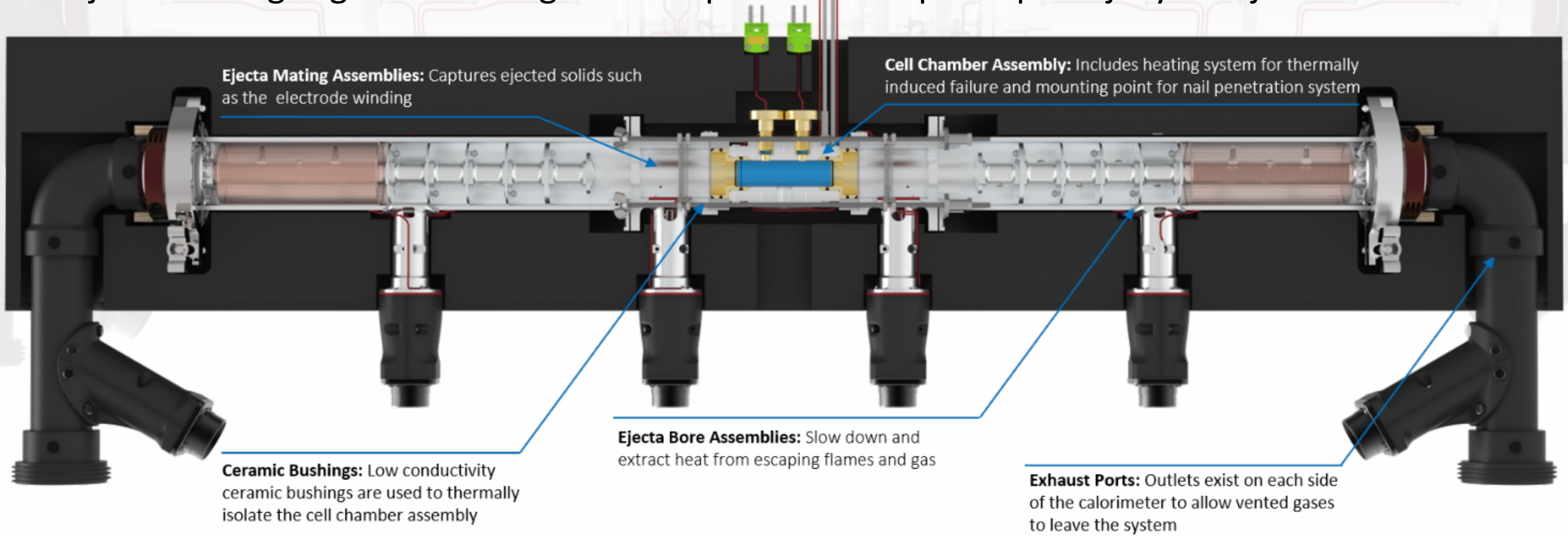
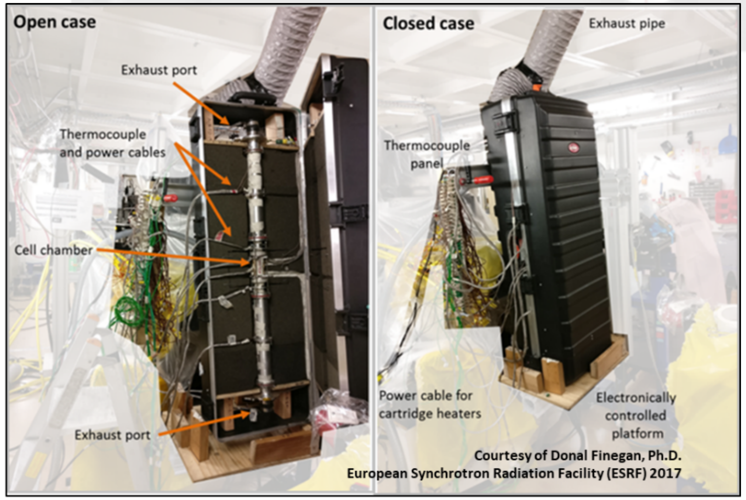


Image submitted to Journal of Power Sources, June 2021.

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **High speed x-ray videography provided by synchrotron facilities can be used to characterize the internal failure mechanisms of a given cell.**
- **The images below depict the FTRC, which is x-ray transparent, coupled with a synchrotron for specialized experiments designed to link internal failure mechanisms to the external thermal behavior of the cell during thermal runaway:**
  - Left Image: S-FTRC at the European Synchrotron Radiation Facility (ESRF) in France.
  - Right Image: S-FTRC at the Diamond Light Source (DLS) Facility in the United Kingdom.



Courtesy of Donal Finegan, Ph.D.
European Synchrotron Radiation Facility (ESRF) 2017

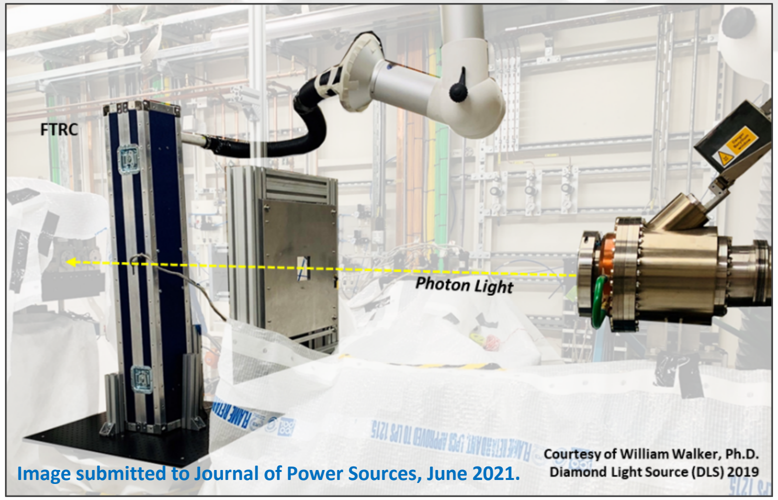


Image submitted to Journal of Power Sources, June 2021.
Courtesy of William Walker, Ph.D.
Diamond Light Source (DLS) 2019

Cell type: Li-ion 18650
Capacity: 3.5 Ah
State of Charge: 100 % (4.2 V)
Bottom vent: No
Wall thickness: Not known
Separator: Polymer
Orientation of cell: Positive end up
Location of ISCD radially: N/A
Location of ISCD longitudinally: N/A
Side of ISCD in image: N/A

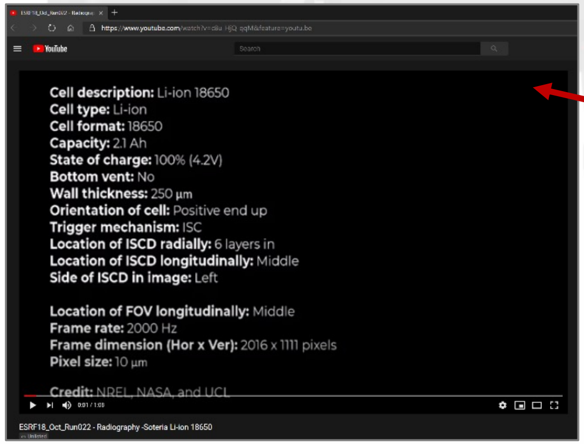
Location of FOV longitudinally: Top
Frame rate: 2000 Hz
Frame dimension (Hor x Ver): 1280 x 800 pixels
Pixel size: 17.8 μm

BATTERY FAILURE DATABANK

- **The results from the FTRC experiments and combination FTRC / synchrotron experiments have been compiled into a resource known as the Battery Failure Databank:**
  - The databank was developed as part of a collaborative effort between NASA Johnson Space Center and the National Renewable Energy Laboratory (NREL).
  - Information in the databank provides engineers and researchers with data to inform models.
- **The databank supports comparison of heat output and mass ejection for:**
  - 18650 format cells, 21700 format cells, and D-cell format cells.
  - Heater plus internal short circuiting (ISC) device trigger, heater (non-ISC) trigger, and nail penetration trigger.
  - Power cells and energy cells.
- **The insights revealed by the databank can be used as inputs for system level thermal models.**

BATTERY FAILURE DATABANK

- **The Battery Failure Databank is a two component system consisting of the following:**
  - A Microsoft Excel™ based component that stores tabular results regenerated from nearly 200 FTRC experiments conducted between 2017 and 2019.
  - An online library of radiographic videos, hosted through NREL's YouTube channel, for more than 300 FTRC experiments conducted at synchrotron facilities between 2017 and 2019.
  - Both components of the databank combined provide means to link internal phenomena with external risks.
  - The first revision of the databank is now publicly available.



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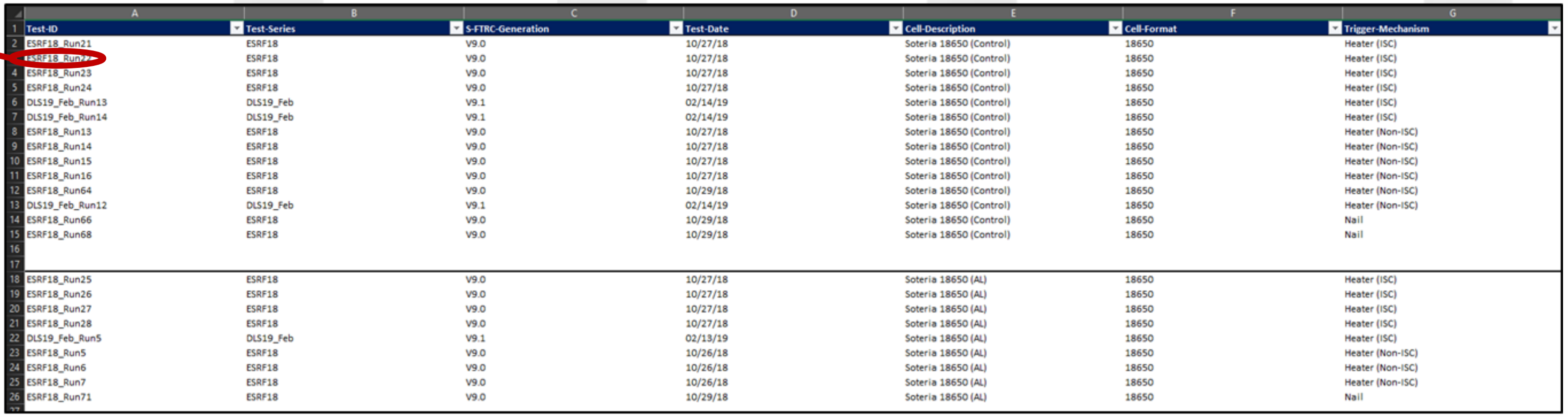
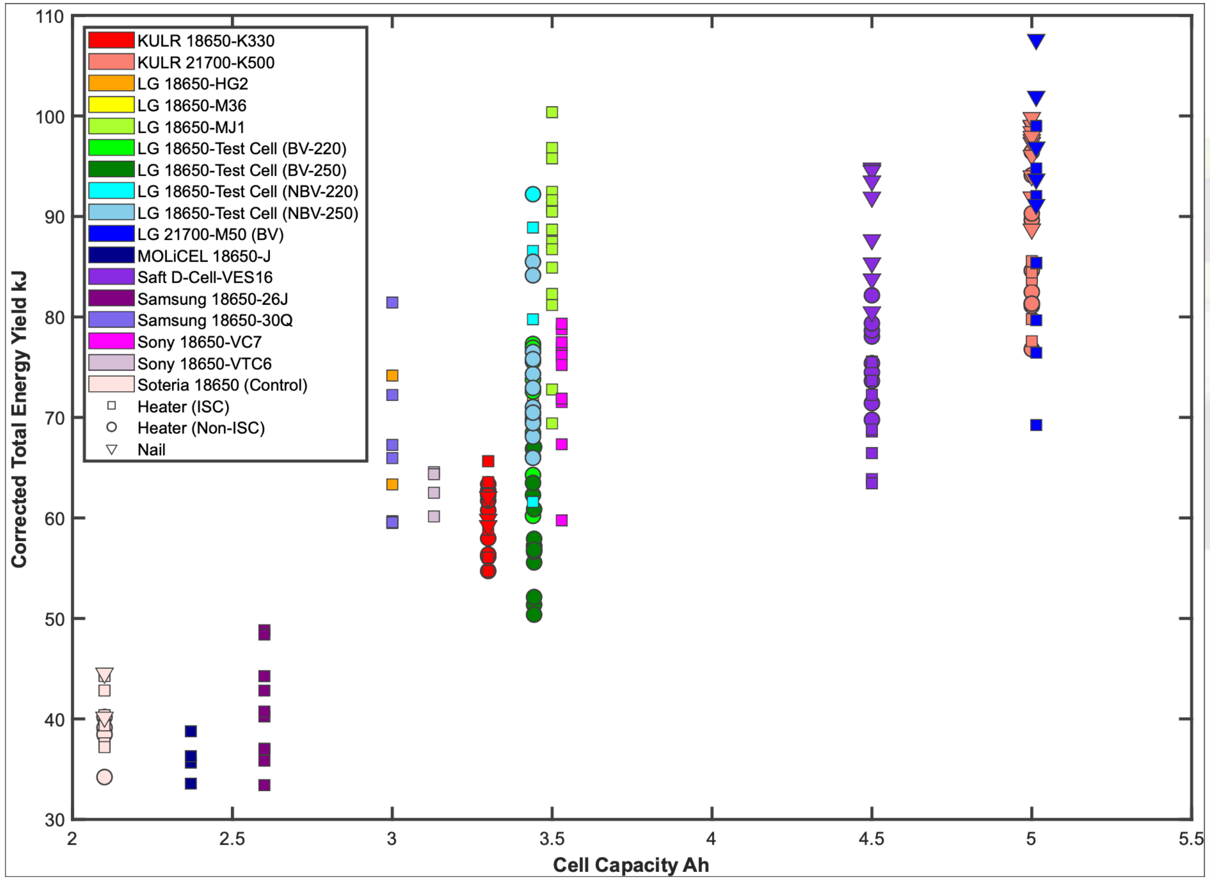


	A	B	C	D	E	F	G
1	Test-ID	Test-Series	S-FTRC-Generation	Test-Date	Cell-Description	Cell-Format	Trigger-Mechanism
2	ESRF18_Run21	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (ISC)
3	ESRF18_Run22	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (ISC)
4	ESRF18_Run23	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (ISC)
5	ESRF18_Run24	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (ISC)
6	DLS19_Feb_Run13	DLS19_Feb	V9.1	02/14/19	Soteria 18650 (Control)	18650	Heater (ISC)
7	DLS19_Feb_Run14	DLS19_Feb	V9.1	02/14/19	Soteria 18650 (Control)	18650	Heater (ISC)
8	ESRF18_Run13	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (Non-ISC)
9	ESRF18_Run14	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (Non-ISC)
10	ESRF18_Run15	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (Non-ISC)
11	ESRF18_Run16	ESRF18	V9.0	10/27/18	Soteria 18650 (Control)	18650	Heater (Non-ISC)
12	ESRF18_Run64	ESRF18	V9.0	10/29/18	Soteria 18650 (Control)	18650	Heater (Non-ISC)
13	DLS19_Feb_Run12	DLS19_Feb	V9.1	02/14/19	Soteria 18650 (Control)	18650	Heater (Non-ISC)
14	ESRF18_Run66	ESRF18	V9.0	10/29/18	Soteria 18650 (Control)	18650	Nail
15	ESRF18_Run68	ESRF18	V9.0	10/29/18	Soteria 18650 (Control)	18650	Nail
16							
17							
18	ESRF18_Run25	ESRF18	V9.0	10/27/18	Soteria 18650 (AL)	18650	Heater (ISC)
19	ESRF18_Run26	ESRF18	V9.0	10/27/18	Soteria 18650 (AL)	18650	Heater (ISC)
20	ESRF18_Run27	ESRF18	V9.0	10/27/18	Soteria 18650 (AL)	18650	Heater (ISC)
21	ESRF18_Run28	ESRF18	V9.0	10/27/18	Soteria 18650 (AL)	18650	Heater (ISC)
22	DLS19_Feb_Run5	DLS19_Feb	V9.1	02/13/19	Soteria 18650 (AL)	18650	Heater (ISC)
23	ESRF18_Run5	ESRF18	V9.0	10/26/18	Soteria 18650 (AL)	18650	Heater (Non-ISC)
24	ESRF18_Run6	ESRF18	V9.0	10/26/18	Soteria 18650 (AL)	18650	Heater (Non-ISC)
25	ESRF18_Run7	ESRF18	V9.0	10/26/18	Soteria 18650 (AL)	18650	Heater (Non-ISC)
26	ESRF18_Run71	ESRF18	V9.0	10/29/18	Soteria 18650 (AL)	18650	Nail

Additional Experiments

DATABANK | CAPACITY VS. TOTAL ENERGY YIELD



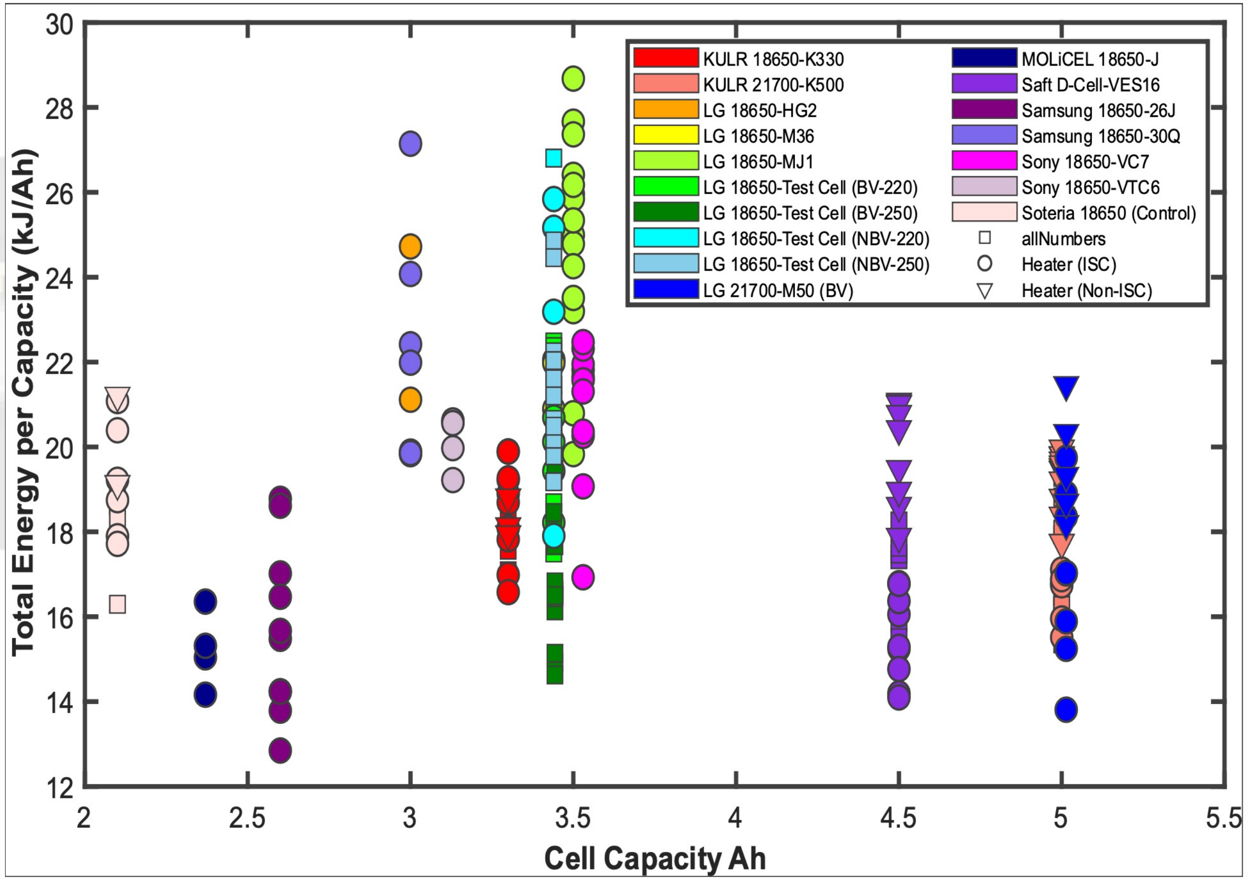
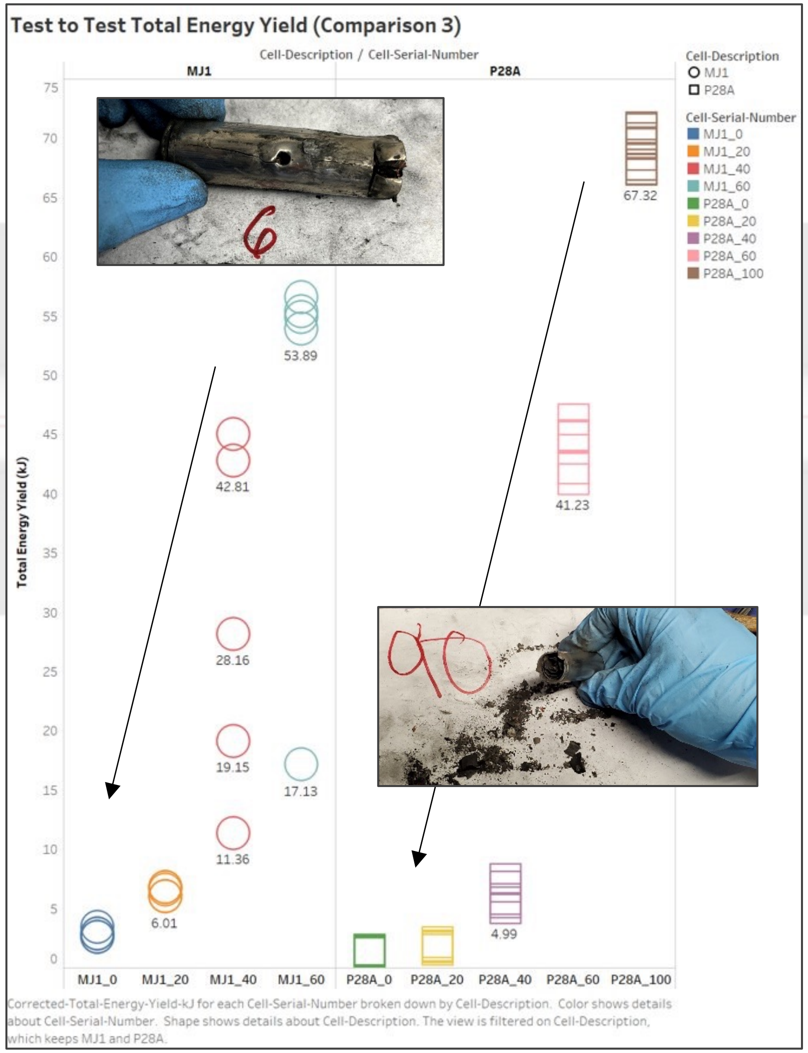
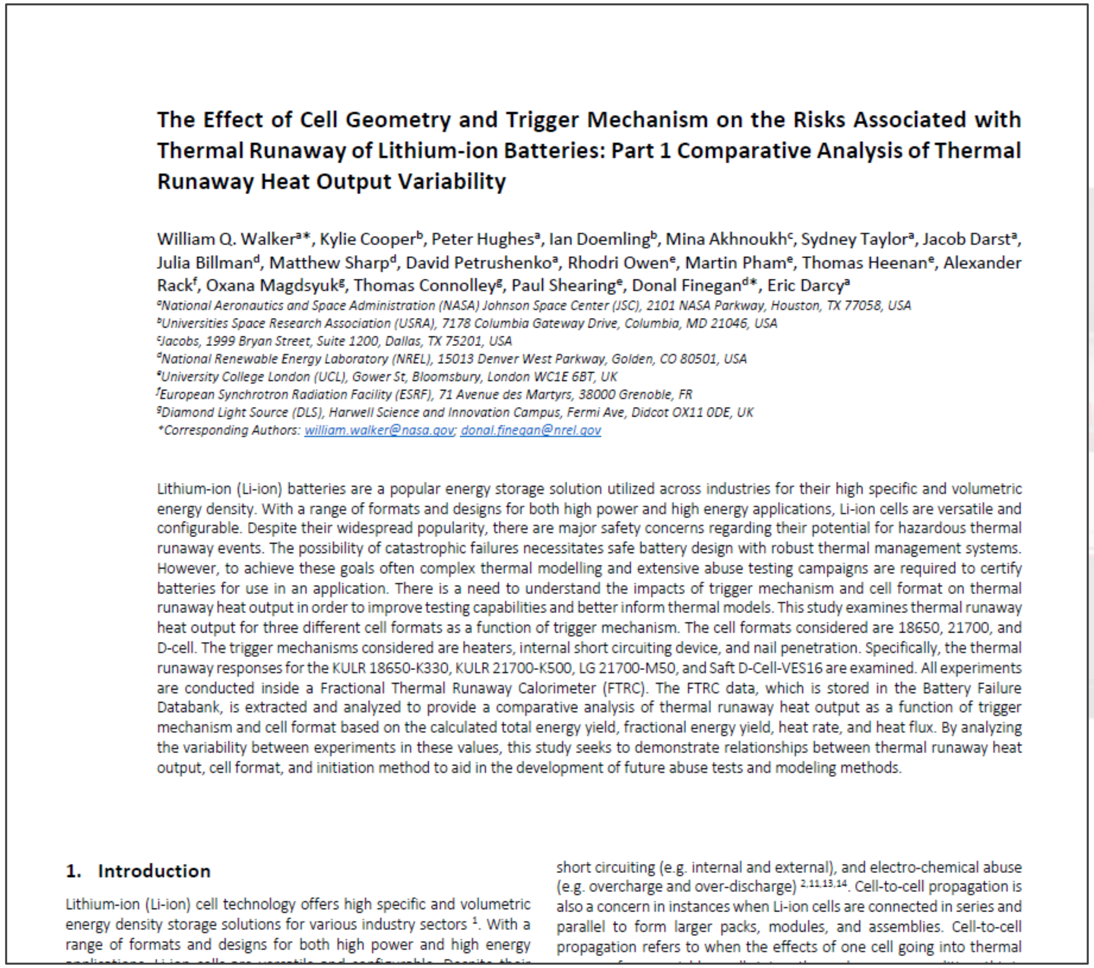


Image Credit: Julia Billman and Donal Finegan, Ph.D. (NREL)

DATABANK | STATE-OF-CHARGE VARIABILITY



COMPARATIVE ANALYSIS STRATEGY



The Effect of Cell Geometry and Trigger Mechanism on the Risks Associated with Thermal Runaway of Lithium-ion Batteries: Part 1 Comparative Analysis of Thermal Runaway Heat Output Variability

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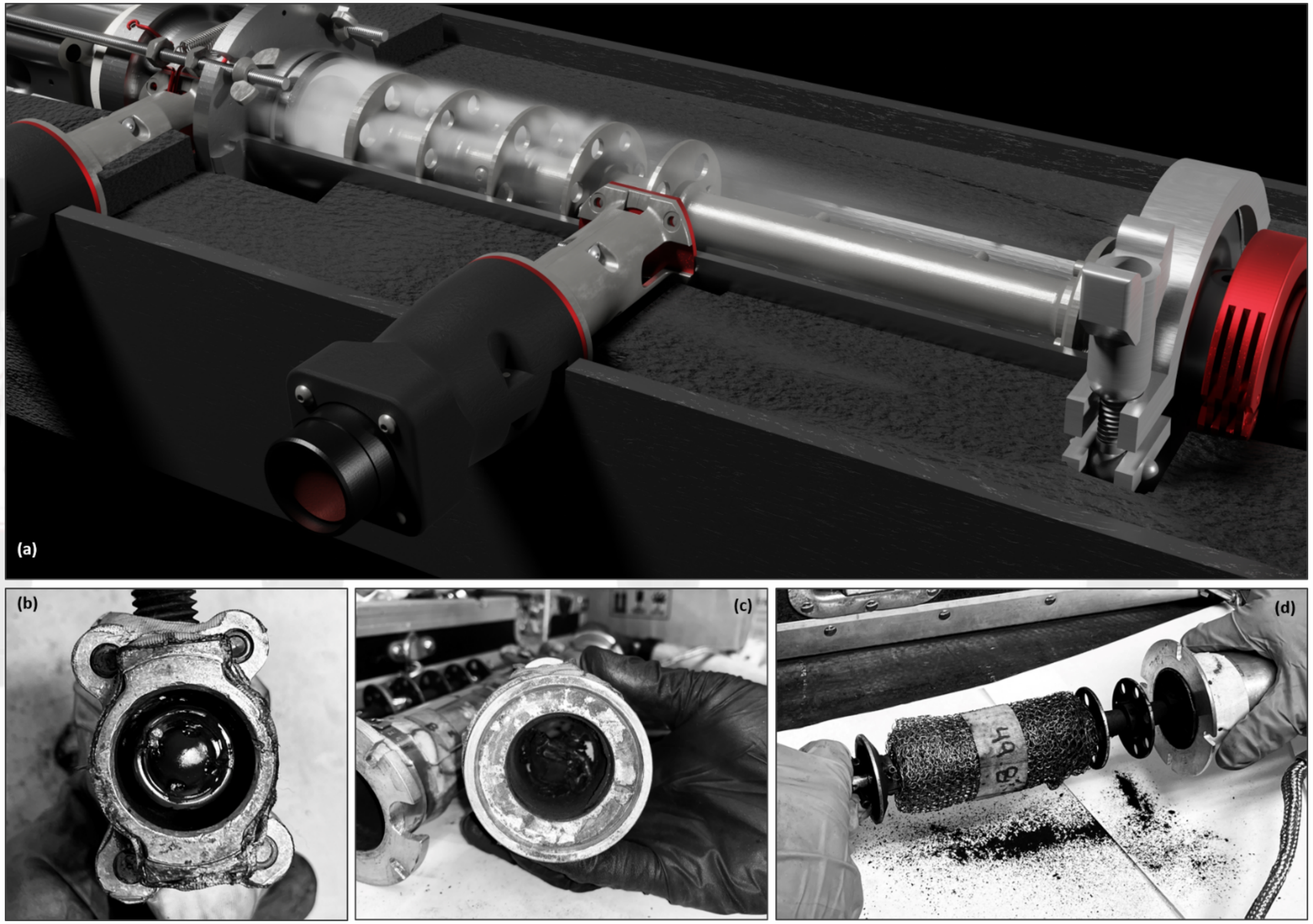
Lithium-ion (Li-ion) batteries are a popular energy storage solution utilized across industries for their high specific and volumetric energy density. With a range of formats and designs for both high power and high energy applications, Li-ion cells are versatile and configurable. Despite their widespread popularity, there are major safety concerns regarding their potential for hazardous thermal runaway events. The possibility of catastrophic failures necessitates safe battery design with robust thermal management systems. However, to achieve these goals often complex thermal modelling and extensive abuse testing campaigns are required to certify batteries for use in an application. There is a need to understand the impacts of trigger mechanism and cell format on thermal runaway heat output in order to improve testing capabilities and better inform thermal models. This study examines thermal runaway heat output for three different cell formats as a function of trigger mechanism. The cell formats considered are 18650, 21700, and D-cell. The trigger mechanisms considered are heaters, internal short circuiting device, and nail penetration. Specifically, the thermal runaway responses for the KULR 18650-K330, KULR 21700-K500, LG 21700-M50, and Saft D-Cell-VES16 are examined. All experiments are conducted inside a Fractional Thermal Runaway Calorimeter (FTRC). The FTRC data, which is stored in the Battery Failure Databank, is extracted and analyzed to provide a comparative analysis of thermal runaway heat output as a function of trigger mechanism and cell format based on the calculated total energy yield, fractional energy yield, heat rate, and heat flux. By analyzing the variability between experiments in these values, this study seeks to demonstrate relationships between thermal runaway heat output, cell format, and initiation method to aid in the development of future abuse tests and modeling methods.

1. Introduction

Lithium-ion (Li-ion) cell technology offers high specific and volumetric energy density storage solutions for various industry sectors [1]. With a range of formats and designs for both high power and high energy

short circuiting (e.g. internal and external), and electro-chemical abuse (e.g. overcharge and over-discharge) [2,11,13,14]. Cell-to-cell propagation is also a concern in instances when Li-ion cells are connected in series and parallel to form larger packs, modules, and assemblies. Cell-to-cell propagation refers to when the effects of one cell going into thermal



Images and text submitted to Journal of Power Sources, June 2021.

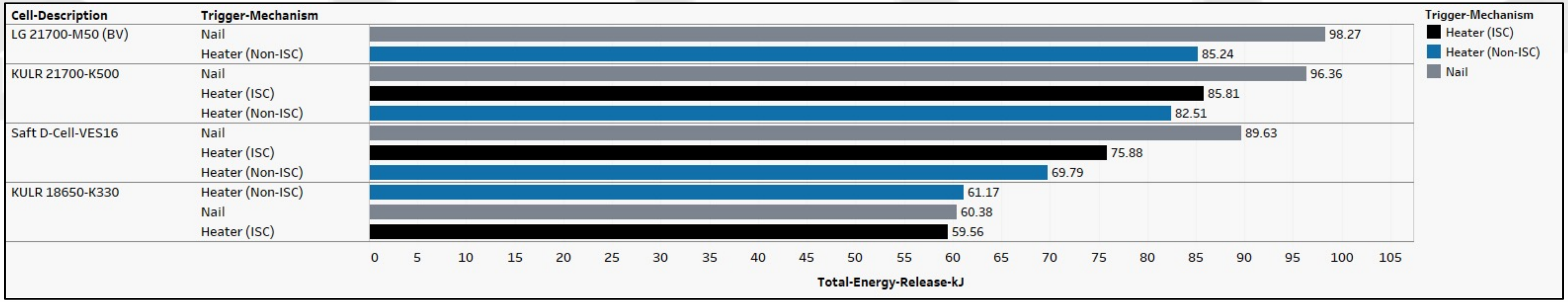
COMPARATIVE ANALYSIS STRATEGY

- **Using results from the Battery Failure Databank, a comparative analysis of thermal runaway heat output as a function of cell format and trigger mechanism is conducted.**
- **Comparisons are based on:**
  - Test to test total energy yield, average total energy yield, and probability density of total energy yield.
  - Average fractional energy yield.
  - Thermal runaway heat rate.
- **The cell and trigger mechanism combinations considered are described in the table below.**

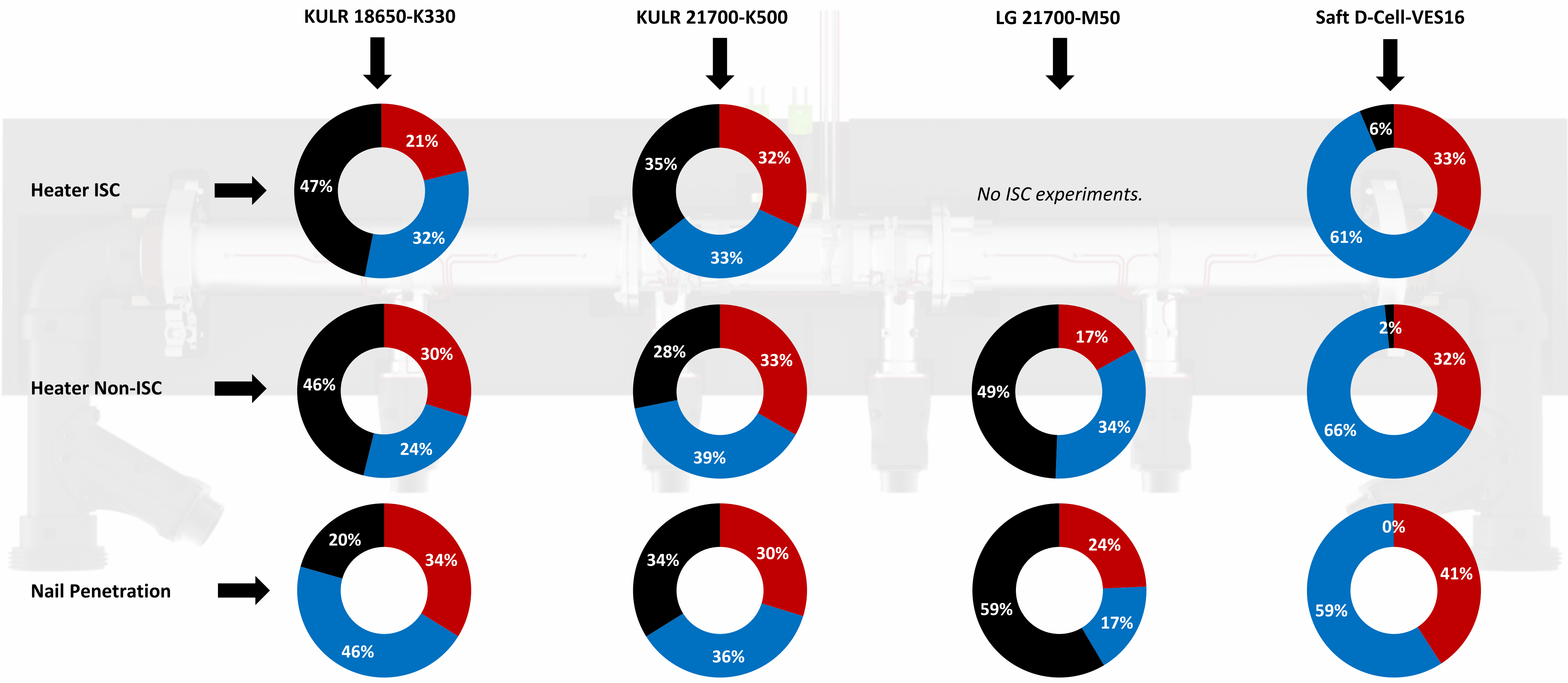
Cell Type	Capacity	Nominal Voltage	Stored Energy	Heater (ISC)	Heater (Non-ISC)	Nail Penetration
KULR 18650-K330	3.3 Ah	3.6 V	11.88 Wh	Yes	Yes	Yes
KULR 21700-K500	5.0 Ah	3.6 V	18.0 Wh	Yes	Yes	Yes
LG 21700-M50	5.01 Ah	3.63 V	18.2 Wh	No	Yes	Yes
Saft VES16-D-Cell	4.5 Ah	3.6 V	16.2 Wh	Yes	Yes	Yes

TOTAL ENERGY RELEASE COMPARISON

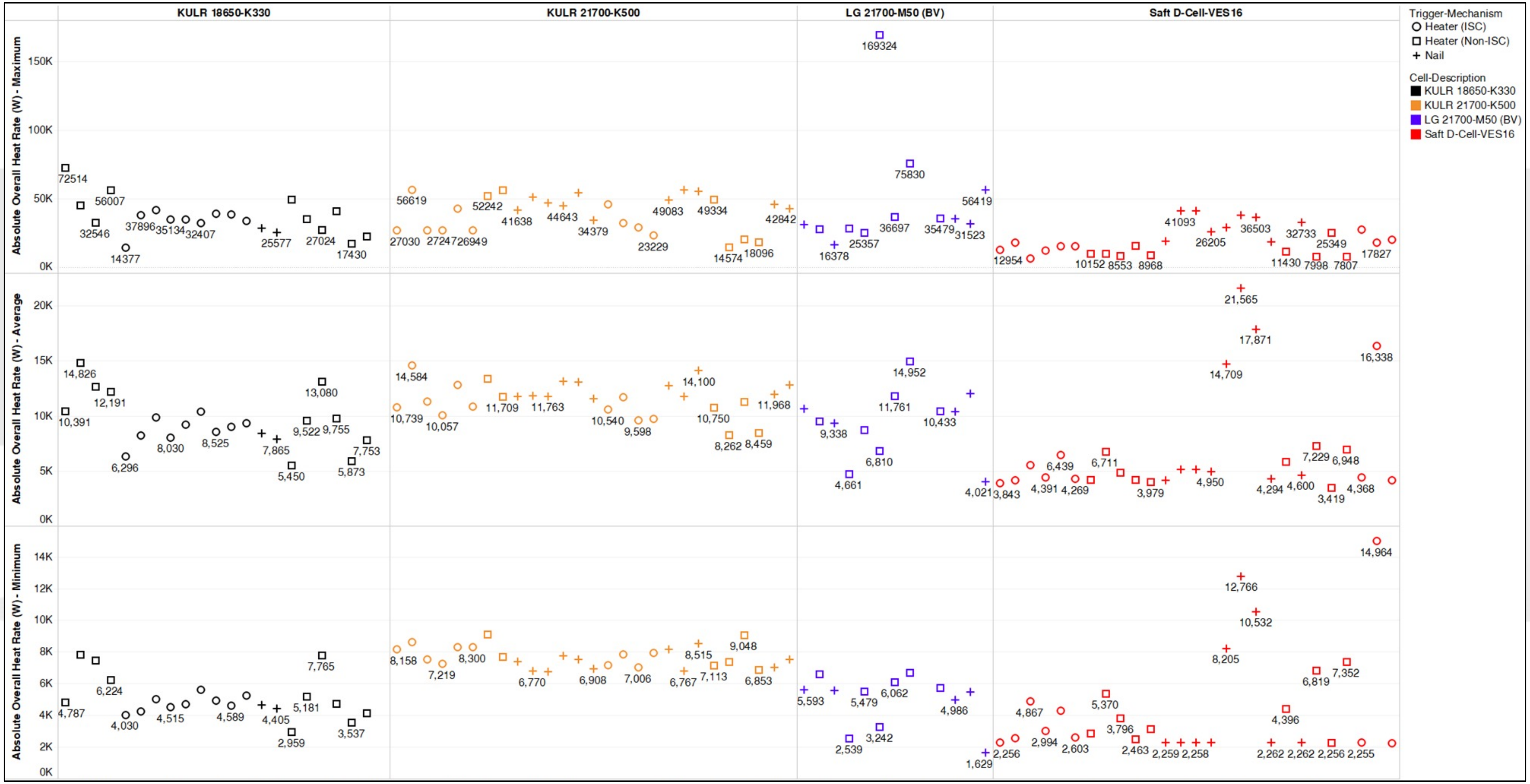
- **The KULR 18650-K330 had an average total energy release of 59.6 kJ for Heater ISC trigger, 61.2 kJ for Heater Non-ISC Trigger, and 60.4 kJ for Nail Penetration trigger.**
- **The KULR 21700-K500 had an average total energy release of 85.8 kJ for Heater ISC trigger, 82.5 kJ for Heater Non-ISC Trigger, and 96.4 kJ for Nail Penetration trigger.**
- **The LG 21700-M50 had an average total energy release of 85.2 kJ for Heater Non-ISC trigger and 98.3 kJ for Nail Penetration trigger.**
- **The Saft D-Cell-VES16 had an average total energy release of 75.9 kJ for Heater ISC trigger, 69.8 kJ for Heater Non-ISC Trigger, and 89.63 kJ for Nail Penetration trigger.**



FRACTIONAL ENERGY RELEASE COMPARISON



THERMAL RUNAWAY HEAT RATE COMPARISON



INFORMING MODELS

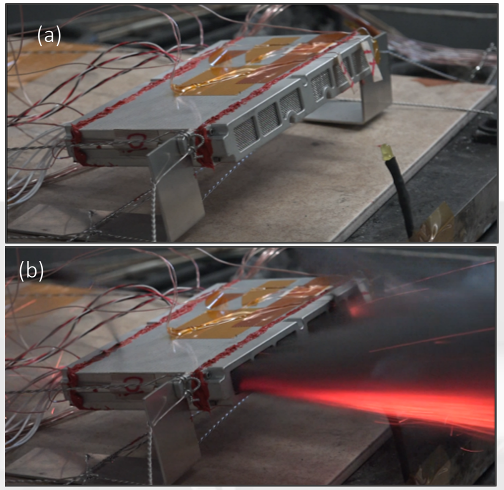
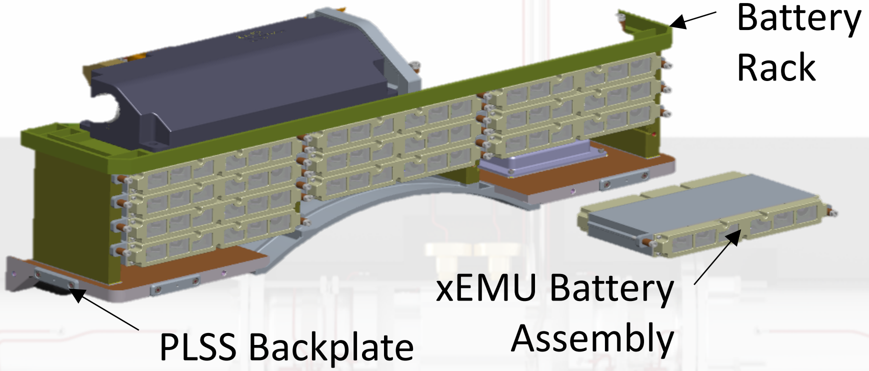
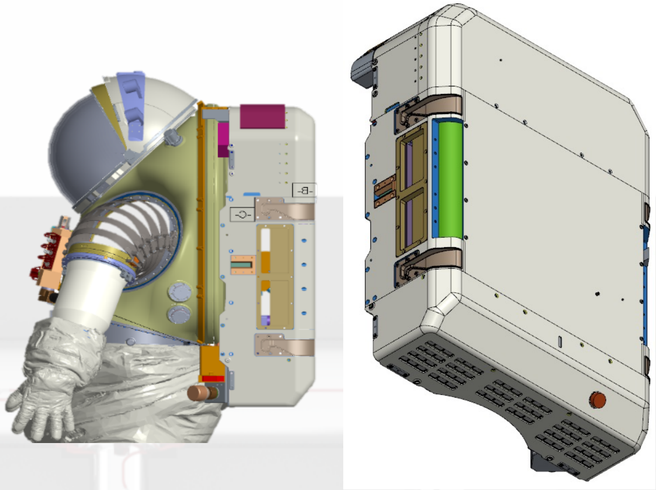
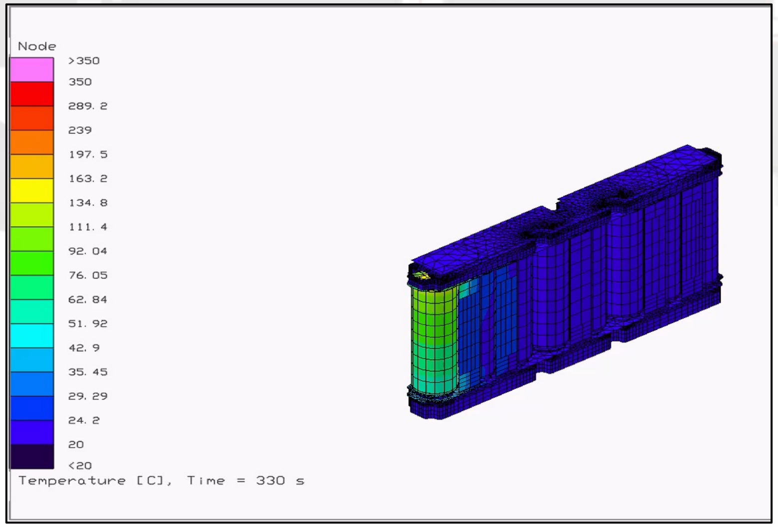
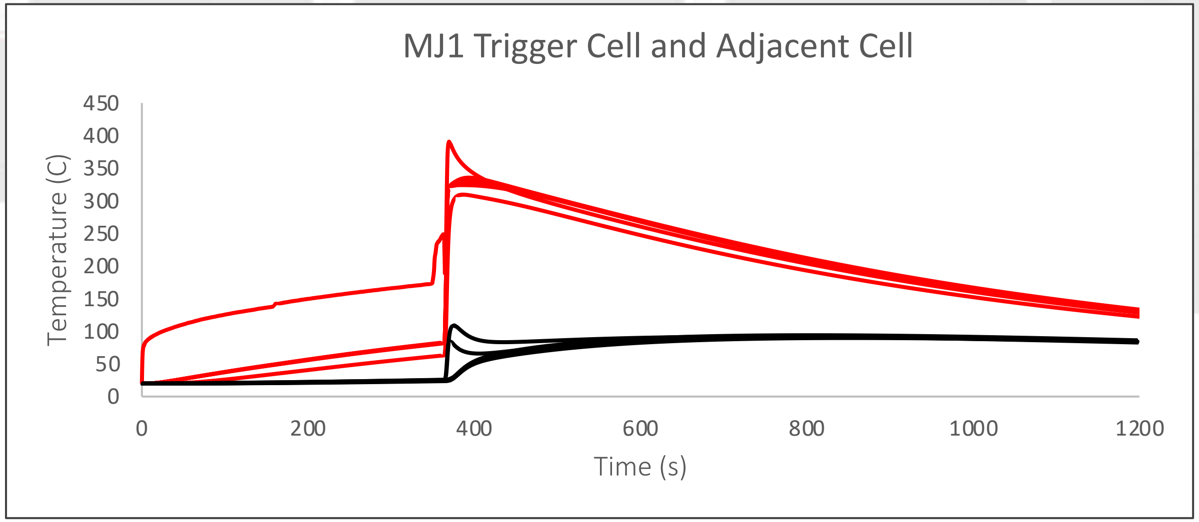


Image Credit: S. Russell









CONCLUSIONS

- **Severity and variability of thermal runaway depends largely on the following:**
  - Cell format and capacity.
  - Cell chemistry.
  - Cell mechanical design features; venting mechanism, casing thickness, mandrel, et…
  - State-of-charge at trigger.
  - Triggering mechanism.
  - The Battery Failure Databank provides ability to understand the influences of these factors in a format that can serve as direct input into thermal modeling activities.

- **Key Takeaway: One must be cognizant of the variability in thermal runaway response that is driven by the aforementioned factors when:**
  - **Designing lithium-ion battery assemblies.**
  - **Performing thermal modeling activities representative of thermal runaway events.**

QUESTIONS?

BACK-UP

CALORIMETRIC TECHNIQUES

- **Accelerating Rate Calorimetry (ARC) [2]:**
  - Cells are heated slowly with the heat, wait, seek method.
  - Used to determine the onset of material decomposition (onset temperature), trigger temperature, cell body heating rates, and total energy release.
  - Slow heating technique can result in early venting of the electrolyte and may not be directly representative of field failure events; each experiment can take up to 1-3 days.
- **Bomb Calorimetry and ARC-Bomb Calorimetry [2]:**
  - Sample is placed in closed steel canister and triggered into thermal runaway.
  - Adequate for tallying total heat output and for capturing ejected solids, liquids, and gases (and subsequently the heat contained in the ejected components).
  - Can be combined with ARC testing for improved thermal performance; however, in this case would have the same limitations as standard ARC testing.

[2] *Walker et. al., "Future Lithium-ion Batteries, Chapter 12 Lithium-ion Battery Safety", Royal Society of Chemistry, Eftekhari, 2019.*

CALORIMETRIC TECHNIQUES

- **Copper Slug Calorimetry (CSC) [2]:**
  - The Li-ion cell is placed inside an insulated copper slug and triggered into thermal runaway.
  - Effective at measuring heat output through cell casing but does not measure heat liberated in the ejecta.
  - Can be used to estimate the rate of mass ejection during thermal runaway.
  - Must be used in conjunction with bomb calorimetry to tally ejected heat.
- **Cone Calorimetry [2]:**
  - Sample is placed under a conic apparatus designed to heat the sample via radiation.
  - Anything ejected from the cell is funneled through the cone and into an exhaust segment where gas samples are collected and analyzed.
  - This test is primarily used to analyze the burning behavior during a thermal runaway event and the heat that is generated due to the burning (i.e. analysis of combustion effects).

[2] *Walker et. al., "Future Lithium-ion Batteries, Chapter 12 Lithium-ion Battery Safety", Royal Society of Chemistry, Eftekhari, 2019.*