COMPARATIVE ANALYSIS OF THERMAL RUNAWAY HEAT OUTPUT AS A FUNCTION OF TRIGGER MECHANISM AND CELL FORMAT

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NASA AEROSPACE BATTERY WORKSHOP
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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.

Focus area for today.

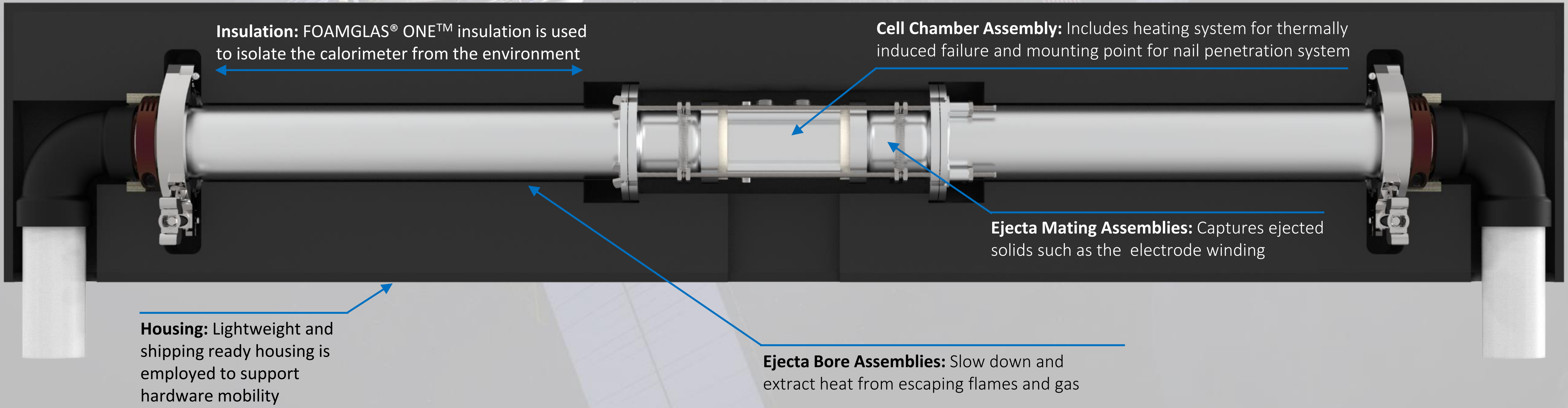
[1] *Crewed Space Vehicle Battery Safety Requirements. JSC-20793 Rev D. JSC Engineering Directorate, Power and Propulsion Division*

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.**

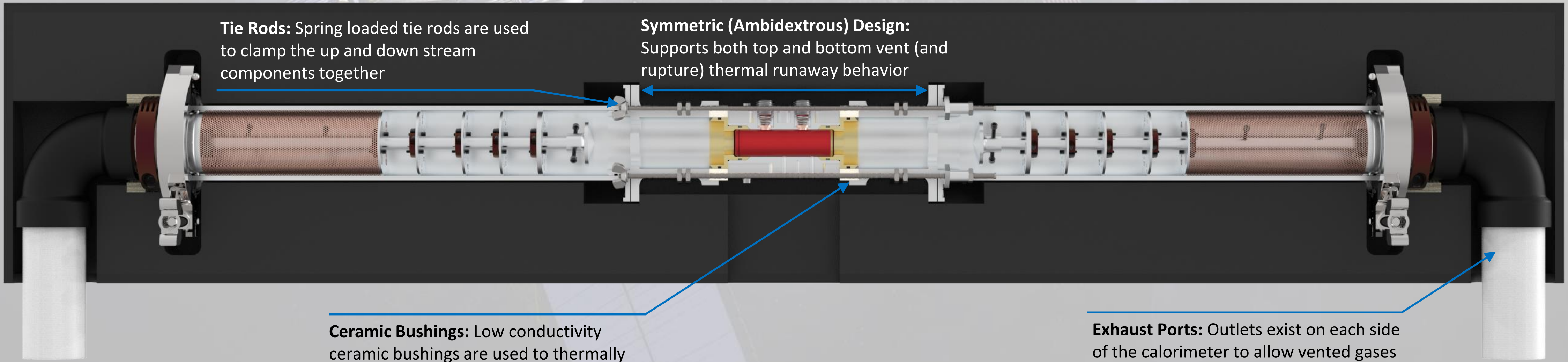
FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **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.



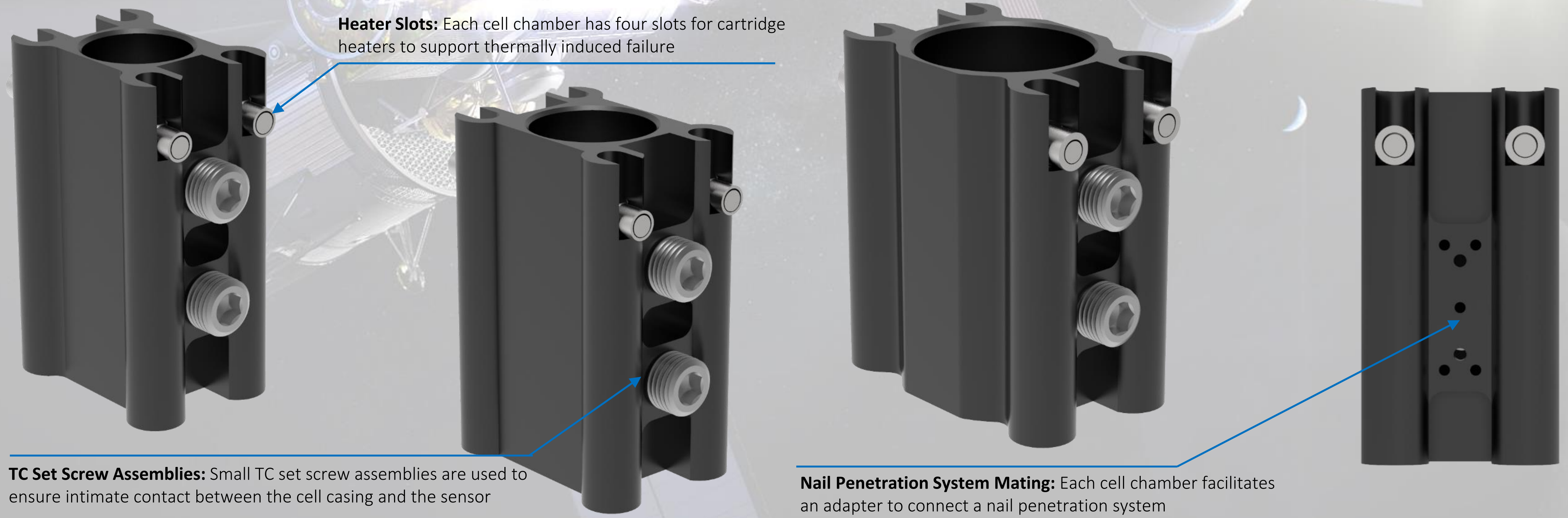
FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **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.



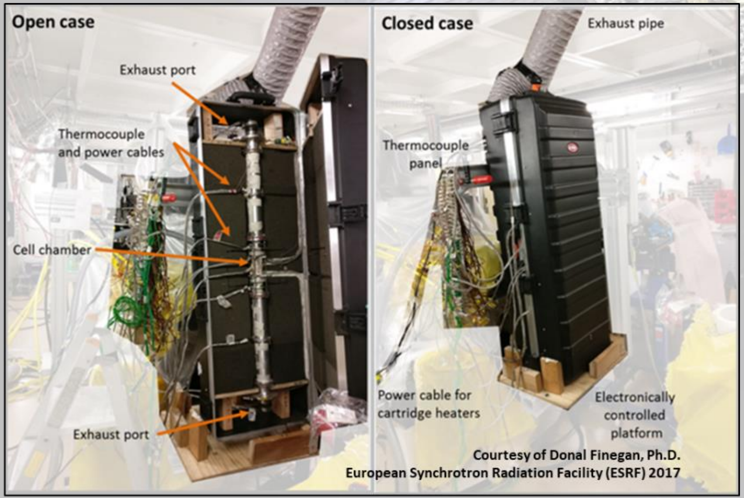
FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **The FTRC is compatible with 18650 format cells, 21700 format cells, D-cell format cells, and pouch cells (more on this capability soon):**
  - Utilizes the same upstream/downstream ejecta mating, ejecta bore, and rod and baffle assemblies (i.e. the only adjustment to test a new cell is to swap out the cell chamber).
  - The current architecture supports cells with up to 5 Ah capacities.



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

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

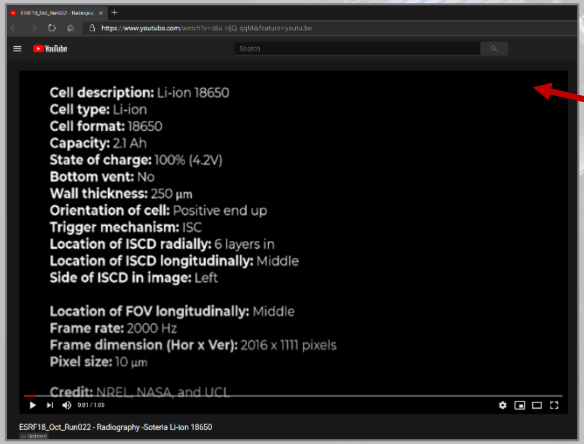
Location of FOV longitudinally: Top
Frame rate: 2000 Hz
Frame dimension (Hor x Ver): 1280 x 800 pixels
Pixel size: 17.8 µm

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.

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 databank will become publicly available **by the end of 2020.**



Hyperlink

Additional Entry Fields

	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

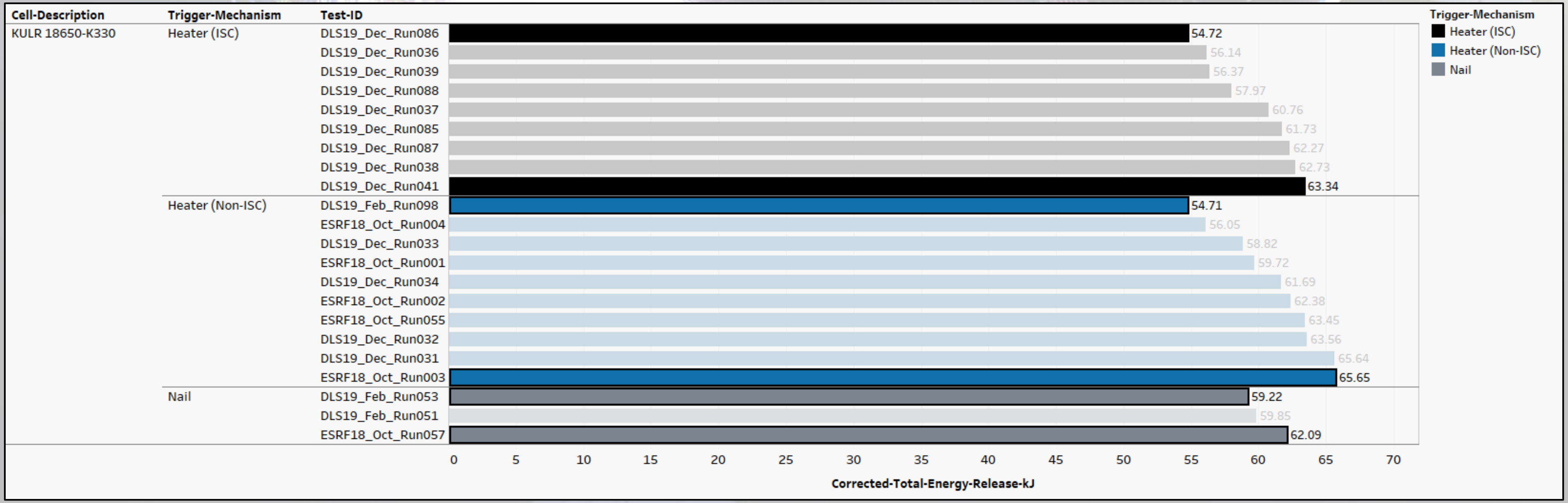
COMPARATIVE ANALYSIS STRATEGY

- **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

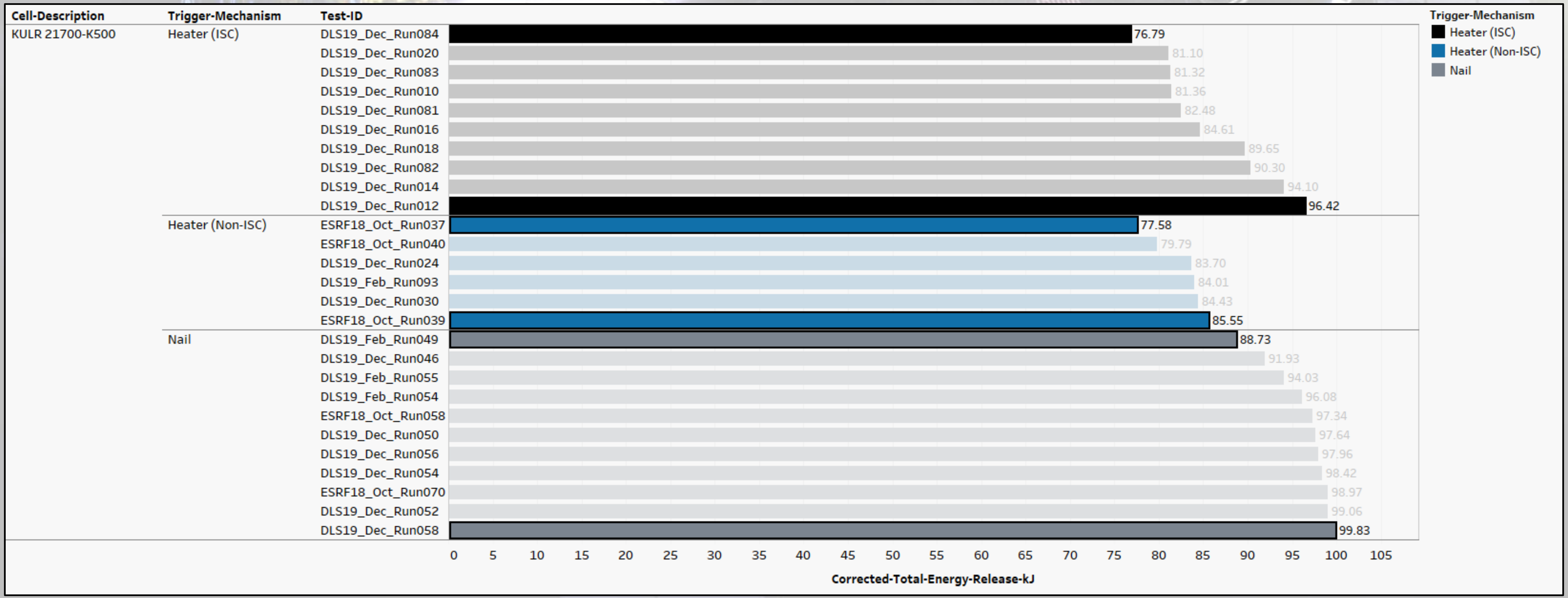
KULR 18650-K330 TOTAL ENERGY RELEASE

- **For the KULR 18650-K330:**
  - 9 runs using **Heater (ISC)** trigger with a total energy yield ranging from 54.7 kJ to 63.3 kJ.
  - 10 runs using the **Heater (Non-ISC)** trigger with a total energy yield ranging from 54.7 kJ to 65.7 kJ.
  - 3 runs using **Nail Penetration** trigger with a total energy yield ranging from 59.2 kJ to 62.1 kJ.



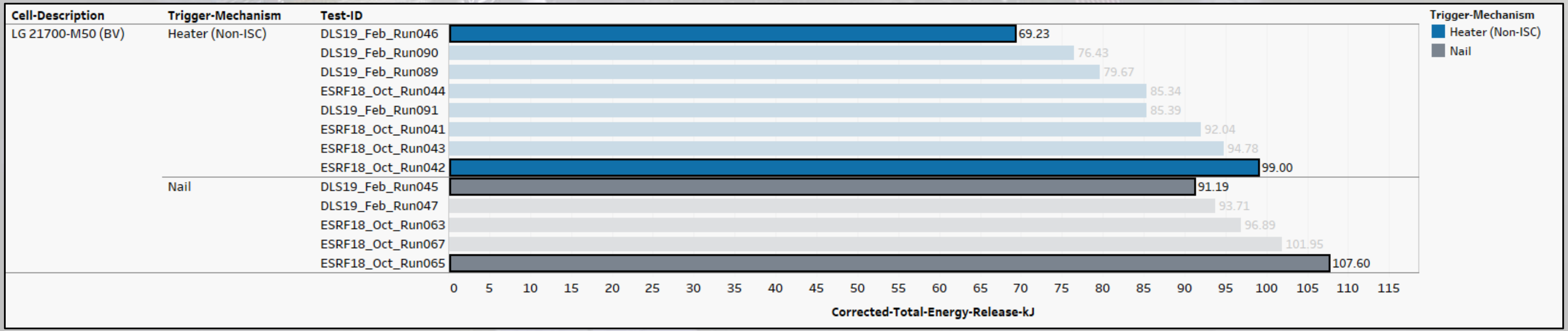
KULR 21700-K500 TOTAL ENERGY RELEASE

- **For the KULR 21700-K500:**
  - 10 runs using **Heater (ISC)** trigger with a total energy yield ranging from 76.8 kJ to 96.4 kJ.
  - 6 runs using the **Heater (Non-ISC)** trigger with a total energy yield ranging from 77.6 kJ to 85.6 kJ.
  - 11 runs using **Nail Penetration** trigger with a total energy yield ranging from 88.7 kJ to 99.8 kJ.



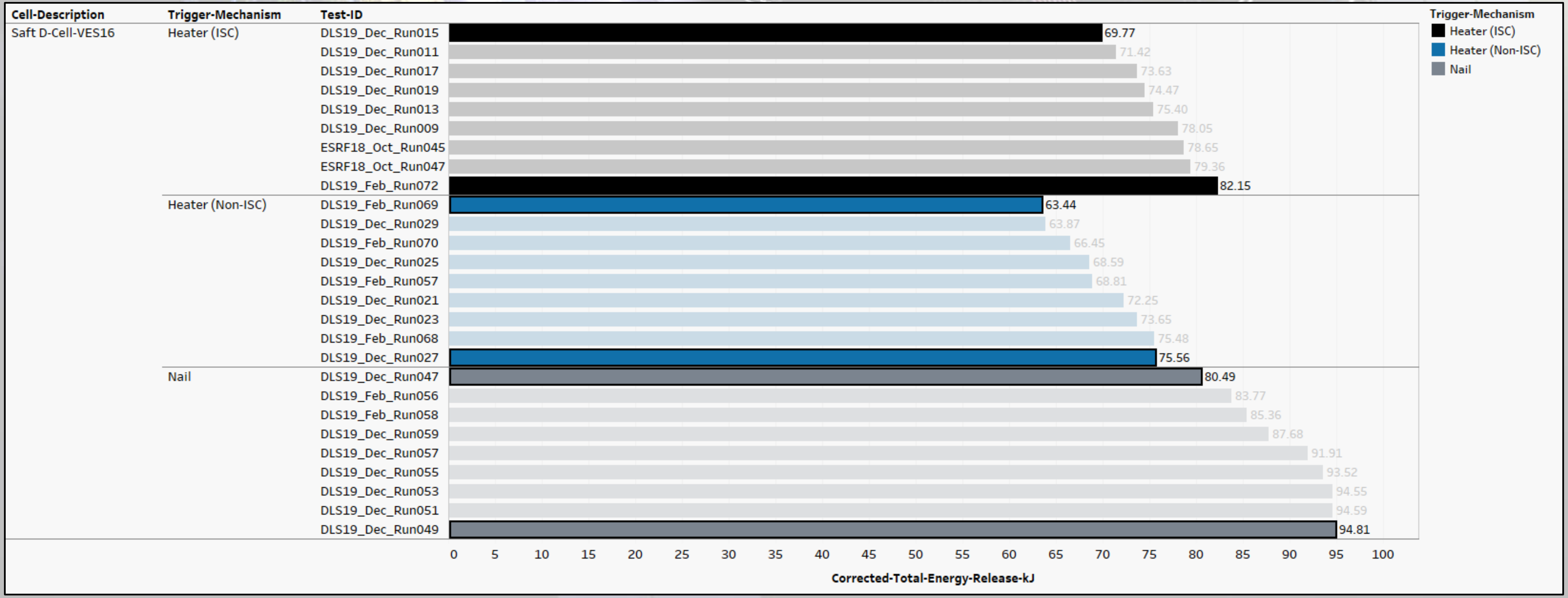
LG 21700-M50 TOTAL ENERGY RELEASE

- **For the LG 21700-M50:**
  - 0 runs using **Heater (ISC)** trigger.
  - 7 runs using the **Heater (Non-ISC)** trigger with a total energy yield ranging from 69.2 kJ to 99.0 kJ.
  - 5 runs using **Nail Penetration** trigger with a total energy yield ranging from 91.2 kJ to 107.6 kJ.



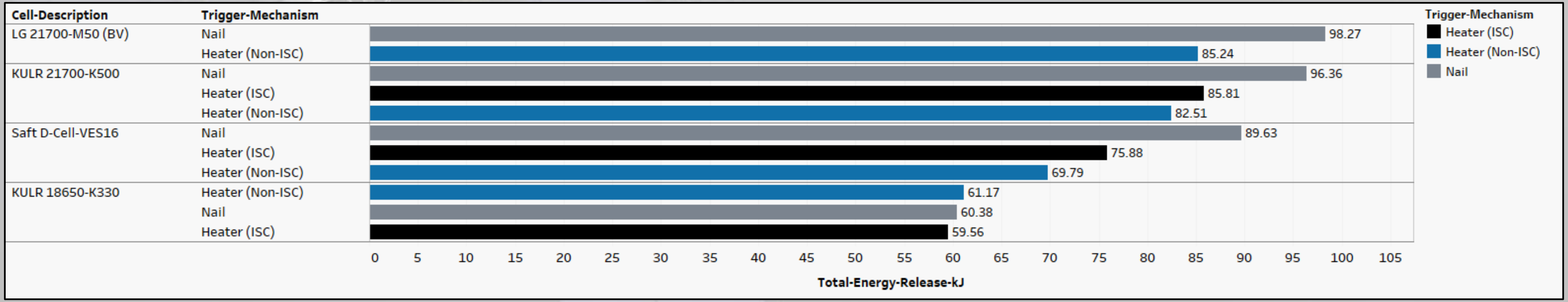
SAFT D-CELL-VES16 TOTAL ENERGY RELEASE

- **For the Saft D-Cell-VES16:**
  - 9 runs using **Heater (ISC)** trigger with a total energy yield ranging from 69.8 kJ to 82.2 kJ.
  - 9 runs using the **Heater (Non-ISC)** trigger with a total energy yield ranging from 63.4 kJ to 75.6 kJ.
  - 9 runs using **Nail Penetration** trigger with a total energy yield ranging from 80.5 kJ to 94.8 kJ.



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.**

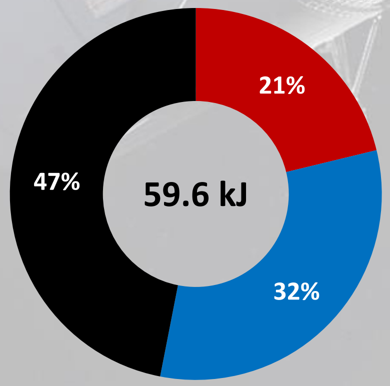


KULR 18650-K330 FRACTIONAL ENERGY RELEASE

- **For the KULR 18650-K330:**
  - The average fractional energy release for **Heater ISC** trigger was 21% through the cell body, 32% through the positive ejecta and gases, and 47% through the negative ejecta and gases.
  - The average fractional energy release for **Heater Non-ISC** trigger was 30% through the cell body, 24% through the positive side ejecta and gases, and 46% through the negative side ejecta and gases.
  - The average fractional energy release for **Nail Penetration** trigger was 34% through the cell body, 46% through the positive ejecta and gases, and 20% through the negative ejecta and gases.

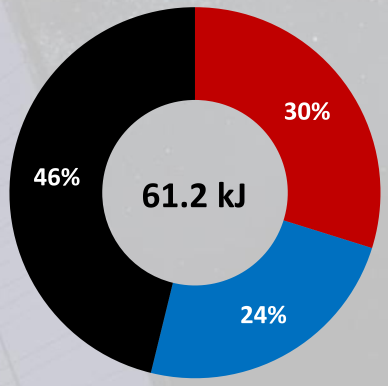
Heater ISC

Cell Body · Positive (+) Ejecta and Gases · Negative (-) Ejecta and Gases



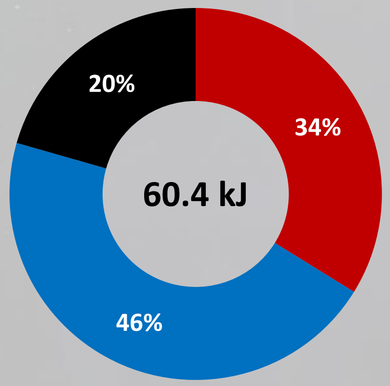
Heater Non-ISC

Cell Body · Positive (+) Ejecta and Gases · Negative (-) Ejecta and Gases



Nail Penetration

Cell Body · Positive (+) Ejecta and Gases · Negative (-) Ejecta and Gases

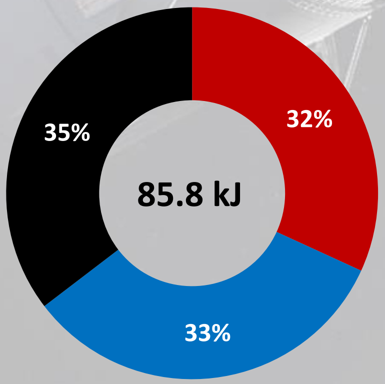


KULR 21700-K500 FRACTIONAL ENERGY RELEASE

- **For the KULR 21700-K500:**
  - The average fractional energy release for **Heater ISC** trigger was 32% through the cell body, 33% through the positive ejecta and gases, and 35% through the negative ejecta and gases.
  - The average fractional energy release for **Heater Non-ISC** trigger was 33% through the cell body, 39% through the positive side ejecta and gases, and 28% through the negative side ejecta and gases.
  - The average fractional energy release for **Nail Penetration** trigger was 30% through the cell body, 36% through the positive ejecta and gases, and 34% through the negative ejecta and gases.

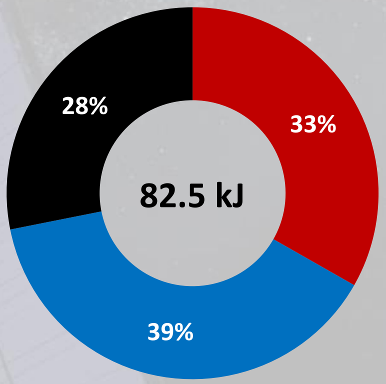
Heater ISC

Cell Body · Positive (+) Ejecta and Gases · Negative (-) Ejecta and Gases



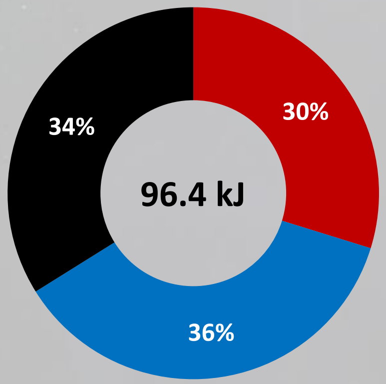
Heater Non-ISC

Cell Body · Positive (+) Ejecta and Gases · Negative (-) Ejecta and Gases



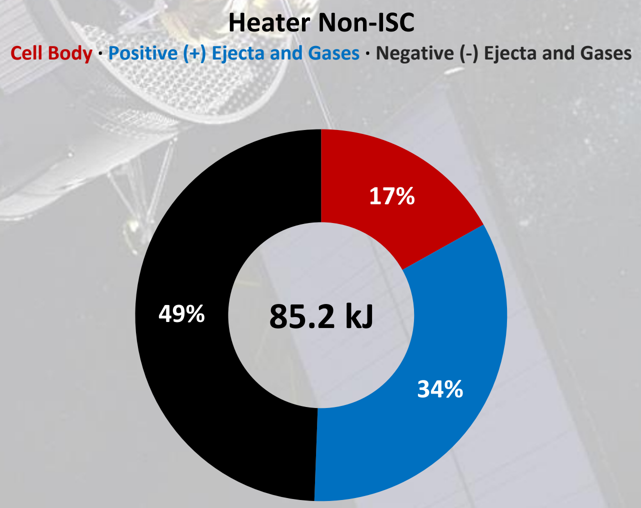
Nail Penetration

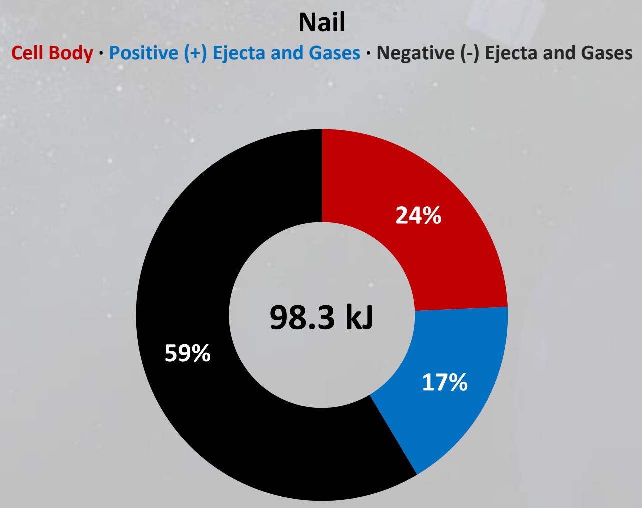
Cell Body · Positive (+) Ejecta and Gases · Negative (-) Ejecta and Gases



LG 21700-M50 FRACTIONAL ENERGY RELEASE

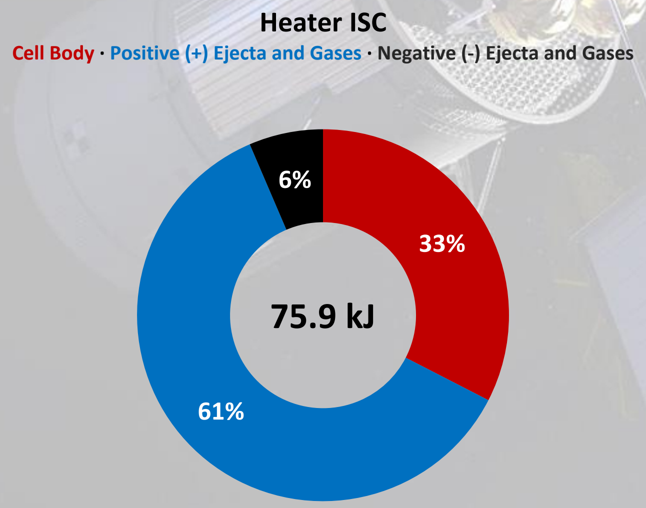
- **For the LG 21700-M50:**
  - There were 0 **Heater ISC** trigger experiments.
  - The average fractional energy release for **Heater Non-ISC** trigger was 17% through the cell body, 34% through the positive side ejecta and gases, and 49% through the negative side ejecta and gases.
  - The average fractional energy release for **Nail Penetration** trigger was 24% through the cell body, 17% through the positive ejecta and gases, and 59% through the negative ejecta and gases.

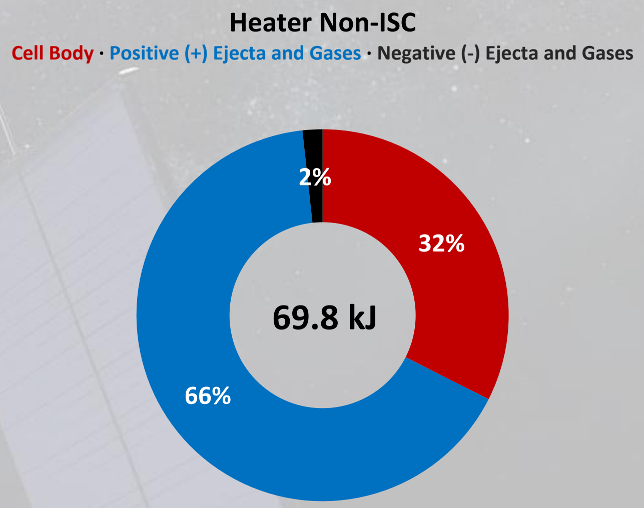


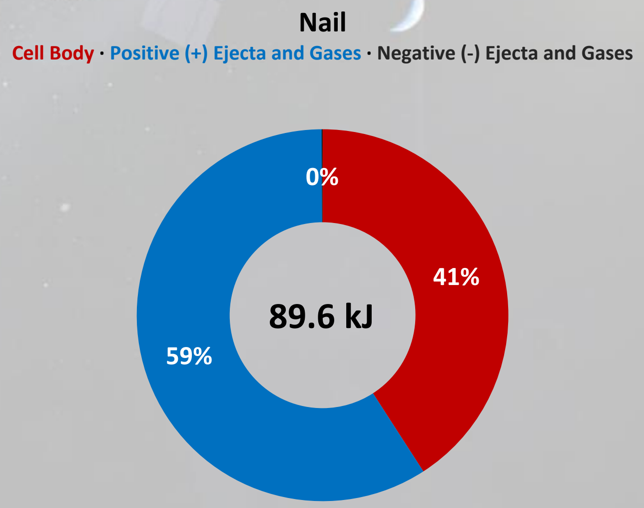


SAFT D-CEL-VES16 FRACTIONAL ENERGY RELEASE

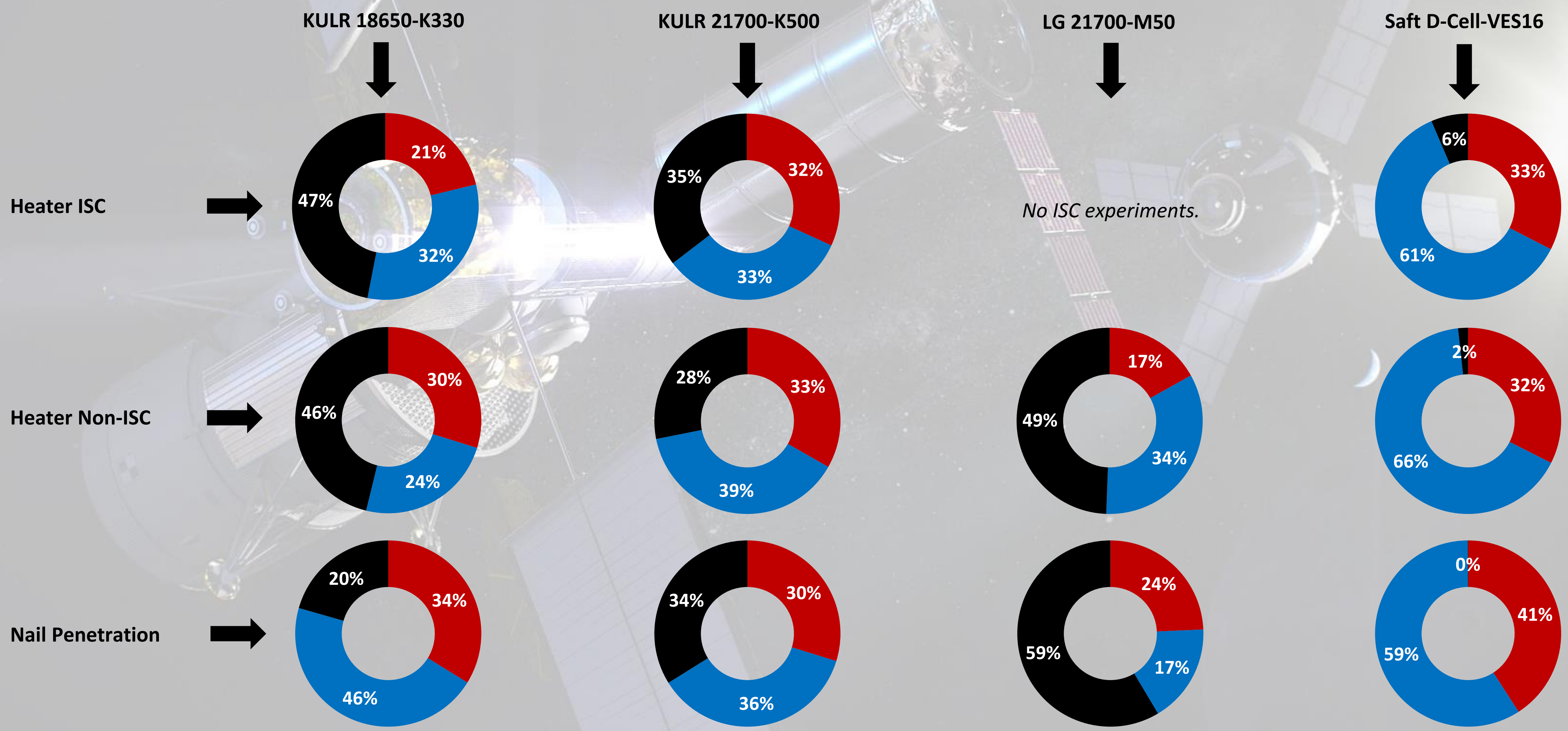
- **For the SAFT D-Cell-VES16:**
  - The average fractional energy release for **Heater ISC** trigger was 33% through the cell body, 61% through the positive ejecta and gases, and 6% through the negative ejecta and gases.
  - The average fractional energy release for **Heater Non-ISC** trigger was 32% through the cell body, 66% through the positive side ejecta and gases, and 2% through the negative side ejecta and gases.
  - The average fractional energy release for **Nail Penetration** trigger was 41% through the cell body, 59% through the positive ejecta and gases, and 0% through the negative ejecta and gases.







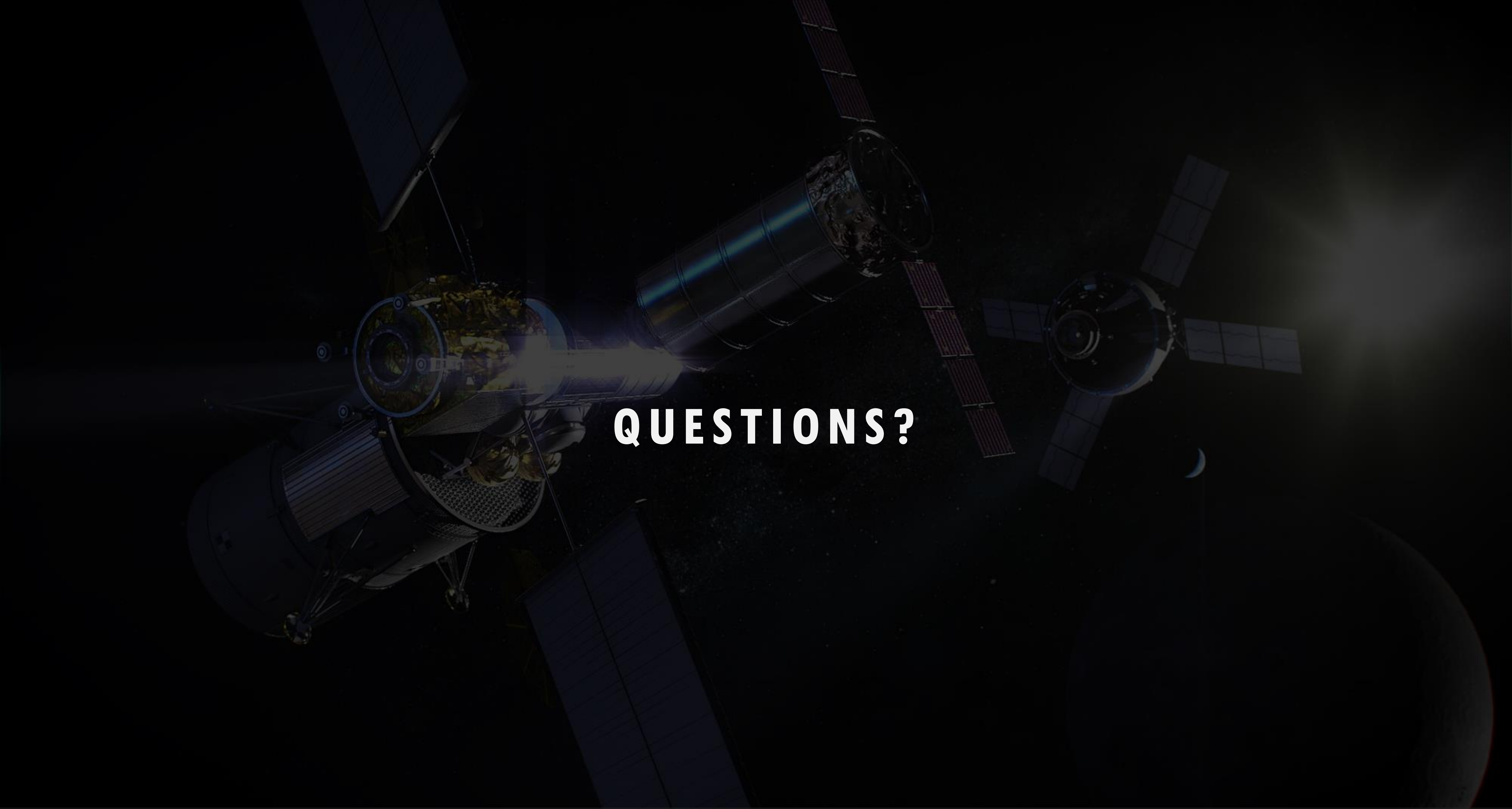
FRACTIONAL ENERGY RELEASE COMPARISON



THERMAL RUNAWAY HEAT RATE COMPARISON

CONCLUSIONS

- **FTRC results as recorded in the Battery Failure Databank were used to facilitate a comparative analysis of thermal runaway heat output as a function of trigger mechanism and cell format:**
  - KULR 18650-K330
  - KULR 21700-K500
  - LG 21700-M50
  - Saft D-Cell-VES16
- **The larger format cells considered in this study appeared to have higher heat output in response to nail penetration trigger vs. heater trigger when compared to the KULR 18650-K330.**
  - Currently exploring whether or not this stands true with other cells that are recorded in the databank.
  - Nail penetration trigger tended to result in the highest fraction of energy released through the cell body when compared to the heater based trigger mechanism.
- **Additional studies are being conducted to compare the measured heat output with the distribution of the ejected content and also with insights found in the corresponding radiographic videos.**



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.*