BATTERY FAILURE DATABANK

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NASA AEROSPACE BATTERY WORKSHOP
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- Designing Safe Batteries
- Fractional Thermal Runaway Calorimetry
- Battery Failure Databank
- Mass and Energy Trends from the Fractional Calorimeter
- Trends Produced by Internal Behaviors seen in the Radiography Data

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.

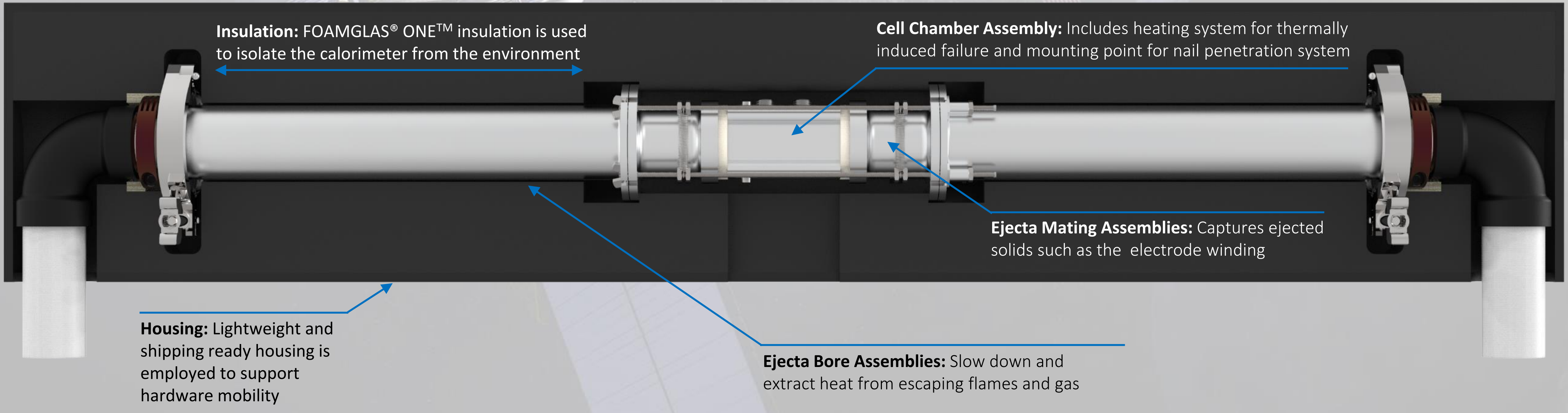
[1] *Crewed Space Vehicle Battery Safety Requirements. JSC-20793 Rev D. JSC Engineering Directorate, Power and Propulsion Division*

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.**

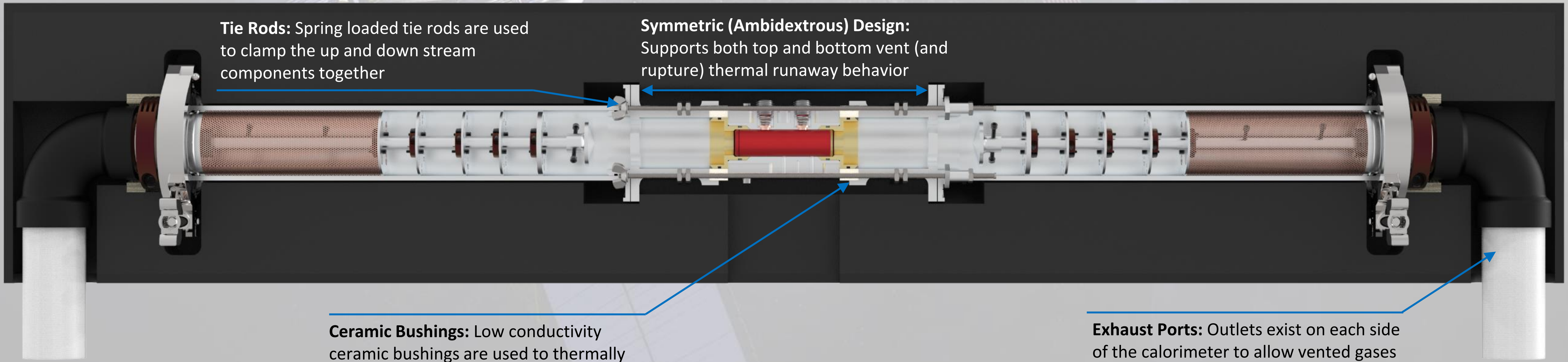
FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **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.



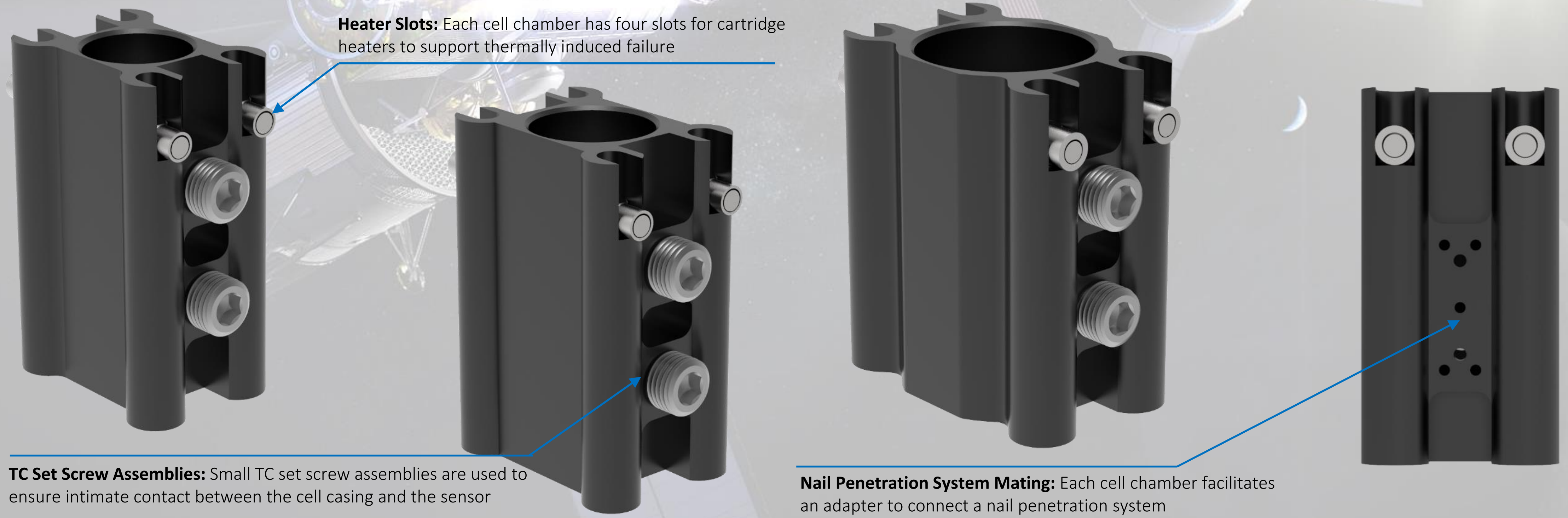
FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **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.



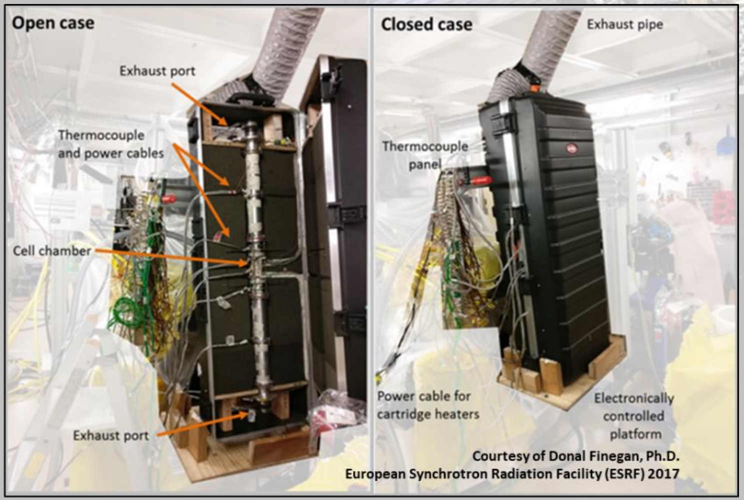
FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **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

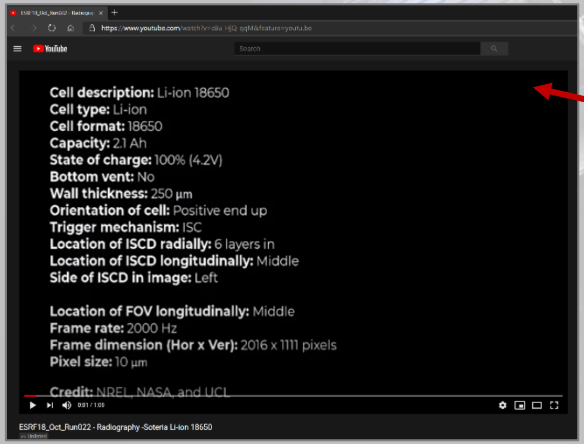
Location of FOV longitudinally: Top
Frame rate: 2000 Hz
Frame dimension (Hor x Ver): 1280 x 800 pixels
Pixel size: 17.8 µm

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.

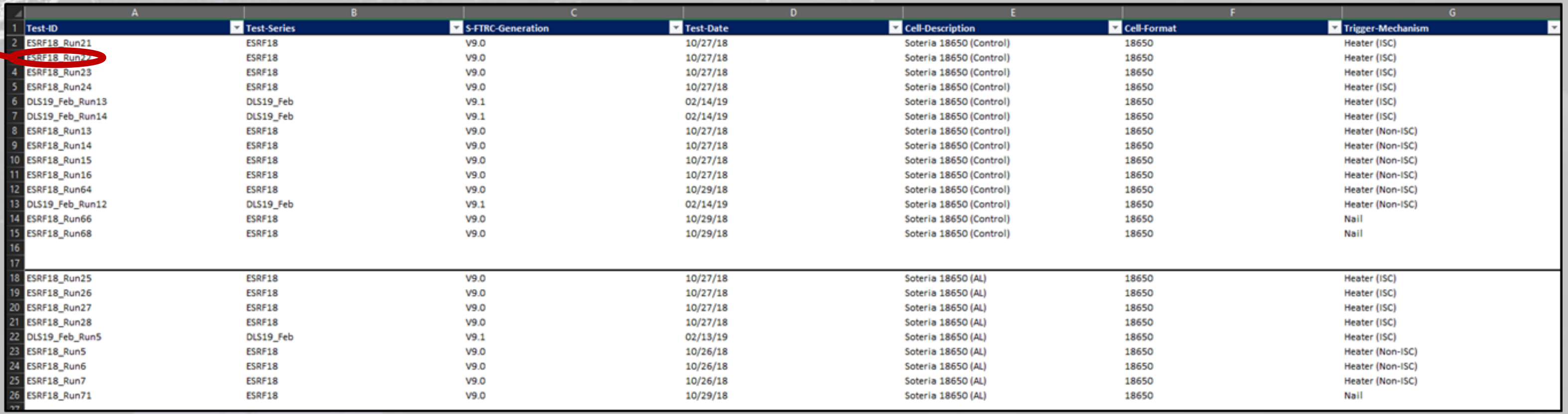
BATTERY FAILURE DATABANK

- **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

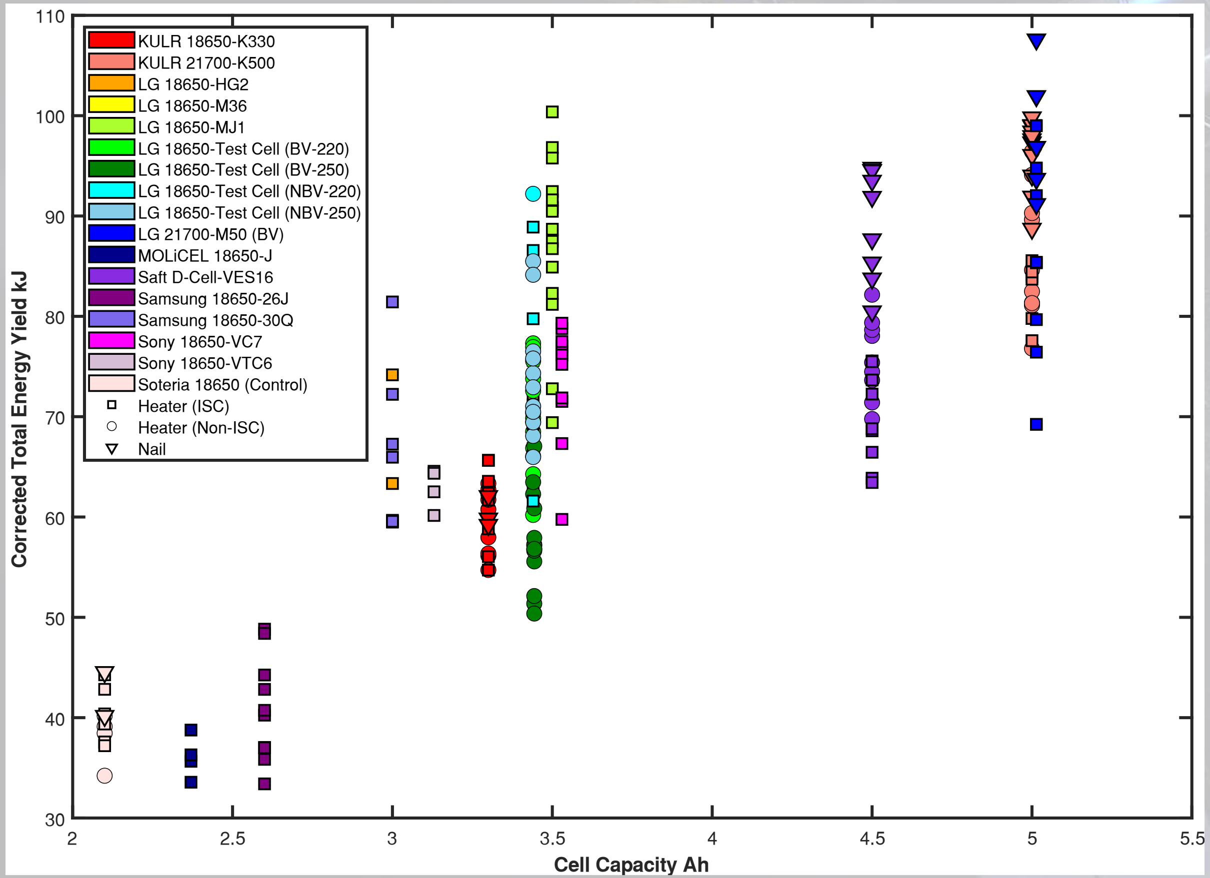
BATTERY FAILURE DATABANK

Cell-Description

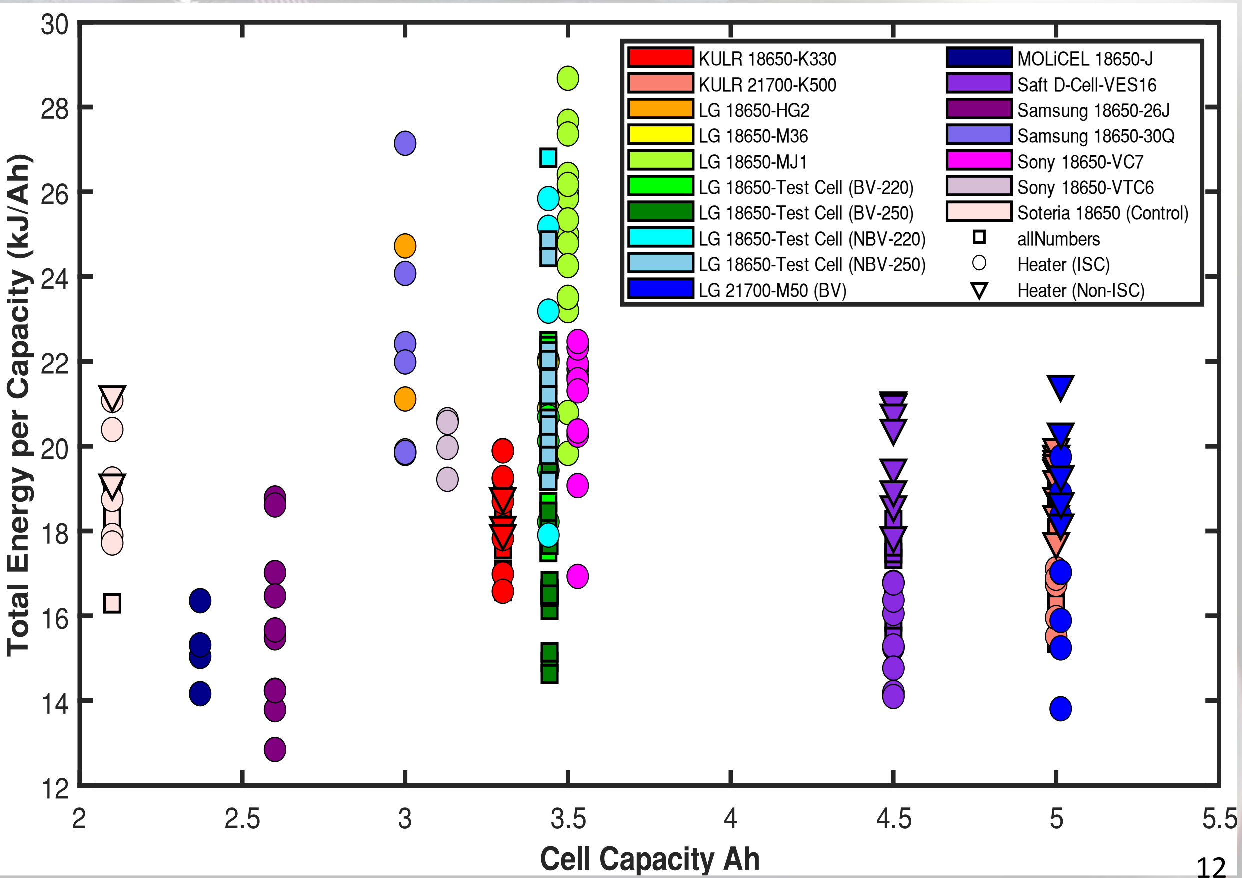
- [x] (All)
- [x] KULR 18650-K330
- [x] KULR 21700-K500
- [x] LG 18650-HG2
- [x] LG 18650-M36
- [x] LG 18650-MJ1 (Korean)
- [x] LG 18650-Test Cell (BV-220)
- [x] LG 18650-Test Cell (BV-250)
- [x] LG 18650-Test Cell (NBV-220)
- [x] LG 18650-Test Cell (NBV-250)
- [x] LG 21700-M50 (BV)
- [x] MOLiCEL 18650-J
- [x] MOLiCEL 18650-Test Cell
- [x] MOLiCEL 18650-Test Cell (DW-Gold)
- [x] MOLiCEL 18650-Test Cell (DW-Silver)
- [x] Saft D-Cell-VES16
- [x] Samsung 18650-26J
- [x] Samsung 18650-30Q
- [x] Sony 18650-VC7
- [x] Sony 18650-VTC6
- [x] Soteria 18650 (AL)
- [x] Soteria 18650 (ALCU)
- [x] Soteria 18650 (ALCUDW)
- [x] Soteria 18650 (ALDW)
- [x] Soteria 18650 (Control)
- [x] Soteria 18650 (CU)
- [x] Soteria 18650 (DW)

ENERGY YIELD AND CELL CAPACITY

- Global Positive trend

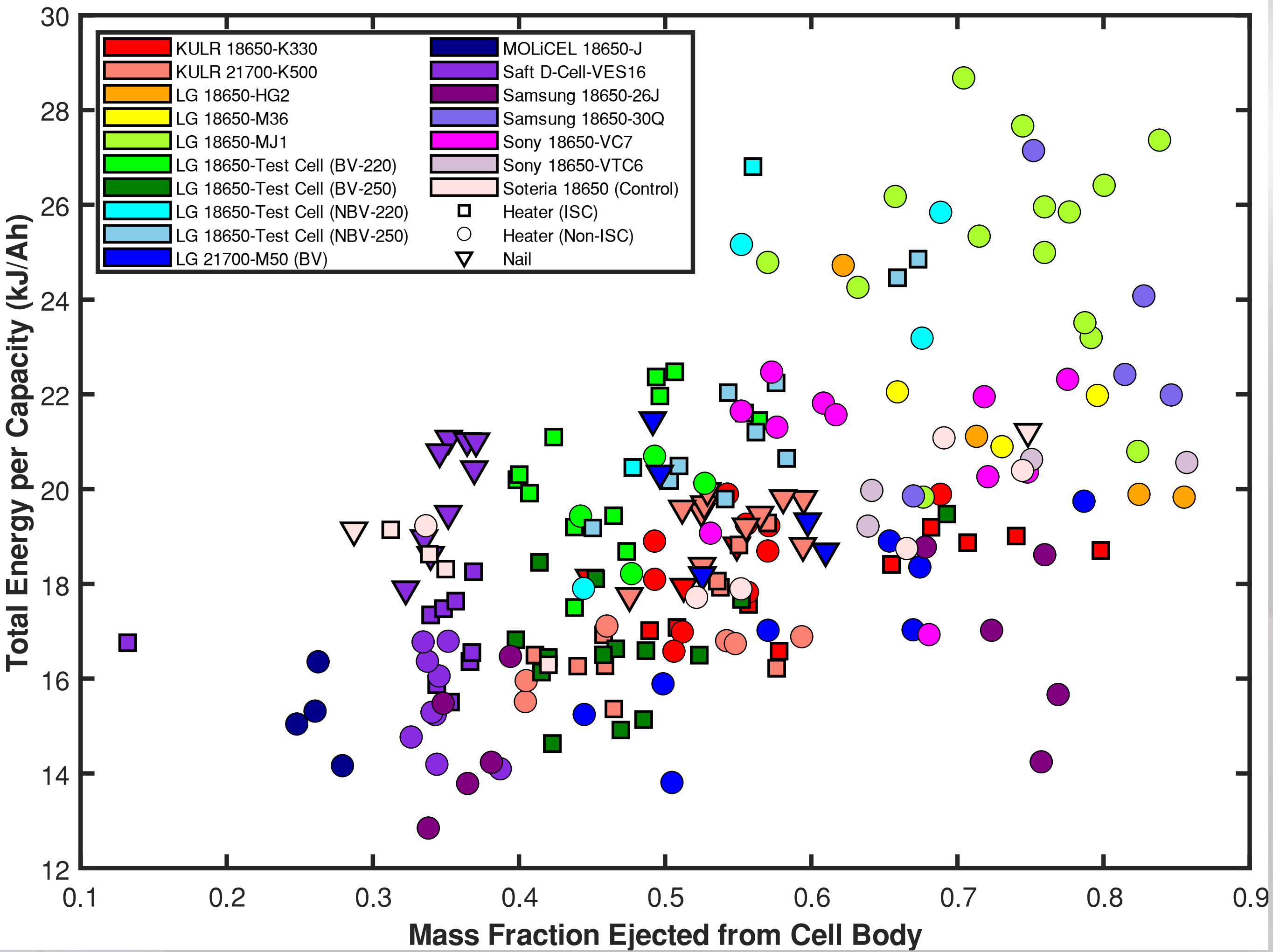


- Mostly 12-24 kJ/Ah



ENERGY YIELD AND MASS FRACTION EJECTED

- Based on mass of cell body after TR
- Global Positive trend across cell types
    - Due to cells with high and low mass ejections



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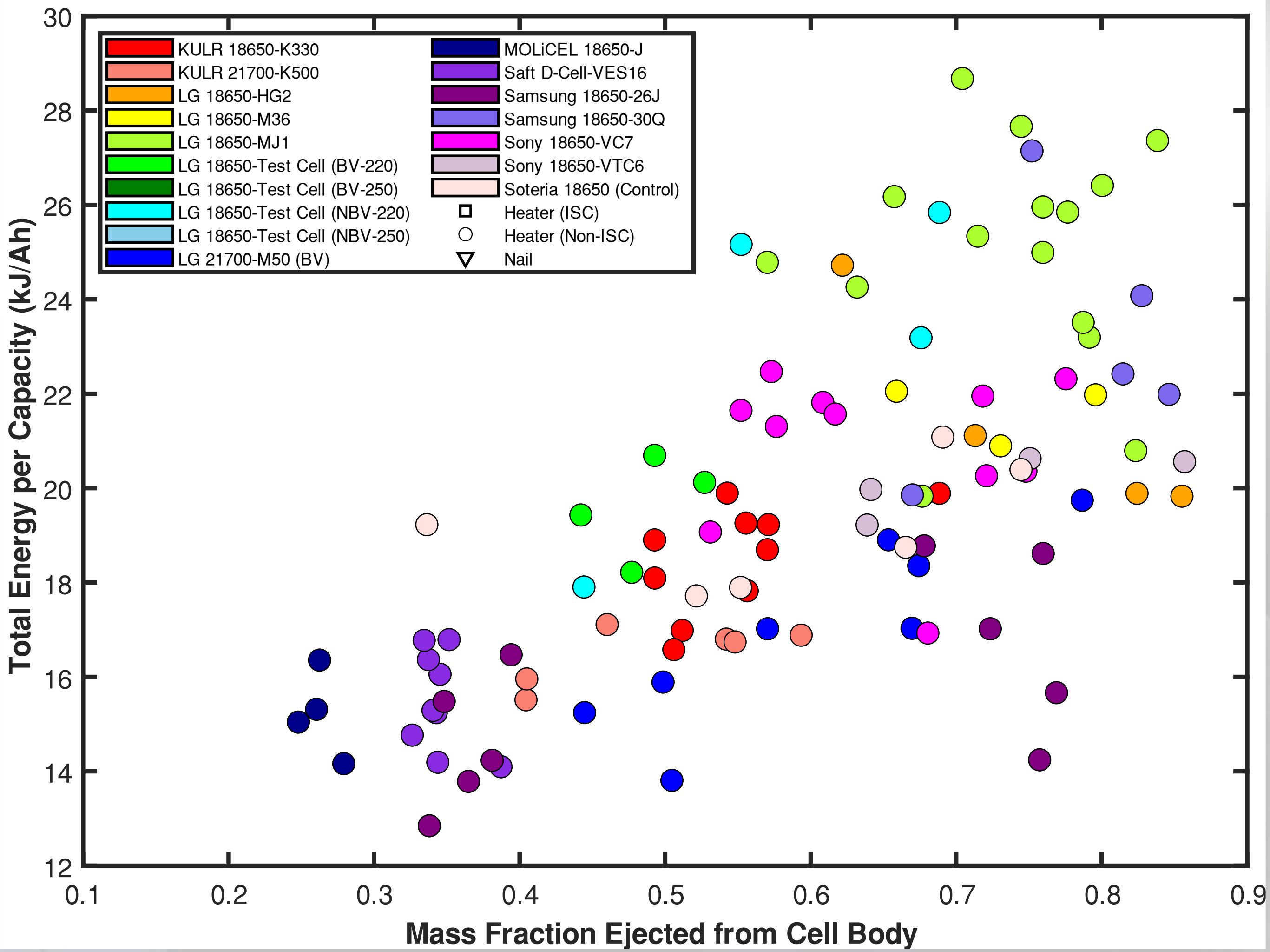

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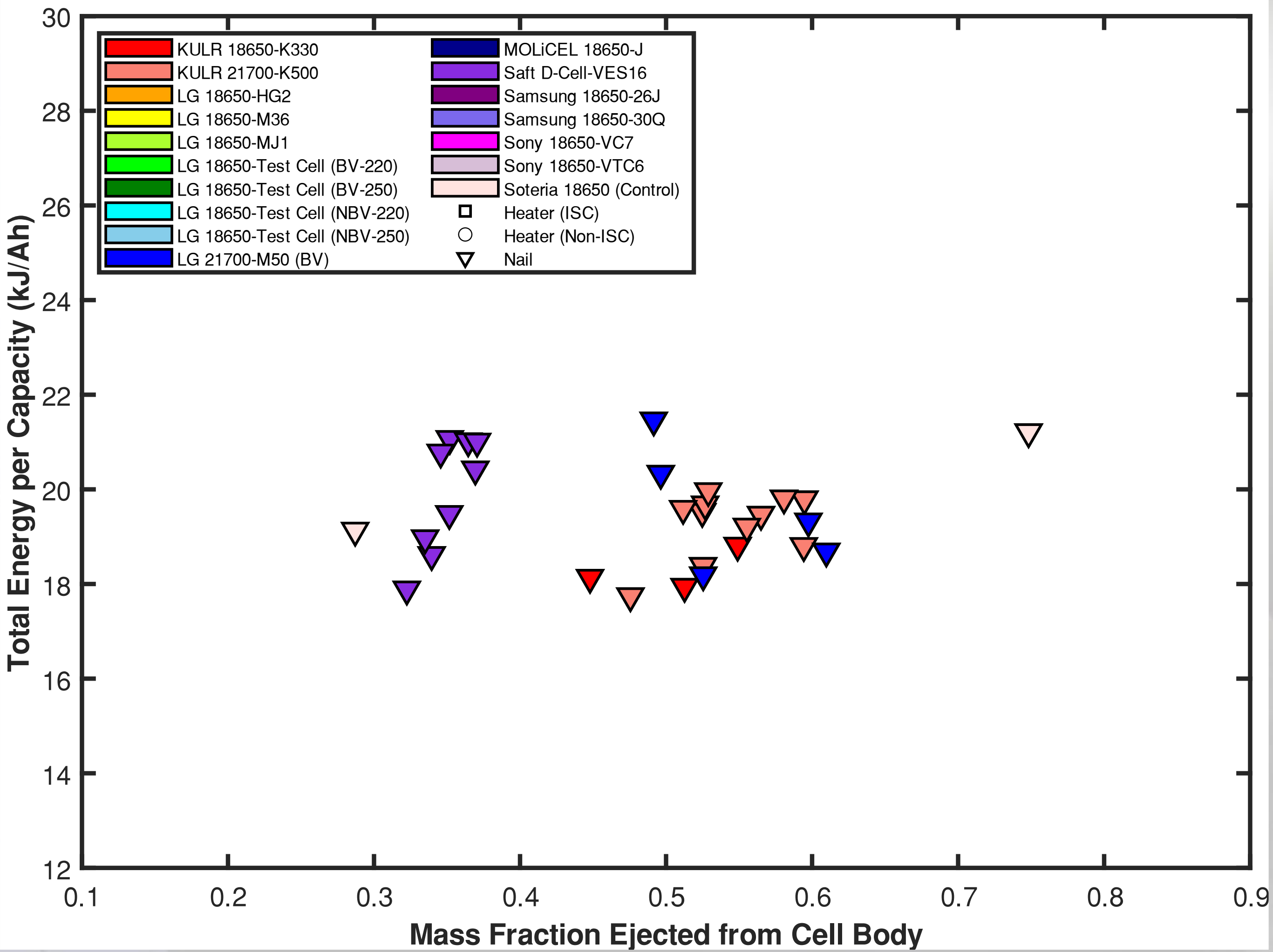

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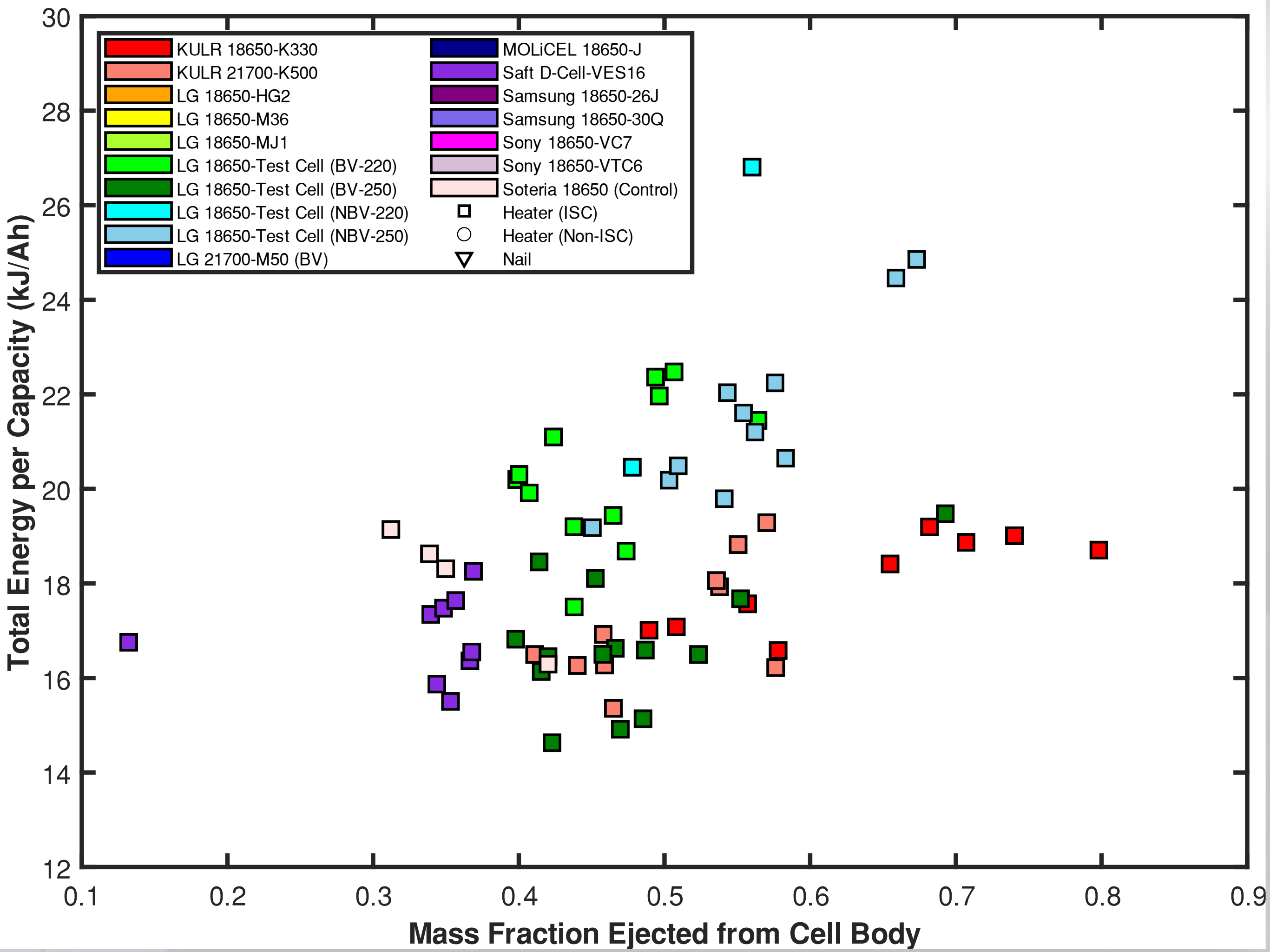
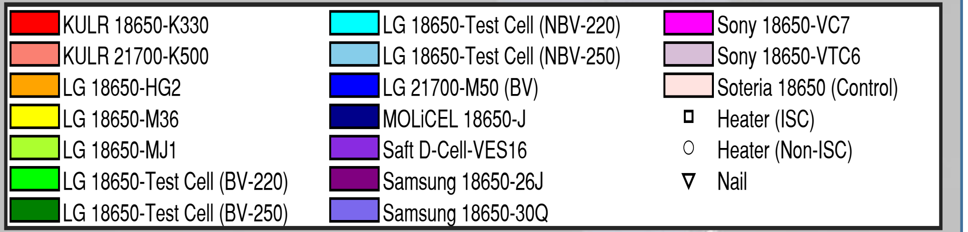
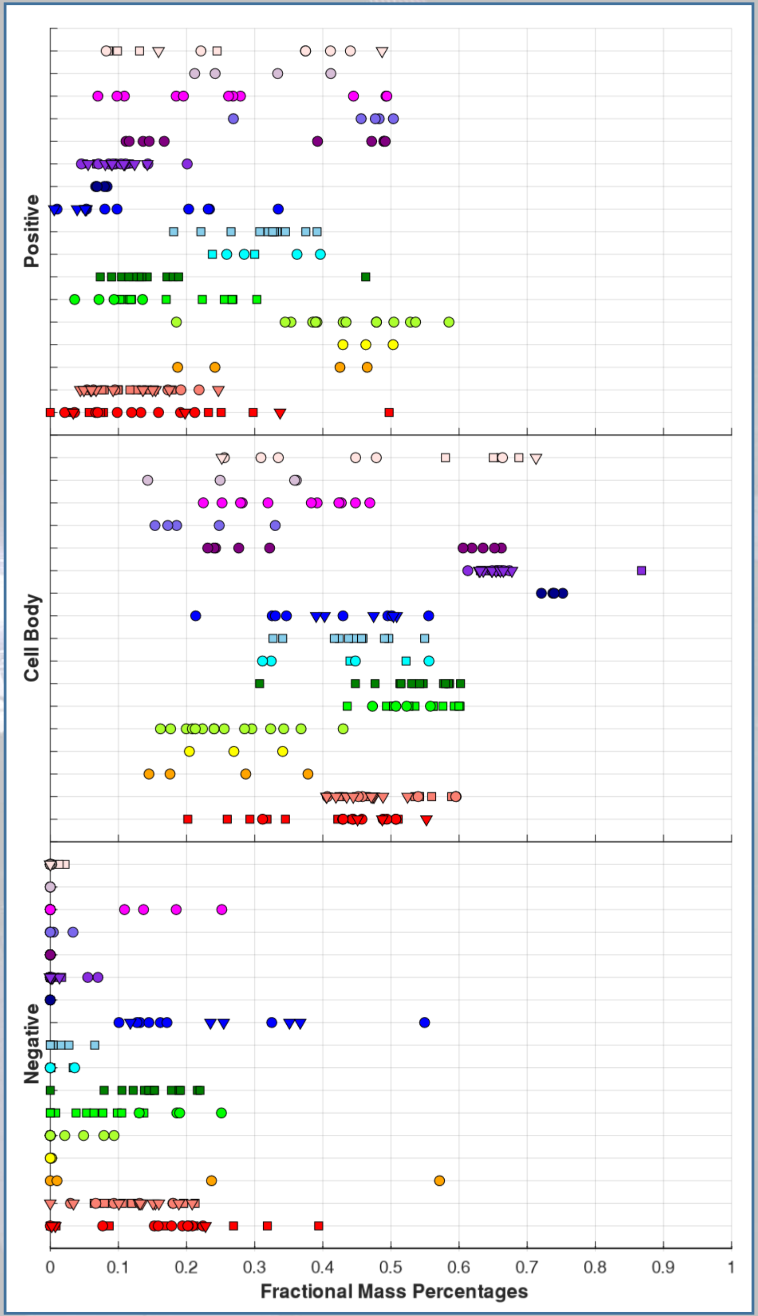
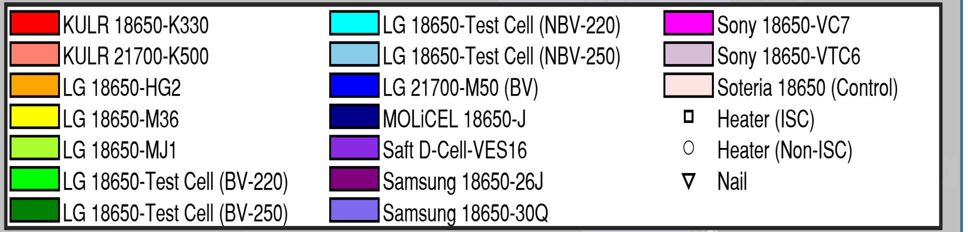




- **Fractional Mass/Energy Trends**
  - Low: +60% mass in cell body
  - Plain: most mass in cell body
  - High: most mass ejected

  - More cell body mass but more positive energy
    - Unrecovered Mass
    - Thermal mass





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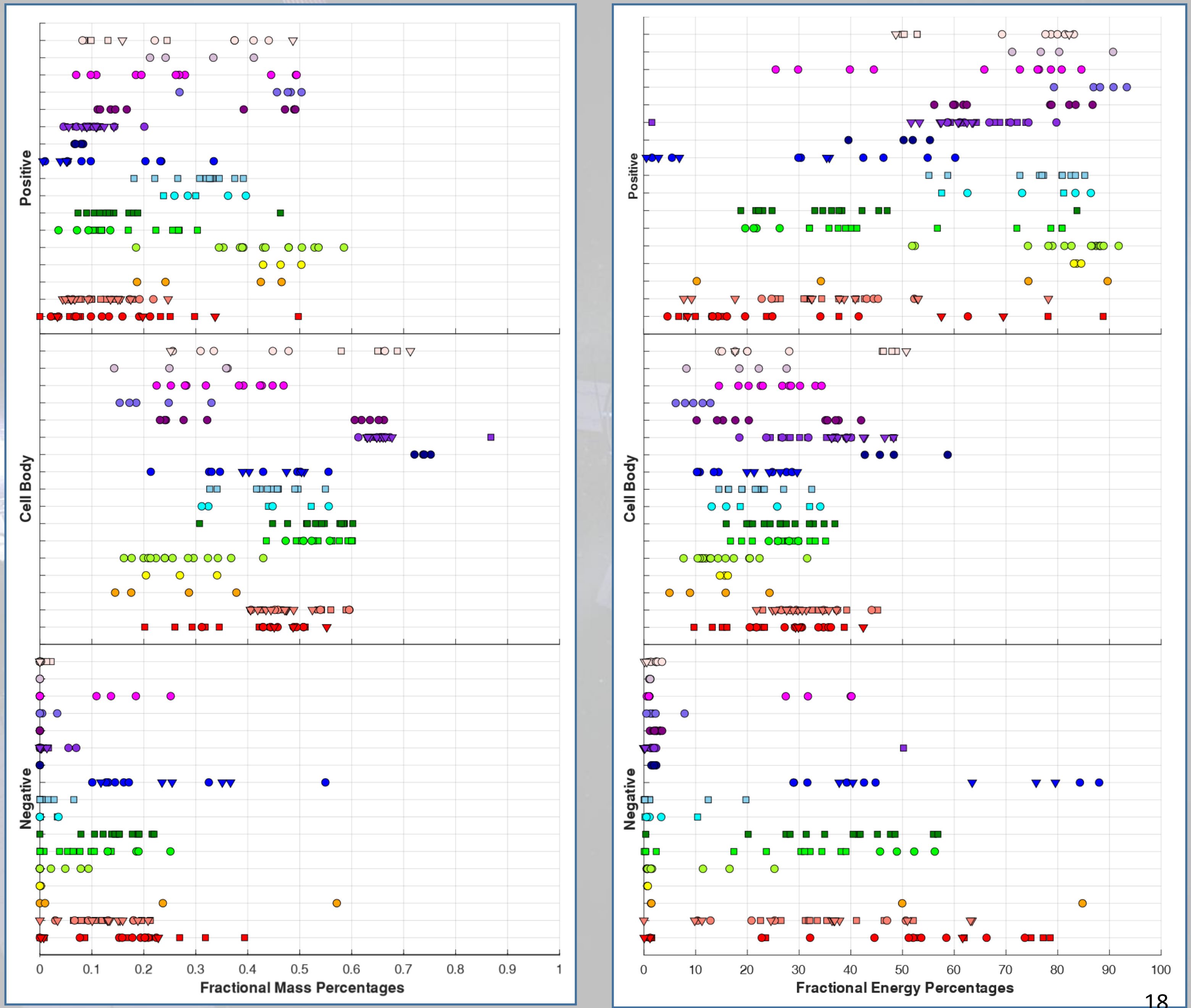

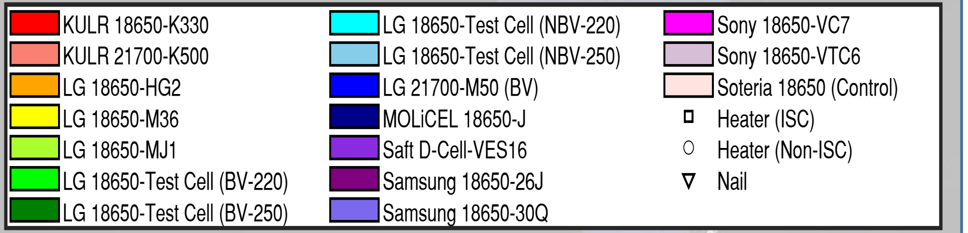

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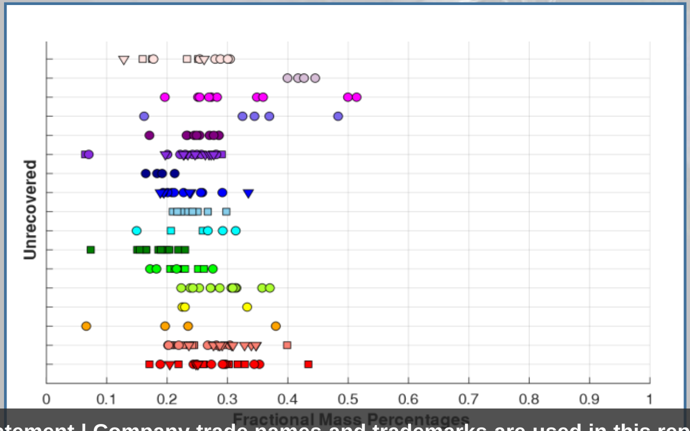
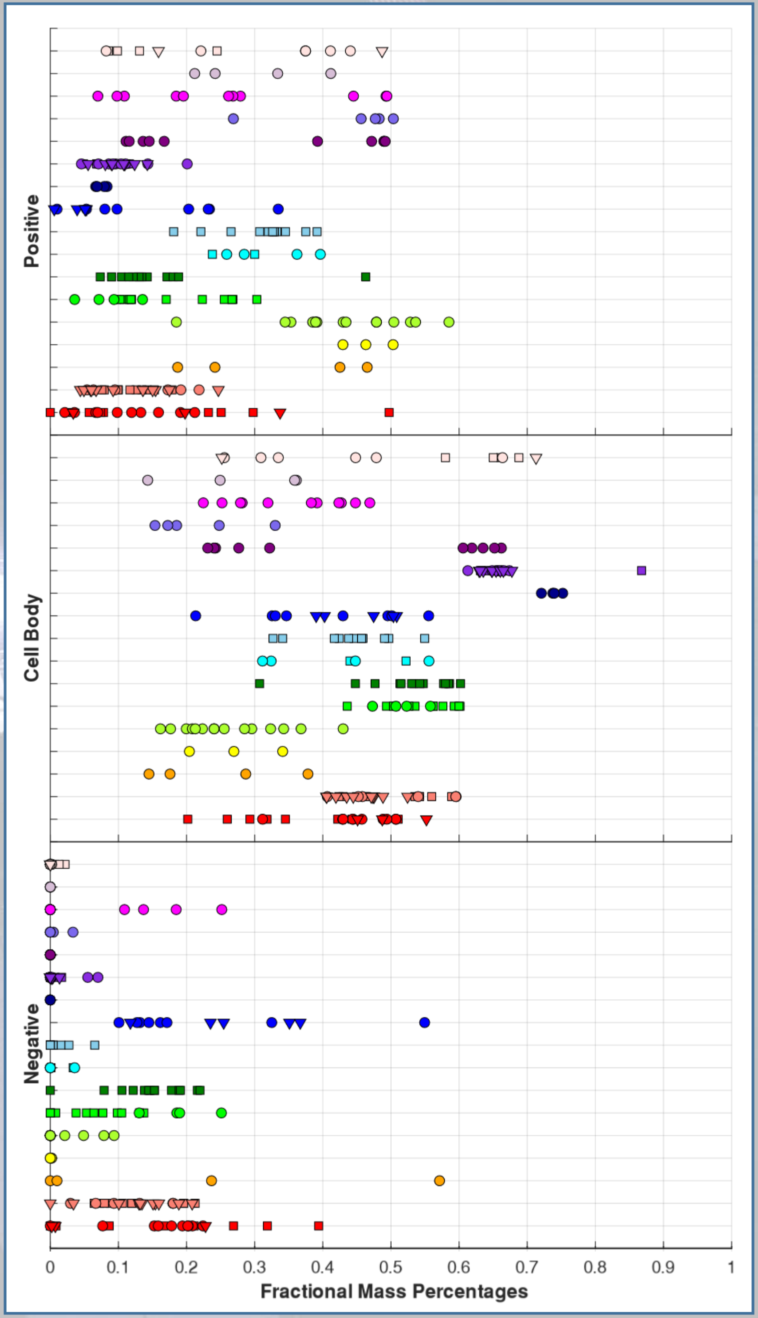
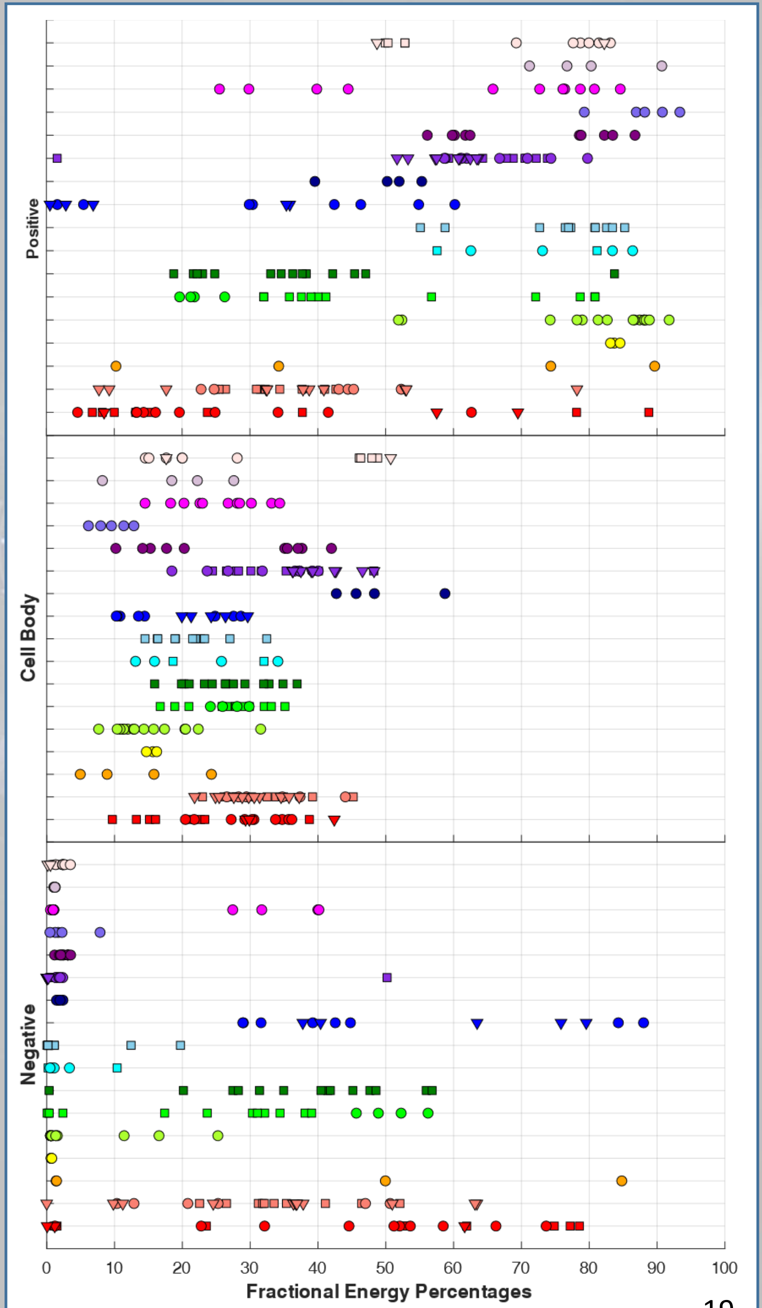
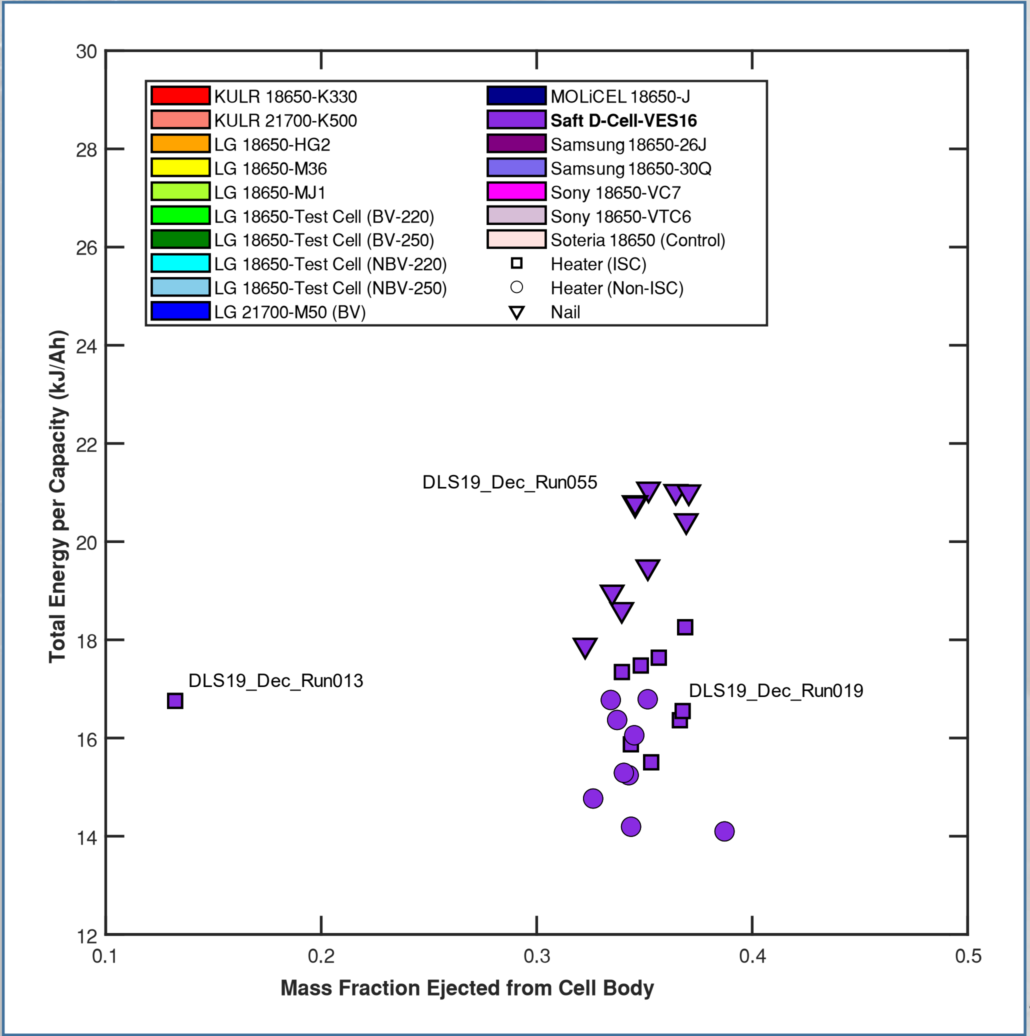






SAFT, THERMAL MASS, AND NAIL TRIGGER

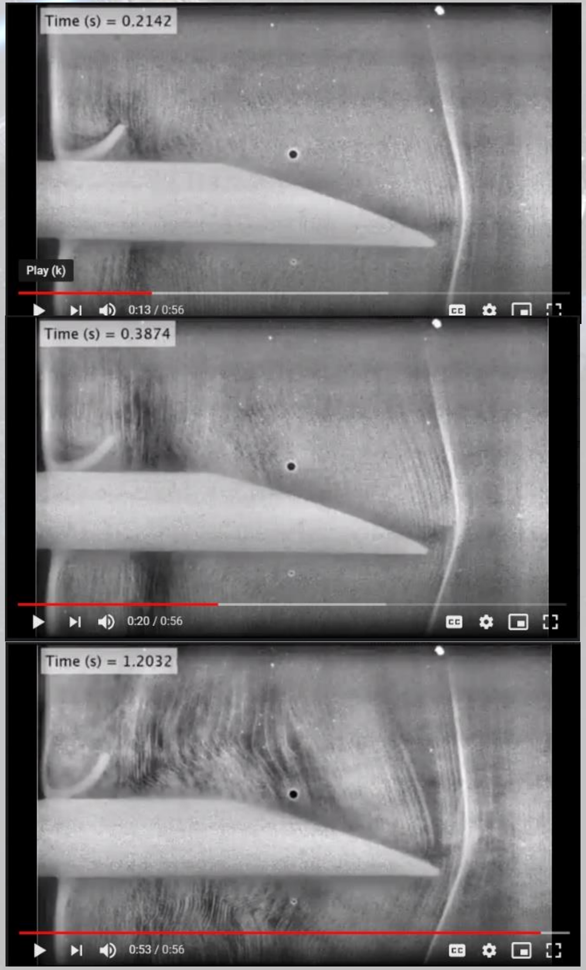
- Nail produced more kJ than other triggers (in all cell types)
- For Saft, nail had higher cell body energy percentages and lower positive energy percentages
- Nail reduces TR energy used for propagation
- **Larger energy due to trigger mechanism.**



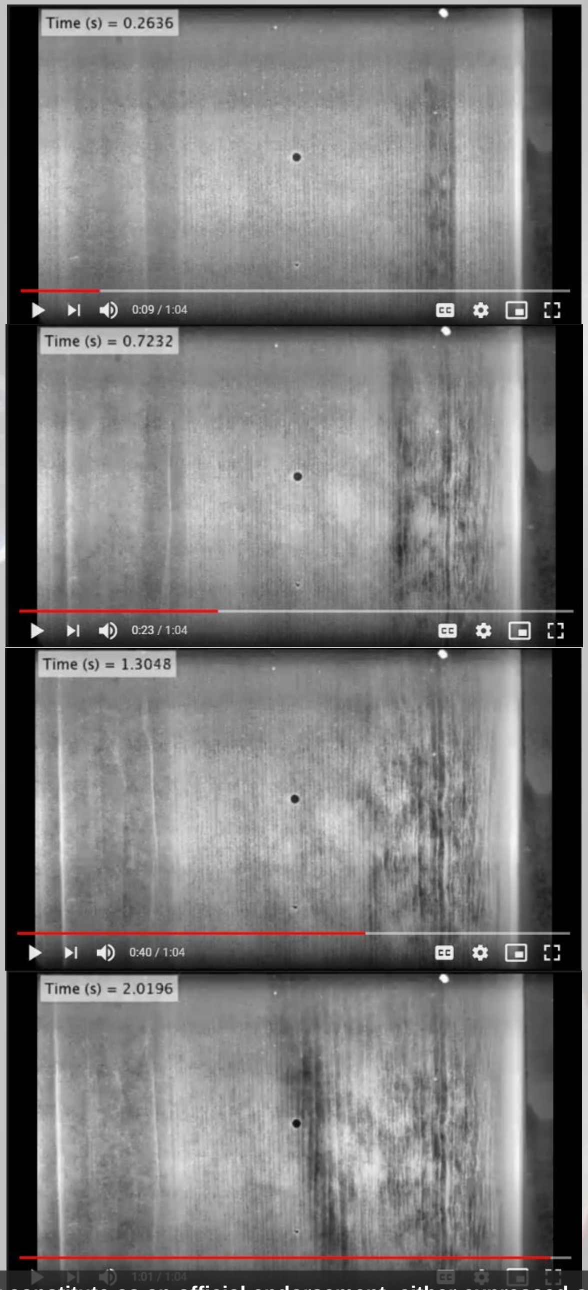
SAFT, THERMAL MASS, AND NAIL TRIGGER

- Run 55, nail: TR propagates radially in ~1s
- Run 19, ISC: Propagation takes >2s

Run 55

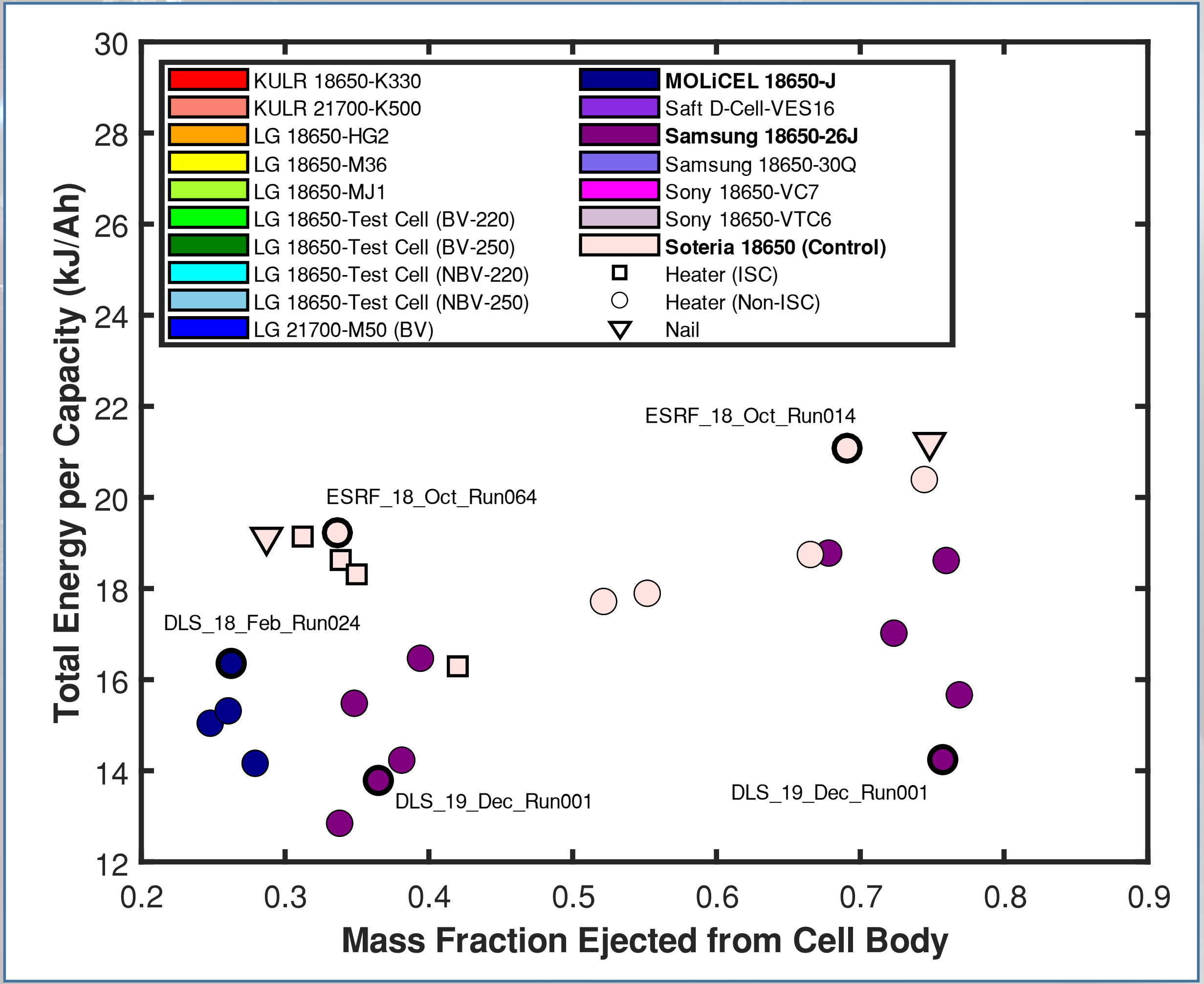


Run 19



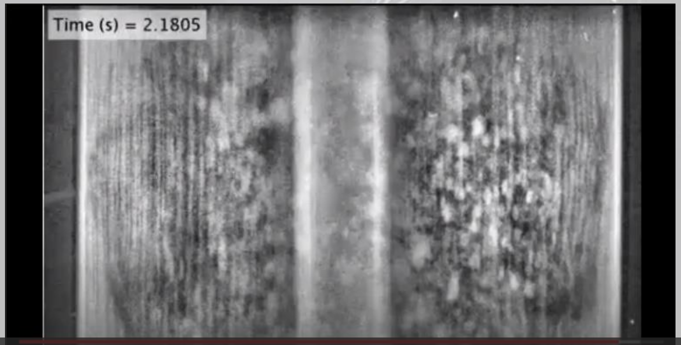
LOW EJECTIONS

- Bi-modal: Higher mass fractions have slightly more energy, and they have more positive mass/energy percentages
- Soteria ISCs are low (because they don't all go at once and block the vent)
- **Invest in mandrels.**

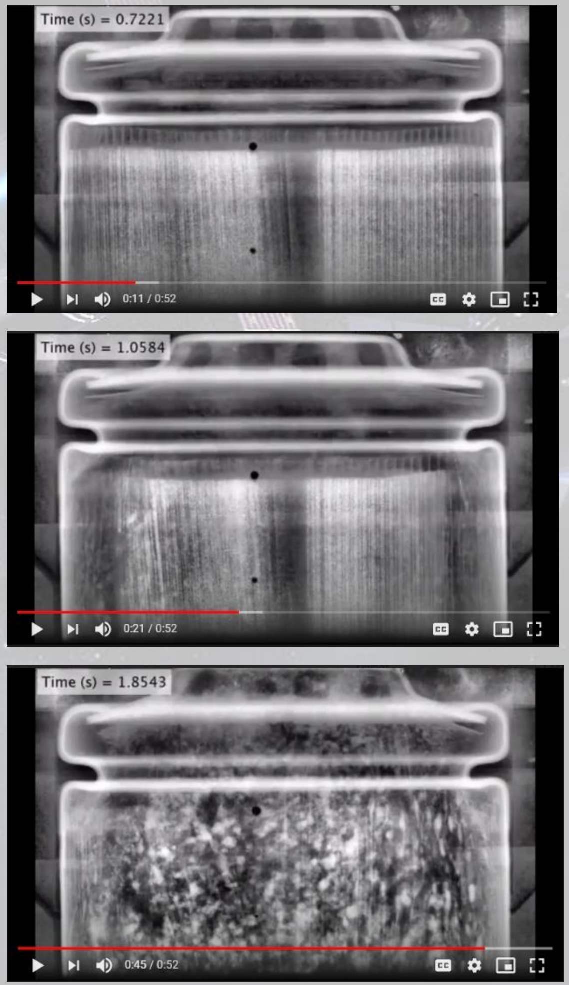


LOW EJECTIONS

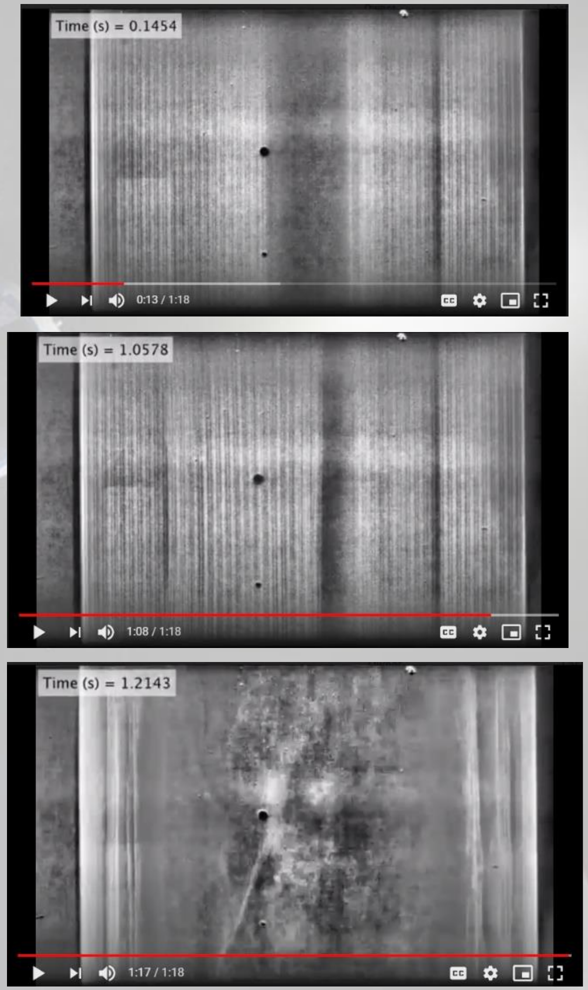
- Run 1: Starts at the edges, globs form, pushes against top vent
- Run 6, the inner wall collapses, left starts to give, bursts.
- MOLiCEL below. Globs, but takes 2s, and takes a feathery while to form. (Invest in mandrels.)



Run 1 (low 26J)

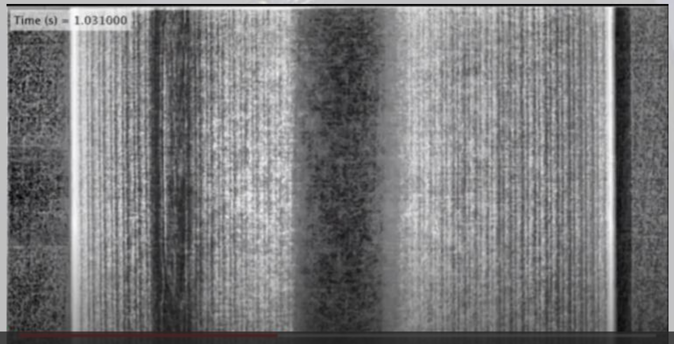


Run 6 (high 26J)

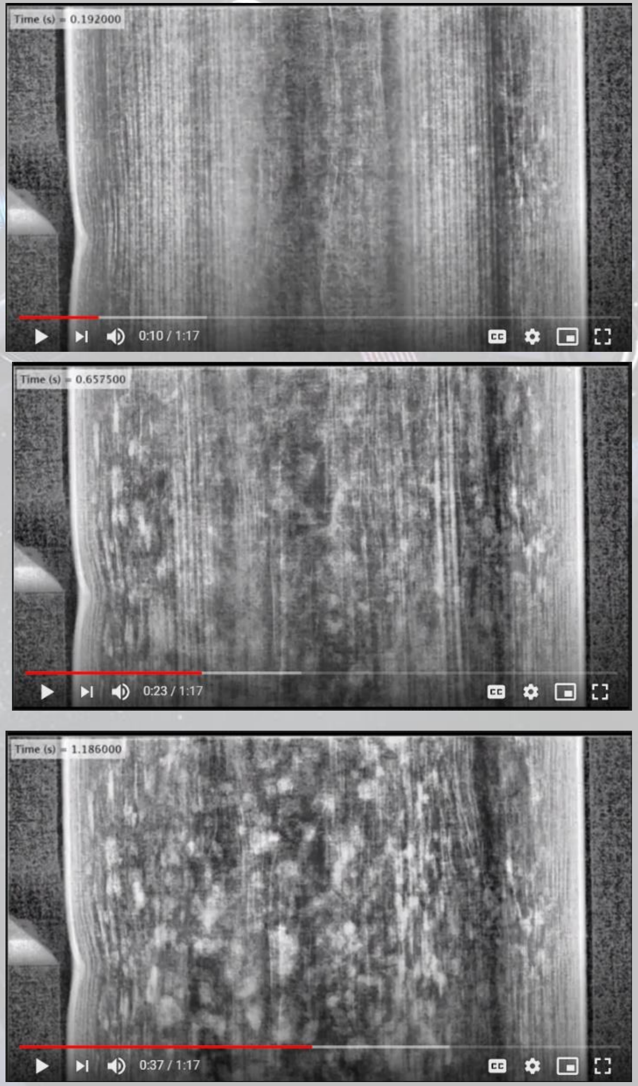


LOW EJECTIONS

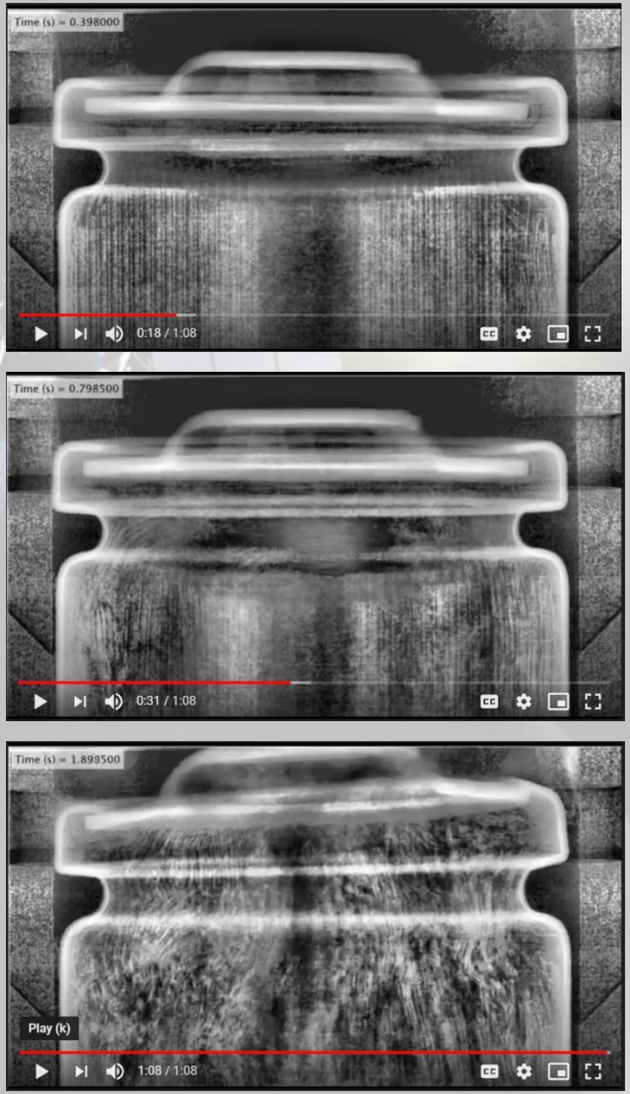
- 64: Core feathers and edges creep up, then still.
- 14: Vents at first, swells, pops
- 22 ISC (below): only one layer goes at a time, so no clogs. It's almost a safety mechanism in this instance.



Run 64 (low Soteria)



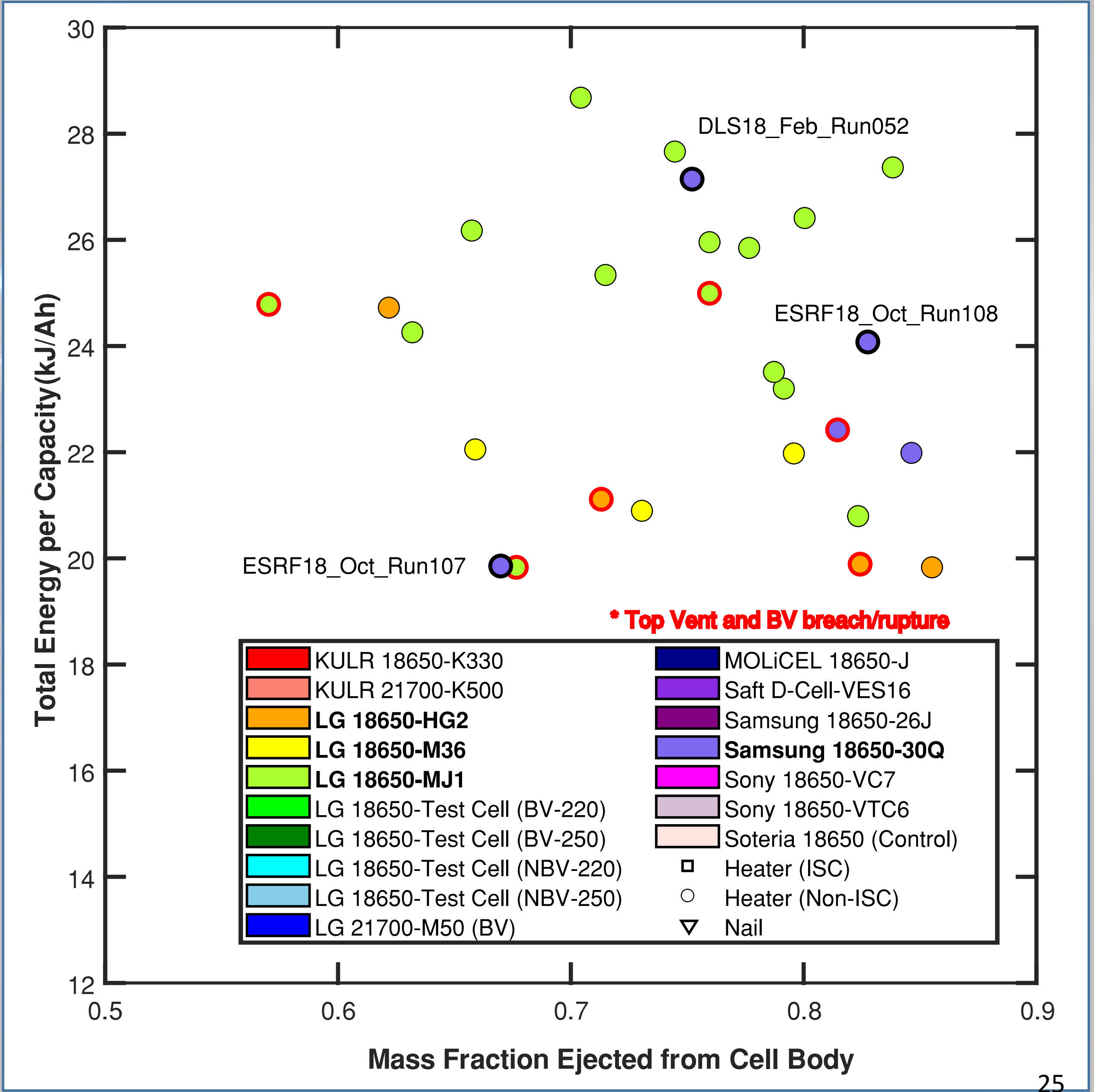
Run 14 (high Soteria)



HIGH EJECTIONS

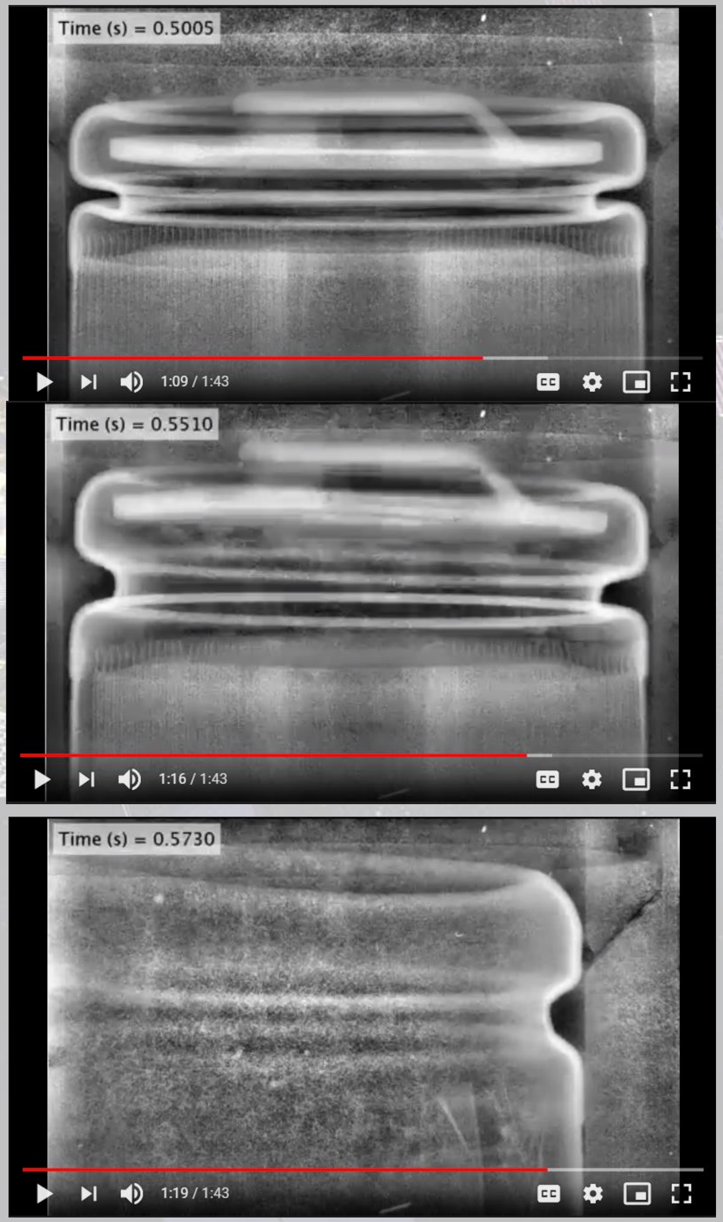
- 30Q & HG2 are high capacity (more layers, thinner layers)
- Most eject mass completely before substantial decomposition
- MJ1 has a different chemistry[1], tight layers, and a 165um thick cell casing. Usually a partially collapsed core. Often doesn't even get the chance to form globs.

[1] https://doi.org/10.1016/j.electacta.2018.11.194



Run 107 (30Q, 67%, 19.86 kJ/Ah)

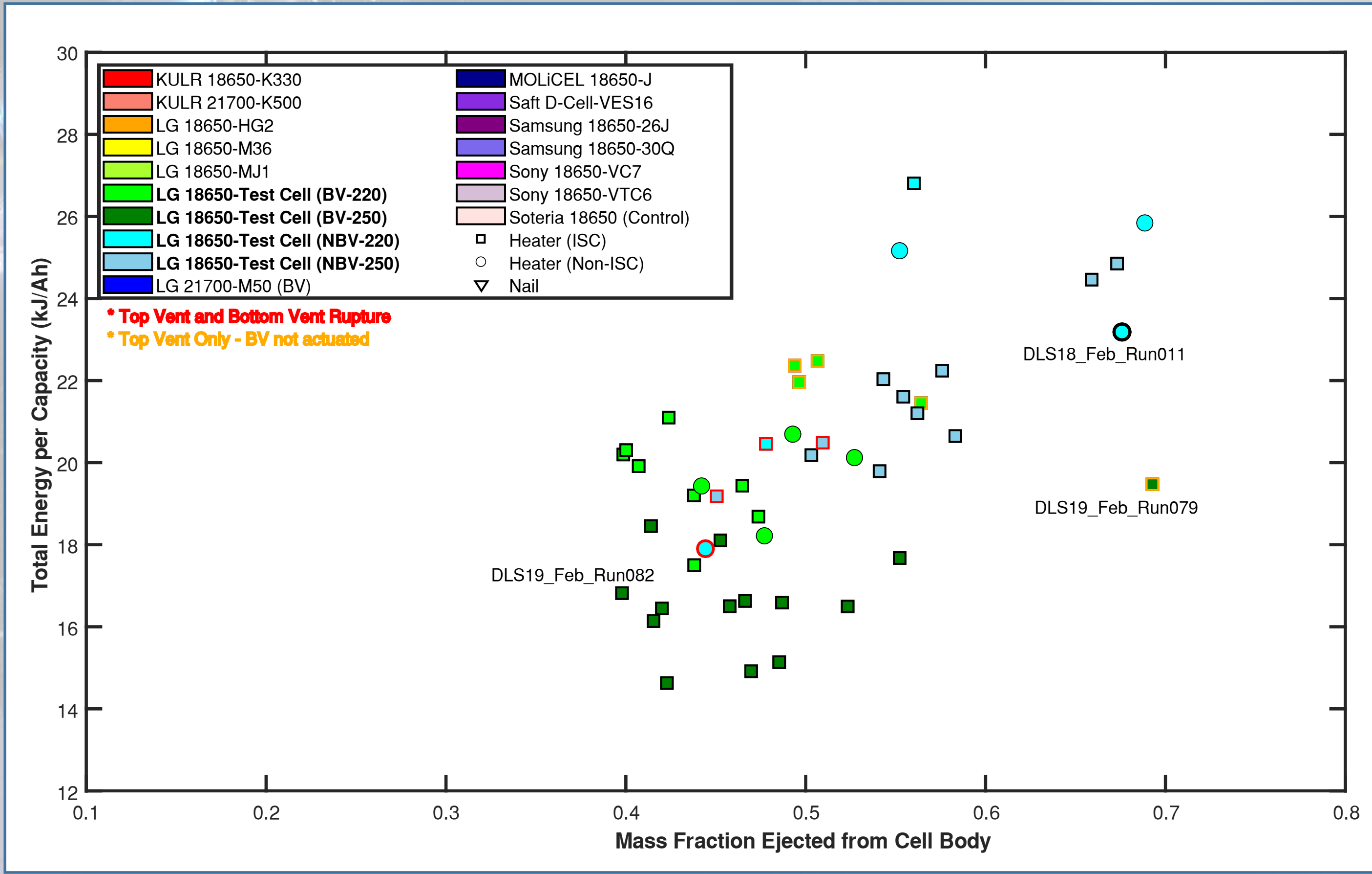
Run 52 (30Q, 75.2%, 27.15 kJ/Ah)



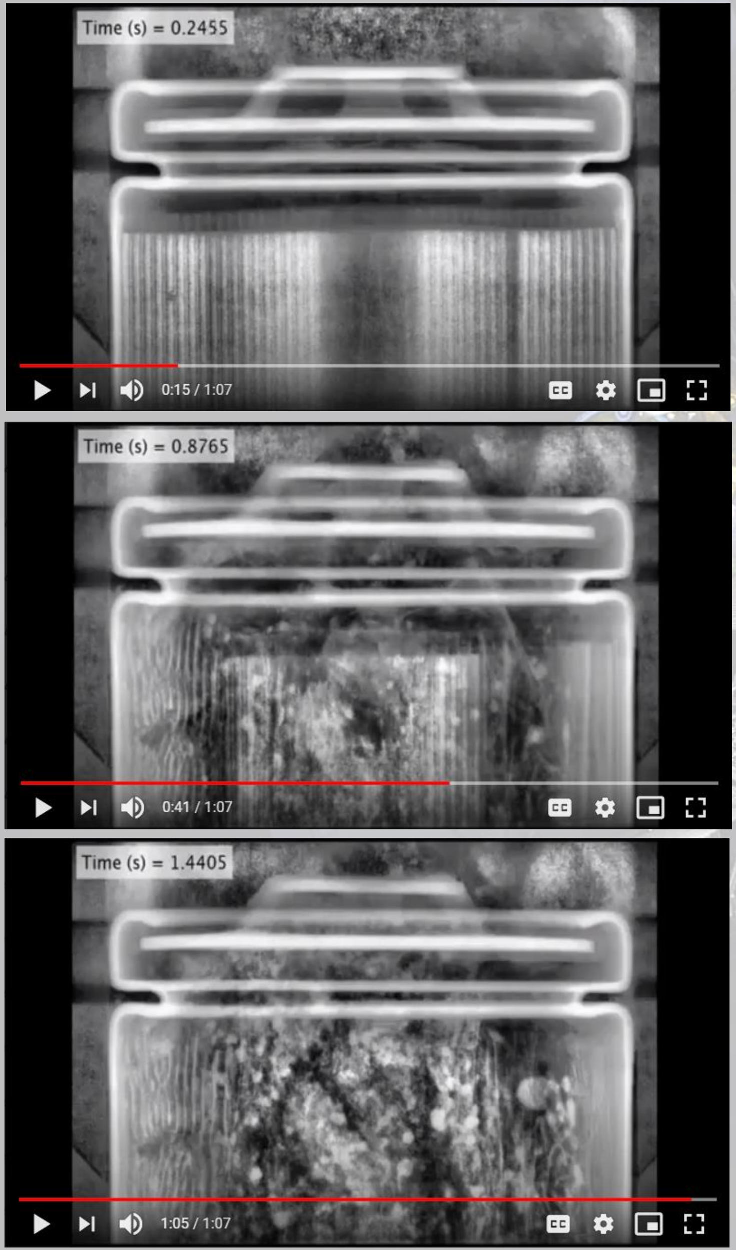
Run 108 (30Q, 82.8%, 24.1 kJ/Ah)

BOTTOM VENTS

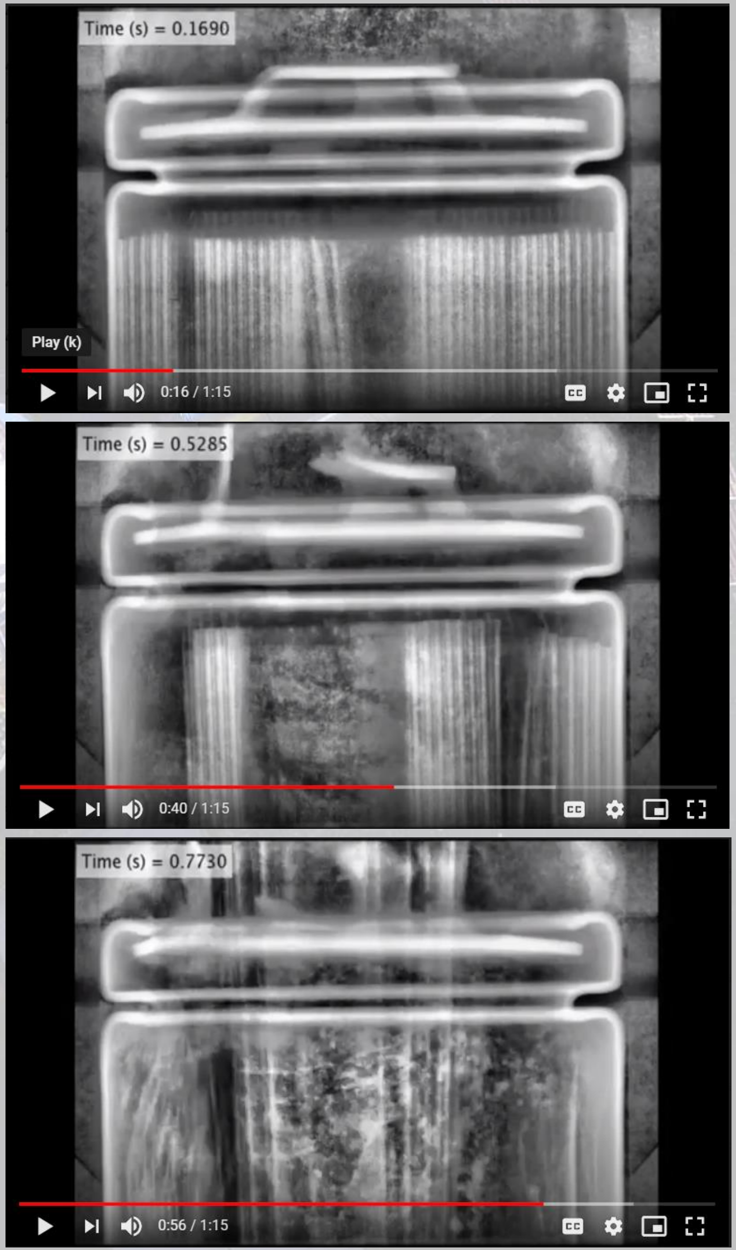
- Cells vent decomposed/partially decomposed material
- The more mass fraction is ejected, the less decomposed it is (and larger feathery layers are ejected)
- BVs and thicker casings produce less energy and vent better



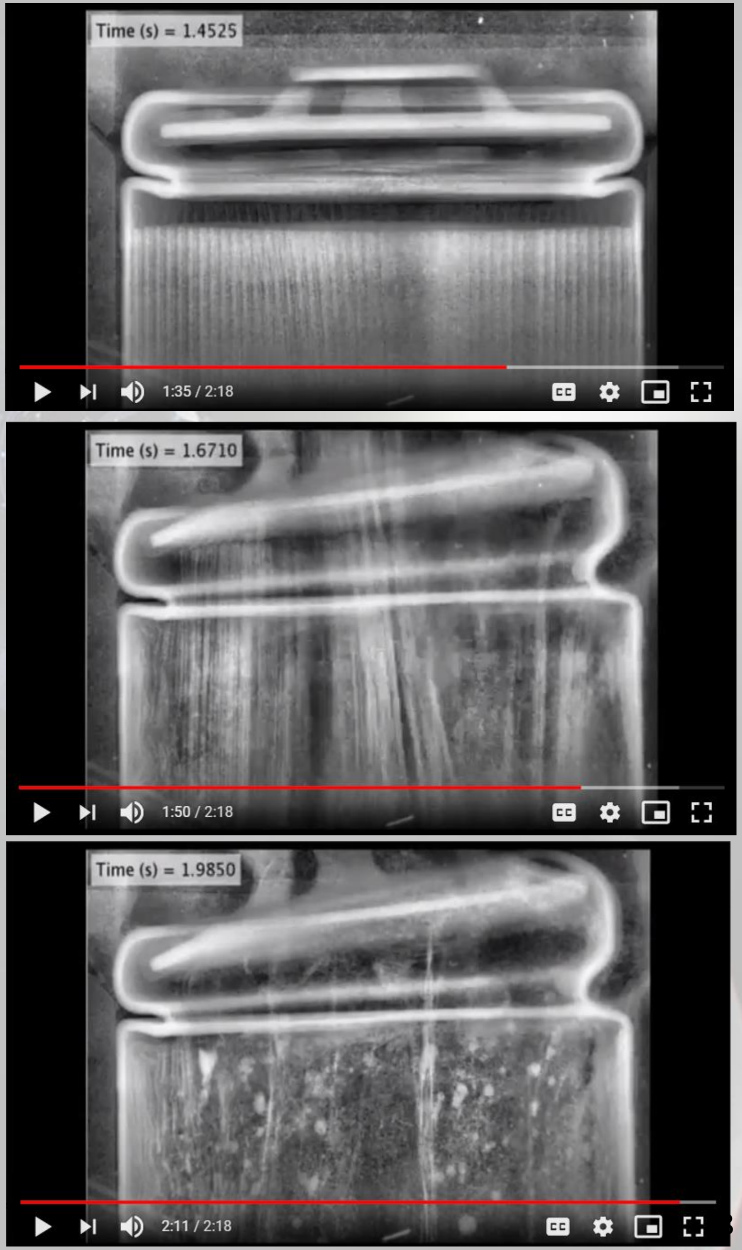
Run 82 (BV-250, 39.8%, 16.8 kJ/Ah)



Run 79 (BV-250, 69.3%, 19.5 kJ/Ah)

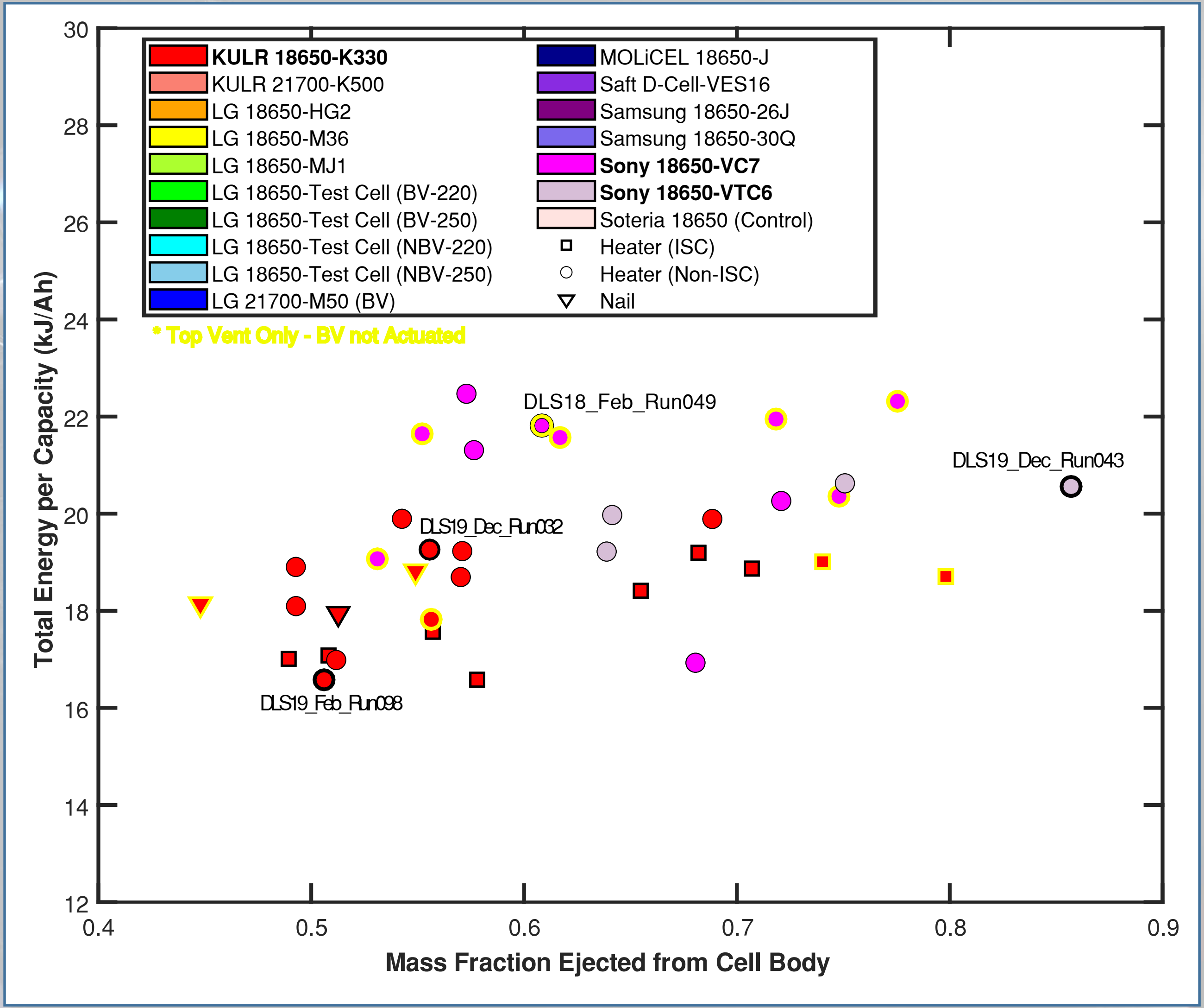


Run 11 (NBV-220, 67.6%, 23.2 kJ/Ah)

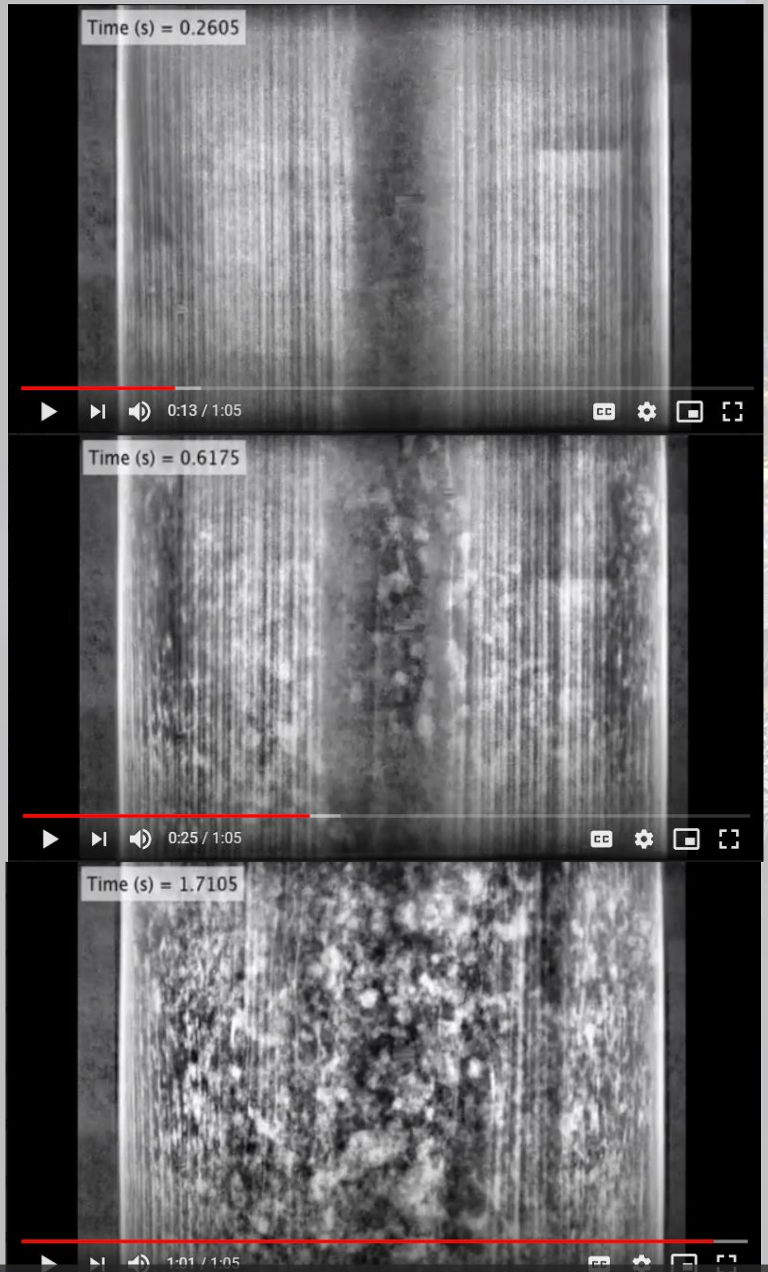


THE OTHER 18650S

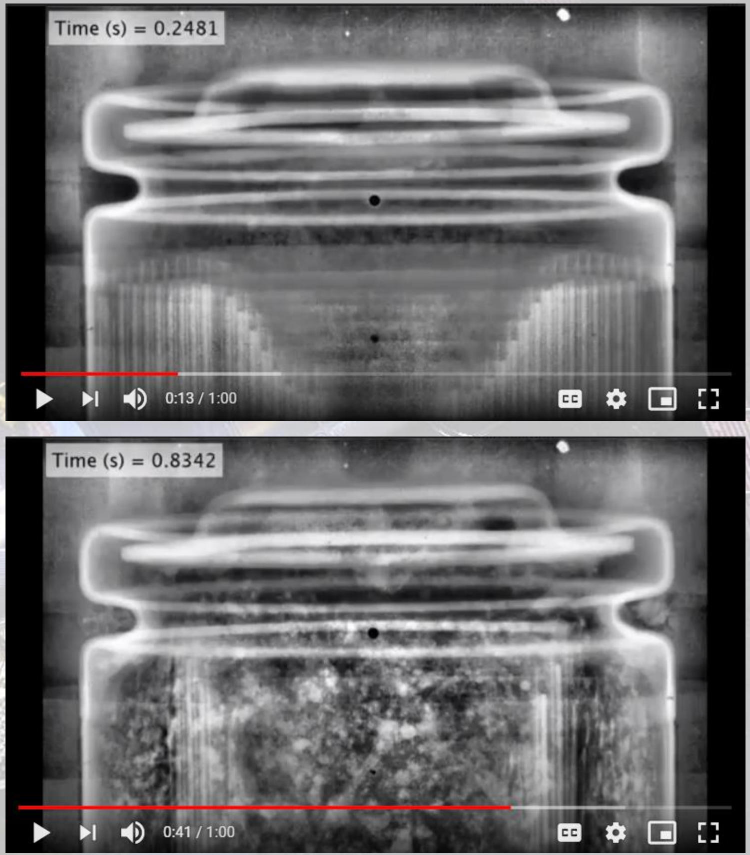
- Mass fraction may have a small effect
  - Globs vs sheets
- Bimodal: different distributions, but same totals
- Cell type is the determining factor here



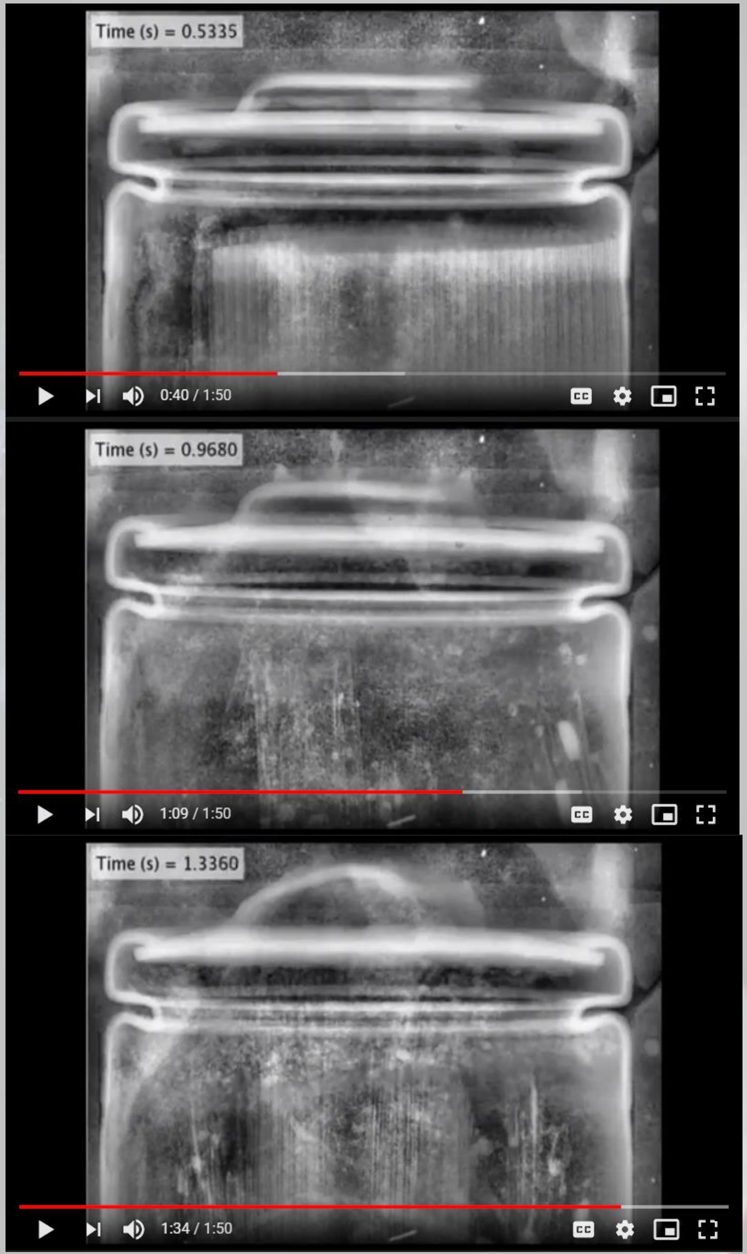
Run 98 (KULR, 50.6%, 16.6 kJ/Ah)



Run 32 (KULR, 55.5%, 19.22 kJ/Ah)

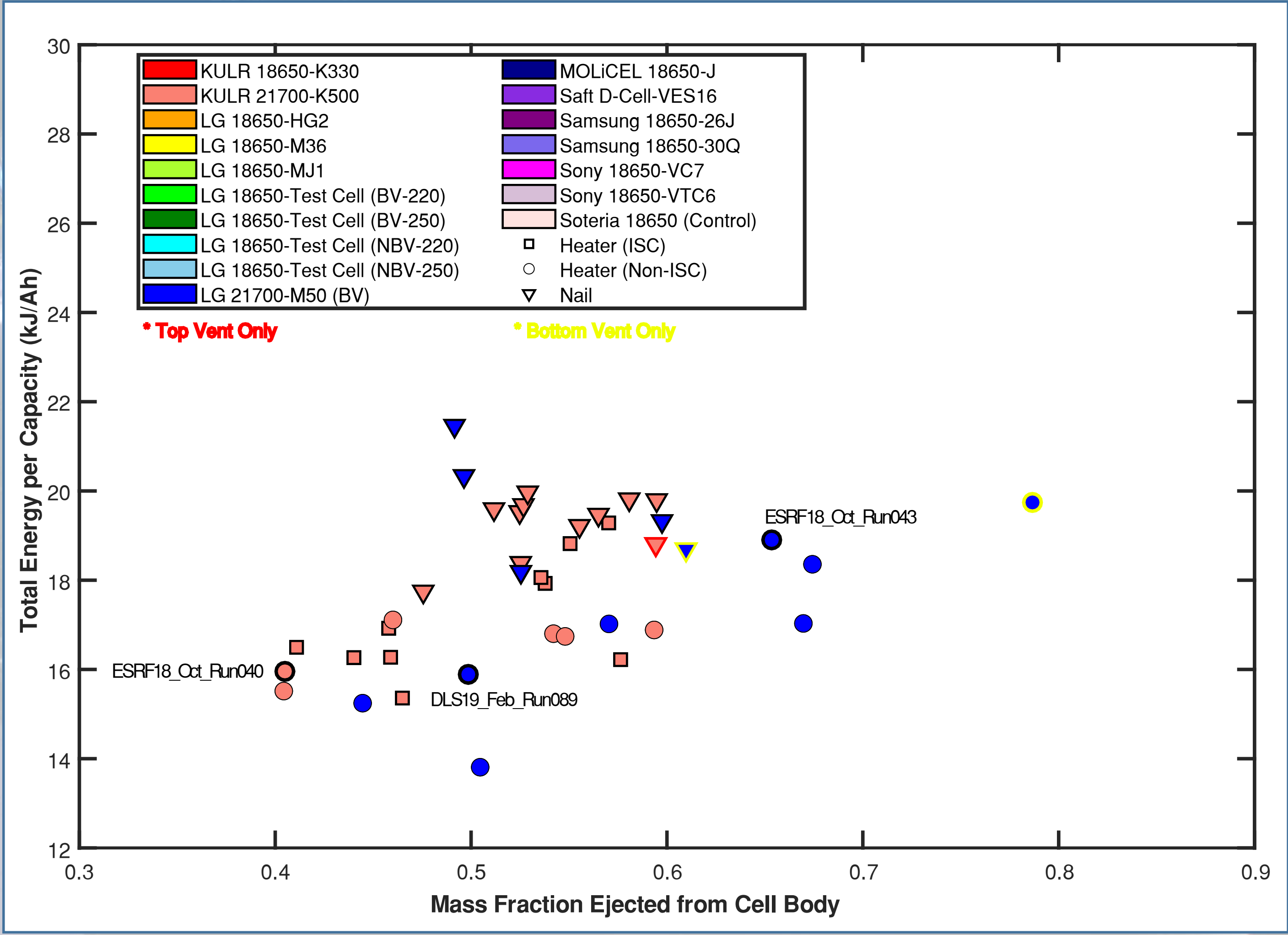


Run 49 (KULR, 60.8%, 21.8 kJ/Ah)

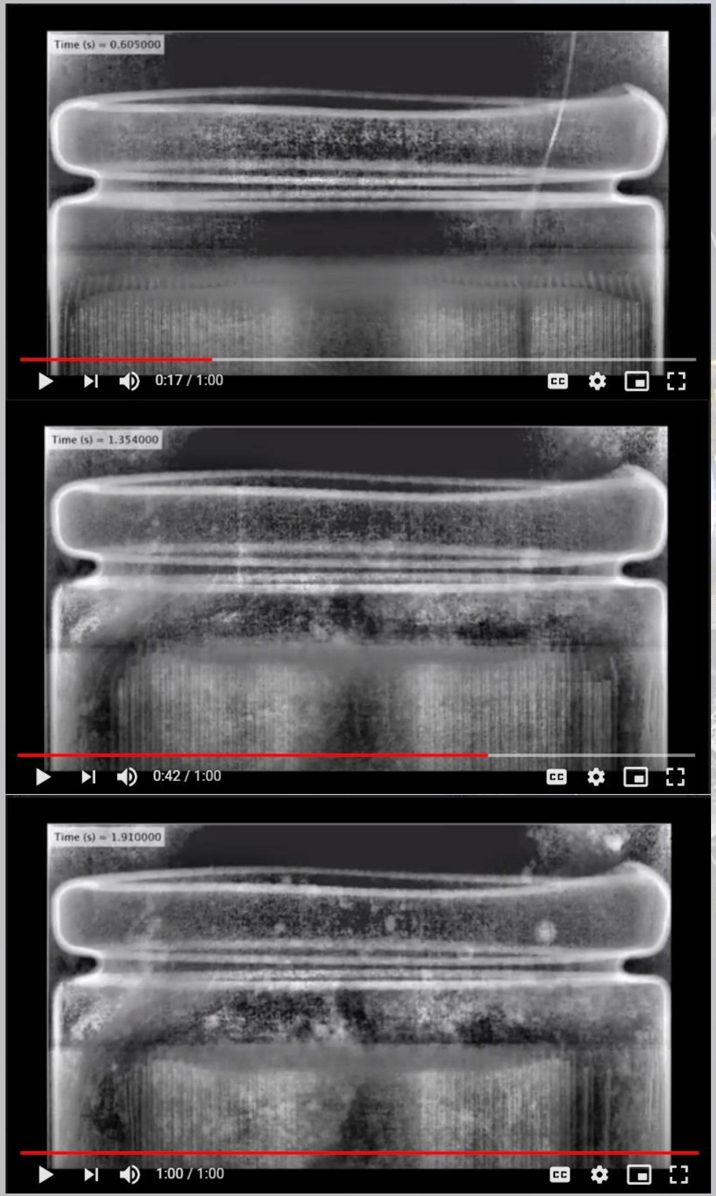


THE 21700S

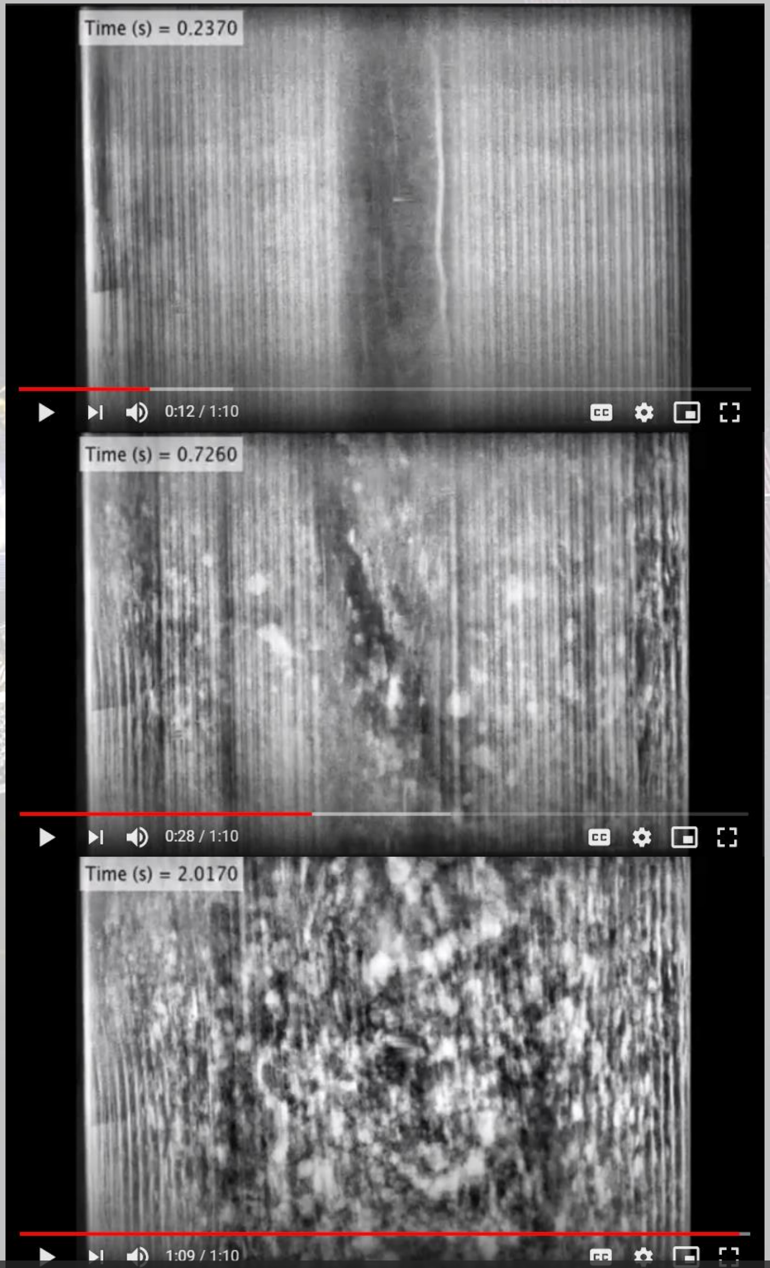
- Nail pins mass, drives mass fraction
- Wide ranges, despite similar behavior



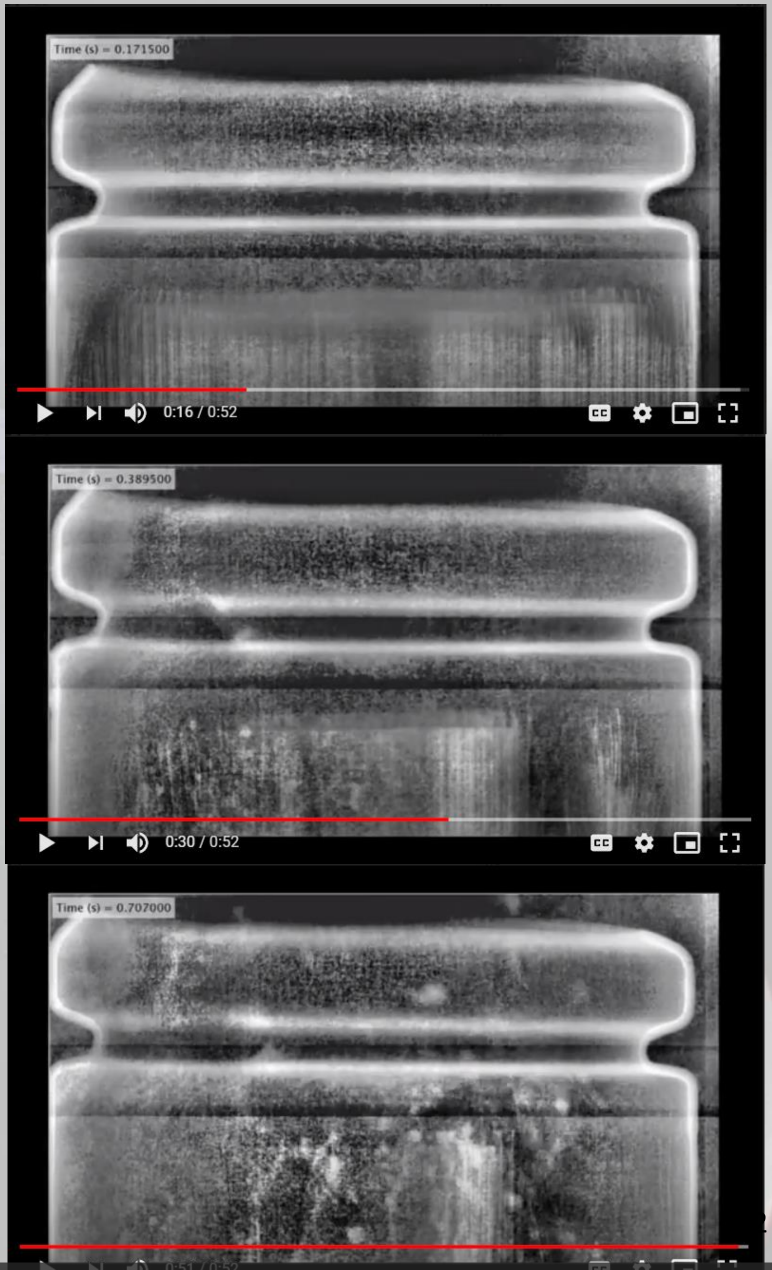
Run 40 (KULR, 40.5%, 16 kJ/Ah)



Run 89 (M-50, 49.9%, 15.9 kJ/Ah)

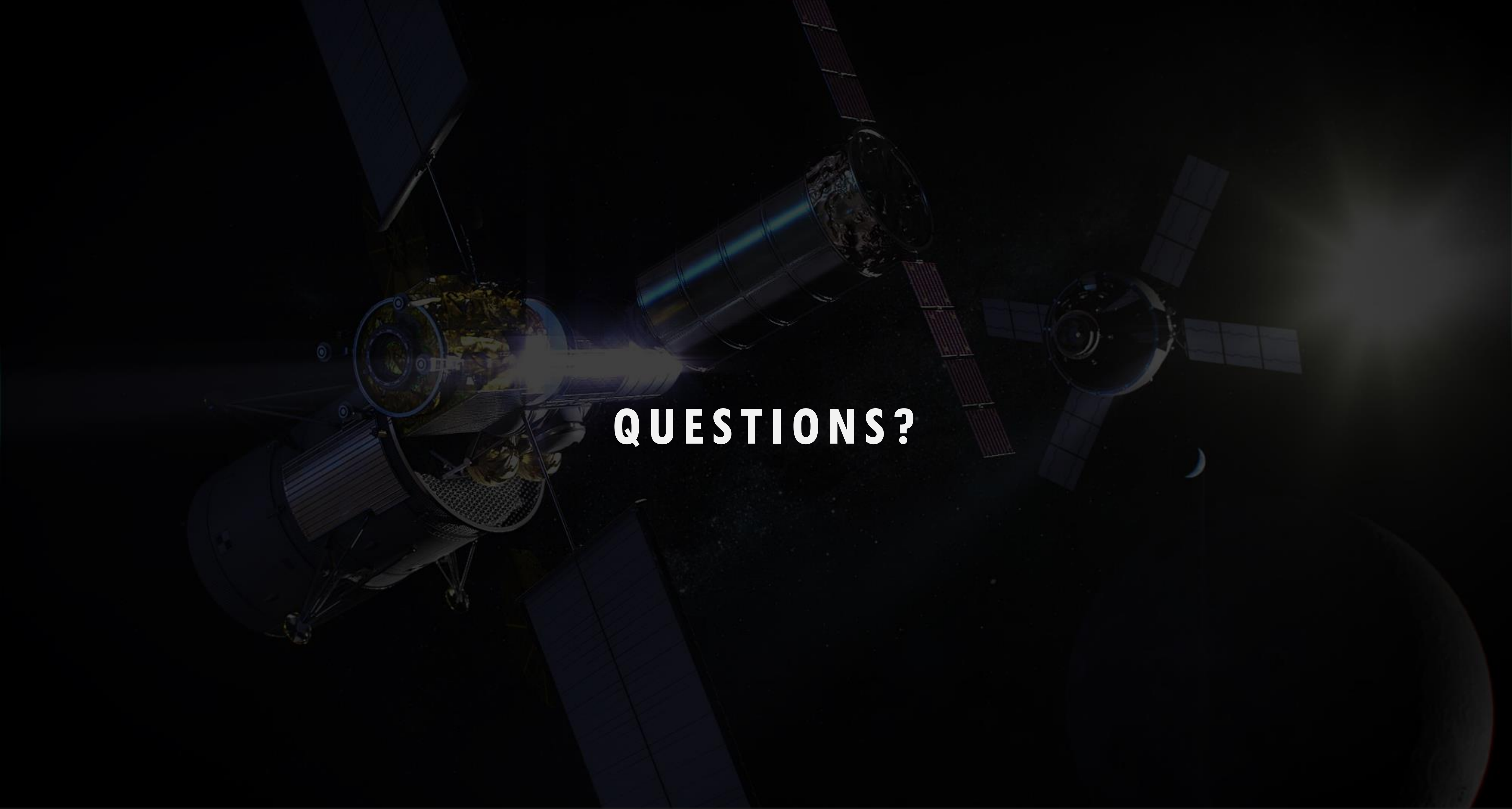


Run 43 (M-50, 65.4%, 18.9 kJ/Ah)



CONCLUSION

- **The results from the FTRC experiments and combination FTRC / synchrotron experiments have been compiled into a resource known as the Battery Failure Databank.**
  - This databank has been used to drive examination of thermal runaway behavior as a function of cell type, cell format, and trigger mechanism.
  - The databank was used to drive the comparisons covered in this presentation
- **Severity and variability of TR depends largely on cell capacity and cell type, and is influenced by how TR progresses**
  - Retaining larger portions of mass in the cell body generally means less energy
  - Vents, cell casings, mandrels, and tolerances, can make TR more predictable
- **Demonstrates stochastic nature of TR**
- **Databank provides an extensive and detailed resource**
  - Many dimensions, cross sections, and levels of analysis


QUESTIONS?