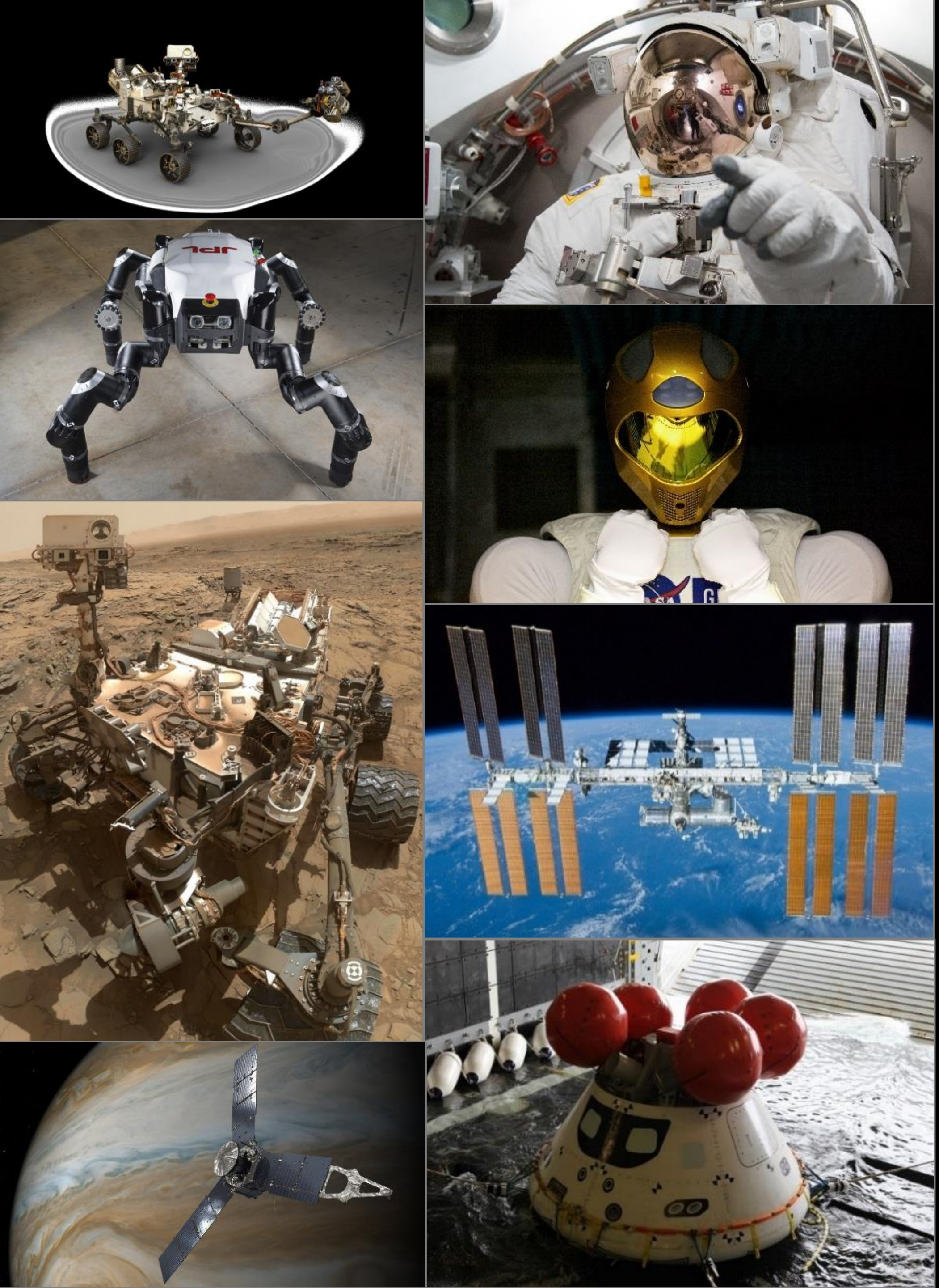

ENHANCING BATTERY SAFETY WITH FRACTIONAL THERMAL RUNAWAY CALORIMETRY

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The Battery Show Europe
May 7th-9th, 2019
Stuttgart, Germany

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[3] *University Space Research Association (USRA)*
[4] *Marshall Space Flight Center (MSFC)*
[5] *NASA Engineering and Safety Center (NESC)*

NASA STRATEGY TO PROTECT AGAINST THERMAL RUNAWAY

- **Following the 2013 Boeing 787 Dreamliner incident, NASA teams developed new definitions for battery design success criteria:**
  - Always assume thermal runaway (TR) will eventually happen
  - Design should ensure that TR event is not catastrophic
  - Demonstrate that propagation to surrounding cells will not occur

- **Thermal management systems designed to mitigate the effects of thermal runaway and prevent cell-to-cell propagation should consider the following[1]:**
  - No two runaway events are the same; even for the same manufacturer and state-of-charge; there is a range of possible outcomes
  - Onset temperature, acceleration temperature, trigger temperature, trigger cell peak temperature and neighbor cell peak temperature
  - Total energy released through sides and top of the cell body
  - Cell failure type (e.g. side wall vs. top), system pressure increase, gases released and ejecta material

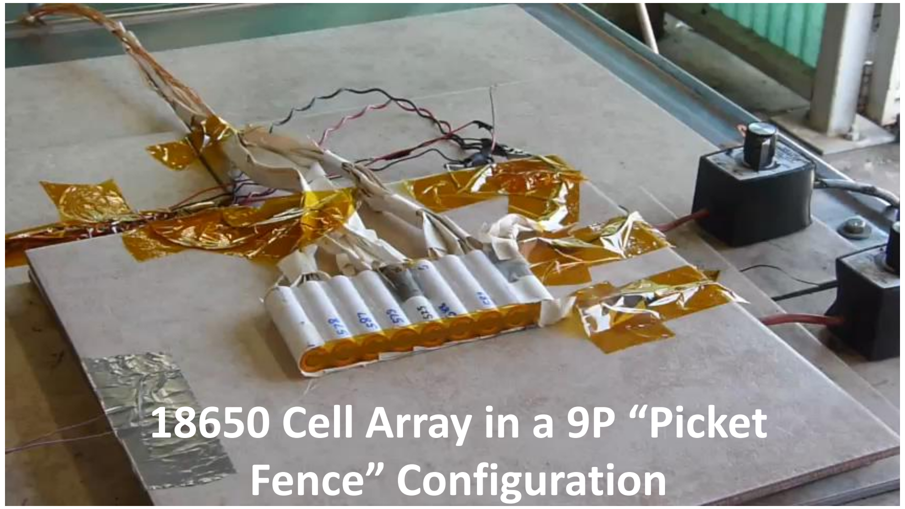
- **Optimization of Li-ion battery assemblies that satisfy the aforementioned strategies requires knowledge of the following:**
  - Total energy output range during TR for a single Li-ion cell
  - Fraction of TR energy transferred through the cell casing
  - Fraction of TR energy ejected through cell vent/burst paths

---

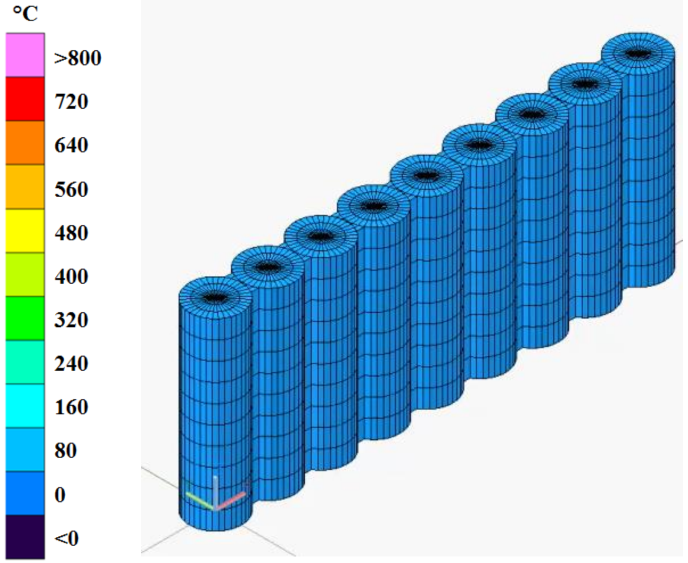
[1] *Crewed Space Vehicle Battery Safety Requirements. JSC-20793 Rev D. JSC Engineering Directorate, Power and Propulsion Division*

MODELING THERMAL RUNAWAY

- **Analytical models of thermal runaway are needed to inform battery thermal design.**
- **However, modeling thermal runaway is complex because:**
  - No two thermal runaways are identical.
  - Cell geometry does not remain intact.
  - Total energy yield may differ greatly between to thermal runaways of the same cell type.
  - Energy yield may also vary due to cell manufacturer, design features (e.g., presence of a bottom vent), etc.
  - The fraction of thermal runaway leaving the cell casing walls (via conduction, convection, and radiation) compared to that leaving the cell as vented effluents is not known and varies from event to event.
- **For successful modeling, the distribution of thermal runaway energies and the fractions of energy (from vented effluents and that leaving the cell through the casing walls) must be quantified.**



18650 Cell Array in a 9P “Picket Fence” Configuration



Thermal Runaway Simulation

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[2] *Rickman et. al., “Considerations for Thermal Modeling of Lithium-Ion Cells for Battery Analysis.” 46th International Conference on Environmental Systems (ICES). 10-14 July 2016.*

MODELING THERMAL RUNAWAY

- Analytical models of thermal runaway are needed to inform battery thermal design.
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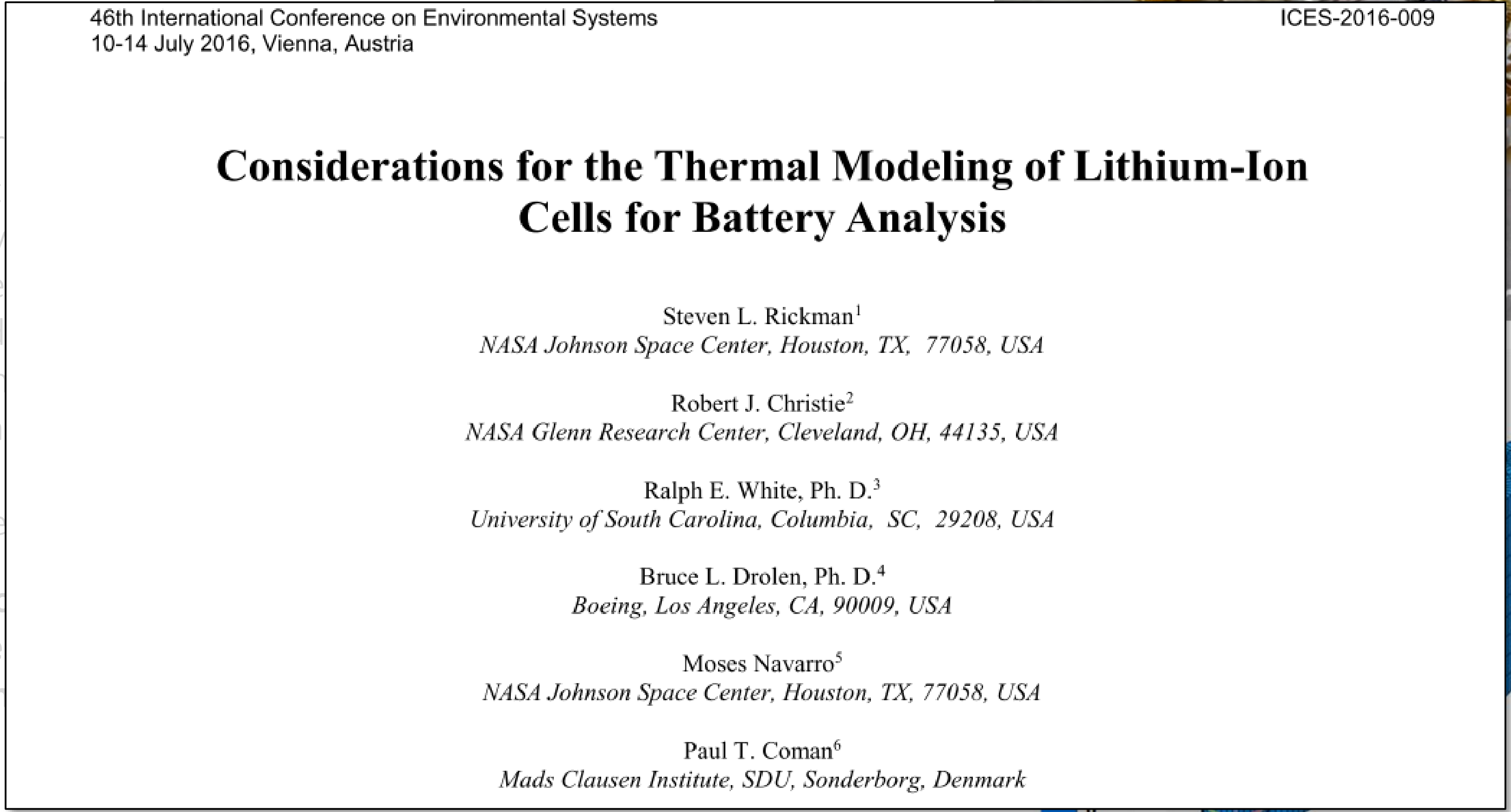

46th International Conference on Environmental Systems
10-14 July 2016, Vienna, Austria
ICES-2016-009

Considerations for the Thermal Modeling of Lithium-Ion Cells for Battery Analysis

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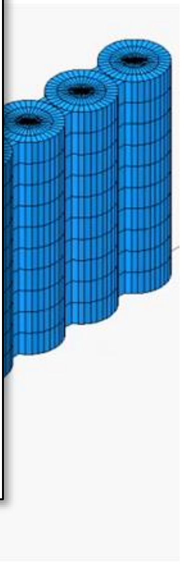
Paul T. Coman[6]
Mads Clausen Institute, SDU, Sonderborg, Denmark



Thermal Runaway Simulation

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[2] *Rickman et. al., “Considerations for Thermal Modeling of Lithium-Ion Cells for Battery Analysis.” 46th International Conference on Environmental Systems (ICES). 10-14 July 2016.*

EXISTING CALORIMETRIC TECHNIQUES

- **Accelerating Rate Calorimetry (ARC)**
  - Used to determine the onset of self heating/thermal runaway in cells.
  - Cells are heated slowly and thermal runaway is not representative of field failures (cell venting a long time prior to the onset of thermal runaway, triggering by other means such as nail penetration).
  - However, due to the slow heating, turnaround time is on the order of days per test.
  - While a tally of thermal energy yield is available, there is no practical means to discern thermal runaway energy fractions (via various heat transfer modes).

- **Bomb Calorimetry**
  - Adequate for tallying total heat output.
  - No practical means of discerning thermal runaway energy fractions.

- **Copper Slug Calorimetry**
  - Effective at measuring heat output through cell casing but does not measure heat liberated in the ejecta.
  - Estimates rate of mass ejection during thermal runaway.
  - Must be used in conjunction with bomb calorimetry to tally ejected heat.
  - No practical means of discerning thermal runaway energy fractions.

---

[3] *Walker et. al., "Decoupling of heat generated from ejected and non-ejected contents of 18650-format lithium-ion cells using statistical methods." J. Power Sources. 2019.*

THE NEED FOR A NEW CALORIMETRIC TOOL

- **While each type of calorimetry available provides some insights into cell thermal runaway, none provide the necessary all of the features required for thermal runaway characterization – an ideal calorimeter would provide:**
  - Rapid triggering of thermal runaway, representative of field failure (such as failures that occur at room temperature).
  - Rapid testing of multiple cells with minimal turnaround time to allow collection of a statistically significant data set (i.e., many tests per day).
  - A means of separately tallying the heating contributions due to vented effluents and heating conducting from and/or convecting and radiating from the cell casing.
- **A new calorimetric tool is needed.**

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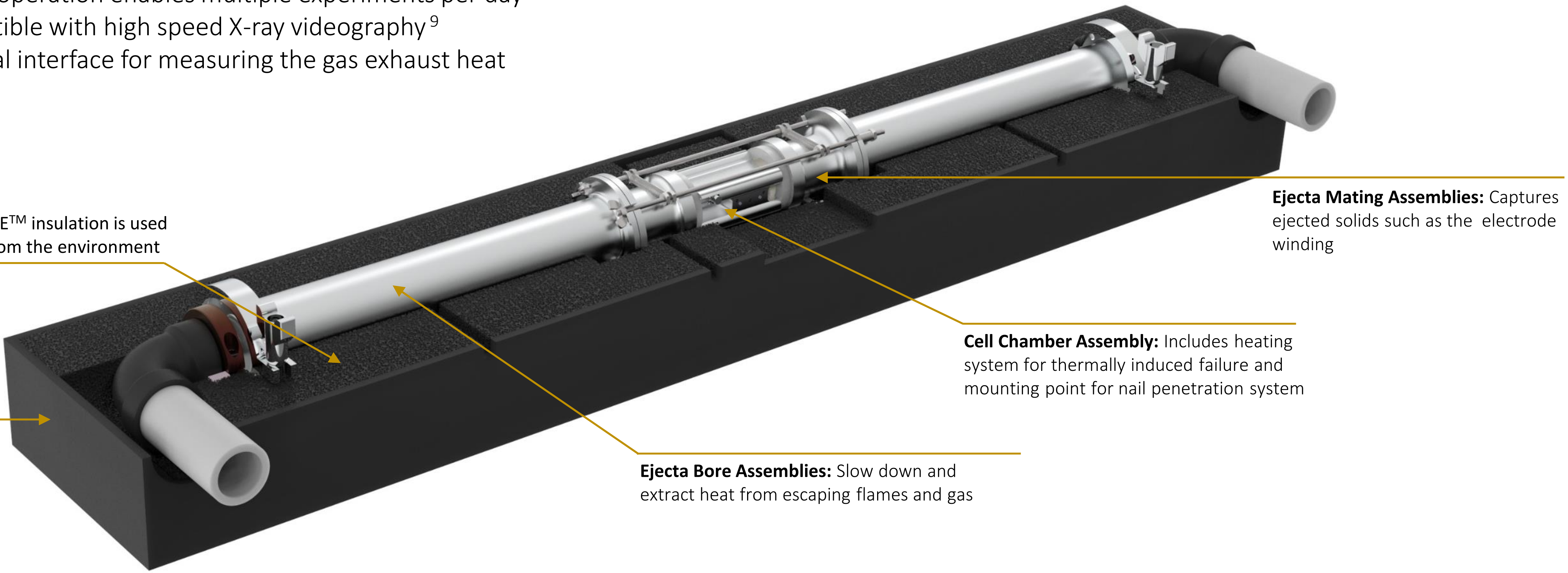
[3] *Walker et. al., "Decoupling of heat generated from ejected and non-ejected contents of 18650-format lithium-ion cells using statistical methods." J. Power Sources. 2019.*

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **As an NESC assessment, NASA developed a new fractional TR calorimetry (FTRC) method for 18650-format Li-ion cells:**
  - Collaborators included NESC, NASA JSC, and SAIC
  - Allows discernment between (1) total heat output and (2) fraction of heat released through the cell casing vs. ejecta material
  - The energy distributions are determined by post processing temperature vs. time for each calorimeter sub-assembly (i.e. $\sum m_i C_{p_i} dT_i$)
  - Ambidextrous configuration accommodates cell designs with bottom vents (BVs)
  - Uses high flux heaters to initiate TR quickly (i.e. relevant to field failure)
  - Simple operation enables multiple experiments per day
  - Compatible with high speed X-ray videography [9]
  - Optional interface for measuring the gas exhaust heat



Insulation: FOAMGLAS® ONE™ insulation is used to isolate the calorimeter from the environment

Housing: Lightweight and shipping ready housing is employed to support hardware mobility

Ejecta Mating Assemblies: Captures ejected solids such as the electrode winding

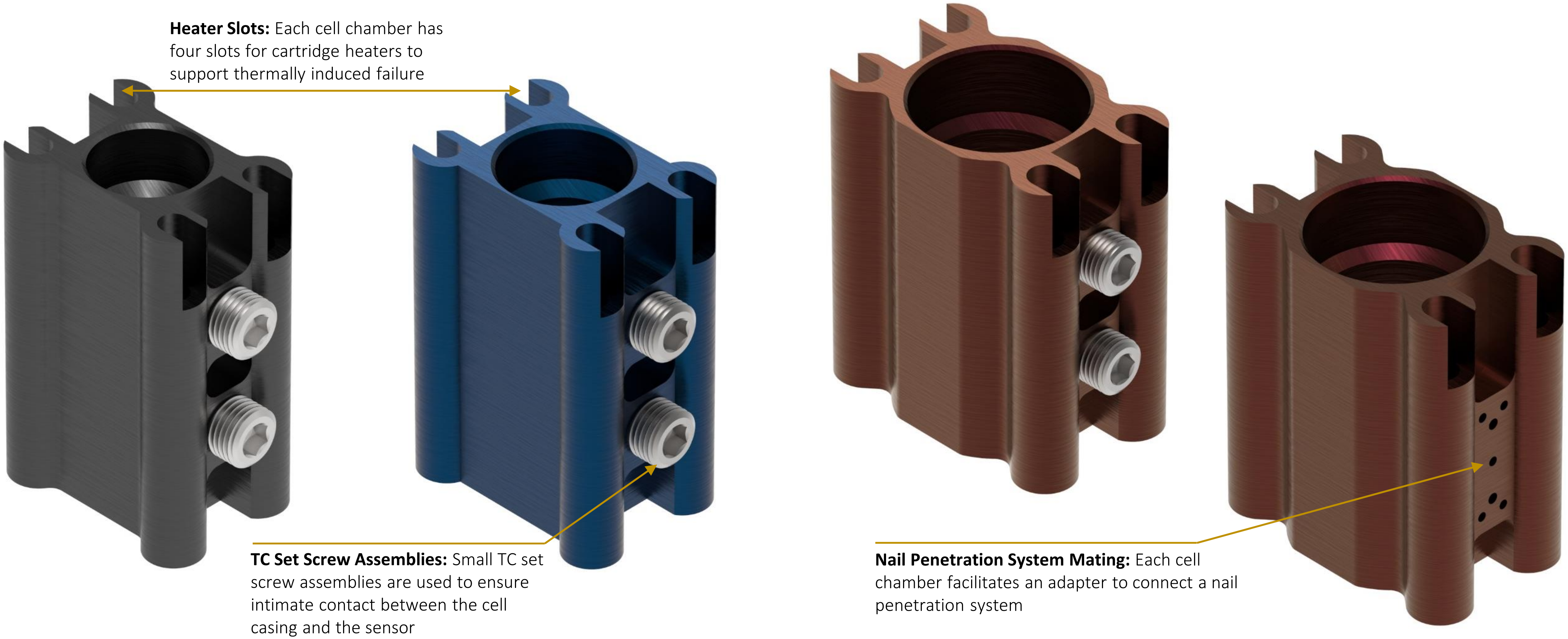
Cell Chamber Assembly: Includes heating system for thermally induced failure and mounting point for nail penetration system

Ejecta Bore Assemblies: Slow down and extract heat from escaping flames and gas

Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **The FTRC currently supports cell chambers designed for the following cell formats: 18650, 21700, and D-Cell:**
  - Utilizes the same downstream FTRC assemblies (i.e. the only adjustment to test a new cell is to swap out the cell chamber)
  - The current architecture supports cells with >5 Ah capacities
  - Stay tuned for new capabilities to support pouch cells and larger format cells…



Heater Slots: Each cell chamber has four slots for cartridge heaters to support thermally induced failure

TC Set Screw Assemblies: Small TC set screw assemblies are used to ensure intimate contact between the cell casing and the sensor

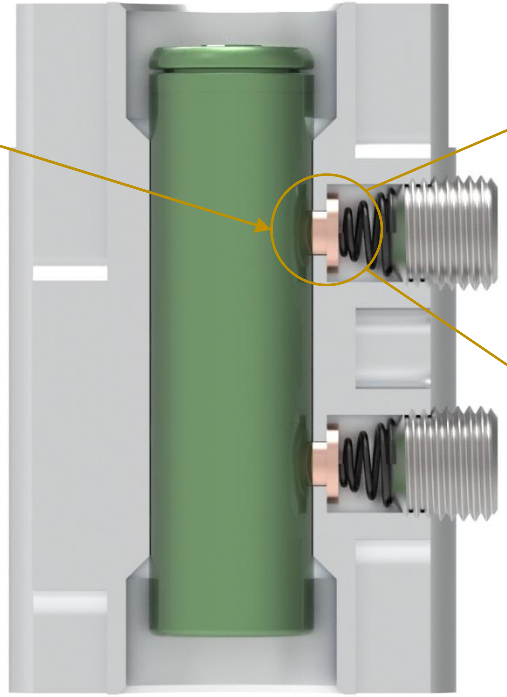
Nail Penetration System Mating: Each cell chamber facilitates an adapter to connect a nail penetration system

Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **Reliable temperature measurement from the side of the cell is critical to accurate calculation of the fraction of thermal runaway energy released through the cell casing:**
  - To support temperature measurement on the cell casing without actually installing a thermocouple, the FTRC cell chambers employ plunger like set screw assemblies that contain an imbedded thermocouple
  - When released, the spring loaded set screw assembly forces intimate contact between the embedded thermocouple and the cell casing

TC Set Screw Assemblies: Used to maintain intimate contact between the cell casing and the thermocouple

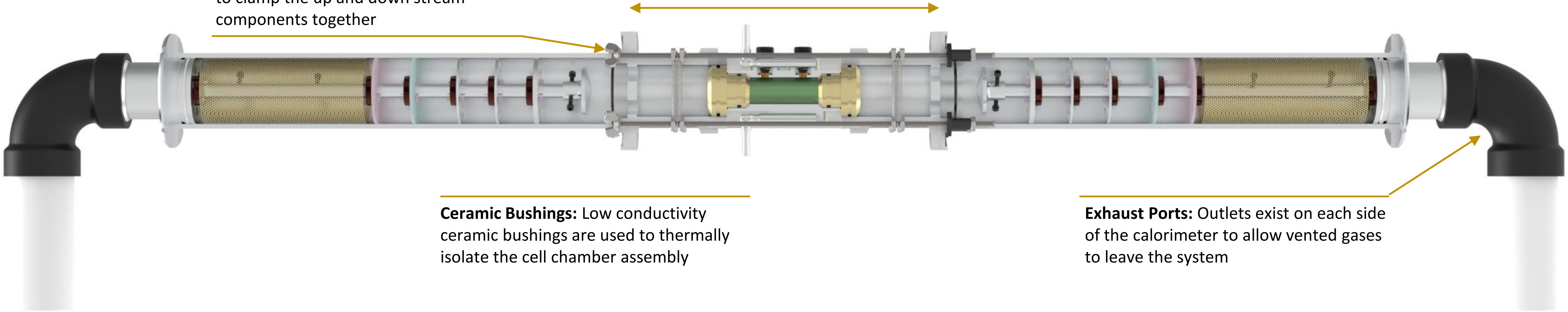


X-Ray Image: Image reveals the contact between the TC set screw assembly and an 18650 Li-ion cells installed in the FTRC during testing at Diamond Light Source in 2019.

Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **The FTRC is designed to not only facilitate testing of different cell types, but to also help characterize directional/fractional thermal runaway failure behavior (i.e. top vent, bottom vent, ruptures from any location, et…)**
- **The cell chamber assembly is isolated from the remainder of the up and down stream calorimeter components with low conductivity ceramic bushings:**
  - Maintaining this thermal isolation is critical to our team's ability to discern the fraction of energy released through the cell casing vs. through the ejecta material
  - The ejecta mating segment is designed to capture and stop complete jellyroll ejections; with this capability, we can also determine the fraction of energy associated with an ejected jellyroll



Symmetric (Ambidextrous) Design: Supports both top and bottom vent (and rupture) thermal runaway behavior

Tie Rods: Spring loaded tie rods are used to clamp the up and down stream components together

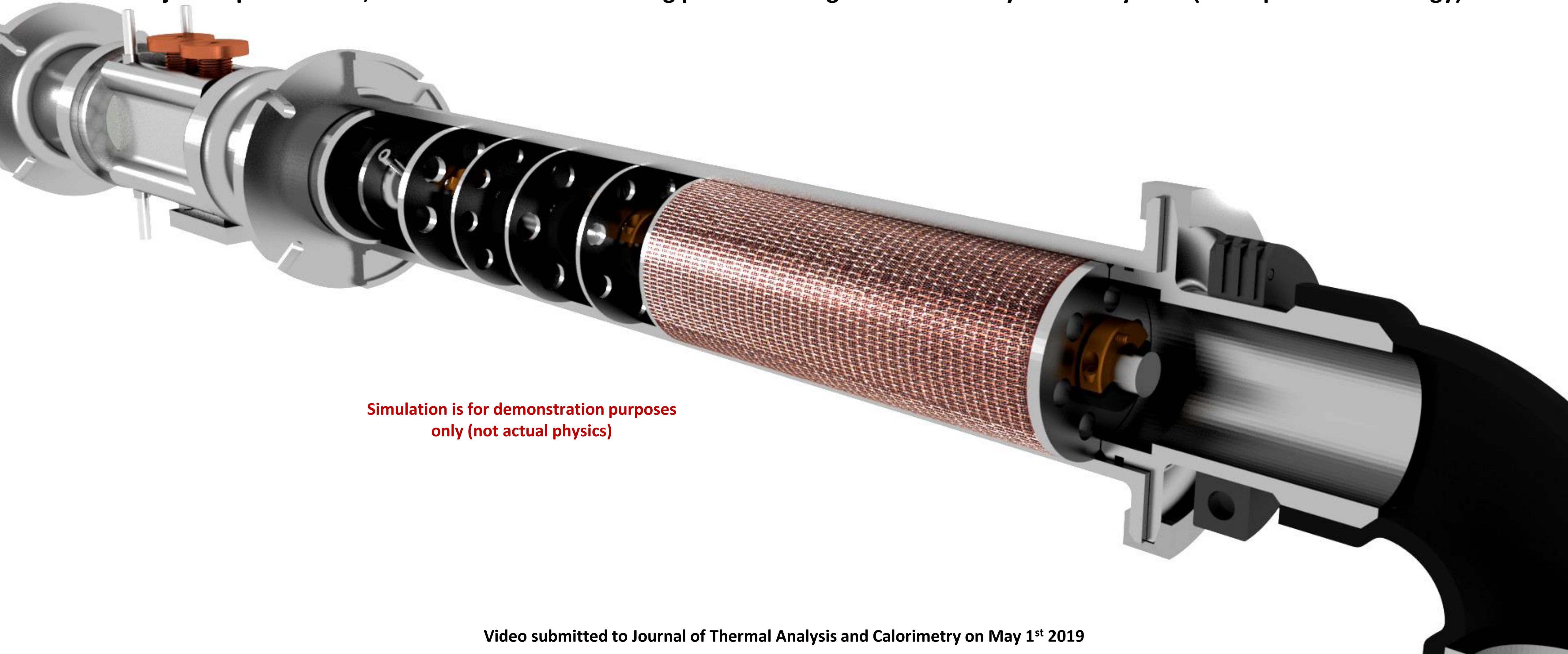
Ceramic Bushings: Low conductivity ceramic bushings are used to thermally isolate the cell chamber assembly

Exhaust Ports: Outlets exist on each side of the calorimeter to allow vented gases to leave the system

Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **The internal baffles and copper mesh are used to create a tortuous path that effectively reduces flow velocity, captures large and fine ejected particulates, and cools down the flowing particles and gases before they exit the system (i.e. captures the energy)**



Simulation is for demonstration purposes only (not actual physics)

Video submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

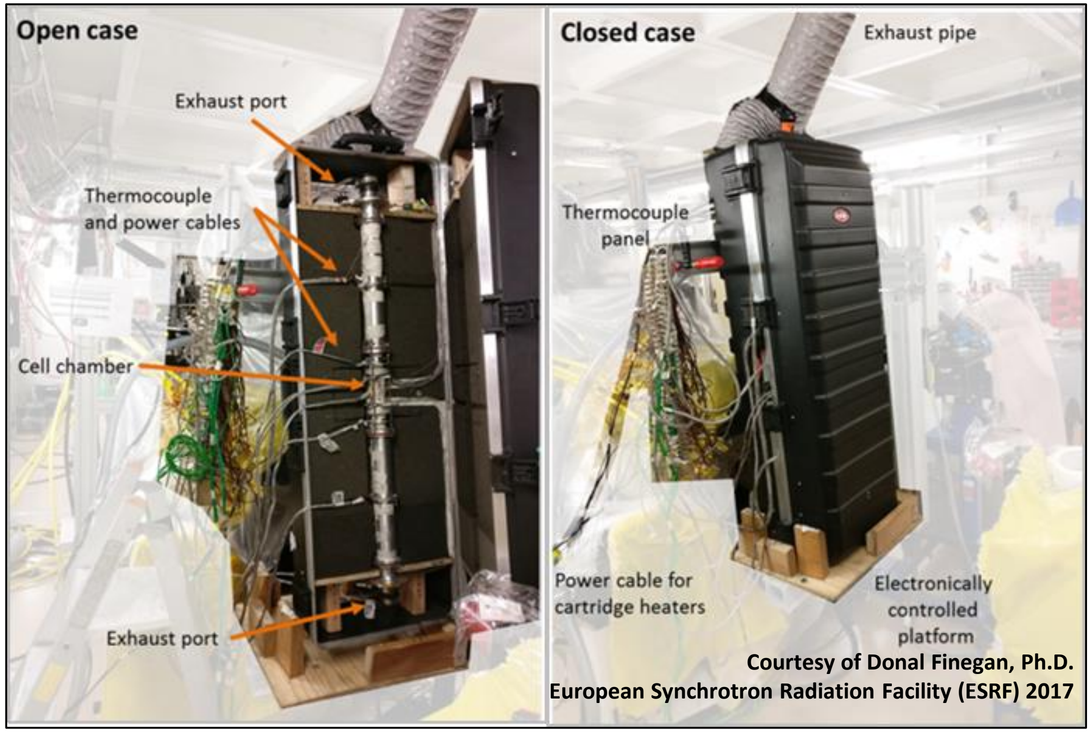
EXAMPLE FTRC TESTING

NASA Johnson Space Center
Energy Systems Test Area (ESTA)
September 27th, 2018
FTRC: LG 18650-HG2

Video submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

FRACTIONAL THERMAL RUNAWAY CALORIMETRY

- **Images below depict the global testing capability of the device:**
  - FTRC testing at the NASA JSC Energy Systems Test Area
  - FTRC testing at the European Synchrotron Radiation Facility (ESRF) for in-situ high speed tomography (left image)
  - FTRC testing at the Diamond Light Source (DLS) Facility for in-situ high speed tomography (right image)

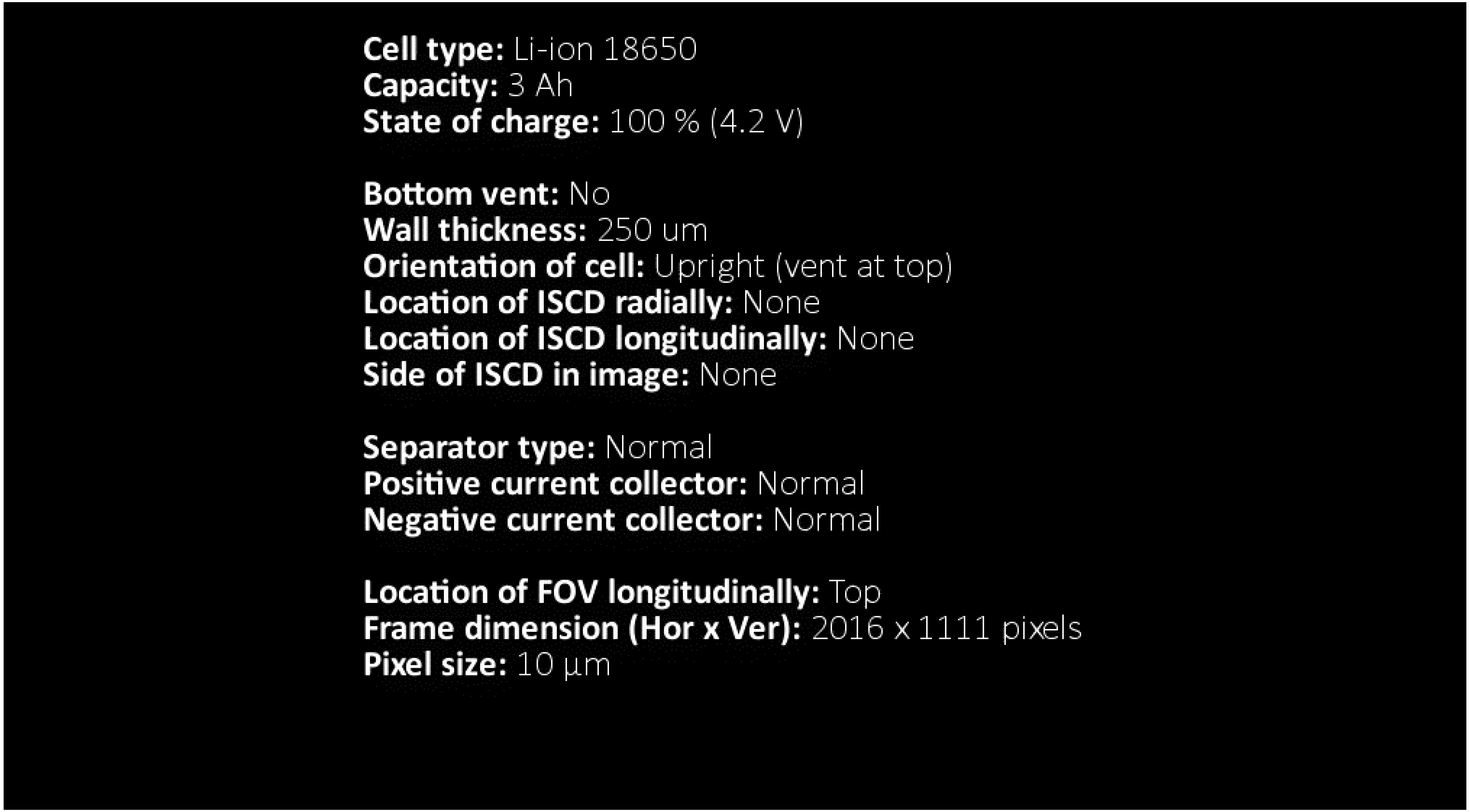


Courtesy of Donal Finegan, Ph.D.
European Synchrotron Radiation Facility (ESRF) 2017

Courtesy of William Walker, Ph.D.
Diamond Light Source (DLS) 2019

Image submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

HIGH SPEED XRAY VIDEOGRAPHY



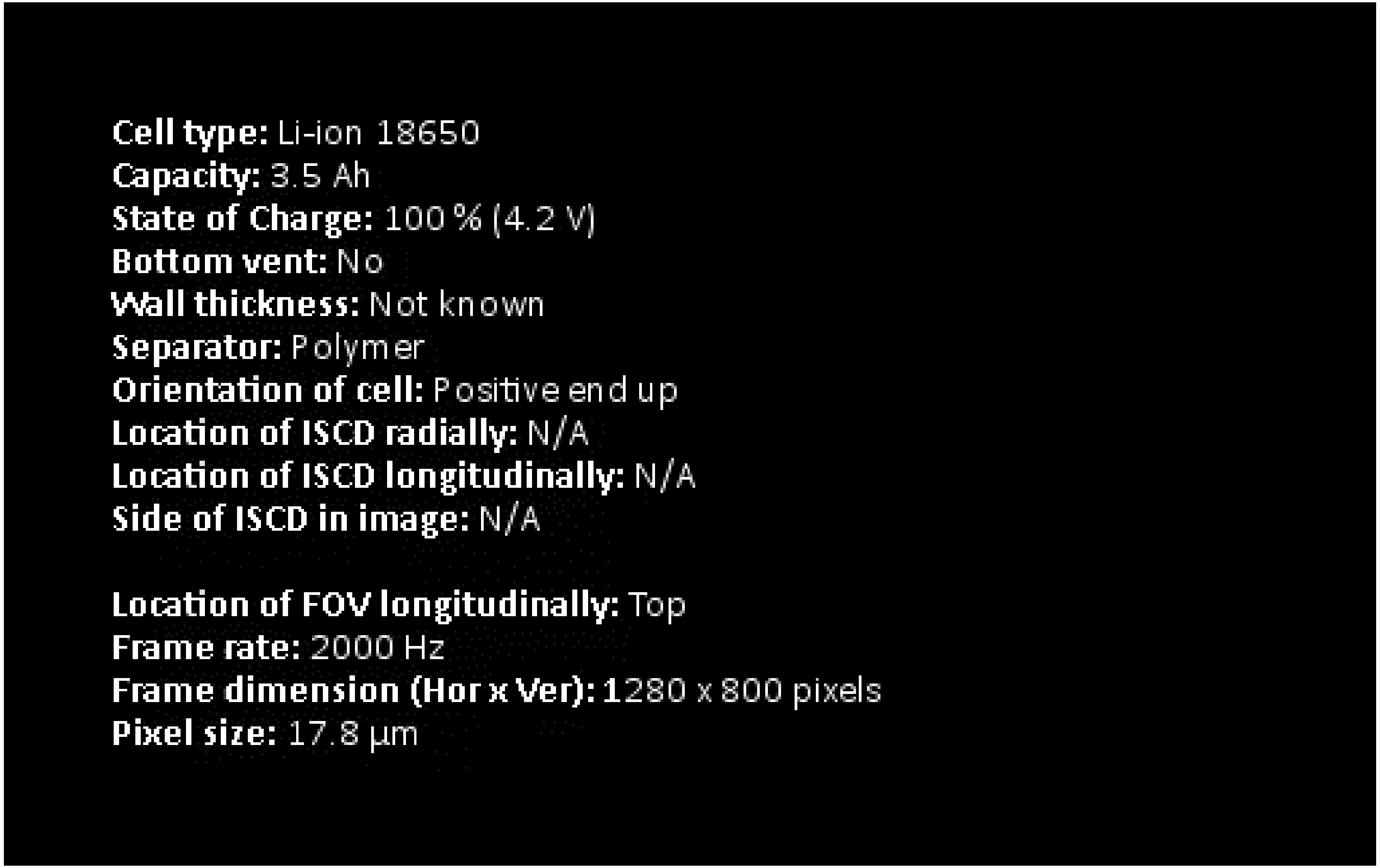
Cell type: Li-ion 18650
Capacity: 3 Ah
State of charge: 100 % (4.2 V)

Bottom vent: No
Wall thickness: 250 um
Orientation of cell: Upright (vent at top)
Location of ISCD radially: None
Location of ISCD longitudinally: None
Side of ISCD in image: None

Separator type: Normal
Positive current collector: Normal
Negative current collector: Normal

Location of FOV longitudinally: Top
Frame dimension (Hor x Ver): 2016 x 1111 pixels
Pixel size: 10 µm

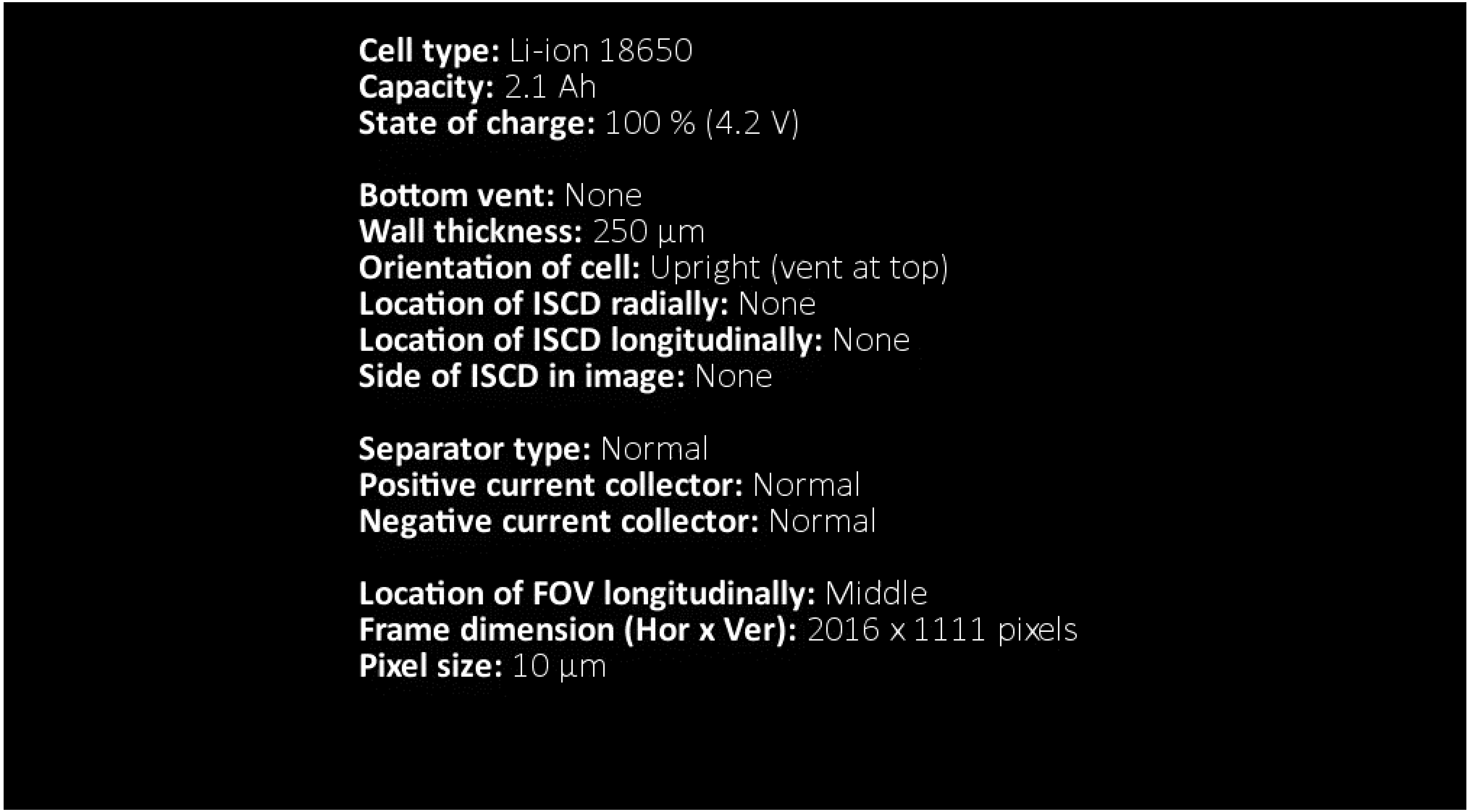
HIGH SPEED XRAY VIDEOGRAPHY



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

HIGH SPEED XRAY VIDEOGRAPHY



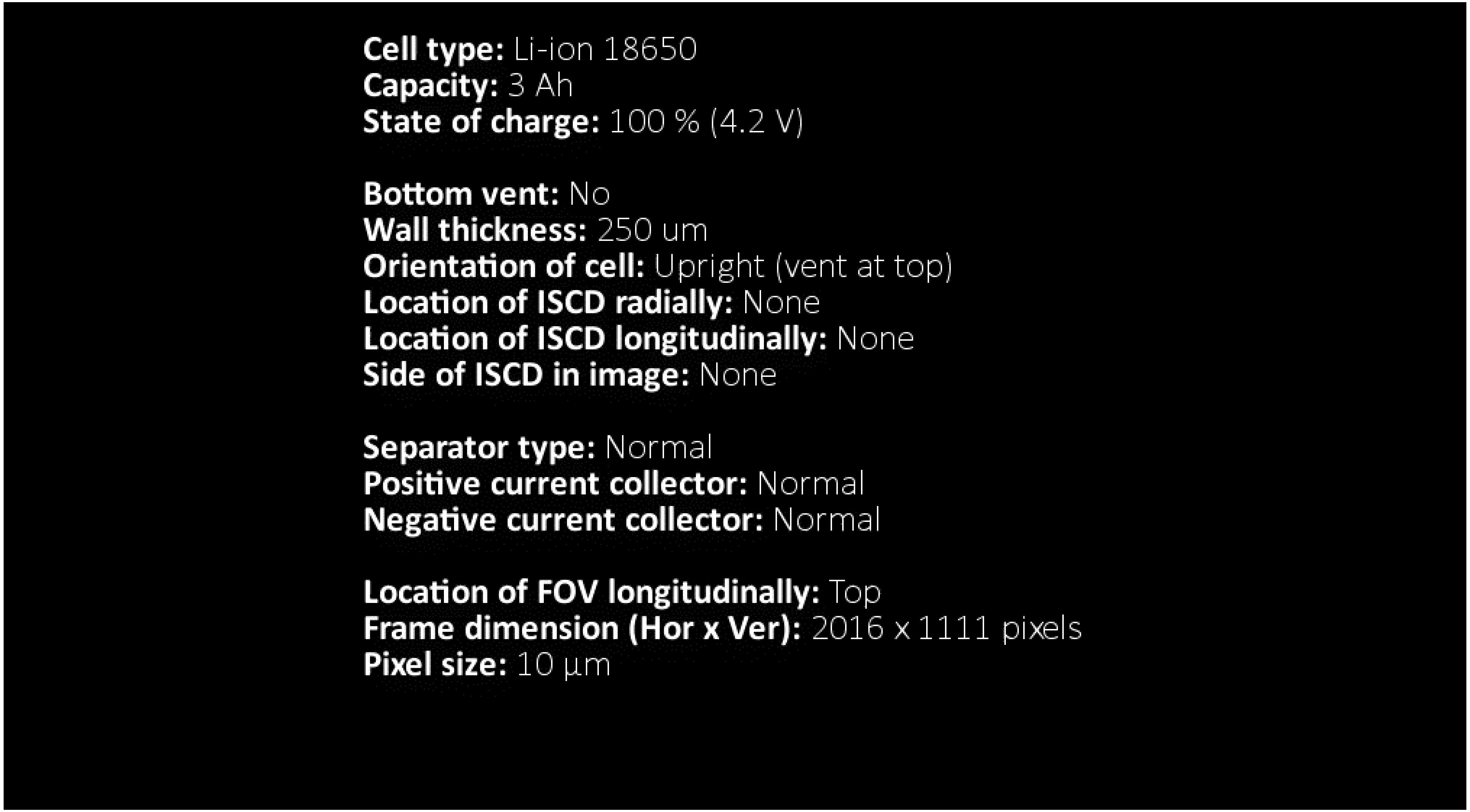
Cell type: Li-ion 18650
Capacity: 2.1 Ah
State of charge: 100 % (4.2 V)

Bottom vent: None
Wall thickness: 250 µm
Orientation of cell: Upright (vent at top)
Location of ISCD radially: None
Location of ISCD longitudinally: None
Side of ISCD in image: None

Separator type: Normal
Positive current collector: Normal
Negative current collector: Normal

Location of FOV longitudinally: Middle
Frame dimension (Hor x Ver): 2016 x 1111 pixels
Pixel size: 10 µm

HIGH SPEED XRAY VIDEOGRAPHY



Cell type: Li-ion 18650
Capacity: 3 Ah
State of charge: 100 % (4.2 V)

Bottom vent: No
Wall thickness: 250 um
Orientation of cell: Upright (vent at top)
Location of ISCD radially: None
Location of ISCD longitudinally: None
Side of ISCD in image: None

Separator type: Normal
Positive current collector: Normal
Negative current collector: Normal

Location of FOV longitudinally: Top
Frame dimension (Hor x Ver): 2016 x 1111 pixels
Pixel size: 10 µm

FTRC RESULTS: CHARACTERIZATION OF TOTAL ENERGY RELEASE

- **Since no two thermal runaway events are the same, test-to-test variability must be taken into consideration for any scientific effort that seeks to characterize the overall range of expected thermal runaway behavior for a given cell type**
- **Used a regression modeling approach to interpret and compare the FTRC results for total thermal runaway energy release for different cell types and varied design feature combinations (e.g. bottom vent, casing thickness, and separator material)**
    - Plot below displays results for a variety of 18650 format cells with capacities ranging between 2.4 Ah to 3.5 Ah
    - Statistical analysis reveals that the distribution of expected total energy release for the cells considered is non-normal and is best characterized with a long right tail; it is also observed that there is a smaller test-to-test standard deviation as cell capacity decreases

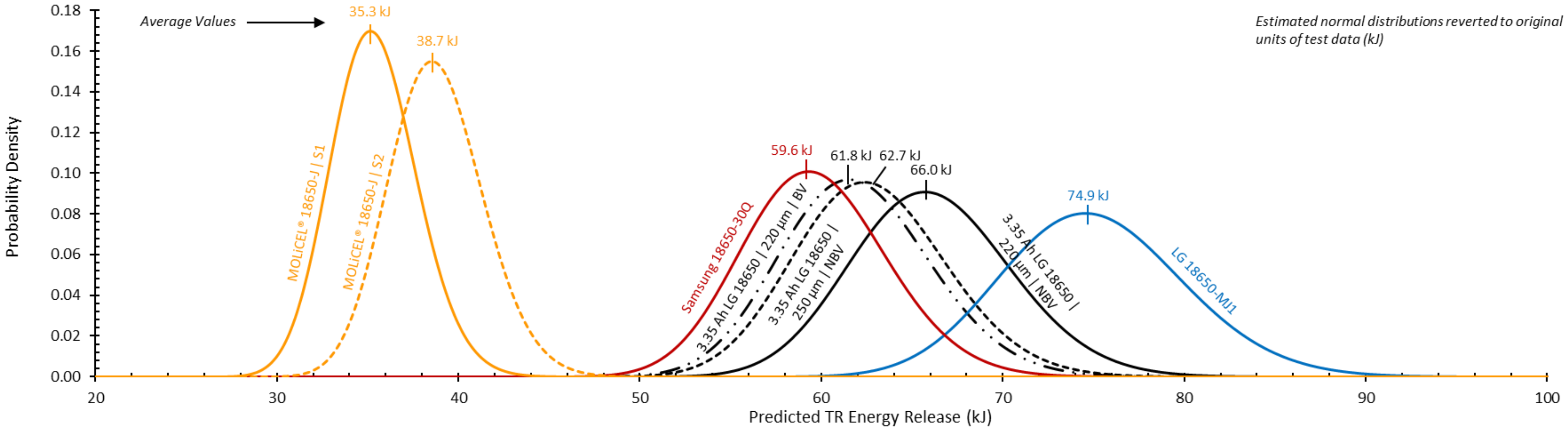


Image courtesy of Walker et. al., J. Power Sources. 2019.

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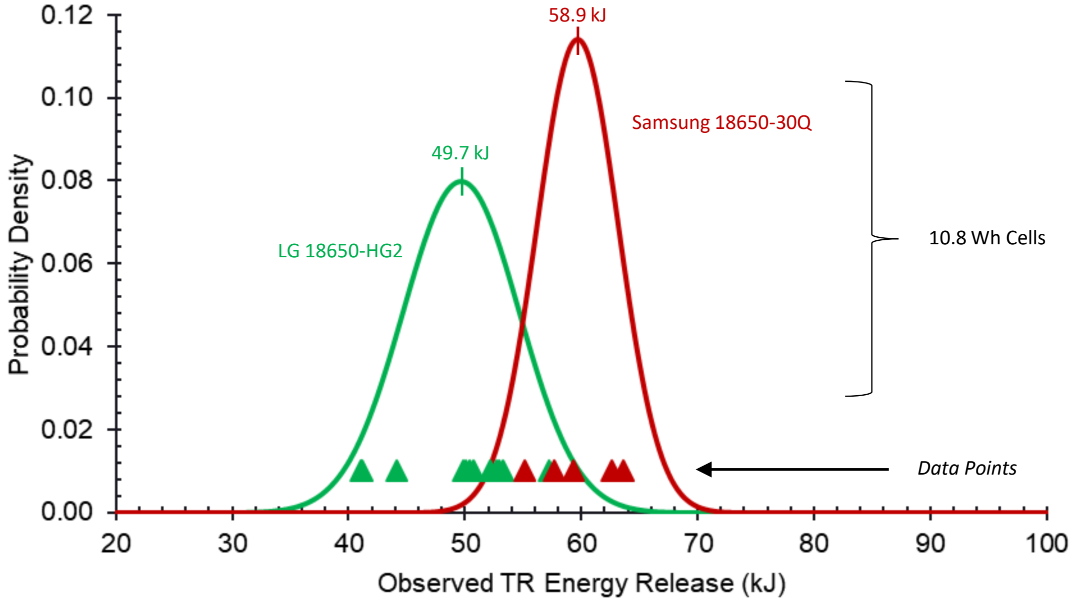
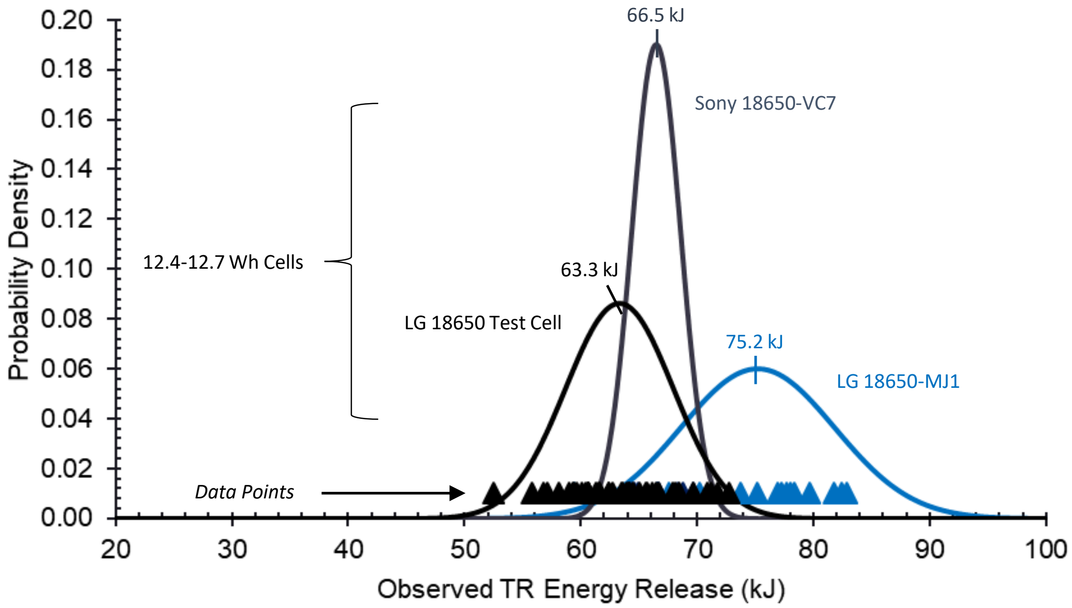
[3] *Walker et. al., "Decoupling of heat generated from ejected and non-ejected contents of 18650-format lithium-ion cells using statistical methods." J. Power Sources. 2019.*

FTRC RESULTS: IMPACT OF CELL LEVEL ENERGY DENSITY

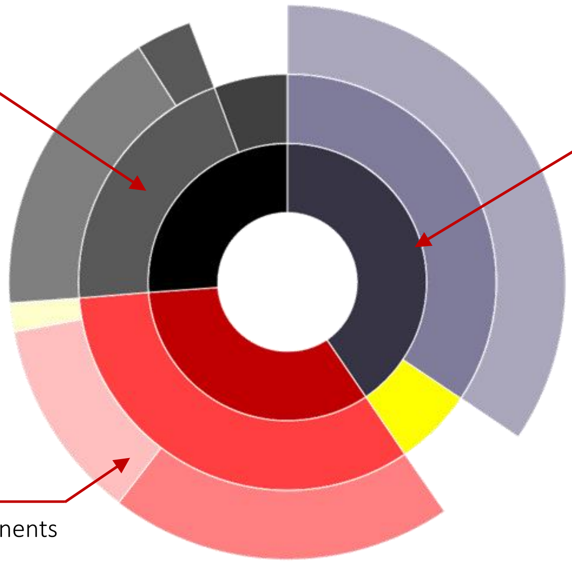
- **There is not a linear relationship between stored electrochemical energy and the total energy released:**
  - The two 10.8 Wh cells have significantly different thermal runaway responses with the Samsung 18650-30Q average total energy release at 59.7 kJ and the LG 18650-HG2 average total energy release at 49.7 kJ
  - The three higher energy cells (12.4 to 12.7 kJ) also have differing thermal runaway responses with the LG 18650 Test Cell average total energy release of 63.3 kJ, the Sony 18650-VC7 average total energy release of 66.5 kJ, and the LG 18650-MJ1 average total energy release of 75.2 kJ





FTRC RESULTS: ENERGY RELEASE FRACTIONS

- **The calculated energy fractions are traceable to every calorimeter assembly, sub-assembly, and individual component**
- **The primary assemblies used for fractional calculations are the following:**
  - Cell Chamber Assembly (Red)
  - Positive Ejecta Mating Assembly (Indigo)
  - Positive Ejecta Bore Assembly (Indigo)
  - Negative Ejecta Mating Assembly (Black)
  - Negative Ejecta Bore Assembly (Black)



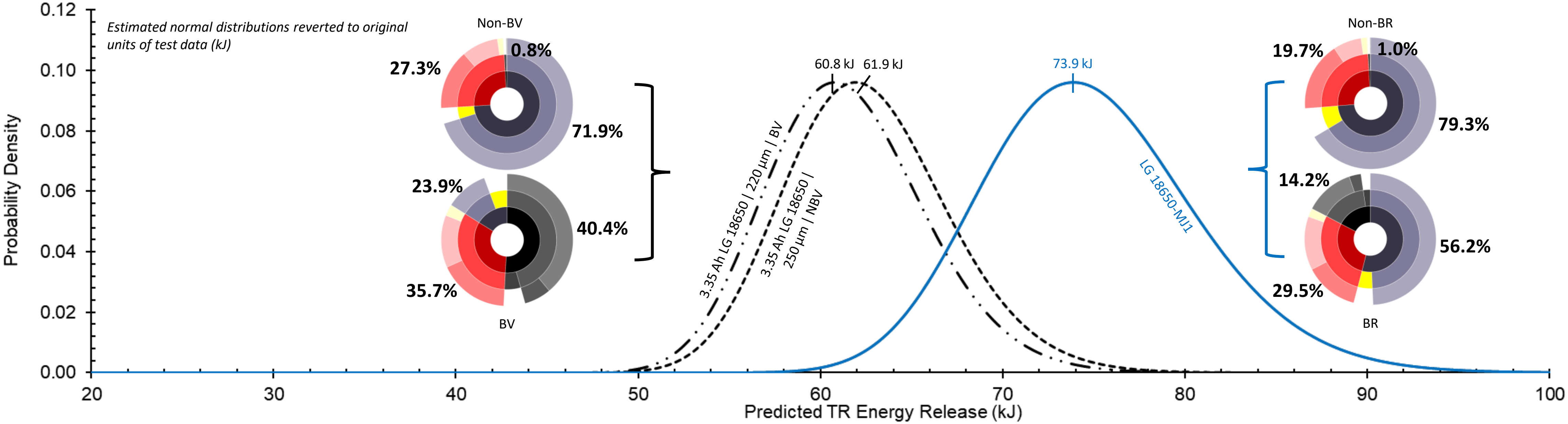
Middle Ring: Indicates calorimeter sub-assemblies

Inner Ring: Characterizes the division of total TR energy release where red corresponds to the cell casing, indigo to the positive ejecta and gases, and black to the negative ejecta and gases

Outer Ring: Corresponds to components of the calorimeter sub-assemblies

FTRC RESULTS: ENERGY RELEASE FRACTIONS

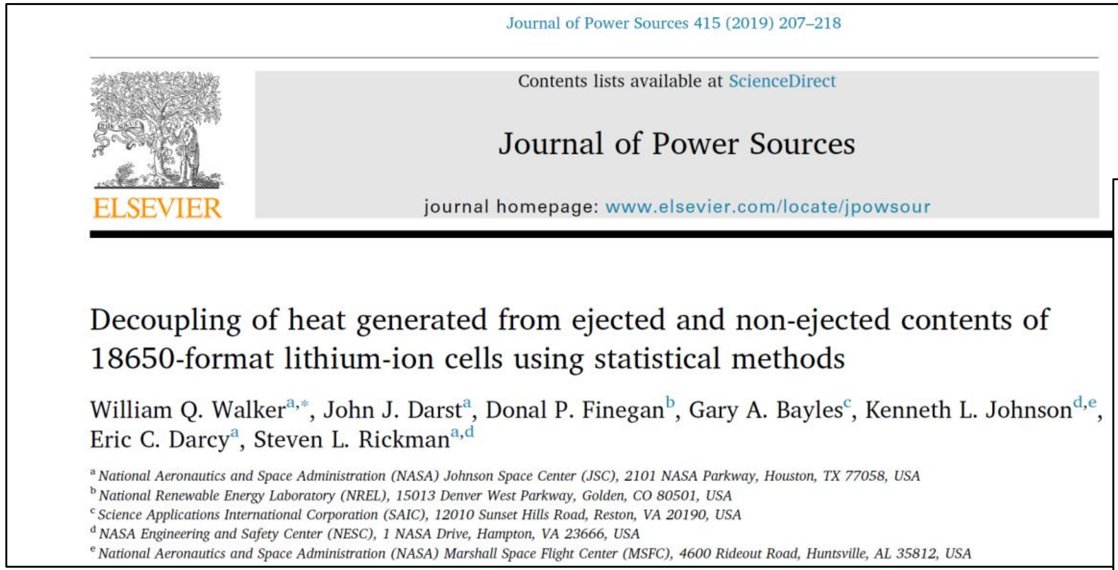
- **The thermal runaway energy release fractions are determined for every cell configuration:**
  - Fractions can be determined from an average of all results for a given cell type or can be an average based on nominal vs. off nominal failure mechanism (e.g. difference between top vent vs. bottom rupture)
  - Fractional analysis is particularly helpful in comparing the distribution of standard vent cells to bottom vent cells
  - Standard cells typically release 20-30% through the cell casing and the remainder through the ejecta material
  - Bottom vent cells tend to release the energy in a three-way split between the casing and the top and bottom ejecta materials
- **The fractions quantify the direct impingement of energy on neighbor cells during runaway events**



Images and data analysis submitted to J. Power Sources August 2018

SUMMARY

- **FTRC techniques and the associated results provide the means to develop optimized Li-ion batteries while also maintaining necessary safety and margin**
- **FTRC, and the associated results, enables the discernment of the fractions of thermal runaway energy released through the cell casing and through the ejecta material:**
  - Due to the variability in thermal runaway responses, we recommend at least 10 runs to establish statistically defendable results
  - Can analyze the spread of heat sources when cells rupture and compare to when they remain intact



Journal of Power Sources 415 (2019) 207–218

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Decoupling of heat generated from ejected and non-ejected contents of 18650-format lithium-ion cells using statistical methods

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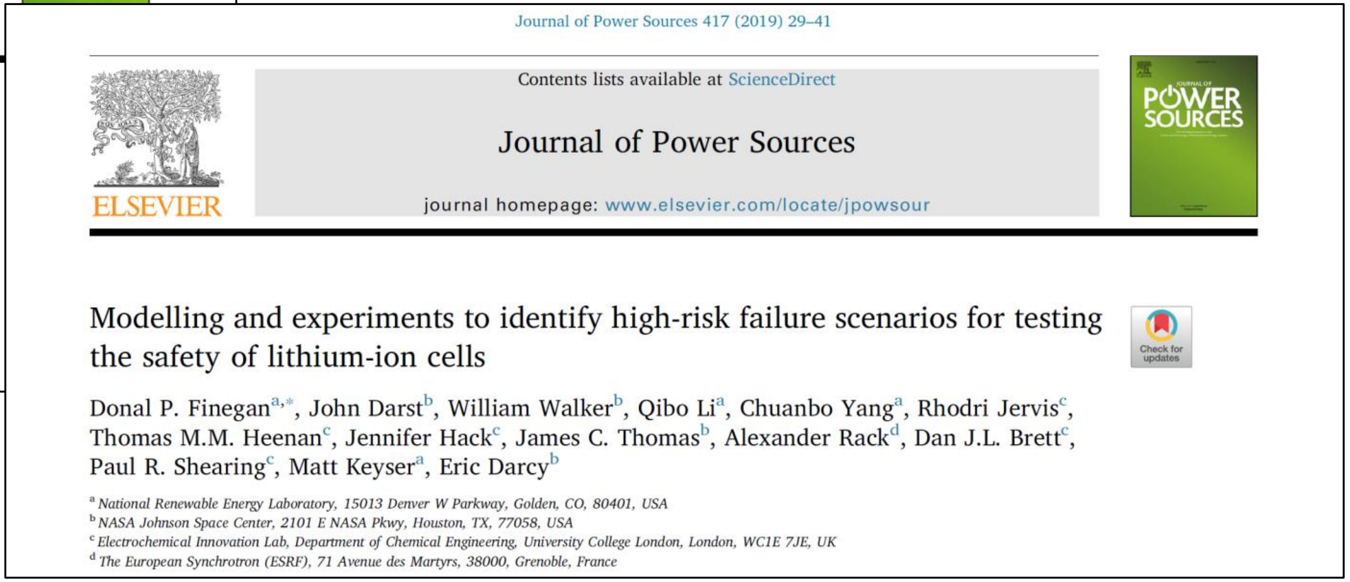
[b] National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80501, USA
[c] Science Applications International Corporation (SAIC), 12010 Sunset Hills Road, Reston, VA 20190, USA
[d] NASA Engineering and Safety Center (NESC), 1 NASA Drive, Hampton, VA 23666, USA
[e] National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC), 4600 Rideout Road, Huntsville, AL 35812, USA



Journal of Power Sources 417 (2019) 29–41

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/jpowsour

Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells

Donal P. Finegan[a,*], John Darst[b], William Walker[b], Qibo Li[a], Chuanbo Yang[a], Rhodri Jervis[c], Thomas M.M. Heenan[c], Jennifer Hack[c], James C. Thomas[b], Alexander Rack[d], Dan J.L. Brett[c], Paul R. Shearing[c], Matt Keyser[a], Eric Darcy[b]

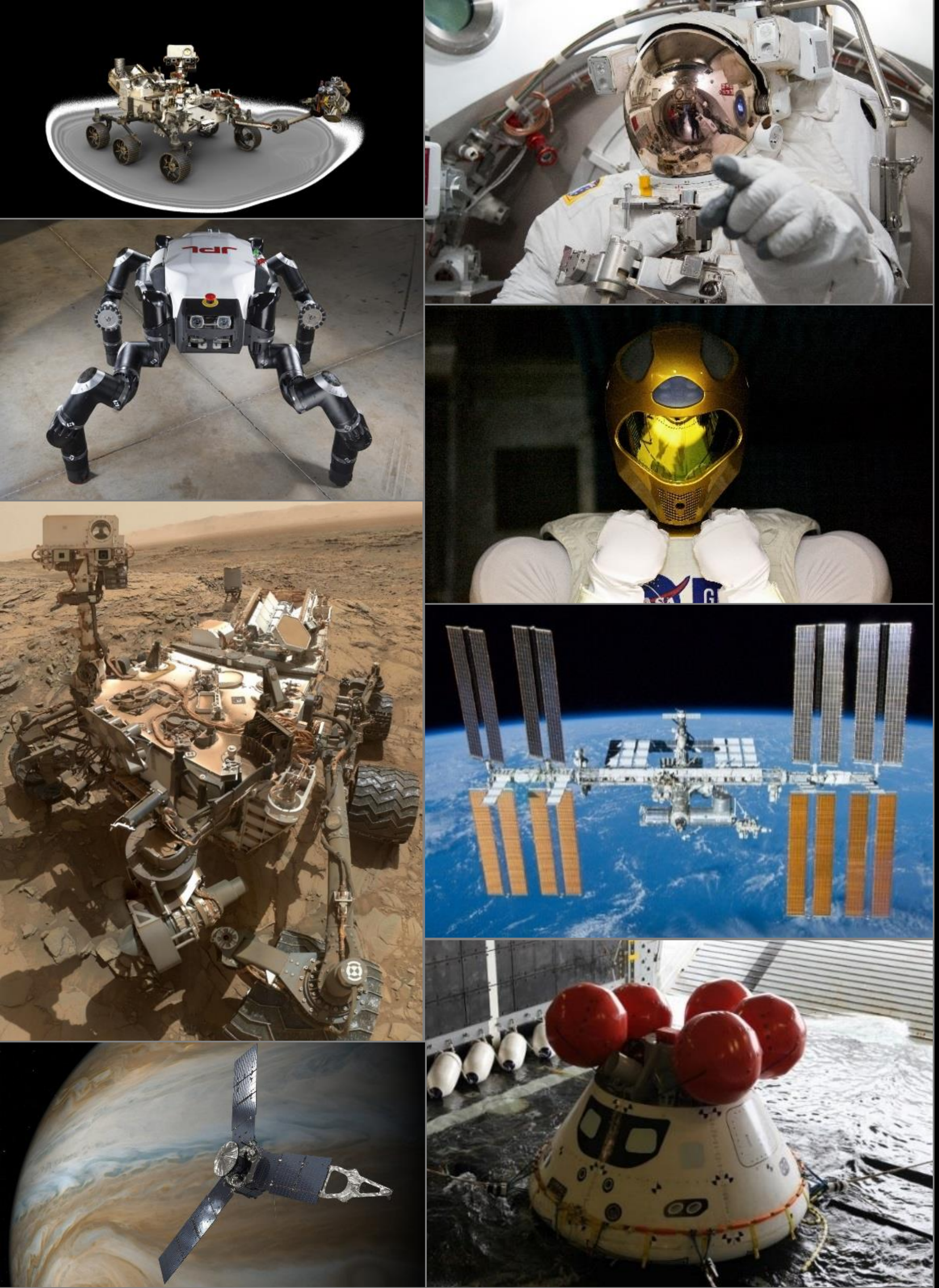
[a] National Renewable Energy Laboratory, 15013 Denver W Parkway, Golden, CO, 80401, USA
[b] NASA Johnson Space Center, 2101 E NASA Pkwy, Houston, TX, 77058, USA
[c] Electrochemical Innovation Lab, Department of Chemical Engineering, University College London, London, WC1E 7JE, UK
[d] The European Synchrotron (ESRF), 71 Avenue des Martyrs, 38000, Grenoble, France

SNEAK PREVIEW OF NEW CAPABILITIES

- Actively working to address the unique challenges associated with pouch cell thermal runaway events which requires a substantially different FTRC architecture
- Not all applications utilize small format Li-ion cells – another effort is underway to develop FTRC for cell's with capacities >100 Ah

ACKNOWLEDGEMENTS

- **NASA Engineering and Safety Center**
  - Steve Rickman and Christopher Iannello, Ph.D.
- **NASA JSC Engineering Directorate (EA):**
  - Power and Propulsion Division (EP)
  - Structural Engineering Division (ES)
- **FTRC Team Members**
- **NASA JSC Energy Systems Test Area (ESTA)**
- **Diamond Light Source (DLS) Facility**
- **European Synchrotron Radiation Facility (ESRF)**



QUESTIONS?