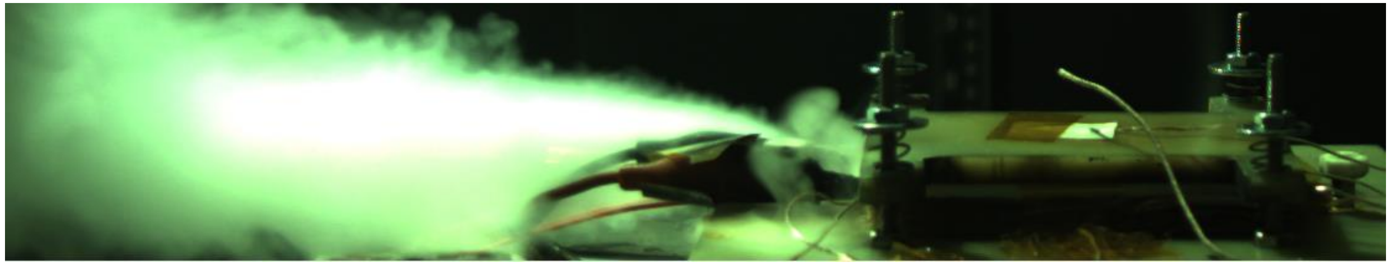
Tenth Triennial International Aircraft Fire and Cabin Safety Research Conference

Burning Characteristics of Lithium-ion Batteries



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Cleveland, Ohio 44135-3191

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Impact from Battery Fires in Space

Lithium-ion Batteries (LIB) are crucial in future power systems, however their prevalence requires the evaluation of their unique risks

Battery Applications in Space

- Spacesuits, research, rovers, and inside sleeping pods

Causes of Thermal Runaway (TR) In Li-ion Batteries

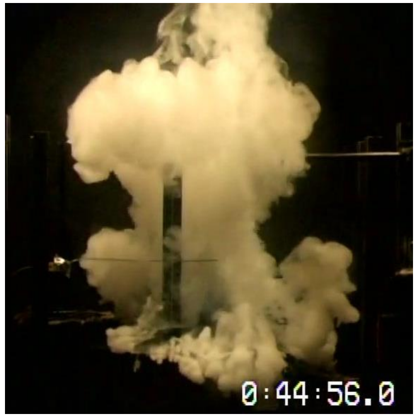
- External (physical abuse, rapid discharge, overcharging, exposure to an external fire)
- Internal (shorts due to dendrites and manufacturing defects)

Uniqueness In Environment

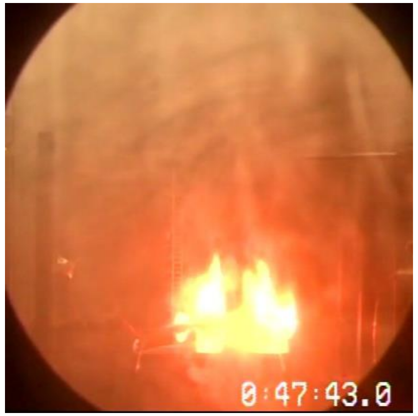
- Confined volume/limited egress, high O_2, and microgravity effects

Vehicle and Crew Impact

- Fire/Heat
- Smoke
- Gases
- Debris



Aggressive Ejection of Electrolyte Vapor



Fire


Smoke


Debris

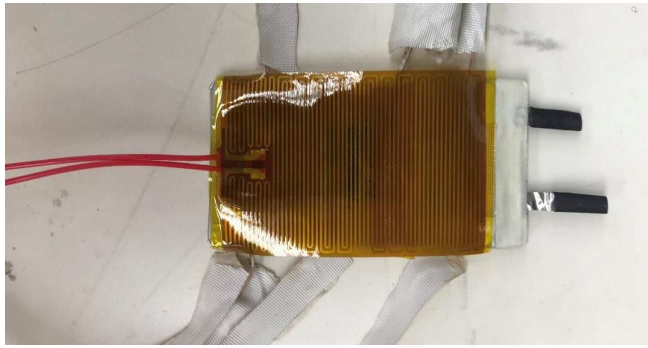
Research Objectives

Li-ion battery fires are being used as the worst-case cabin fire events due to the potential catastrophic impact

- Quantify the burning characteristics (of ignition and failure process) and energy release from a Li-ion pouch cell followed by battery packs (w/o chassis)
- Quantify gas emissions and aerosols from pouch cells and tablet battery packs

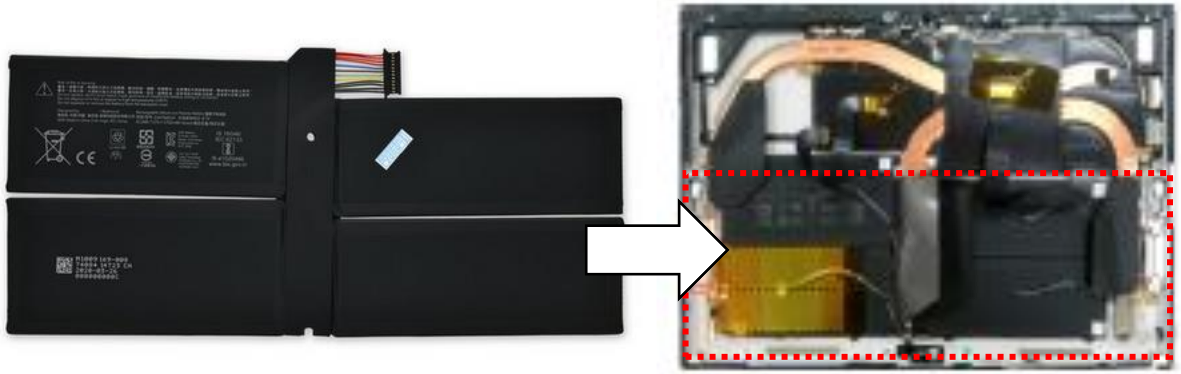
Experimental data will be used to quantify the impact of Li-ion battery fires on the vehicle and crew. Data will contribute to:

- Risk assessment analysis
- Technology development (smoke detectors)
- Development of safety equipment
- Cleanup procedures
- Fire suppression and fire response protocols
- Use measured heat release rates and rate of production of toxic products in simulations of fires in spacecraft



9.25 Wh Single Pouch Cell

Future Test Campaigns

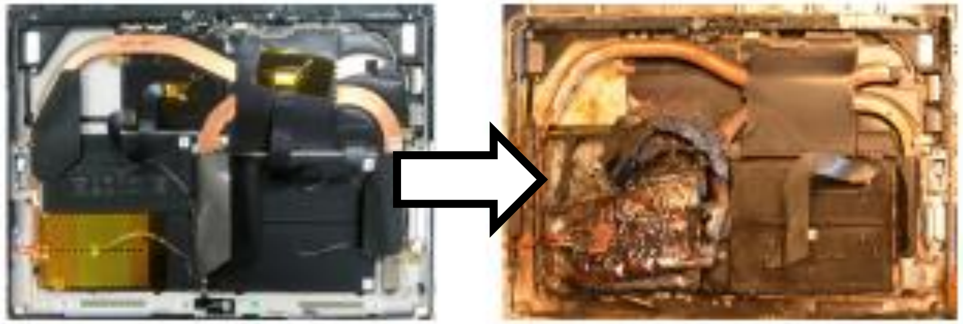


45 Wh Multi-Battery Pack

Previous Work

In 2018, NASA White Sands Test Facility (WSTF) conducted battery tests on laptops using an external, electric heating coil (Harper et al. 2018). In 2019, patch heaters were added to tablets and laptops.

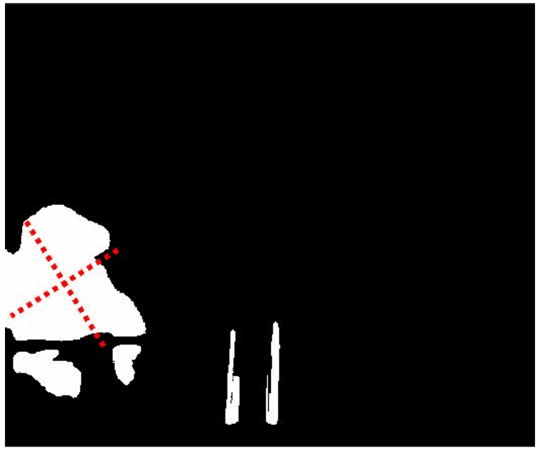
Electric Coil



Patch Heater

Available Hardware/Limited Data

- Limited dataset for gas emissions
- Particulate measurements (TSI DustTrak Aerosol monitor)
- Obscuration
- Surface thermocouples
- Portable water extinguisher
- Smoke eater



Feasibility of calculating the HRRs from the measurement of flame heights (Padilla et al. 2019-2021)

2021 Battery Fire Investigations

Design of Experiment (DOE) software was used to design the test matrix

- Factor A: State of charge (30% SOC, 100% SOC)
- Factor B: Heating Rate- slow (0.17 ℃/s) and fast (0. 73 ℃ /s) heating
- Factor C: Orientation (Horizontal, Vertical)

Interactions

- AB, AC, BC, ABC
- A 2^3 factorial design was conducted with only 2 repetitions per test condition- A total of 16 tests were conducted.
- Analysis of Variance (Anova) analysis was performed to identify the significant effects among factors and response variables
- Average values and 1 standard deviation away from the mean will be presented

Measurements (response variables)

- Temperature
- Mass loss, peak heat release rate (HRR), and gas emissions (CO, CO_2, O_2)

Hazard Parameters	Significant Measurements	2021
		Pouch Cells
Thermal- HRR		x
	Temperature	x
	Time to Ignition	x
	Growth Time	x
	Peak HRR	x
Gas/Solid Emissions		
	Mass Loss	x
	Venting Rate	x
Fire-Flaming Fragments		x
Flaming combustion		
	TR Propagation Studies	
	Flame Size	
Contamination		x
Aerosol Products		
	Obscuration	x
	Particulate Measurements	x
Gaseous Products		
	CO, CO2, and O2	x
	Toxic gases	x

Battery and Ignition Approach

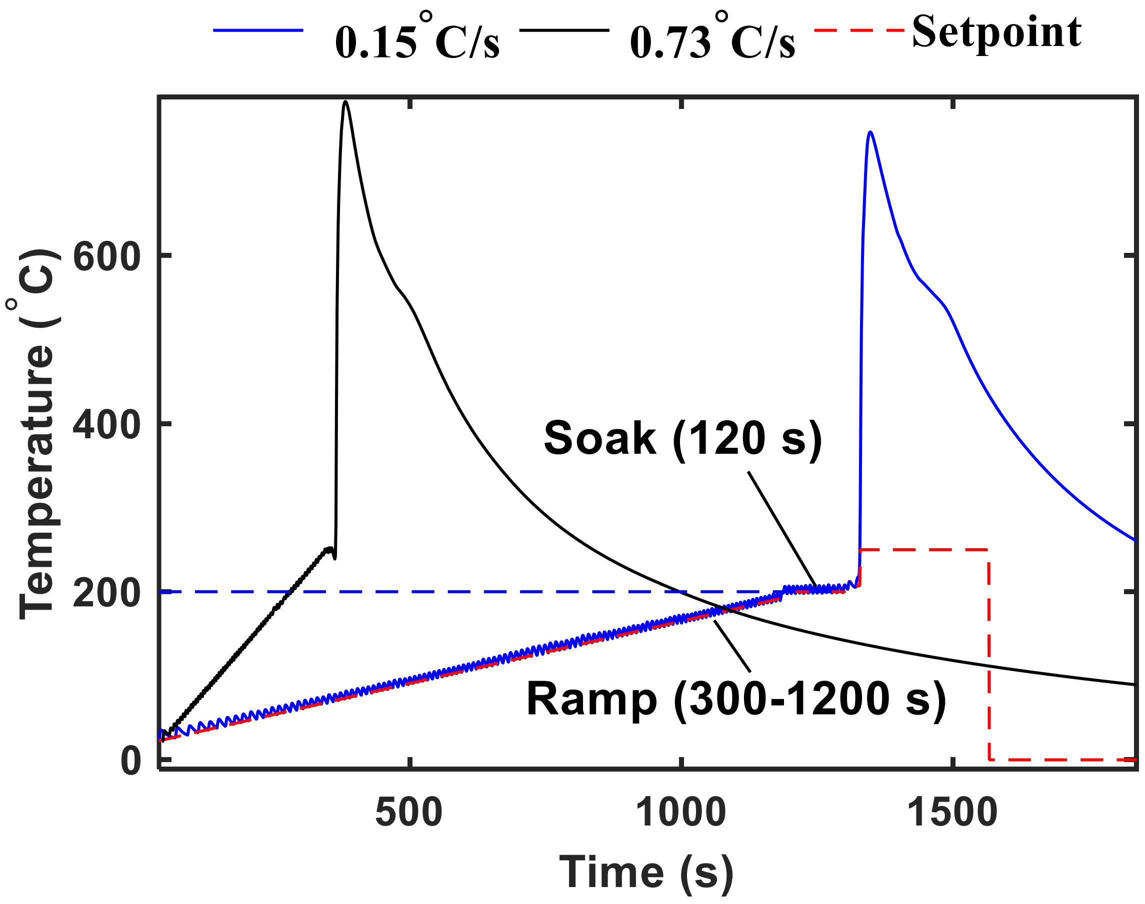
Battery Information

2.5 Ah (9.25 Wh) Li-ion pouch cell with $LiCoO_2$ (cathode) and graphite (anode). Nominal voltage is 3. 7 V

- Cells were conditioned and charged initially to 30% (3.2V) and 100% SOC (4.2V)
- Battery dimensions: $0.21 \times 1.85 \times 3.74\ in^3$
- Initial mass for individual cells ~ 47 g

Ignition Method

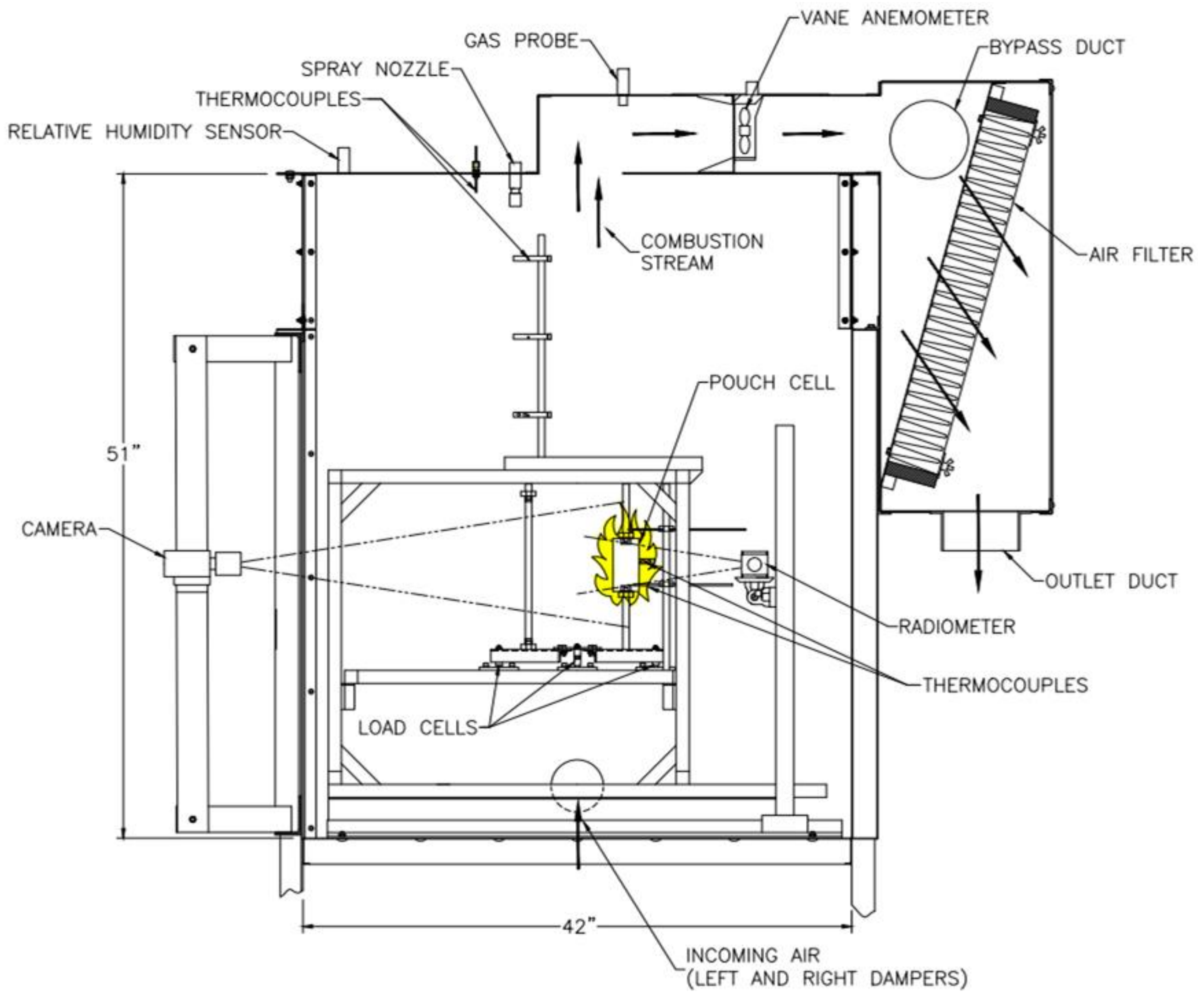
- Cell was forced into thermal runaway with a 90 W heater and a 10 W flux on a 3" × 3" area. Heater is located under the cell
- Heating ramp is controlled by using a PID controller with a TC attached between the cell and heater for feedback
- Heater was powered off when TR was reached



Battery Test Facility

Available Diagnostics and Data

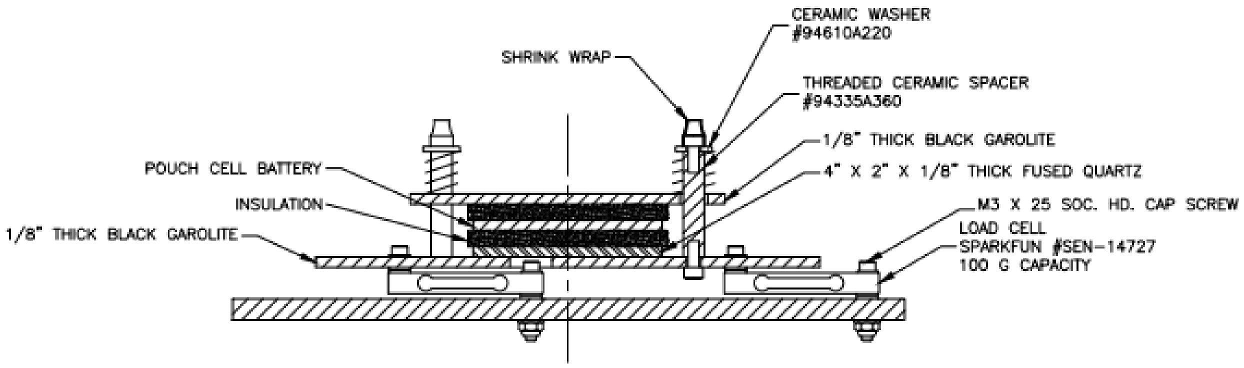
- Six Type K thermocouples were used to measure surface cell temperatures and surrounding plume
- Cameras (front, side, and top view)
- Gas probe collects combustion products (CO, CO_2, and O_2) and used for oxygen consumption calorimetry and gas toxicity
- Mass loss (load cells)
- Cell voltage measurements (capture roll off due to internal short, failure indicator)
- Radiometers
- Environmental humidity sensors temperature (TC is located on the ceiling ~2 ft away from pouch cell)



53 ft^3 (1.5 m^3) Test Chamber (Side View)

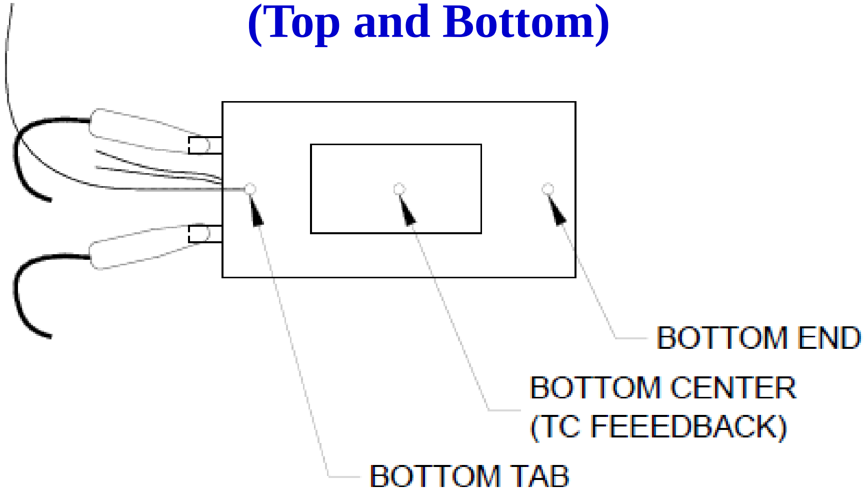
Test Configurations

Horizontal Orientation

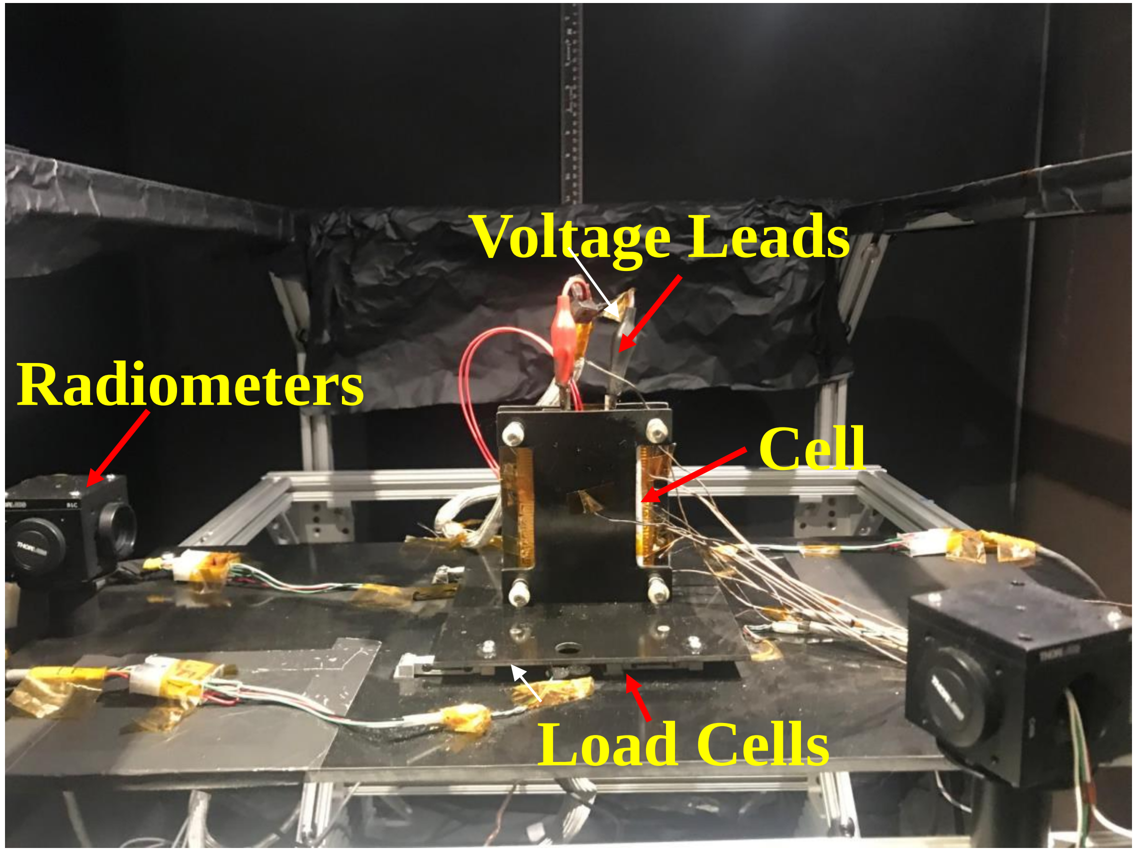


Thermocouple Positions

(Top and Bottom)



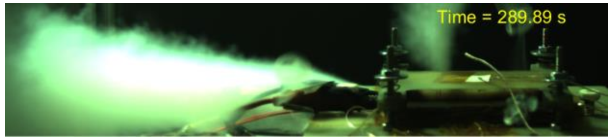
Vertical Orientation



Results

Thermal Runaway Process

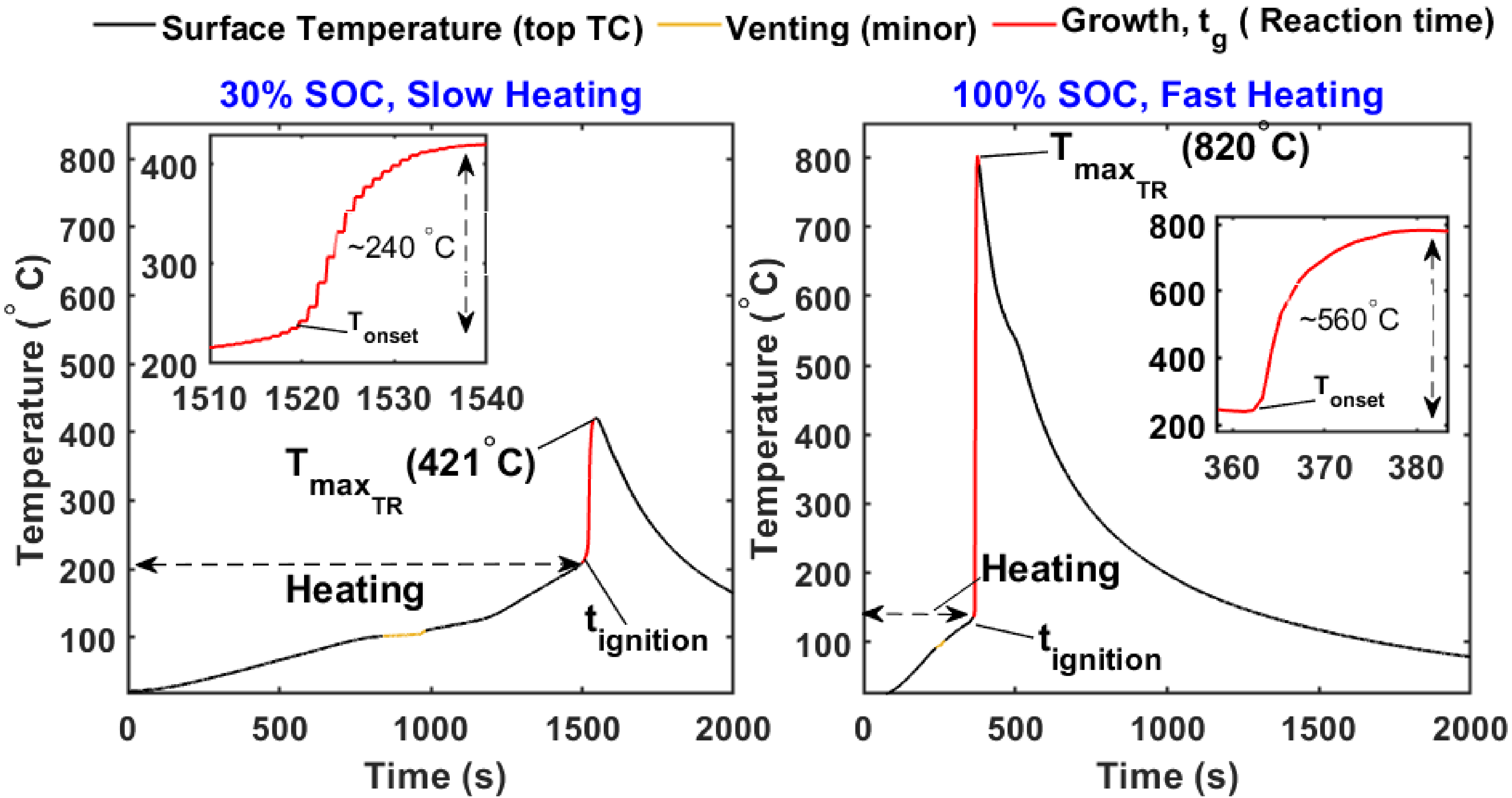
Pre-heating
(cell bulged, weak venting)



Aggressive Venting

Sparks/Fire (~2 s)

Highly Obscured



Only Horizontal Orientation is Shown-no appreciable difference is observed in the vertical orientation

Impact of Heating Rate on TR Timescales

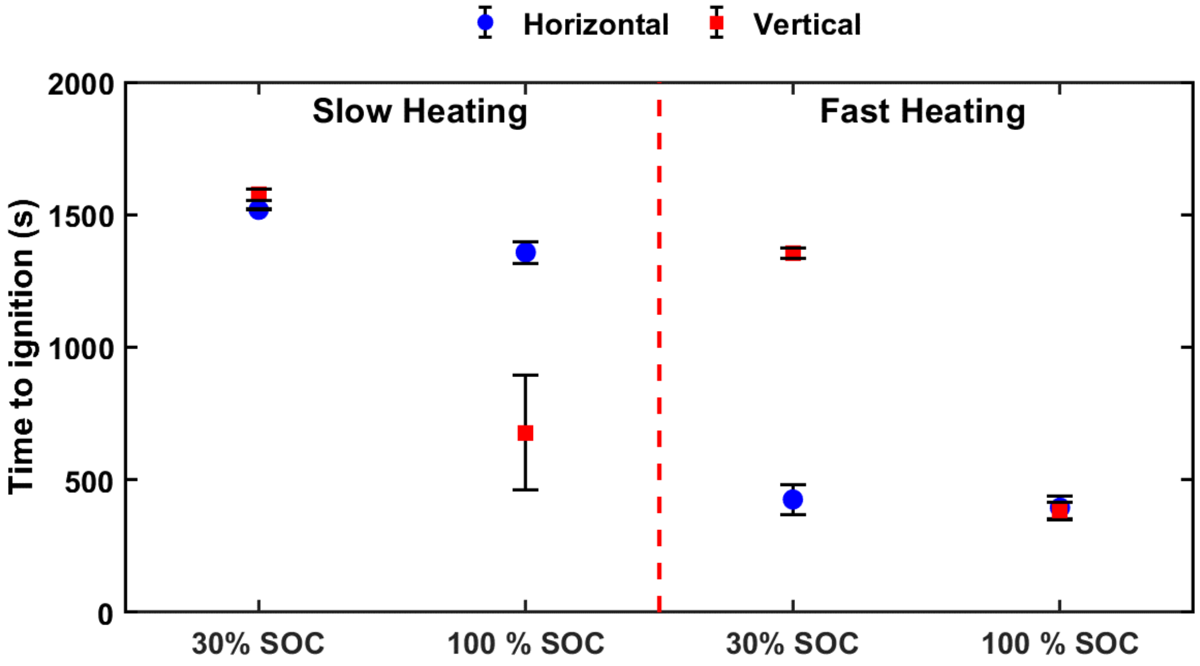
Time to Ignition, $t_{ignition}$

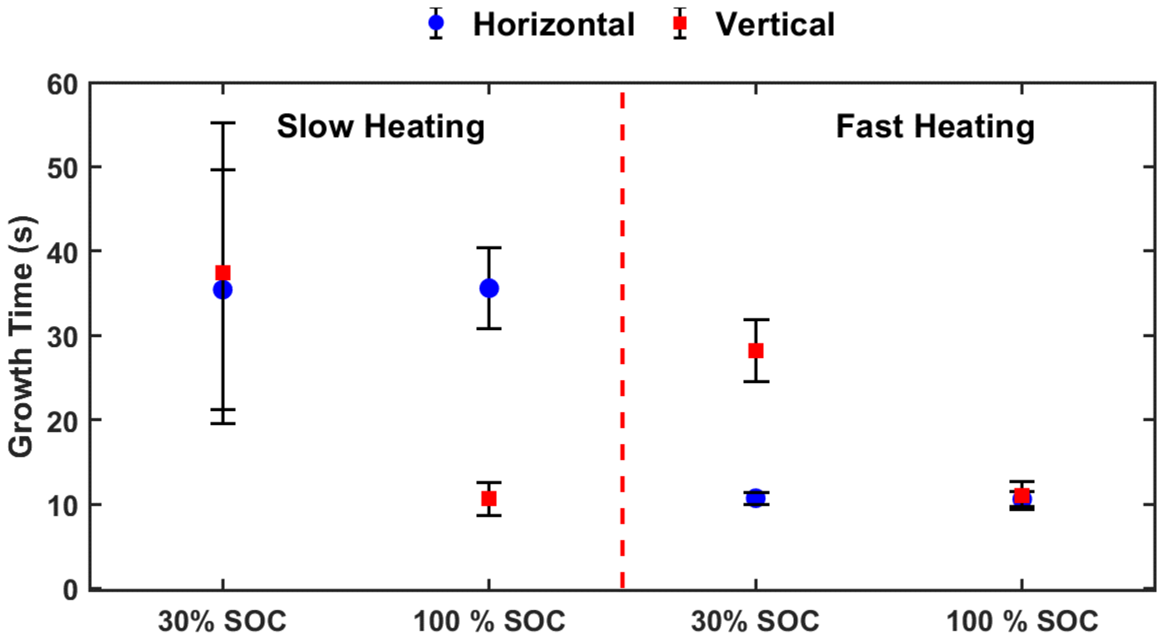
- Time to ignition of the 30% SOC cells was longer than for 100% SOC conditions

- At 100% SOC and fast heating
  - Combustion event also was shorter in duration, which may result in insufficient time to allow chemical reactions to release thermal energy
  - Less time to address a fire and execute mitigation strategies

Growth Time, t_g

- At 30% SOC an increase in temperature between 150-250 ℃ is observed in a 25-50s window
- At 100% SOC, over 500 ℃ increase is observed within a 10s window

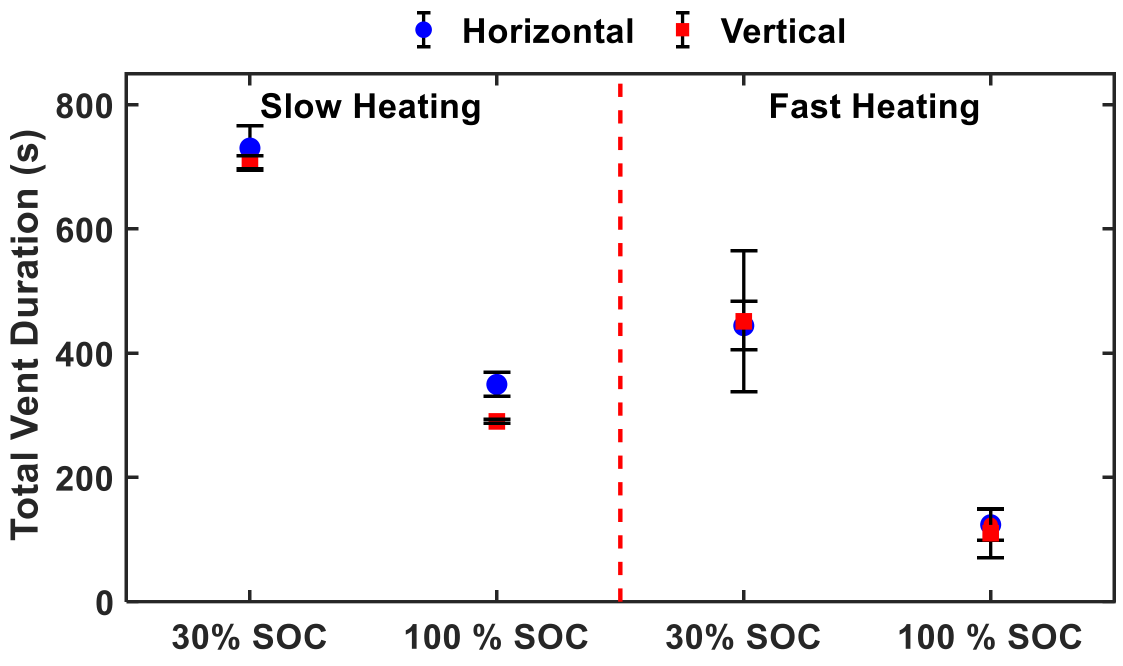


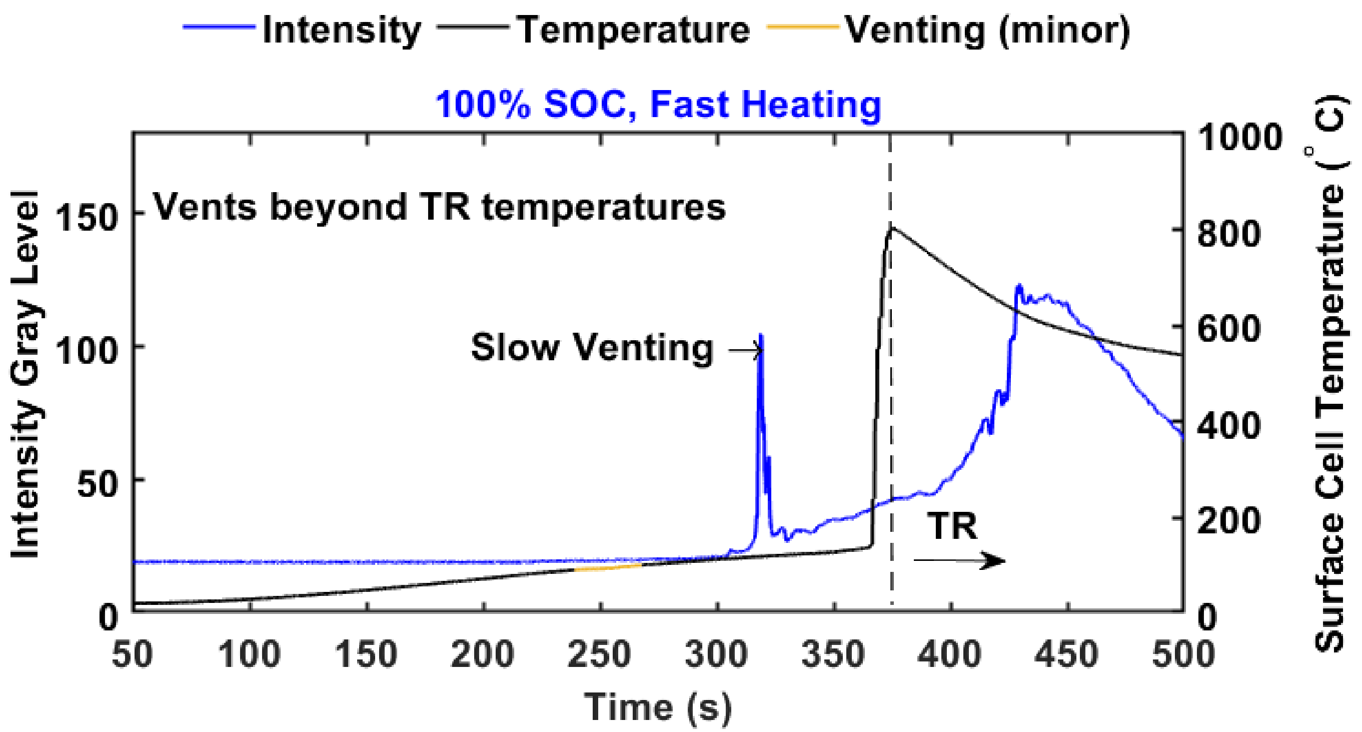


Gas Release (Venting)

Impact Effect on Venting From SOC and Heating

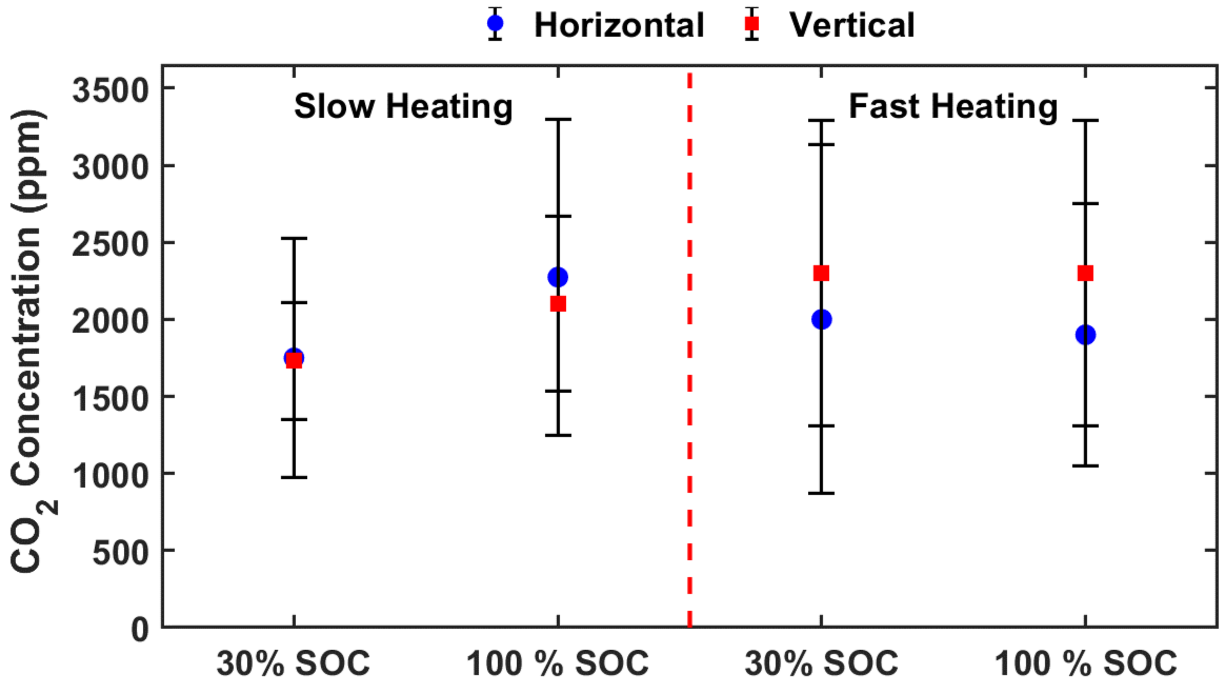
- Temperature and image data show that venting begins between 90 ℃ to 120 ℃
- Venting time increases at 30% SOC and reduces at 100% SOC (slow and fast heating)



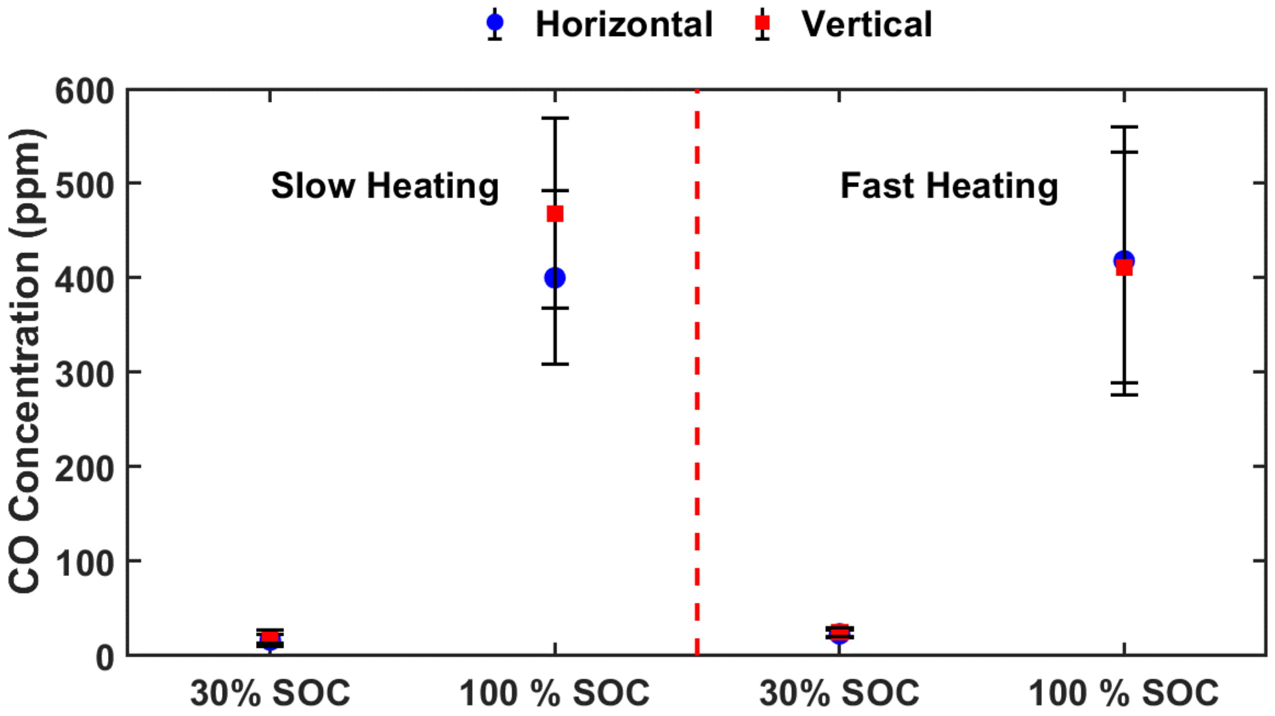


Total Vent Time was Captured from Video

Gas Release (Venting)

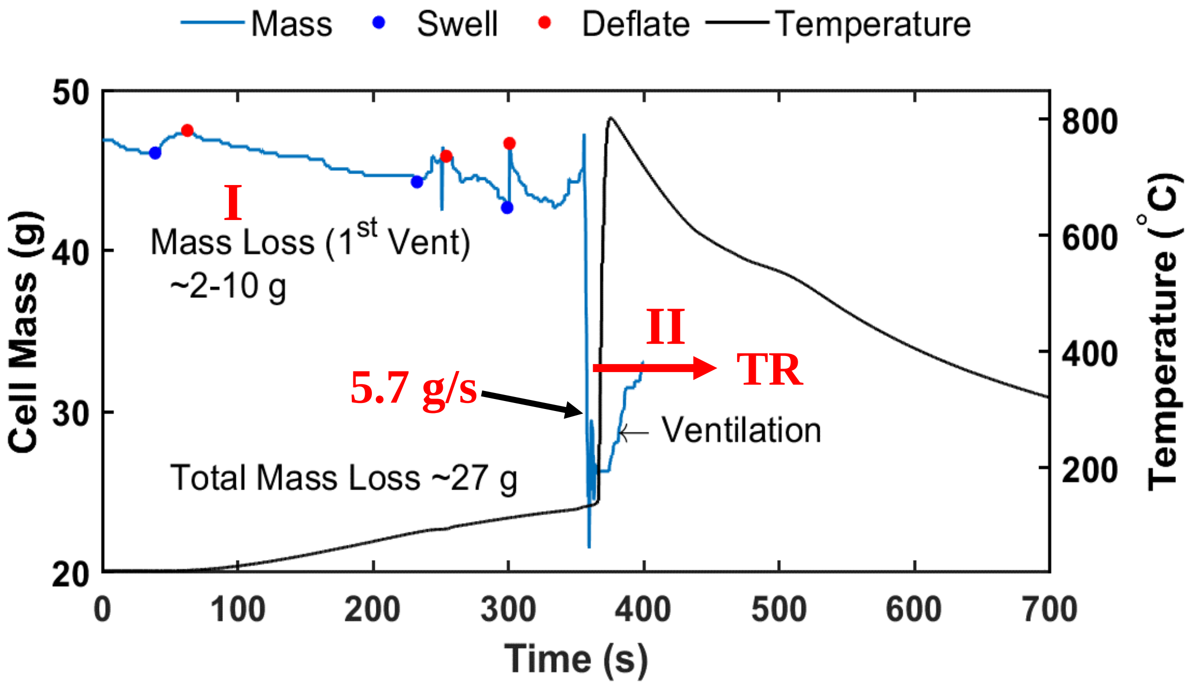


CO_2 is the Most Abundant Gas Observed in Battery Fires



State of Charge Impacts CO Emissions

Mass Loss

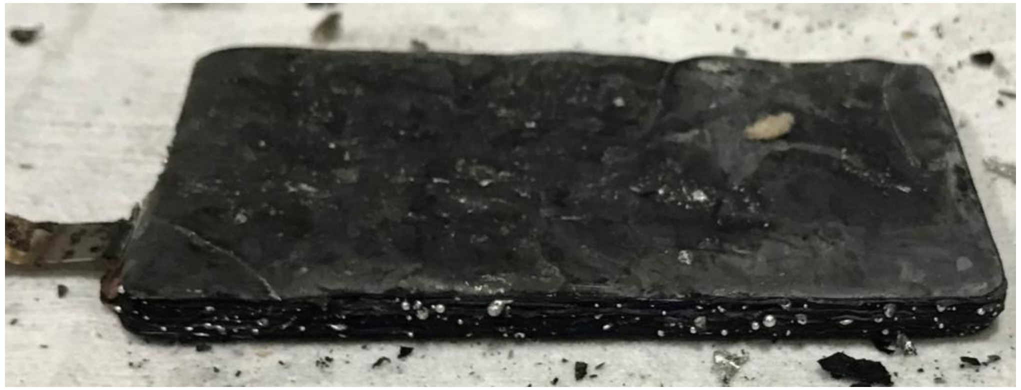


100% SOC, Fast Heating, Horizontal Orientation

I- Volatile organic components were released (PVDF, electrolyte, $LiPF_6$, etc.) leaving behind metals

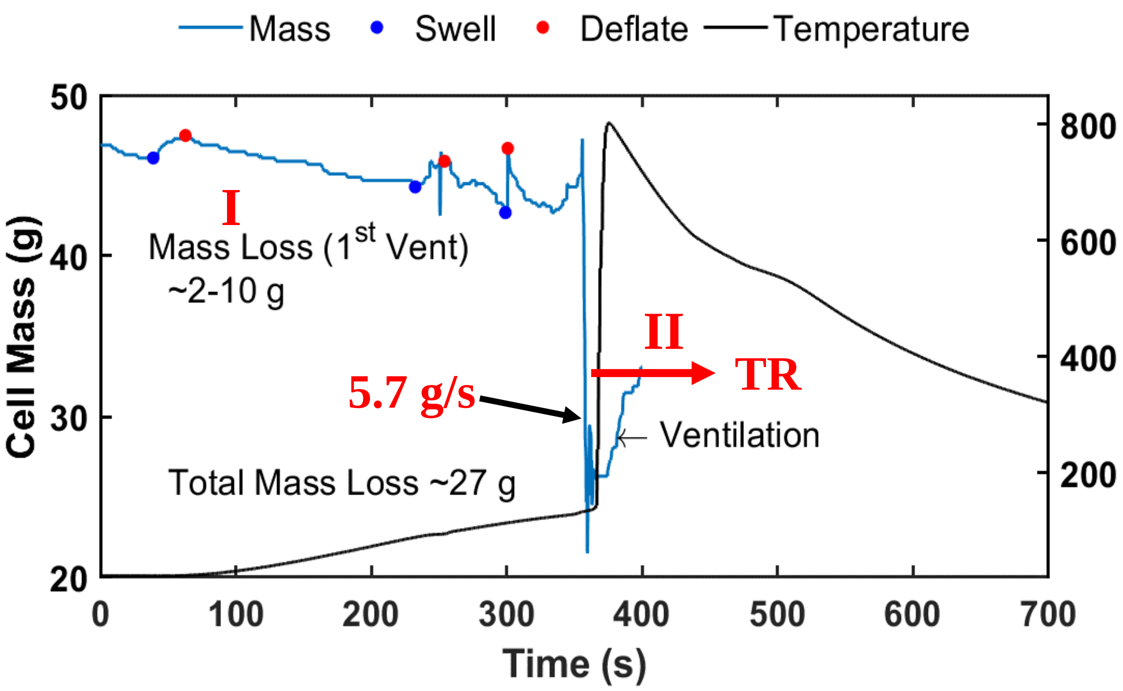
II- Both metals and volatile organic compounds were released, therefore a larger loss in mass was left to burn post TR

30% SOC (Slow Heating)

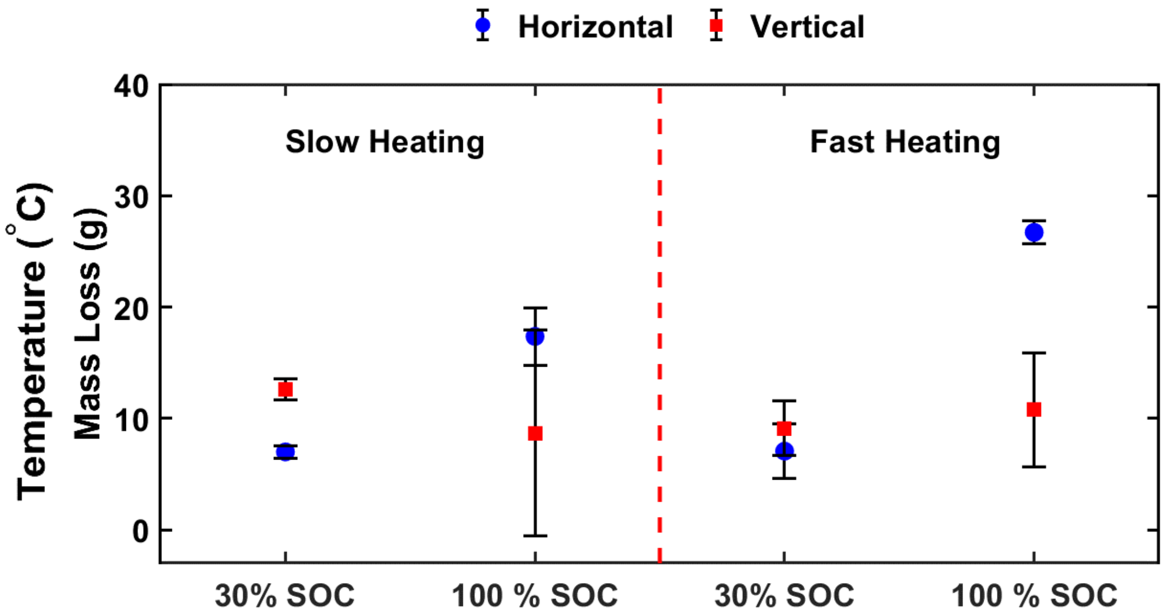


100% SOC (Slow and Fast Heating)

Mass Loss



100% SOC, Fast Heating, Horizontal Orientation



Summary Mass Loss Across All Test Conditions

I- Volatile organic components were released (PVDF, electrolyte, $LiPF_6$, etc.) leaving behind metals

II- Both metals and volatile organic compounds were released, therefore a larger loss in mass was left to burn post TR

- Higher mass loss for 100% SOC (slow and fast heating). Spans from 5.3-27.4 g

Peak Heat Release Rate Analysis

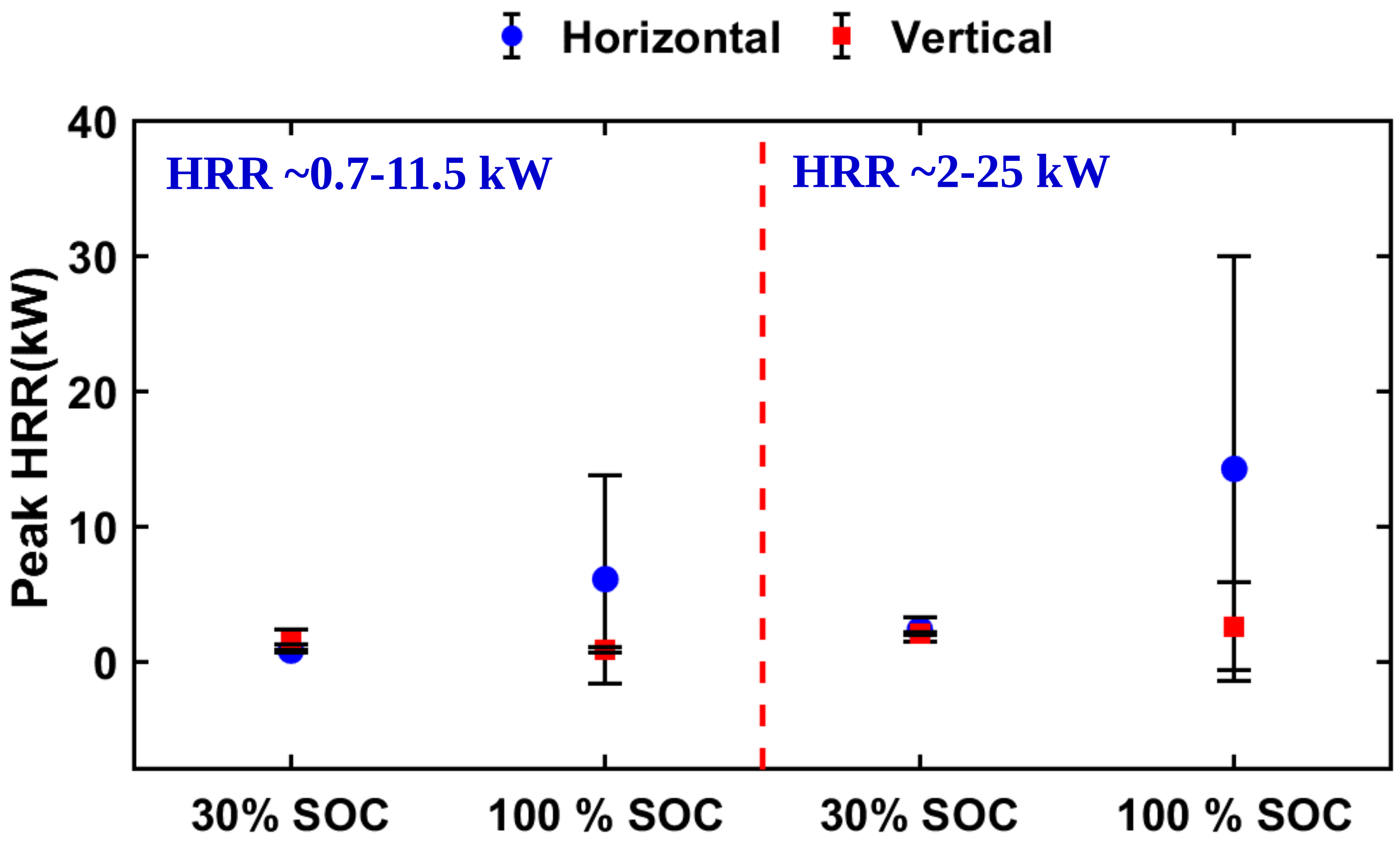
Fuel Consumption Rate

Peak HRR(kW)

$$\dot{q} = \chi \Delta H_c \dot{m}$$

where,

$\dot{m}$ is the mass loss rate (g/s)
H_c is the heat of combustion, 6.4 kJ/ g (Fu et al. 2015)
χ is the combustion efficiency (0.78) (Fu et al. 2015)



Example Peak HRR Calculation from cone calorimeter data found in literature for 100%

Therefore 0.78 x 6.4 kJ/g x 0.7 g/s = 3.5 kW peak
Or overall ~ 6.4 kJ/g x 27g lost = 173 kJ by combustion

Anova Summary from DOE

Measurements

	Factors			Interactions				
	A-Heating Rate	B- State of Charge	C-Orientation	AB	AC	BC	ABC	Model Significance
Maximum TR Temperature								
Time to Ignition								
Onset to TR								
Growth Time								
Mass Loss								
Vent Duration								
CO								
CO_2								F-value of 0.52 P-value 0.7993
Peak HRR								F-value of 0.87 P-value 0.5671

Significant

Not Significant

Conclusions

Single pouch cell tests were conducted at NASA GRC and were forced into TR using a patch heater. A design of experiment software was used to identify significant factors influencing burning and energy release characteristics in pouch cells at TR.

- The fire behavior of the cell with 30% SOC was less severe than that with 100% SOC
- A large amount of debris (carbon-based anode material and copper foil) were ejected from the cell with 100% SOC during the transition from jet sparks to fire
- Maximum TR temperatures exceed 750 ℃ within a small ~10s window
- Low levels of CO were detected in 30% SOC conditions and large concentrations for CO_2 consistent across all SOC and heating rate
- During TR mass loss was observed to be highest at a higher SOC with ejecta gaseous and solid debris
- Heat release rate increases with SOC
- Future tests will focus on multi-battery packs and full laptops

Acknowledgement

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- NASA Glenn Research Center
- Case Western Reserve University
- Dan Gotti, Universities Space Research Association
- Anthony Ogorzaly, HX5 LLC

Thank you!

Questions?

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Universities Space Research Association

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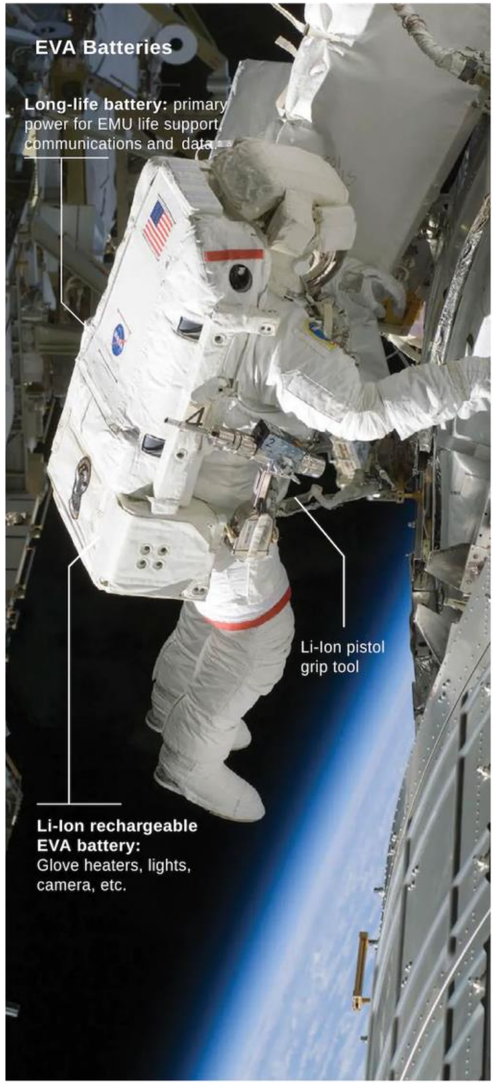
Battery Applications in Space



Existing Guidelines for Li-ion Batteries in Space Applications

- NASA Glenn Research Center
  Guidelines on Lithium-ion Battery Use in Space Applications
- NASA Johnson Space Center
  - *Crewed Space Vehicle Battery Safety Requirements- JSC-20793 Rev D* (Jeevarajan et al. 2014)
  - Packaging Requirements for Launch, On-Orbit Storage and Disposal of Batteries- JSC-63322 Rev B (Delafuente et al. 2019)

Research methods for prevention and mitigation of thermal runaway propagation

- Energy release in cylindrical cells
- Packaging requirements Stowage mitigation studies (Delafuente, David, 2019

Example Anova Summary from DOE

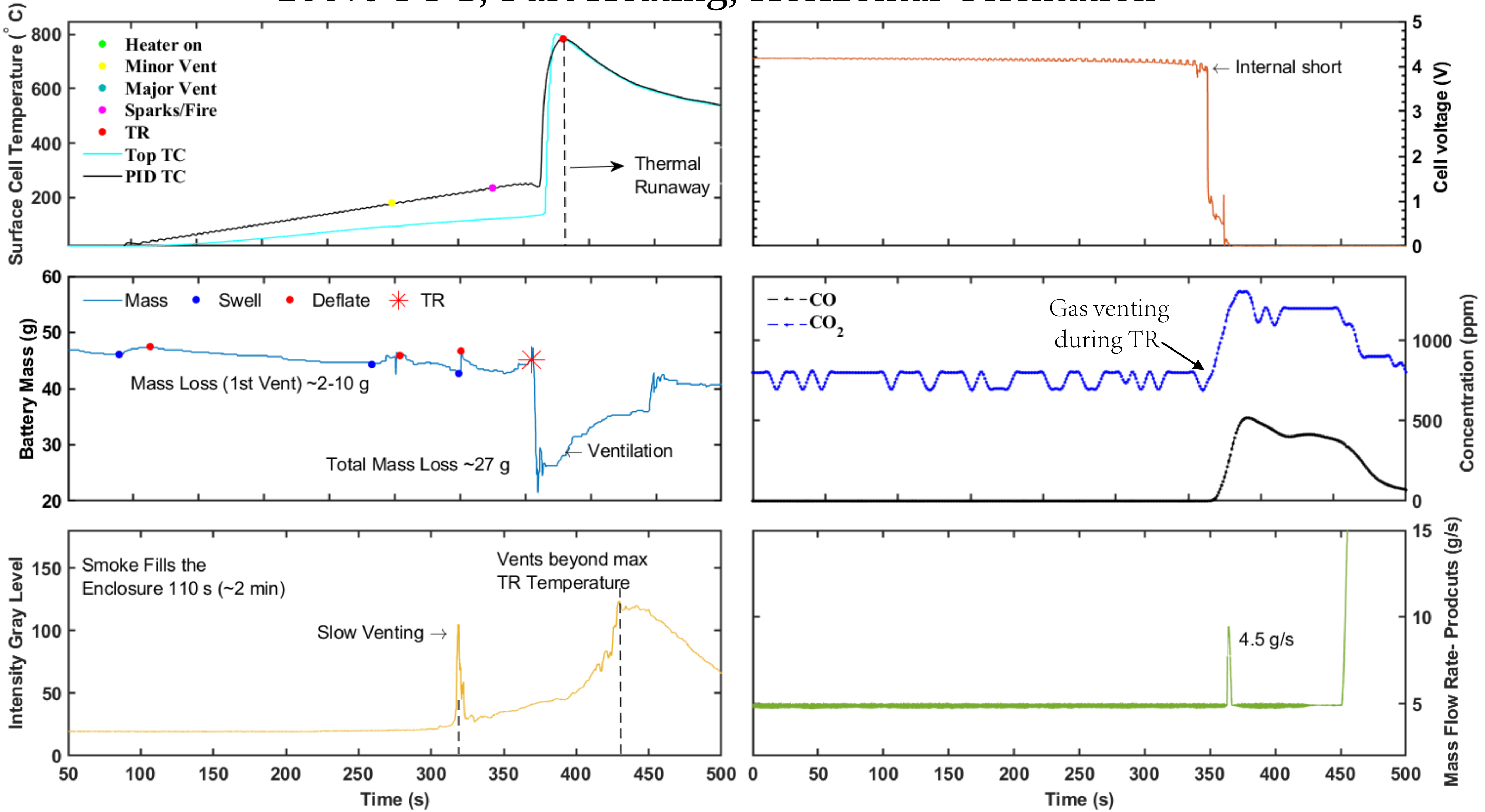
Significant | **Response to Onset to TR** | Not Significant

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	29780.67	7	4254.38	19.64	0.0002	Significant
A-Heating Profile	4818.03	1	4818.03	22.24	0.0015	
B-State of Charge	17403.72	1	17403.72	80.32	< 0.0001	
C-Orientation	96.71	1	96.71	0.4463	0.5229	
AB	4676.05	1	4676.05	21.58	0.0017	
AC	701.76	1	701.76	3.24	0.1096	
BC	1297.47	1	1297.47	5.99	0.0401	
ABC	786.94	1	786.94	3.63	0.0931	
Pure Error	1733.34	8	216.67			
Cor Total	31514.02	15				

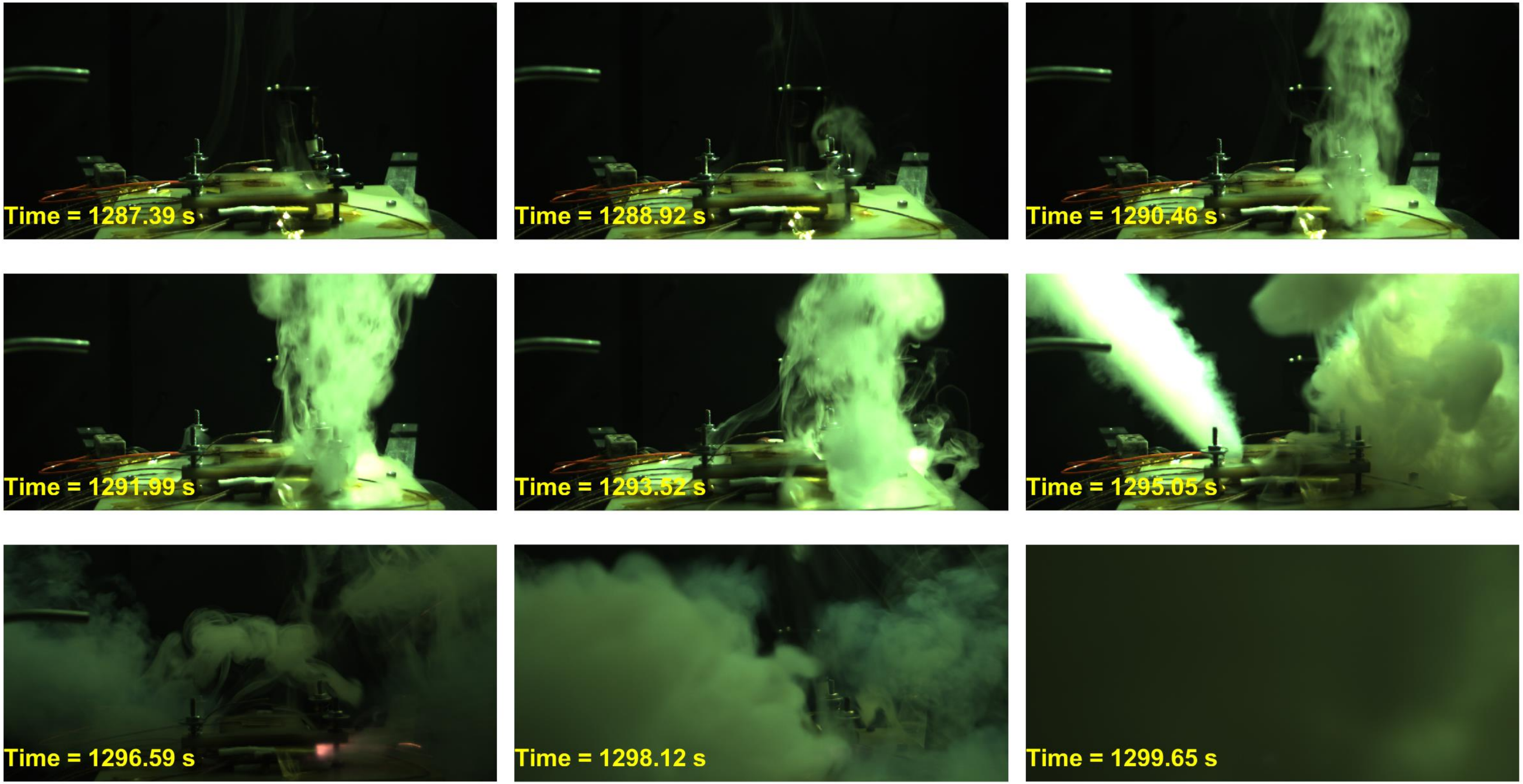
The Model F-value of 19.64 implies the model is significant. There is only a 0.02% chance that an F-value could occur due to noise
P-values less than 0.05 indicate model terms are significant. In this case A, B, AB, BC are significant model terms

Timeline of TR Events

100% SOC, Fast Heating, Horizontal Orientation



Slow Heating at 100 % SOC



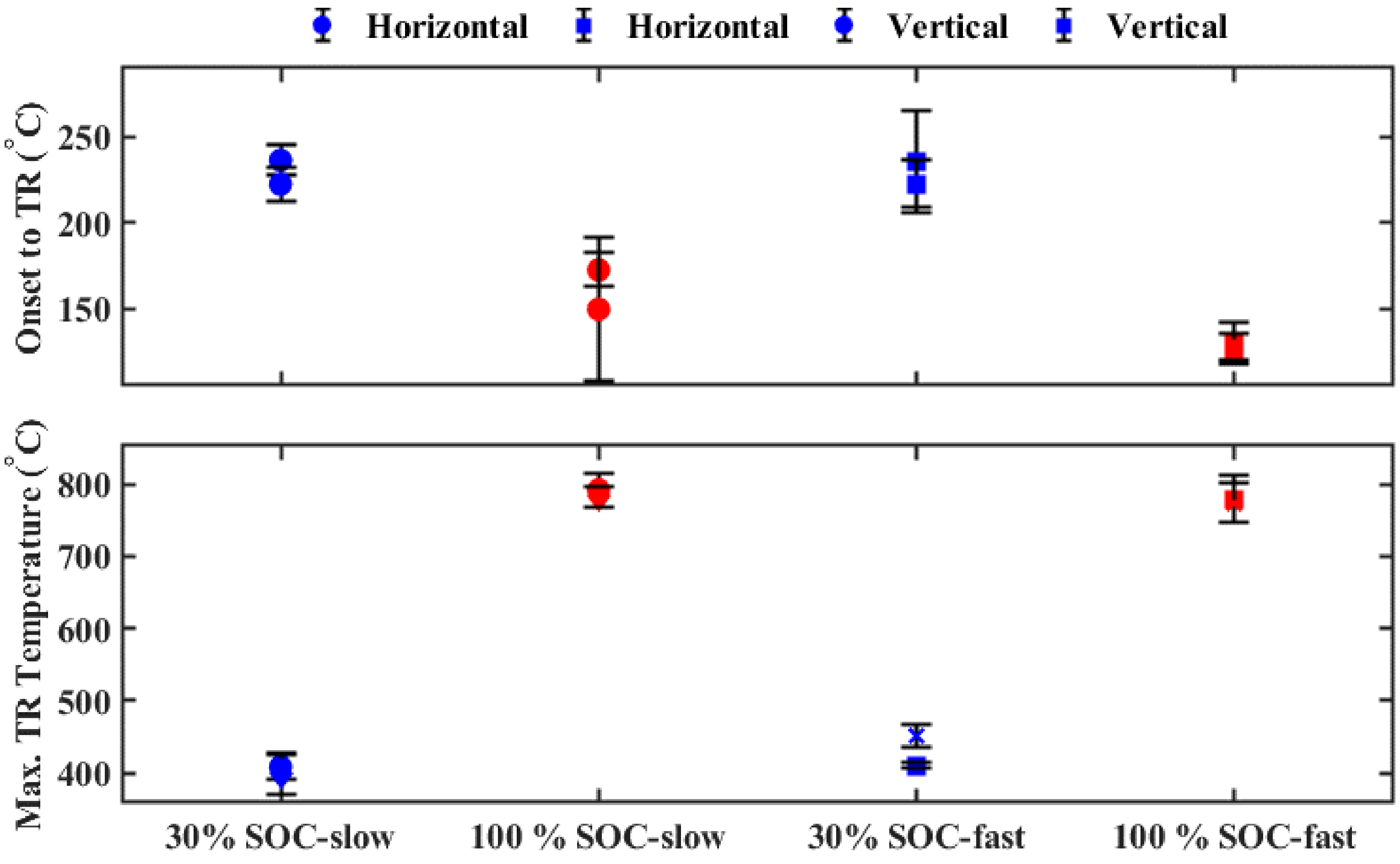
Onset and Maximum TR Temperatures

Impact from 30% SOC

- Onset to TR occurs at temperatures above 220 ℃
- Peak TR temperatures can be between above 400℃

Impact from 100% SOC

- Onset to TR occurs at temperatures below 200 ℃
- Peak TR temperatures are above 700℃



Minimal influence from heating rate and orientation on onset and maximum TR temperatures