Hazardous Product Detection and Environmental Clean-up Removal in Spacecraft Vehicles from Fire Induced Li-Ion Fires

Spacecraft Fire Experiment

Rosa E. Padilla
Thomas B. Miller, Daniel L. Dietrich,
Gary Ruff, and David L. Urban

NASA 2019 Battery Workshop

Combustion Systems and Reacting Processes Branch
NASA Glenn Research Center
Cleveland, OH 44070

Universities Space Research Association

November 19-21, 2019

Energetic Sources in Spacecraft

Potential fires in spacecraft are catastrophic hazards

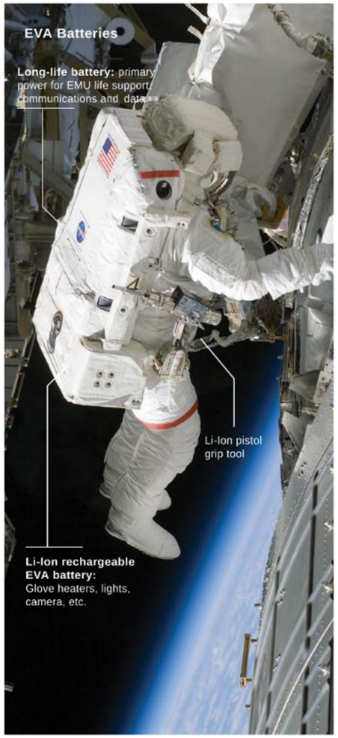
- Pressure rise in the vehicle
- Spread and growth of a fire in spacecraft
- Toxic products that can harm the crew
- Crew response, performance of air handling system and fire detectors

Approximately 100 laptops are found inside the ISS

- Lenovo T61P/A31P ThinkPads
  (Panasonic 18650 cylindrical cells)
- Microsoft Surface Pro Tablets
  (Pouch Cells, 42 Wh)

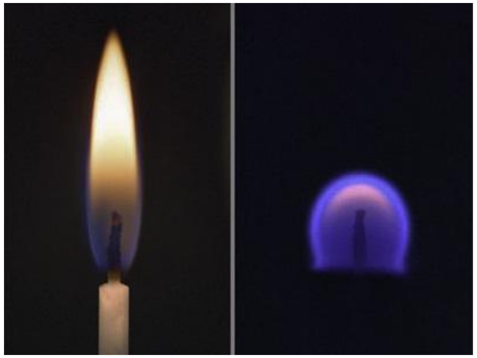
Causes of Runaway in Li-ion Batteries

- Charging or discharging
- Internal short (defect)
- Heating



e.g. Helmet light, pistol grip tool, EMU.
Nickel Metal Hydride or Lithium Manganese Dioxide based cells

Combustion Studies in Microgravity Conditions at *Glenn Research Center*



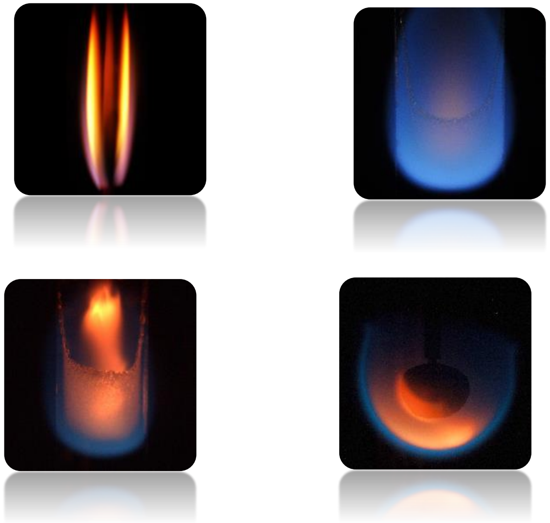
1-g vs. 0-g, spherical, soot-free and blue flame (right image)

In the absence of buoyant flows, other heat and mass transfer mechanisms dominate, hence flame structures are different in microgravity

- Cooler flames
- Flame shape
- Slower propagating flames
- Ignition
- Changes to smoke properties

Examples of Past and Ongoing Projects

- Flame Extinguishment Experiment (FLEX)
- Gaseous Combustion – ACME
- Solid Fuel Ignition and Extinction (SoFIE)



Ferkul & Olson et al. 2017

Spacecraft Fire Safety Demonstration (Saffire)

Saffire I-III & Saffire IV-VI

Objectives:

- Study flame spread of large fires (spread rate, heat release, mass consumption)
- Vary flow speed, elevated O_2 (fuels e.g. Cotton, nomex, PMMA, SIBAL)
- Fire monitoring and response

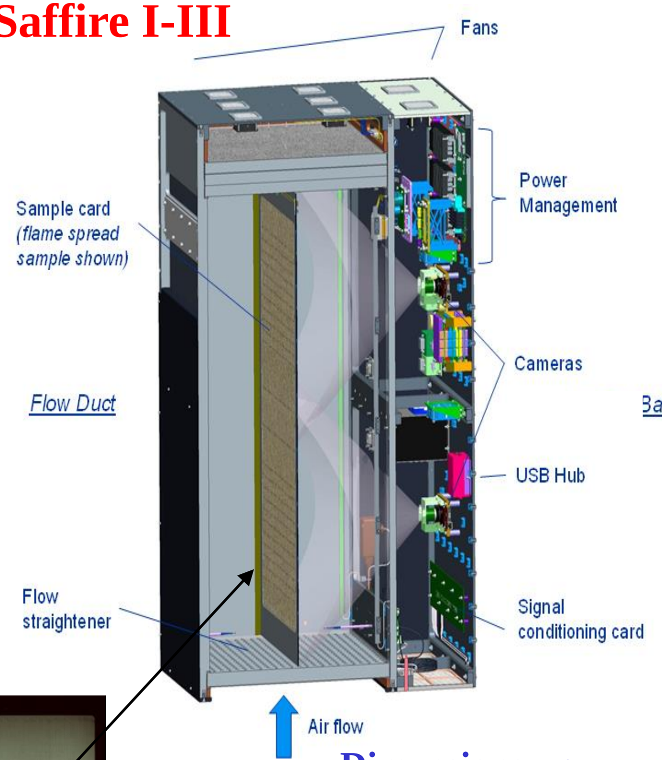
Saffire VII-VIII

Develop an experimental concept to study lithium ion battery fires and conduct tests inside the Cygnus cargo vehicle upon re-entry

Objectives:

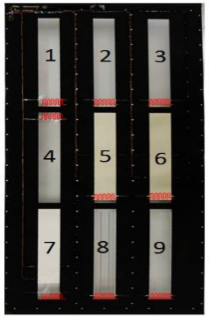
- Fire size, fire duration, heat release rates, toxic products
- Fire detection
- Monitoring
- Post clean up
- Data will be used for modeling e.g. to predict fire behavior in a spacecraft, such as pressure increase inside a sealed cabin (Brooker and Dietrich et al. 2015, 2017)

Saffire I-III



Dimensions are approximately 53-by 90-by 133-cm

SIBAL Fabric
(75% cellulose & 25% fiberglass
40 cm wide by 50 in length



Fuel Sample Holder

Fire Studies Involving Li-ion Batteries

- Controlled fires for fire response training inside of a structure (i.e. homes, cars, submarines, mines, aircraft) and uncontrolled forest fire response

- Cabin crew procedures for "Fire- Fighting" (FAA/TC-TN14/40, DOT/, TC-15/59, 15/40), Safety Alerts for Operators (SAFO) 09013

- Underwriters Laboratories battery cargo fires standards (lithium-ion based)

- NASA's efforts to redesign Li-ion batteries for spaceflight applications (JSC-20793-RevD requirements)

(a)

(b)

Galley or Cargo Storage bags

FAA Fire Safety, Systems Meeting, Tablet Tests in the Cockpit or Galley Compartment Setup, 2017

UPS (Boeing 747-400F) jumbo cargo flight with a large shipment of Li-ion Batteries undergoes thermal runaway

Calorimetry Comparisons with Different Cell Styles and Chemistries

Limited data is available for characterizing tablet fires (lithium ion based)

Thermal Capacitance (Slug) Calorimeter (Quintiere et al. 2016)

- Combustible gases being ejected may not be captured

Accelerating Rate Calorimeter

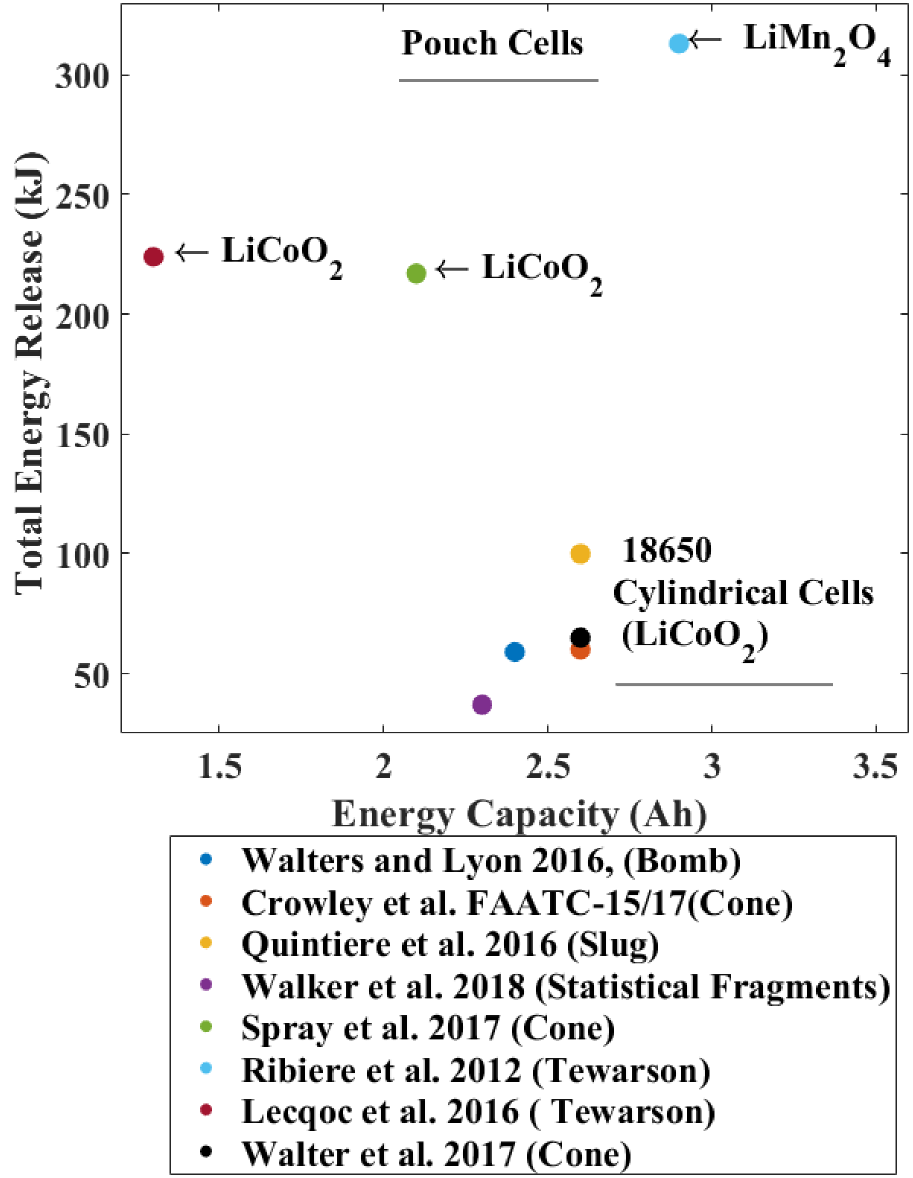
- Adequate for determining onset and maximum thermal runaway temperatures
- Challenging to discriminate TR energy

Cone Calorimeter

- Small samples are required
- Oxygen consumption

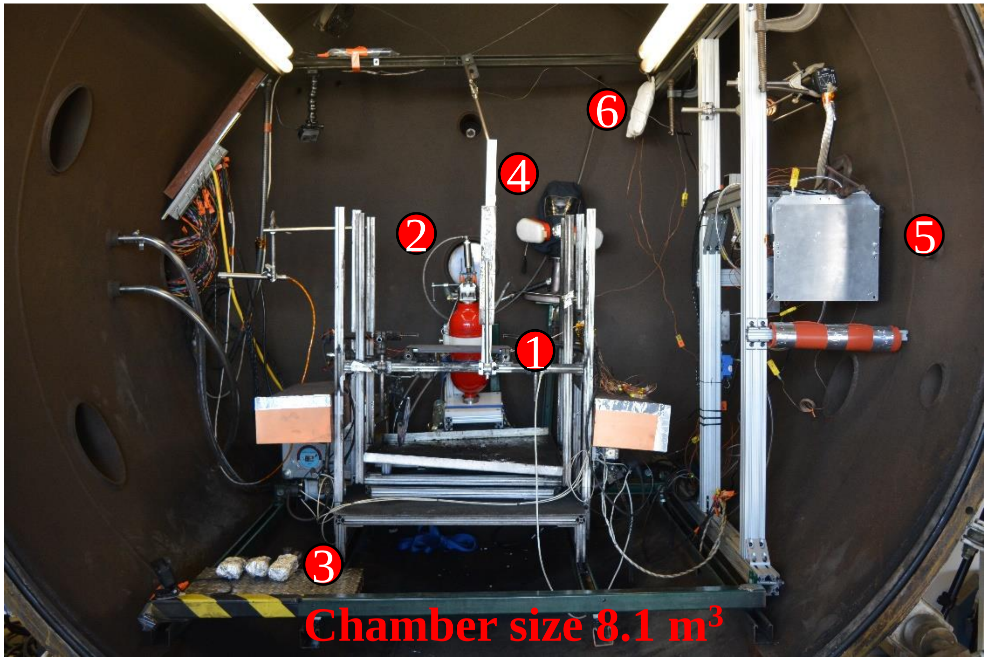
JSC Calorimeter (Walker et al. 2018)

- Feasible for 18650 cylindrical cells
- Total heat output and fraction of heat released through the casing vs. ejecta material



Results

Emulating an Orion Environment
(*White Sands Test Facility*)



2 **Fire Suppression**
- Portable fire extinguisher (Water based)

3 **Detection**
- Dragger sensors for HCL, O_2, CO, and CO_2 measurements
- Particulate measurement (PM 2.5, PM10)
- Obscuration (%/ft) unit

4 **Protection from Toxic Gases**

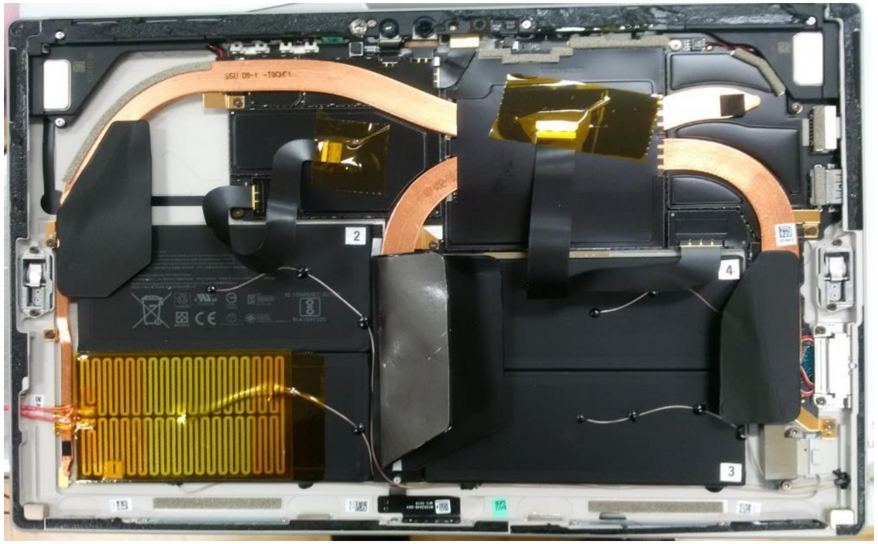
Contingency Breathing Apparatus (CBA)

5 **Post-fire cleanup**

Orion ECLSS hardware including the Smoke Eater

1 **Test Article**
- Force TR on a 45 Wh Microsoft Surface Pro Tablet
- 95 Wh ("worst case fire") Dell XPS 15

Ignition Method and Battery Pack Specifications



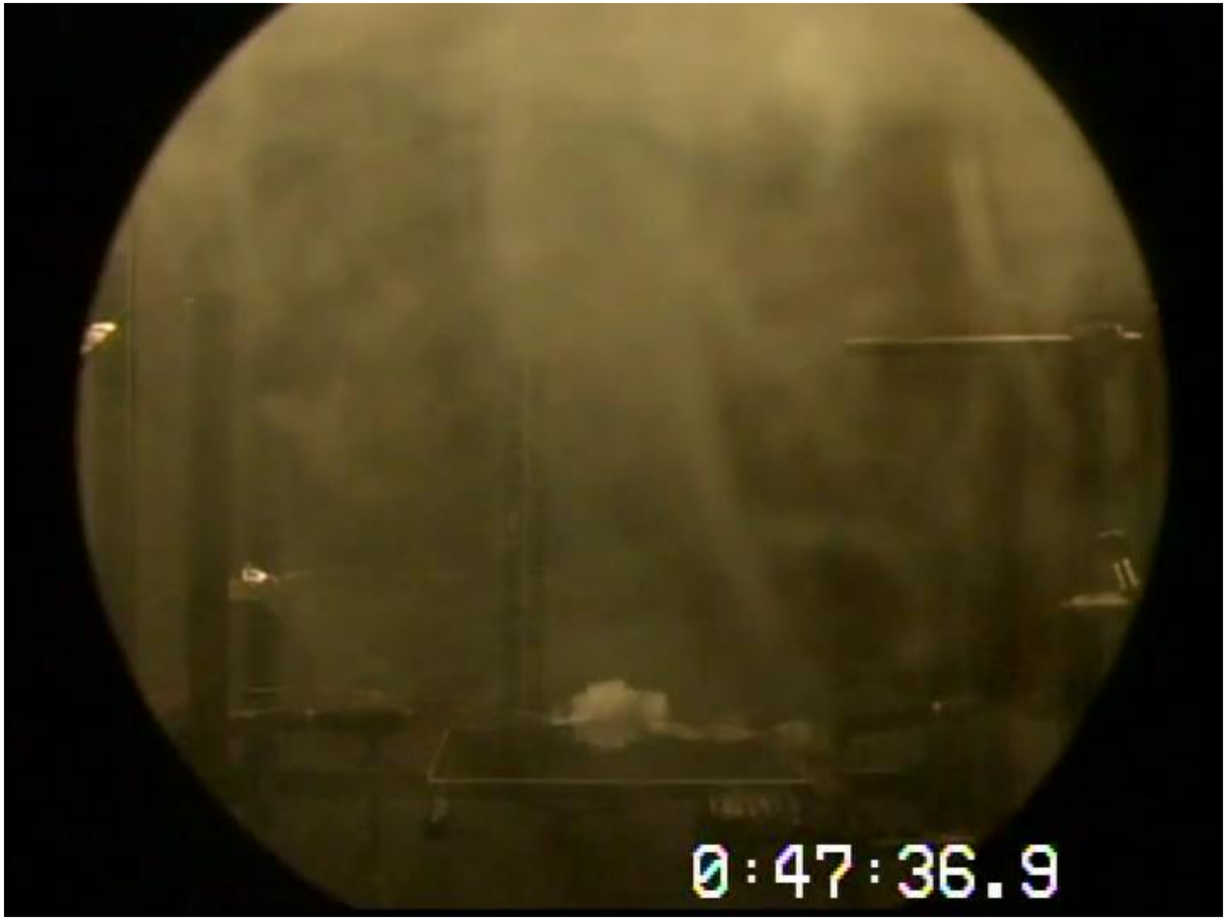
4 Type K thermocouples are placed on each pouch cell & 1 for feedback control

A 60 W thin film polyimide heater is placed on a single cell

All wiring was carefully routed through a left port hole that was drilled

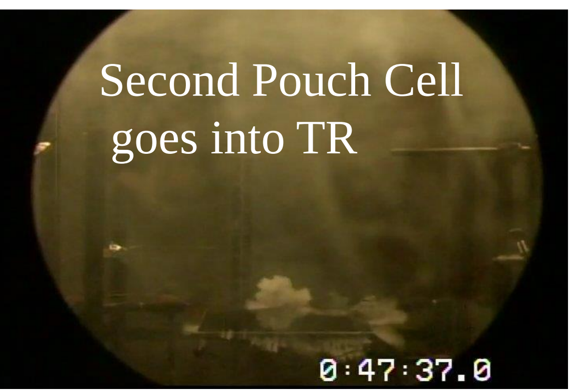
Description	Values
Cell type and Chemistry	4 pouch cells in 2S2P $LiCoO_2$
Voltage (V)	3.785
Capacity (Ah)	2.97/cell
Power (Wh)	45
Individual Pouch Cell Dimensions (in)	Left pouches- 4.2”x 2.1” x 0.125” Right pouches- 4.2”x 1.8” x0.125”
Single pouch cell weight (g)	42.3
Electrochemical Energy (kJ)	162

Surface Pro Tablet Fires (Video)



Combustion Timeline for a Surface Pro Tablet Fire

Vent Period Lasts: 10-15 s



Fire Duration: from 20-30 s

Image Processing for Fire Size Measurements

Measure Heat Release Rate using Heskestad's Correlation

$H = 0.235(\dot{Q}^{2/5})$-1.02D

where,

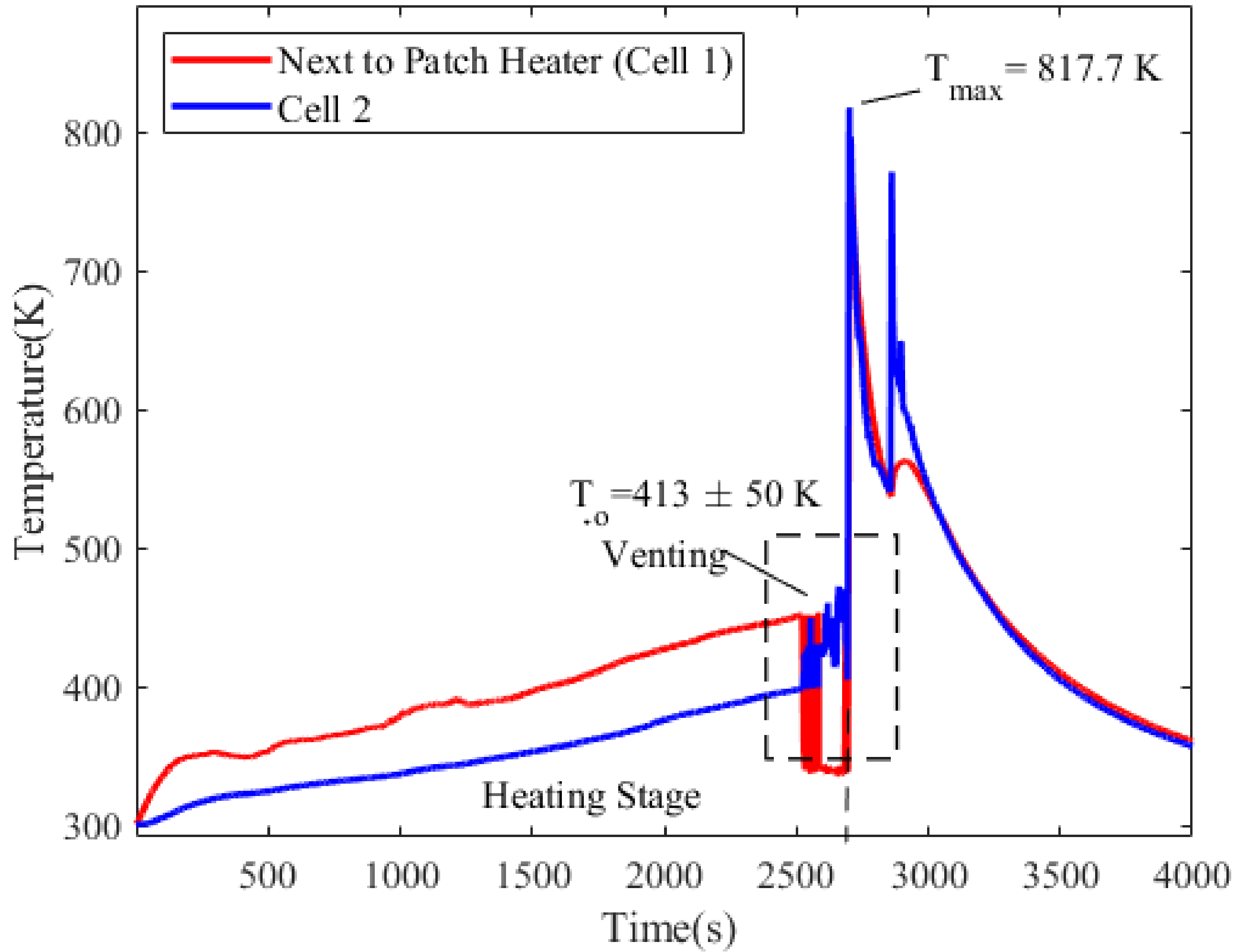
H (m)= Major Length

D(m)= Minor Length

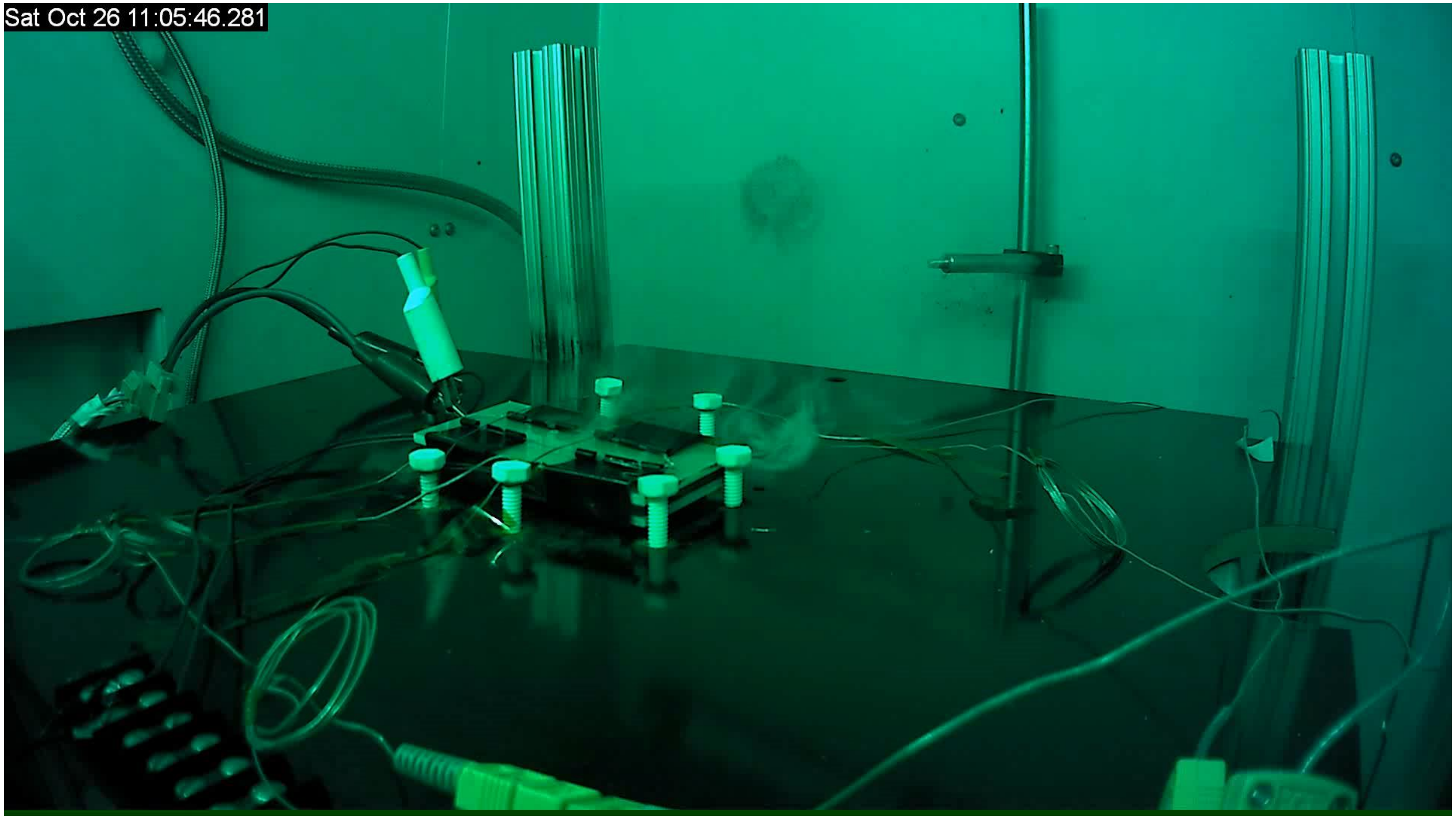
$\dot{Q}$(kW)= Heat release rate

- Automated analysis that converts a color image to binary and apply filters
- Convert pixels to real dimensions

Thermal Runaway Behavior for Tablet Fires

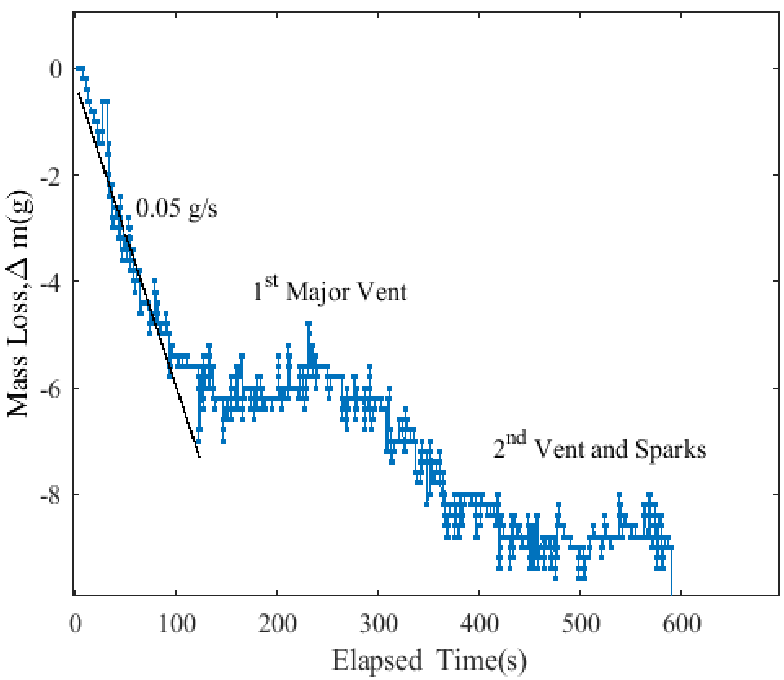


Single Pouch Cell from a Surface Pro Tablet Battery Pack (Video)



Venting lasts between 11-25 s and no sustained fire is observed

Mass Loss for a Single Pouch Cell and Tablet Fire



Single pouch cell- Initial and final mass (g): 46, 37 (after 2nd vent), respectively

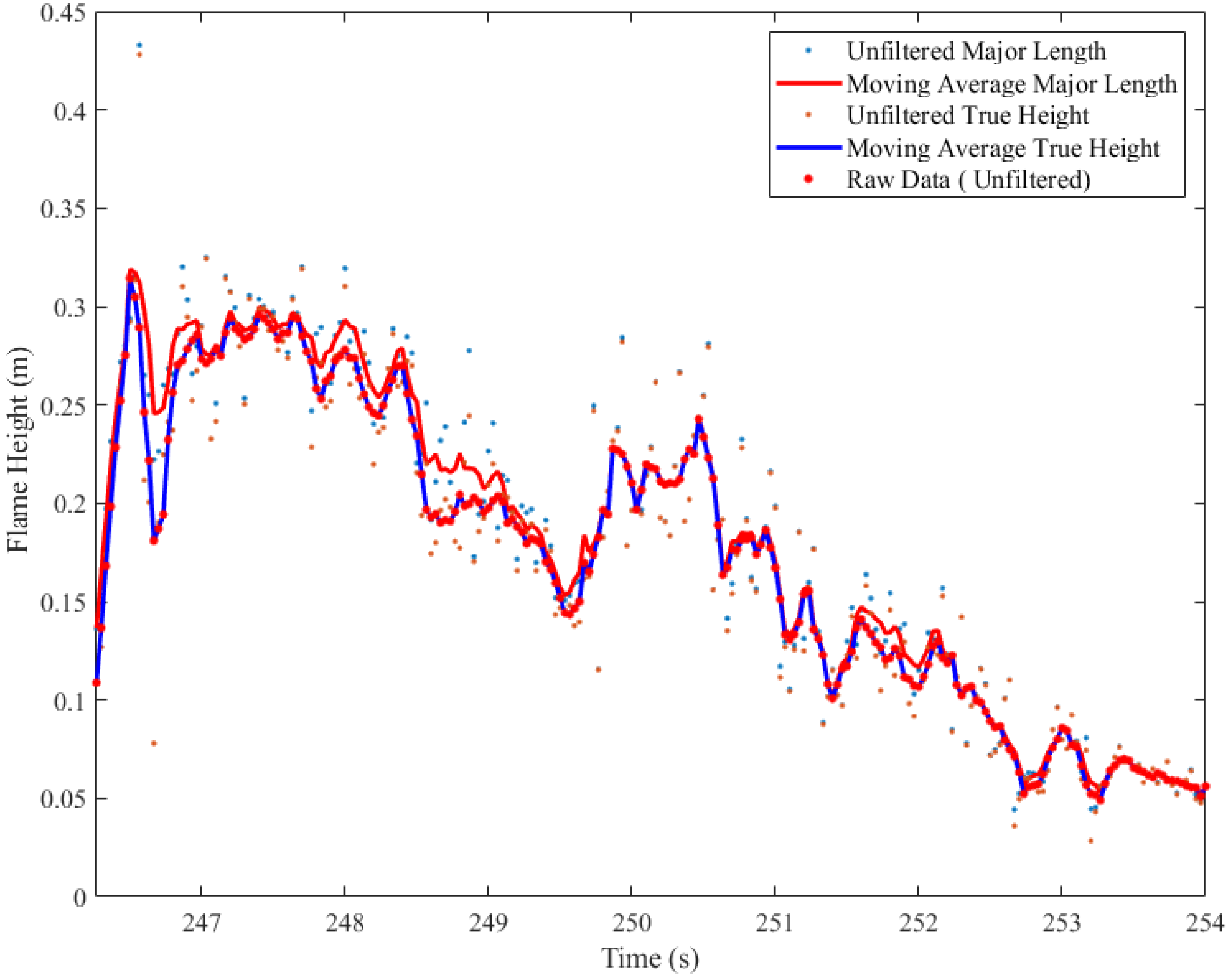
Sample size of 3 pouch cells: 6-10 g of mass was lost

Surface Pro tablet mass loss: ~65 g (initial weight 784 g)

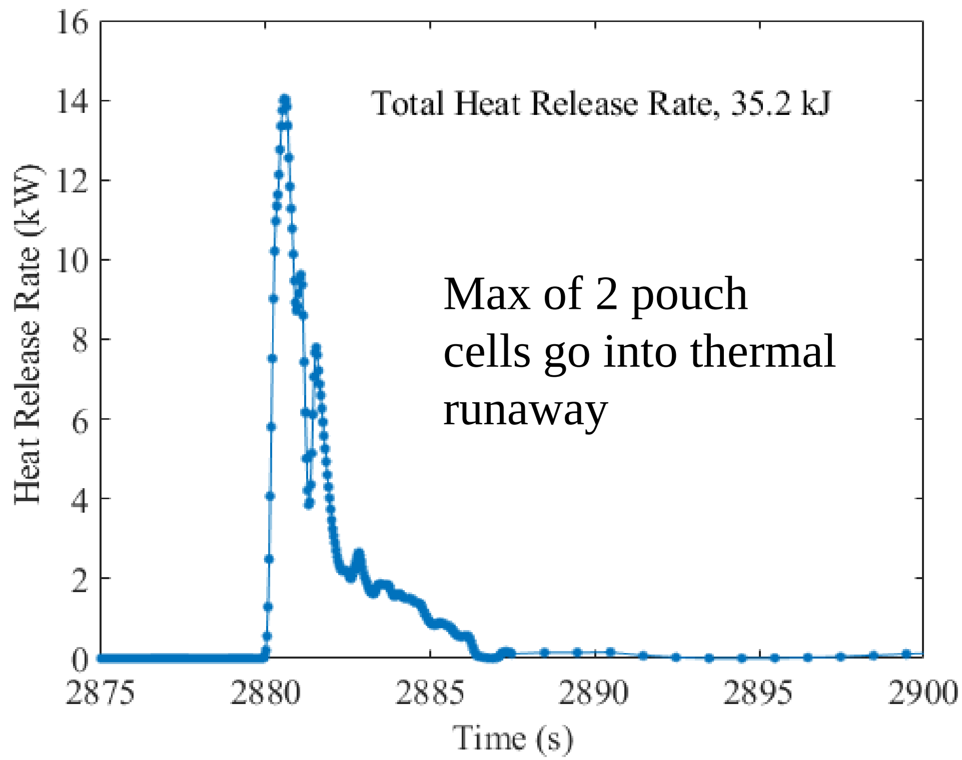
A max of 2 pouch cells go into TR (without water suppressing the fire)

Pouch cells on the right side from the battery pack

Flame Height

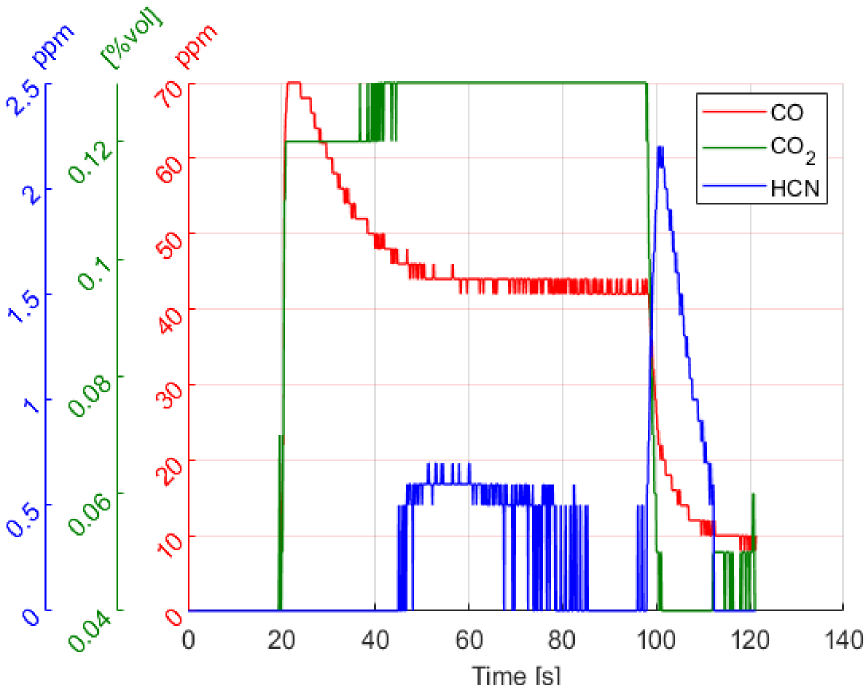


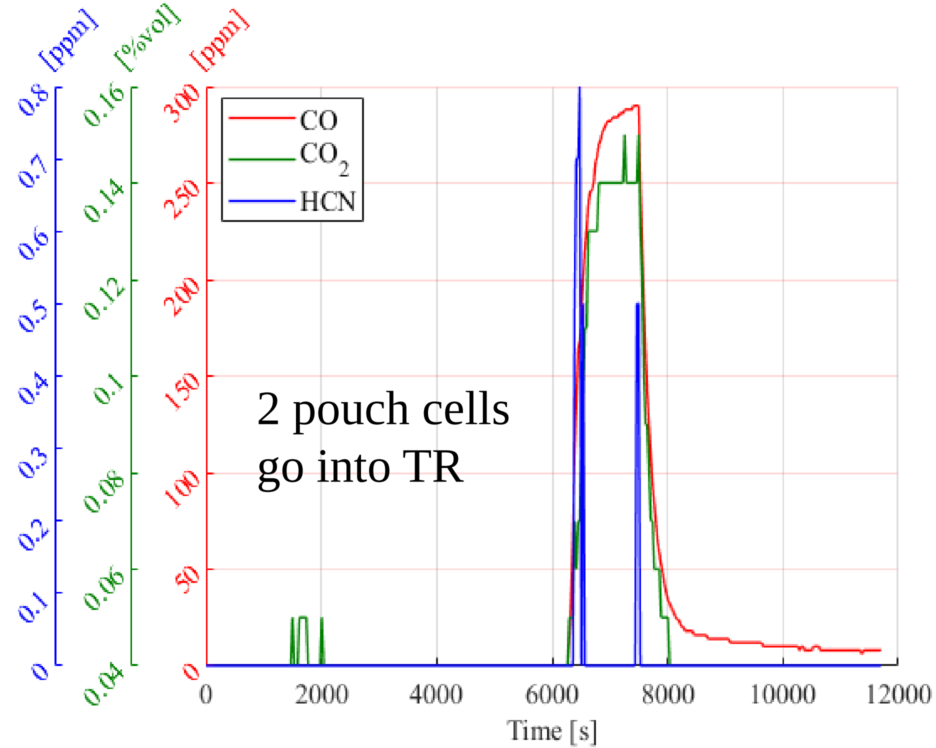
Heat Release Rate and Total Energy Release



Observation	Max time to reach Max HRR (s)	Total Heat Release, THR (kJ)	Fire Duration (s)	Fire Suppression
2 failed pouch cells	**0.3**	**35.2**	**40**	**No**
1 failed pouch cell	**1.4**	**24.3**	**34**	**Yes**

Species Production from Surface Pro Tablet Fires (Patch Heater)



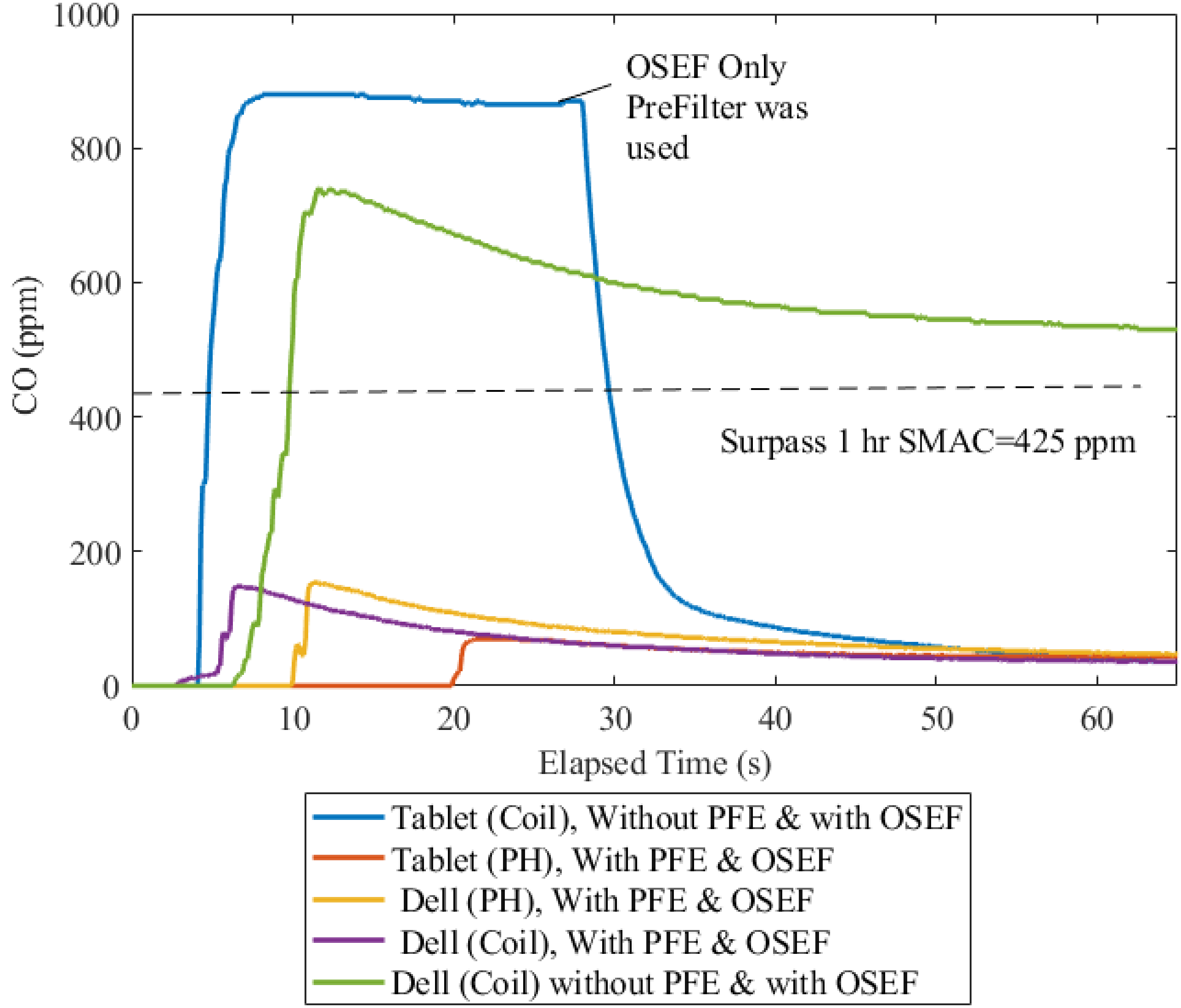


Fire was suppressed & OSEF is available

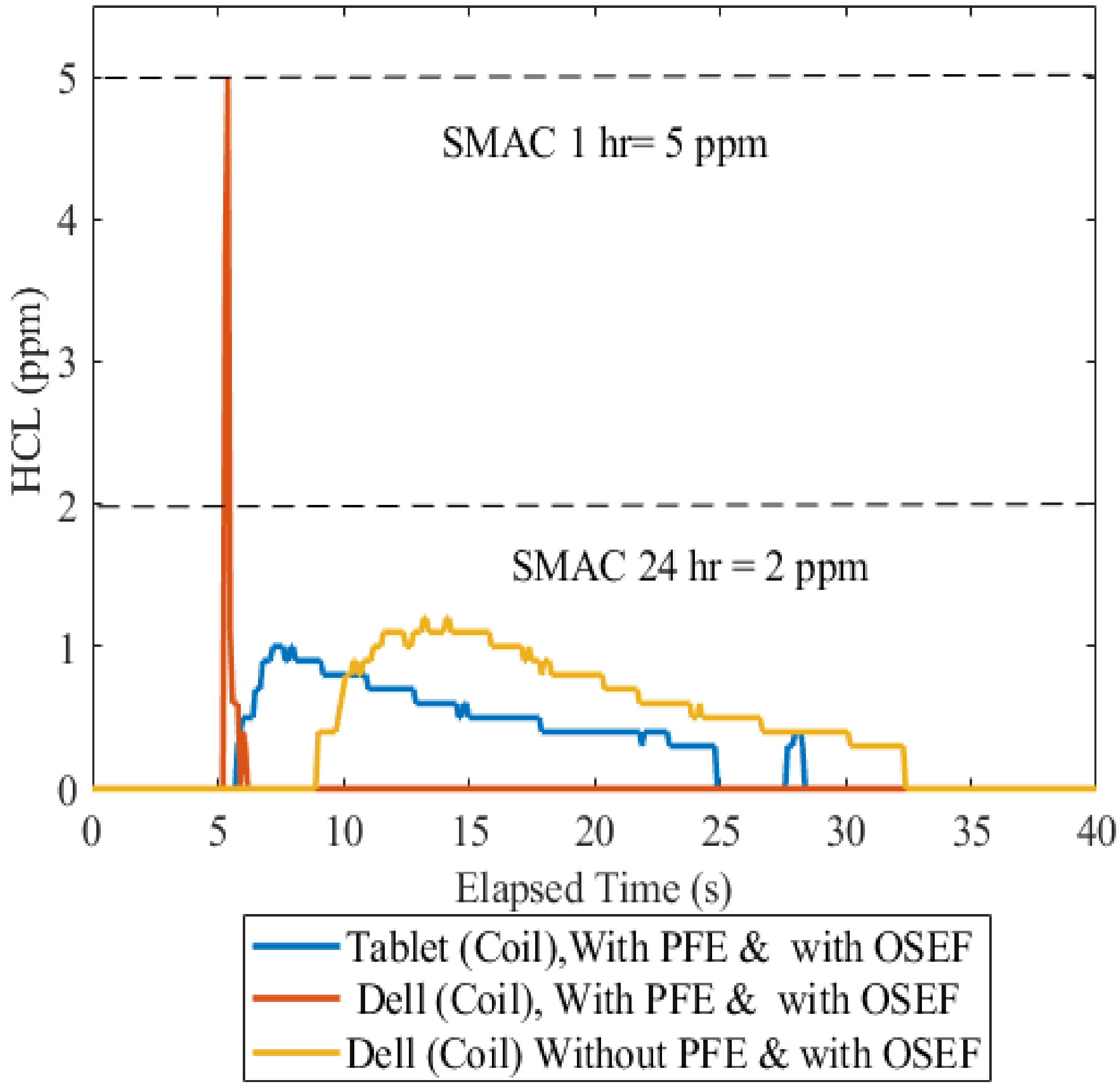
Without fire suppression & OSEF

Gas	SMAC 1 hr ppm (mg/m³)	SMAC 24 hr ppm (mg/m³)	SMAC 7 day ppm (mg/m³)
CO	425 (485)	100 (114)	55 (63)
CO_2	20000 (35000)	13000 (23000)	7000 (13000)
HCN	8 (9)	4 (4.5)	1 (1.1)

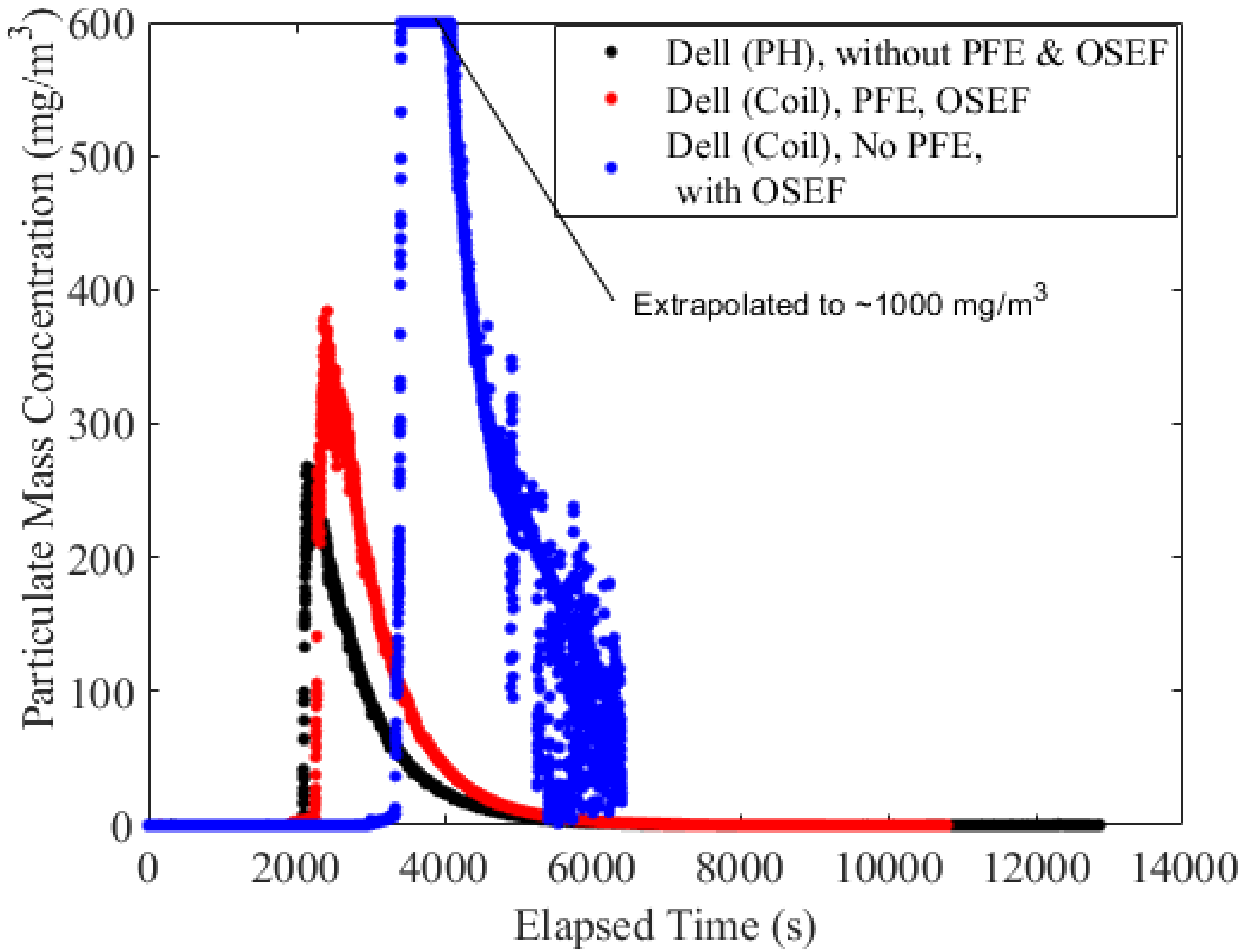
Comparisons of CO for the Dell and Surface Pro Tablet based on OSEF Performance



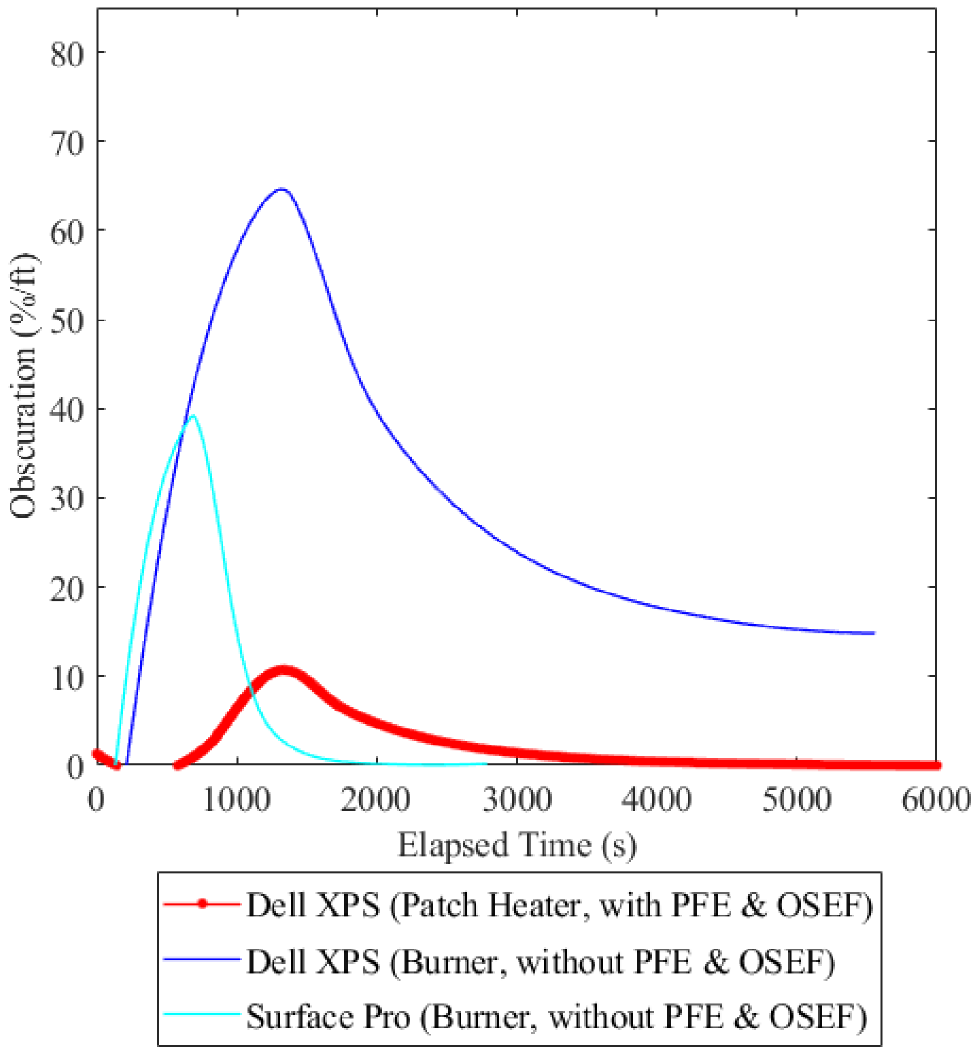
Comparisons of HCL for the Dell and Surface Pro Tablet Based on OSEF Performance

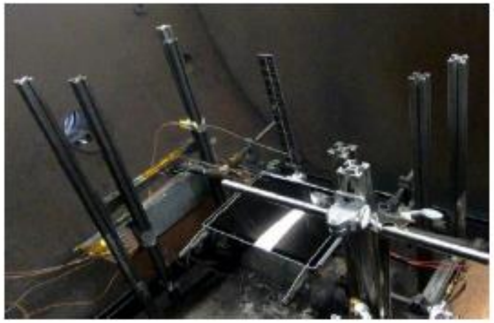


Particulate Matter Comparisons with the Dell XPS



Visibility Comparisons Based on Environmental Cleanup



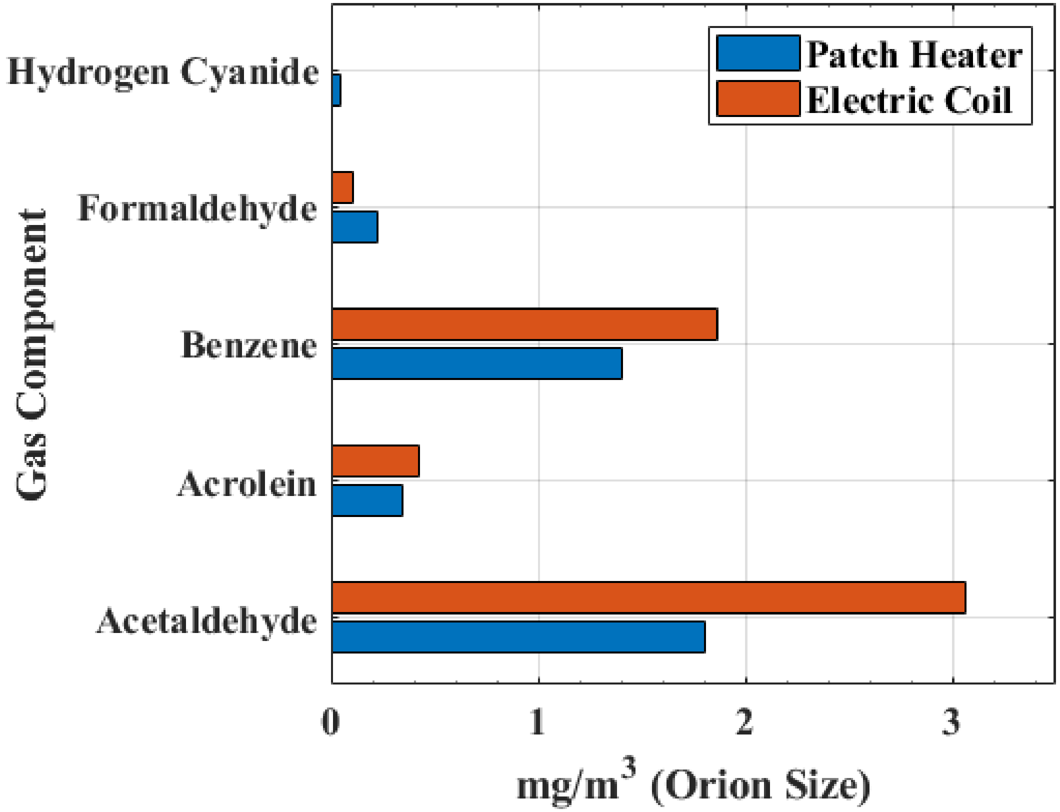


Additional Toxic Gases for a Dell XPS after Fire Suppression

Test Condition:

Sample was initiated 10 seconds after completion of firefighting procedures ("Open flame"+30 s + PFE complete + 10 s)

*CO levels also surpassed the 7 day allowable (not shown)



Gas	SMAC 1 hr mg/m³	SMAC 24 hr mg/m³	SMAC 7 day mg/m³
Acetaldehyde	18	10	4
Benzene	35	10	1.5
Formaldehyde	1.0	0.6	0.12

Toxic Gases for a Dell XPS

Electric Coil

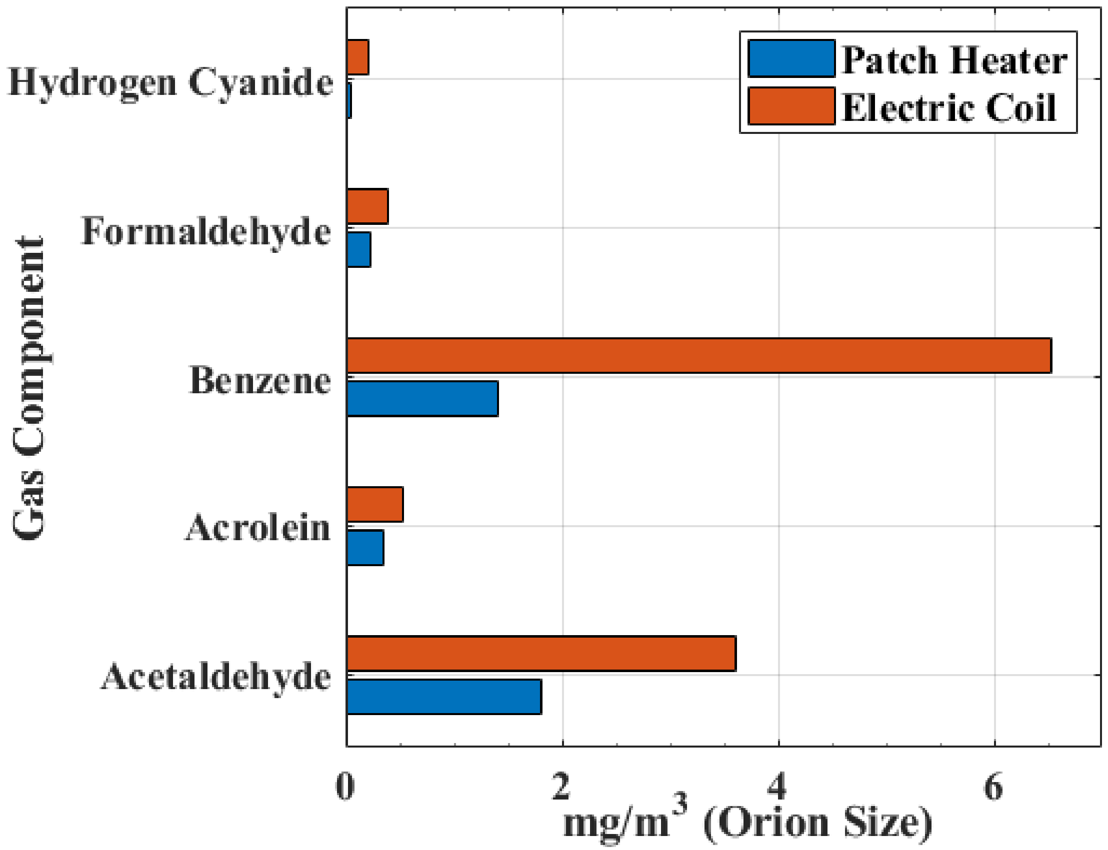
- Sampling occurred 2 hours after the flame self-extinguished ("Flame extinguishes"+30 s+2 hours)

Patch heater

- Sampling occurred 10 s after PFE ("Open flame"+30 s + PFE complete + 10 s)

*CO levels also surpass the

7 day allowable (not shown)



Gas	SMAC 1 hr mg/m^3	SMAC 24 hr mg/m^3	SMAC 7 day mg/m^3
Acetaldehyde	18	10	4
Benzene	35	10	1.5
Formaldehyde	1.0	0.6	0.12

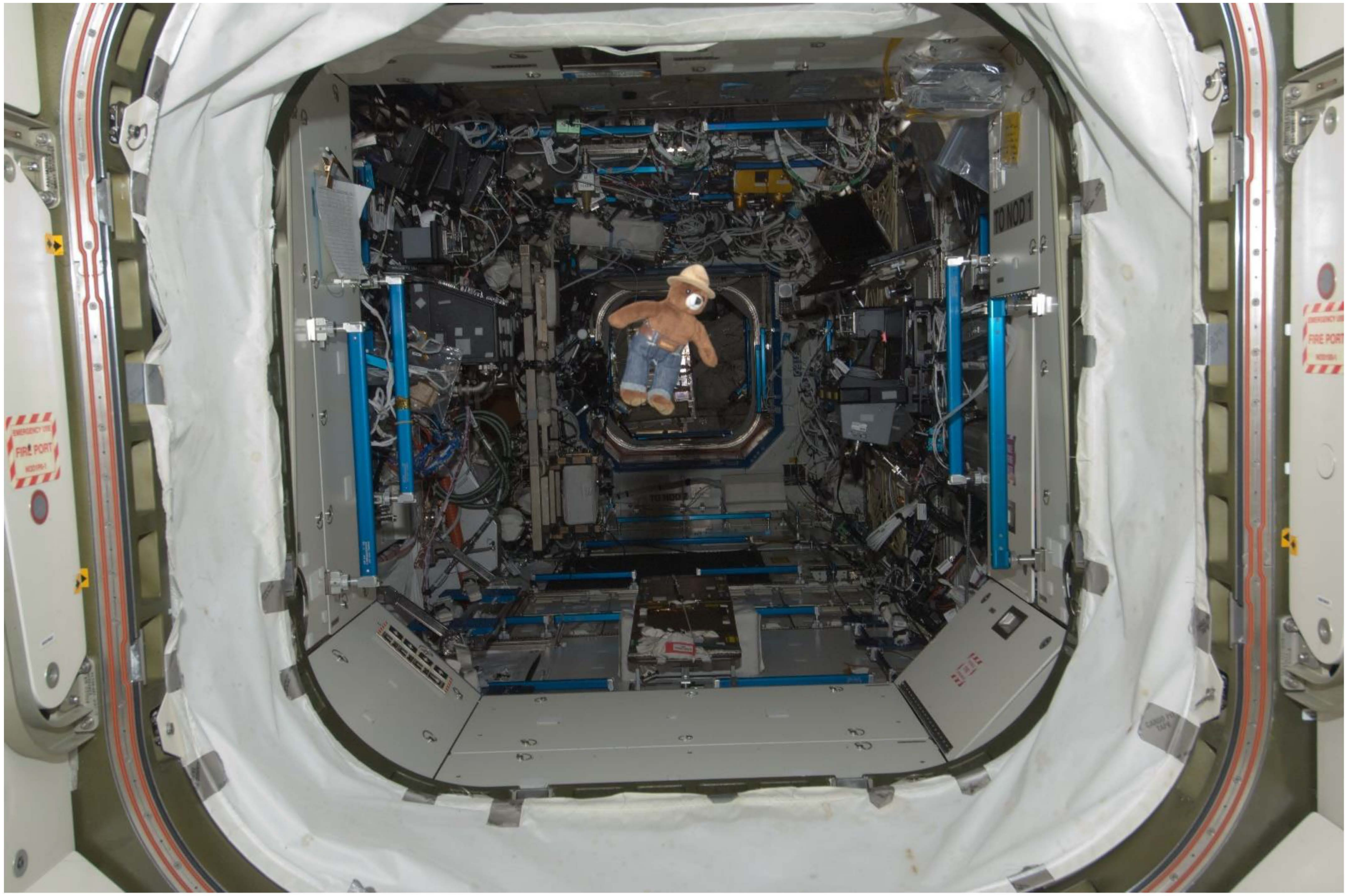
Conclusions

- Tablet fires show an outburst of electrolyte that vents and lasts for 10-15 s followed by a fire that lasts between 20-40 s
  - A total energy release between 24.3- 33.3 kJ and flame heights that reach up to 0.4 m
  - Pouch cell surface temperatures reach maximum temperatures between 817-900 K
  - Maximum of 2 pouch cells going into thermal runaway
- Surface Pro Tablet with the patch heater ignition method
  - Lower tox levels (below SMAC levels), particulate concentrations and obscuration per foot
- "Worst case" fire demonstrations with the Dell XPS 15 (95 Wh) and the electric coil ignition method show
  - CO surpasses the SMAC thresholds and OSEF 1 hr SMAC requirement
  - Higher particulate concentrations
  - Visibility exceeds threshold levels for vehicles

Acknowledgements

- Johnson Space Center and White Sands Test Facility (Alfredo Juarez, Ilse Alcantara, Chris Nagel and Super Test team)
- NASA Glenn Research Center (George Saad and instrumentation team)
- USRA (Jay Owens, Gordon Berger, John Easton, Dan Gotti, Safety Committee)

Thank You!!



Universities Space Research Association

rosa.e.padilla@nasa.gov

References

- Brooker, John E., Dietrich, D. L, Suleyman A. Gokoglu, and Urban, D. L, Modeling and Analysis of Realist Fire Scenarios in Spacecraft, 45th International Conference on Environmental Systems, 12-16 July, Bellevue, Washington
- Dietrich, D. L., Ruff, G. A., and Urban, D. L., Determination of Realistic Fire Scenarios in Spacecraft," 43rd International Conference on Environmental Systems, No. AIAA-2013-3411, American Institute of Aeronautics and Astronautics, Vail, Colorado, July 2013.
- Ferkul, P. et al. Results of Large-Scale Spacecraft Flammability Tests 47th International Conference on Environmental Systems Charleston, South Carolina, July 16-20, 2017
- Olson, S. L., Ferkul, P. V., and T'ien, J. S., Near-Limit Flame Spread Over a Thin Solid Fuel in Microgravity,“ Proceedings of the Combustion Institute, Vol. 22, 1988, pp. 1213 (1222).
- Quintiere et al, Fire Hazards of Lithium ion Batteries, James G. Quintiere, Sean B. Crowley, Richard N. Walters, Richard E. Lyon, and David Blake, February 2016, DOT/FAA/TC-TN15/17
- Quintiere et al On measuring energy from Li-ion Batteries in Runaway and Combustion J. G. Quintiere Qdot LLC with VTEC Lab
- Ribière, Perrine, Sylvie Grugeon, Mathieu Morcrette, Simeon Boyanov, Stéphane Laruelle, and Guy Marlair. "Investigation on the fire-induced hazards of Li-ion battery cells by fire calorimetry." *Energy & Environmental Science* 5, no. 1 (2012): 5271-5280.
- Urban, D.L., Griffin, D., Ruff, G.A., Cleary, T., Yang, J., Mulholland, G., and Yuan, Z.-G.,“Detection of Smoke from Microgravity Fires,” SAE Paper No. 2005-01-2930, 35th International Conference on Environmental Systems, Rome, Italy, July 2005. Ward, B.J., “CEV Combustion Product Monitoring,” Make Engineering, Inc. Report MEIGMI09-2-FR-1, October 2009
- William Walker, John Darst, Donal Finegan, Kenneth Johnson, Eric Darcy, Steven Rickman, Statistical Characterization of Commercial 18650 Format Lithium-ion Cell Thermal Runaway Behaviro Based on Calorimetric Testing Results, NASA Battery Workshop 2019
- Lecocq Amandine, Gebrekidan Gebresilassie Eshetu, Sylvie Grugeon, Nelly Martin d, Stephane Laruelle Guy Marlair Scenario-based prediction of Li-ion batteries fire-induced toxicity, Journal of Power Sources 316 (2016) 197-206
- Allowable Concentrations for Spacecraft, Toxicology Group Environmental Factors Office Habitability and Environmental Factors Division Space Life Sciences Directorate 2017