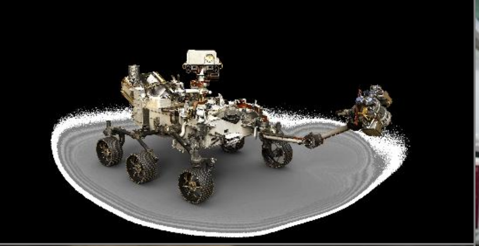





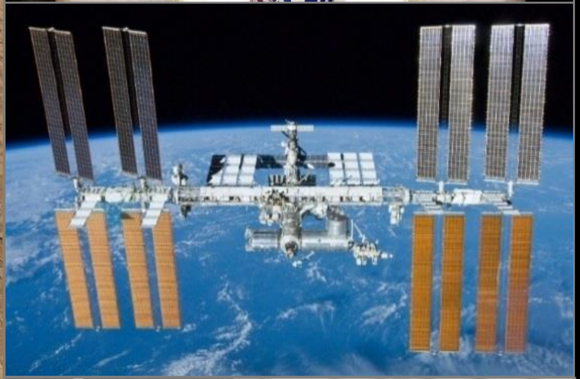


STATUS AND PRELIMINARY RESULTS FOR THE LARGE FORMAT FRACTIONAL THERMAL RUNAWAY CALORIMETER (L-FTRC)

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NASA STRATEGY TO PROTECT AGAINST THERMAL RUNAWAY

- **Following the 2013 Boeing 787 Dreamliner incident, NASA teams developed new definitions for battery design success criteria for human space exploration:**
  - 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 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
  - The need for these data points was one of the primary drivers for the development of the fractional thermal runaway calorimeter (FTRC)

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

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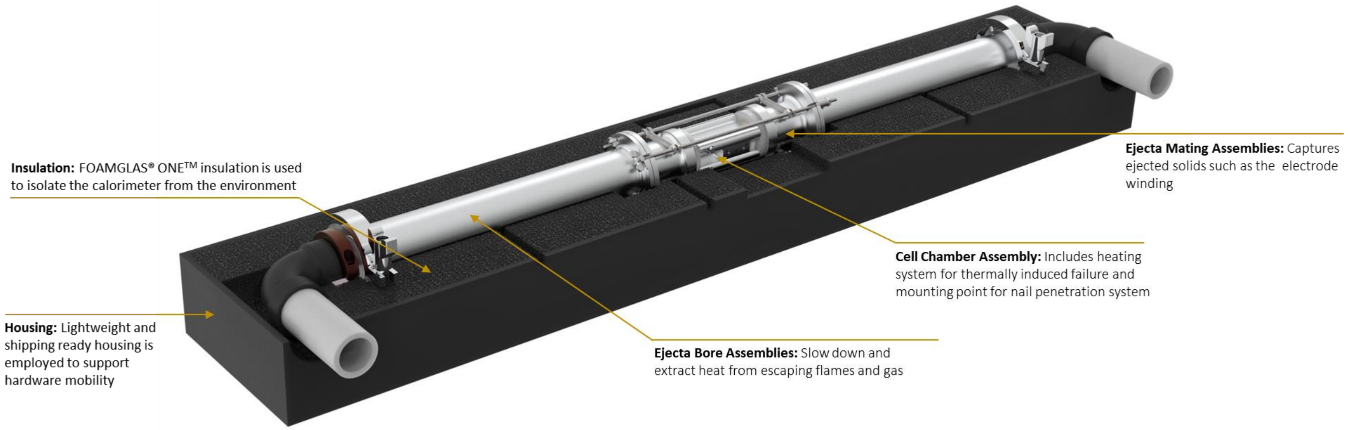
FRACTIONAL THERMAL RUNAWAY CALORIMETRY (FTRC)

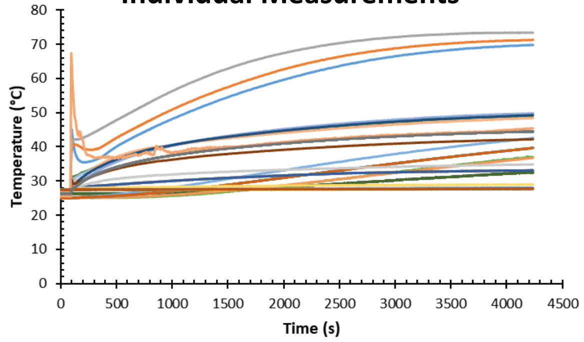
- **NASA recently developed a small format fractional thermal runaway calorimetry (S-FTRC) method for Li-ion cells (18650, 21700, & D formats ranging up to 5 Ah in capacity) which provides data necessary for discerning (1) total heat output and (2) the fraction of heat released through the cell casing vs. ejecta material:**
  - The energy distributions are determined by post processing temperature vs. time for each calorimeter sub-assembly (i.e. $\sum m_i C_{p_i} dT_i$)
  - Uses high flux heaters or nail penetration to initiate TR quickly (i.e. relevant to field failure)
  - Simple operation enables multiple experiments per day
  - Optional interface for measuring the gas exhaust heat



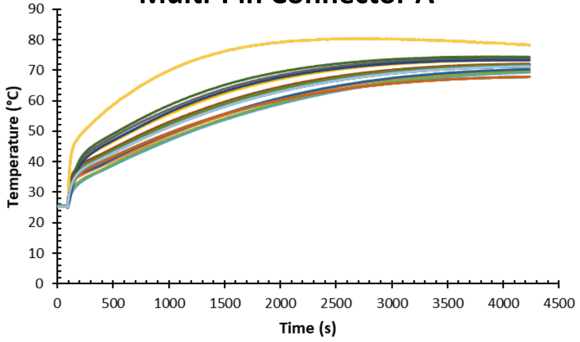
- **After the success of the S-FTRC there was a desire to develop similar capability for larger format Li-ion cells:**
  - A new NESC assessment was initiated in early 2018 to develop a large format fractional thermal runaway calorimeter (L-FTRC) capable of supporting cell formats with capacities greater than 100 Ah
  - This NESC lead assessment involves collaboration with the NESC, NASA Johnson Space Center, NASA Glenn Research Center, SAIC, and USRA
  - A recent test series was conducted at the NASA JSC Energy Systems Test Area (ESTA) with the L-FTRC where 14 134 Ah GS Yuasa Li-ion cells were triggered into thermal runaway via nail penetration; this presentation provides description of the preliminary results from this test series
  - No pictures or images depicting the L-FTRC will be shown in this presentation

- **The primary goal for the L-FTRC is to characterize both the total thermal runaway energy release and the fractions of energy released through the cell casing vs. the jellyroll vs. the ejected gases and effluents:**
  - This is accomplished by calculating the $\sum m_i C_{p_i} dT_i + Heat\ Loss$ of the calorimeter hardware and then by dividing said energy calculations based on sub-assembly; different sub-assemblies represent the fractions of energy released for each area of interest (cell body, jellyroll, ejecta)
  - The images below depict a sample thermal profile of the L-FTRC components after a 134 Ah GS Yuasa cell is triggered into thermal runaway via nail penetration

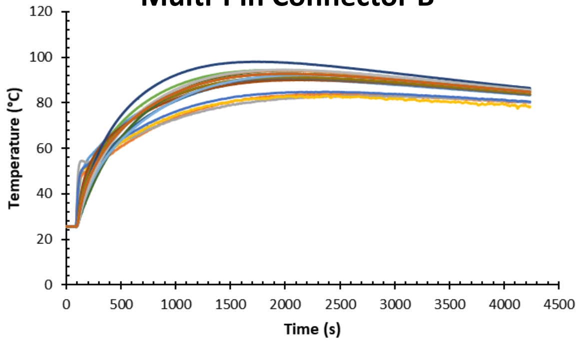
Individual Measurements



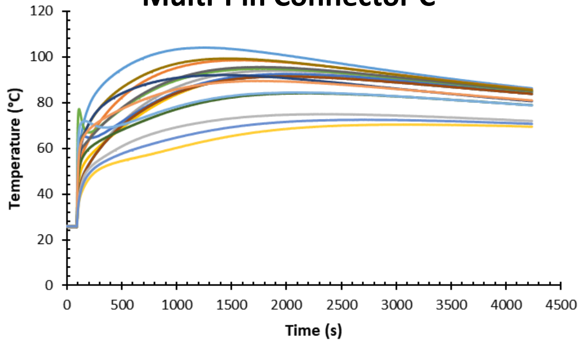
Multi-Pin Connector A



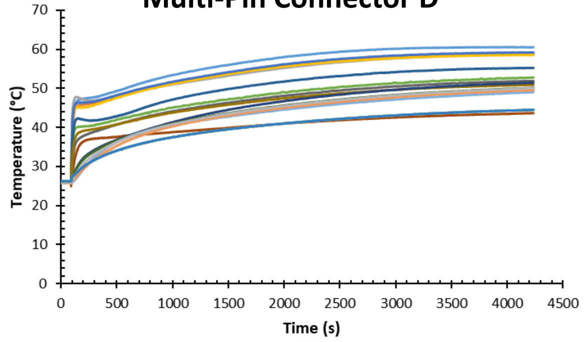
Multi-Pin Connector B



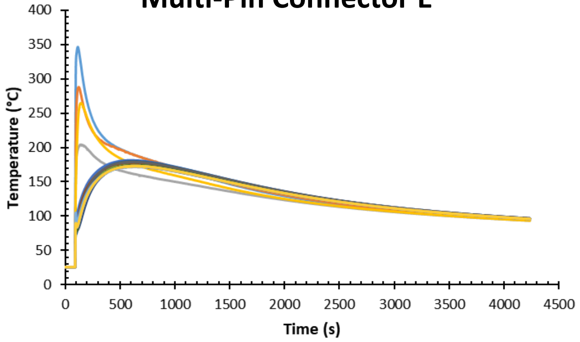
Multi-Pin Connector C



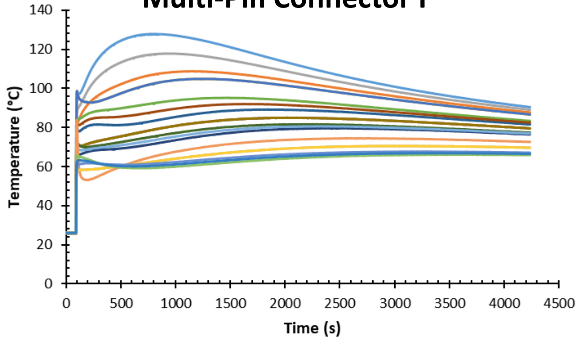
Multi-Pin Connector D



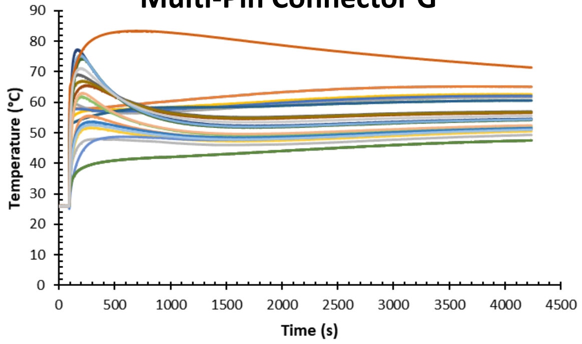
Multi-Pin Connector E



Multi-Pin Connector F

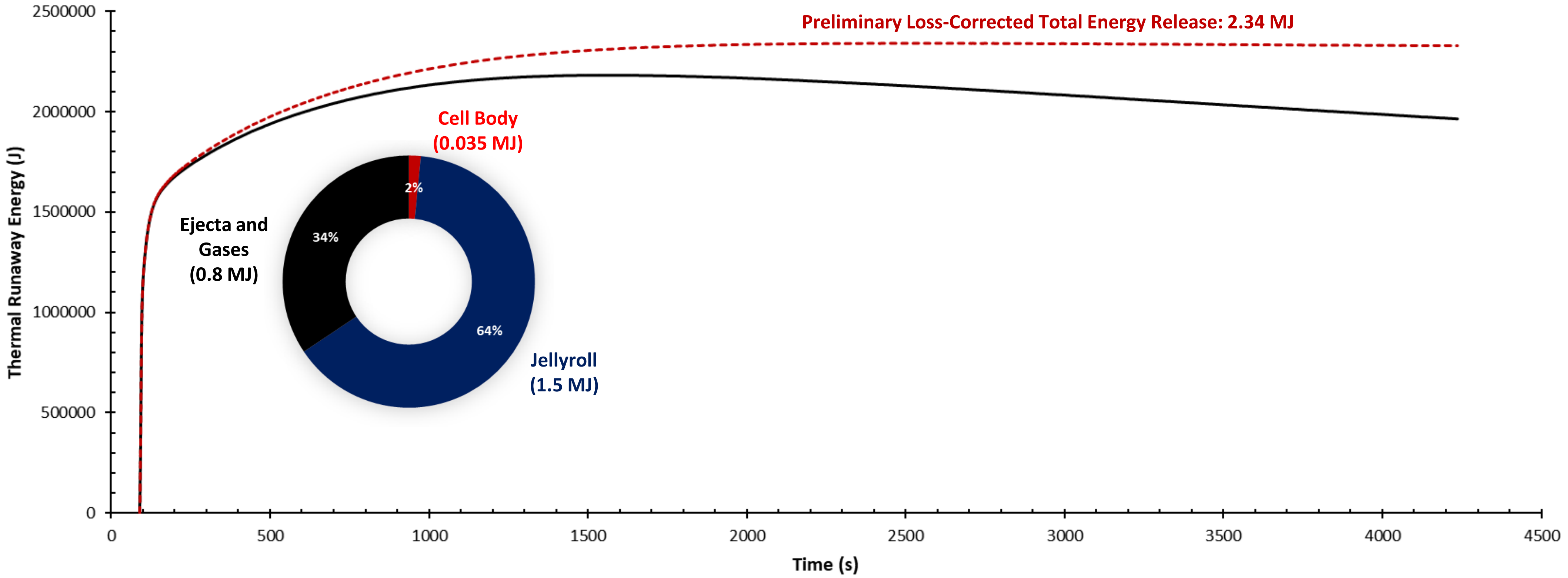


Multi-Pin Connector G

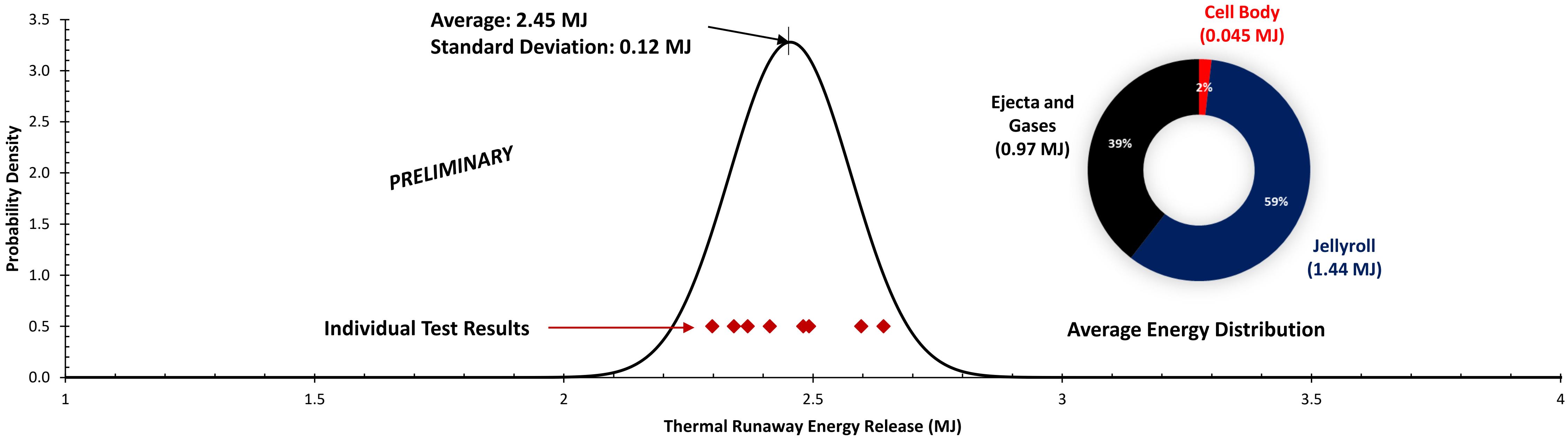


PRELIMINARY ENERGY CALCULATIONS

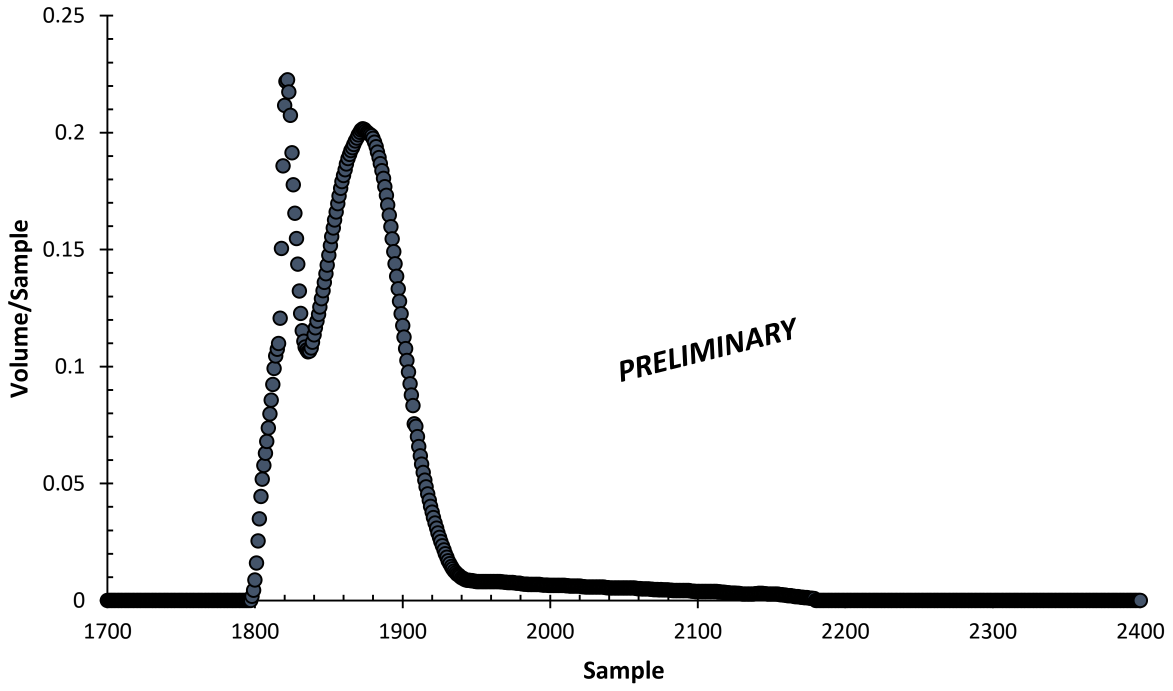
- **Using the aforementioned $\sum m_i C_{p_i} dT_i + Heat\ Loss$ calculations, the baseline and loss-corrected total energy releases as a function of time from trigger can be calculated:**
  - Approximately 1500 s are required for the total energy to be "realized" by the system (this is a function of the thermal mass of the system)
  - Until the data is vetted more thoroughly, the same technique used with S-FTRC data will be used to calculate the fractions; i.e. the distribution of energy 15 s after trigger will be assumed to be representative of the thermal runaway energy fractions
  - The corresponding preliminary total energy curves and energy fractions for the previously shown temperature profiles are given below

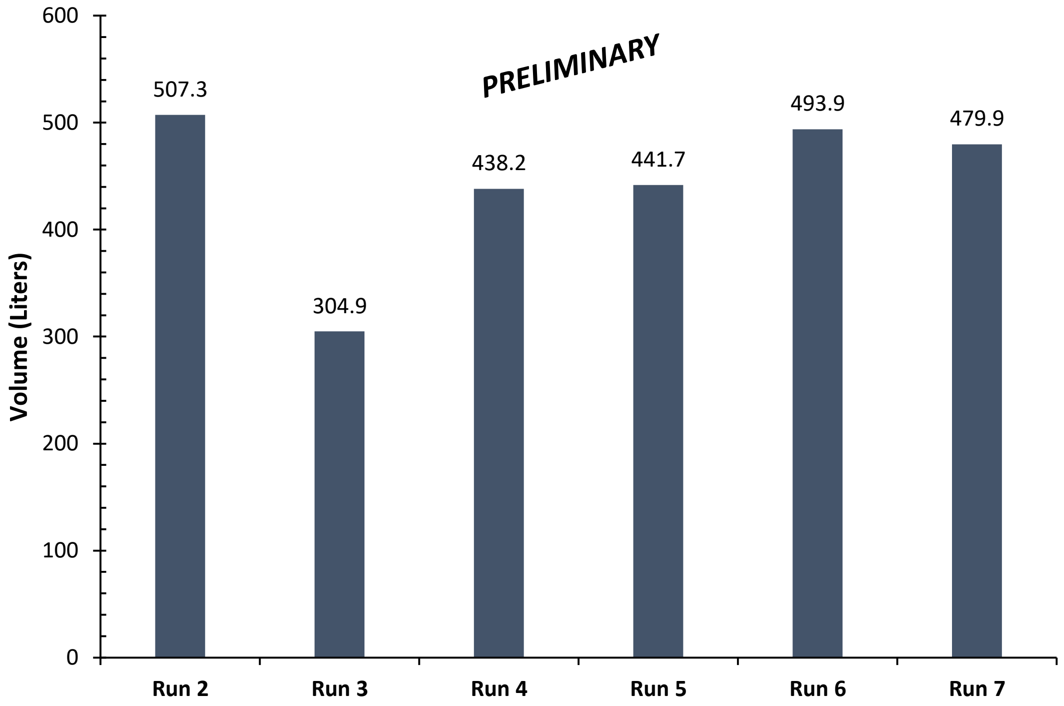


- **Since no two TR events are the same, test-to-test variability must be taken into consideration for any scientific effort that seeks to characterize the overall range of expected thermal runaway behavior for a given cell type**
- **It is helpful to consider the variability of thermal runaway energy release as a statistical distribution to help answer the following questions:**
  - What is the highest probability energy release? What is the lowest?
  - What is the absolute maximum energy release one could expect? Minimum?
  - We recommend 10 experiments to characterize this distribution; the results for 8 of our experiments are shown below.



- **A secondary goal for this assessment was to determine the volume, composition, and energy fractions of the gas that is expelled from the cell during thermal runaway:**
  - Our system allows us to measure the flow rate of gases as they exit through a specialized exhaust path
  - The flow rate is integrated over time to calculate the total volume of expelled gases
  - A sample flow rate plot (for the same example experiment used previously) is shown to the bottom left and a plot showing the total expelled gases (for the experiments that used the gas collection system) is shown to the bottom right





Plot Credit: Ryan P. Brown (NASA JSC) and Gary Bayles (SAIC)

SUMMARY OF PRELIMINARY FINDINGS

- **Note that all findings are preliminary and are subject to change as calculations are refined**

- **A large format fractional thermal runaway calorimeter (L-FTRC) for Li-ion cells with capacities greater than 100 Ah was developed and testing capabilities were demonstrated:**
  - The device supports the discernment of both total energy release and the fractions of energy released through the cell casing vs. the jellyroll vs. the ejecta materials and gases
  - A test series was conducted at the NASA JSC ESTA where 14 134 Ah GS Yuasa cells were triggered into thermal runaway via nail penetration
  - Thermal data, gas flow data, and gas samples were collected

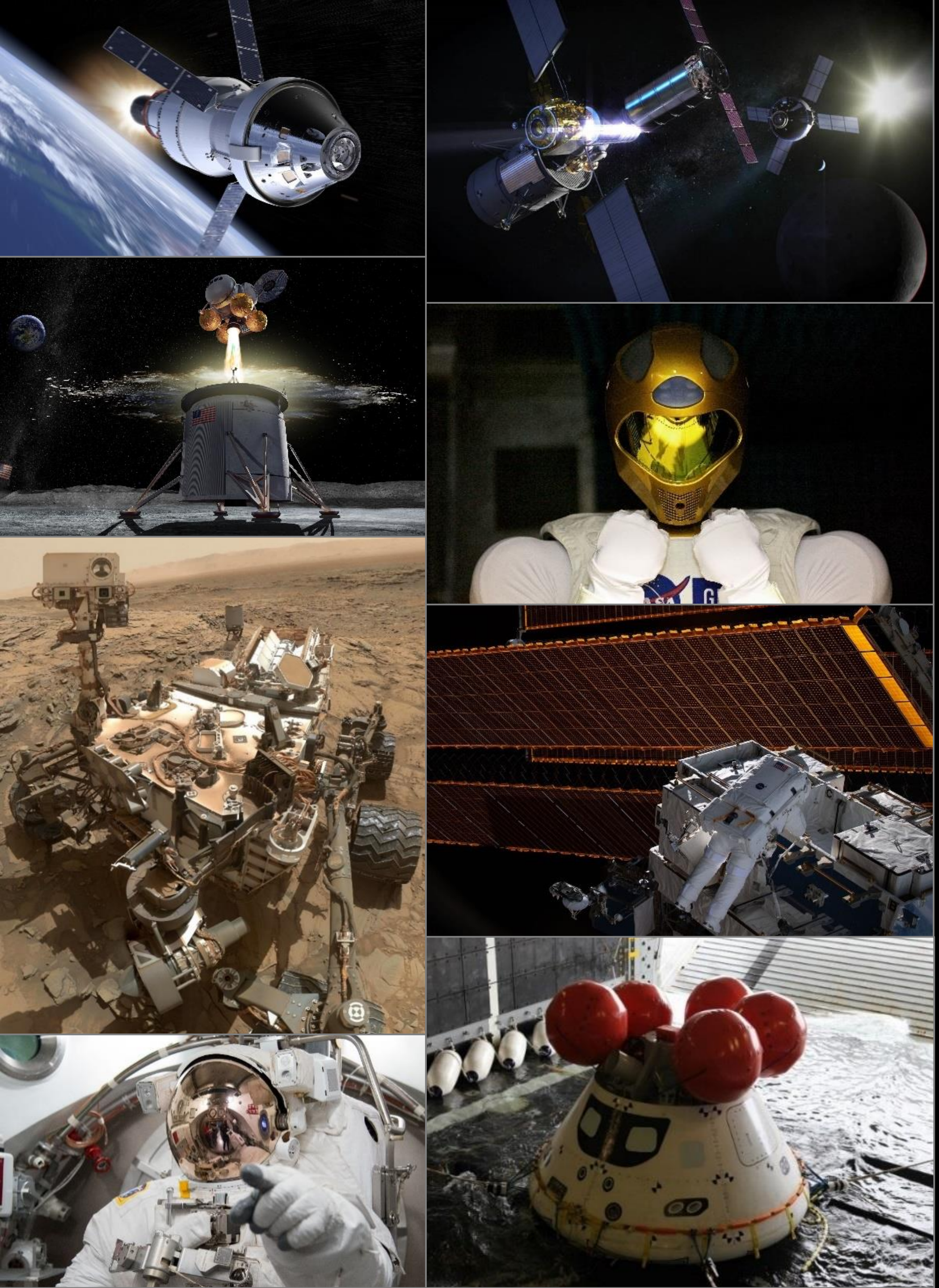
- **PRELIMINARY FINDING: Of the 8 experiment data sets processed thus far, the average total energy release is 2.45 MJ with a standard deviation of 0.12 MJ; the corresponding average distribution of energy is 2% through the cell casing, 59% through the jellyroll and 39% through the ejecta and gases:**
  - These values will be updated as the remaining 6 sets of data are processed
  - Further work will be conducted to distinguish the fraction of energy in the ejecta vs the gas

- **PRELIMINARY FINDING: Gas collection and flow rate measurement was conducted for 6 of the experiments; the average total volume of expelled gases is 444.3 L**

- **The collected gas samples will be analyzed in the near future to determine gas composition**

ACKNOWLEDGEMENTS

- **NASA Engineering and Safety Center (NESC)**
  - Steve Rickman, Kenneth Johnson, 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)**



QUESTIONS?