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

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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)

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\(^1\) Crewed Space Vehicle Battery Safety Requirements. JSC-20793 Rev D. JSC Engineering Directorate, Power and Propulsion Division
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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. $\sum m_iC_p dT_i$)
- 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 $\sum m_i C_p i dT_i + \text{Heat Loss}$ 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.
Using the aforementioned \( \sum m_i C_{pi} dT_i + \text{Heat Loss} \) 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.

### Preliminary Energy Calculations

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Body</td>
<td>0.035</td>
</tr>
<tr>
<td>Jellyroll</td>
<td>1.5</td>
</tr>
<tr>
<td>Ejecta and Gases</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Total Energy Release: 2.34 MJ
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.

**Preliminary Evaluation of Total Energy Release Variability**

- Average: 2.45 MJ
- Standard Deviation: 0.12 MJ

**Individual Test Results**

- **Cell Body** (0.045 MJ) 2%
- **Jellyroll** (1.44 MJ) 59%
- **Ejecta and Gases** (0.97 MJ) 39%

**Average Energy Distribution**

- Thermal Runaway Energy Release (MJ)
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.
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.
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QUESTIONS?