Thermal Analysis on Large Format Lithium-Ion Batteries in Thermal Runaway

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Contents

Introduction to Thermal Runaway

– **What is Battery Thermal Runaway?**

Battery Thermal Runaway (TR) occurs when a cell's internal heat generation surpasses its ability to dissipate heat. This heat generation may occur though several failure modes, and runaway behavior greatly varies based on failure mode, geometry, and chemistry.

– **Why does Battery TR occur?**

TR typically occurs when a cell experiences elevated temperatures from mechanical, electrochemical, and thermal abuse. Failures from manufacturing errors, overcharge, over-discharge, and internal short circuit all can lead to battery TR. Once self heating occurs in the cell, there is expected to be heating due to the decomposition of the electrolyte, cathode/anode, SEI (Solid Electrolyte Interface), and remaining electro-chemical energy.

Introduction to Thermal Runaway

– **Why do we care about Battery Thermal Runaway?**

Li-ion Cells are very energy dense, which is valuable for spacecraft power and mass constraints. However, these cells can enter thermal runaway and can eject hot materials and gases that may be damaging to mission hardware or toxic to life.

– **What do we do?**

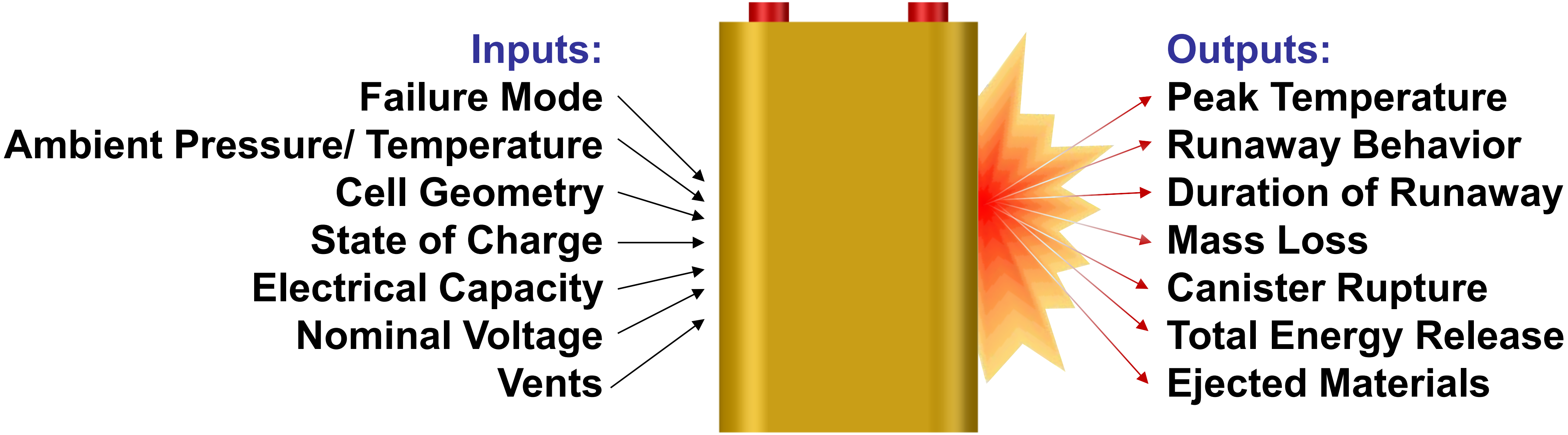
NESC recommendations

- Assume battery TR will always occur and ensure design has passive propagation resistance
- Battery Pack design should prevent catastrophic damage by demonstrating the battery will not propagate surrounding to cells if just one instance of cell thermal runaway occurs.
- Thermal Runaway calorimetry can be useful to characterize the total energy release of cells and how much of that heat is dissipated in the vented gasses or though the cell canister.

Battery Thermal Runaway Considerations

Thermal runaway events are inherently inconsistent, even if the cell type, SOC, and remaining initial conditions are the same.

- To better conduct analysis on cells in thermal runaway, it is useful to consider the total thermal output as a statistical distribution, and for a worst case use an example representing the upper bound of that distribution.
- NESC Recommends 10 experiments to characterize the distribution. For preliminary analysis where testing may not be available, cells of similar characteristics with L-FTRC (Large – Format Functional Thermal Runaway Calorimetry) may be used for insight



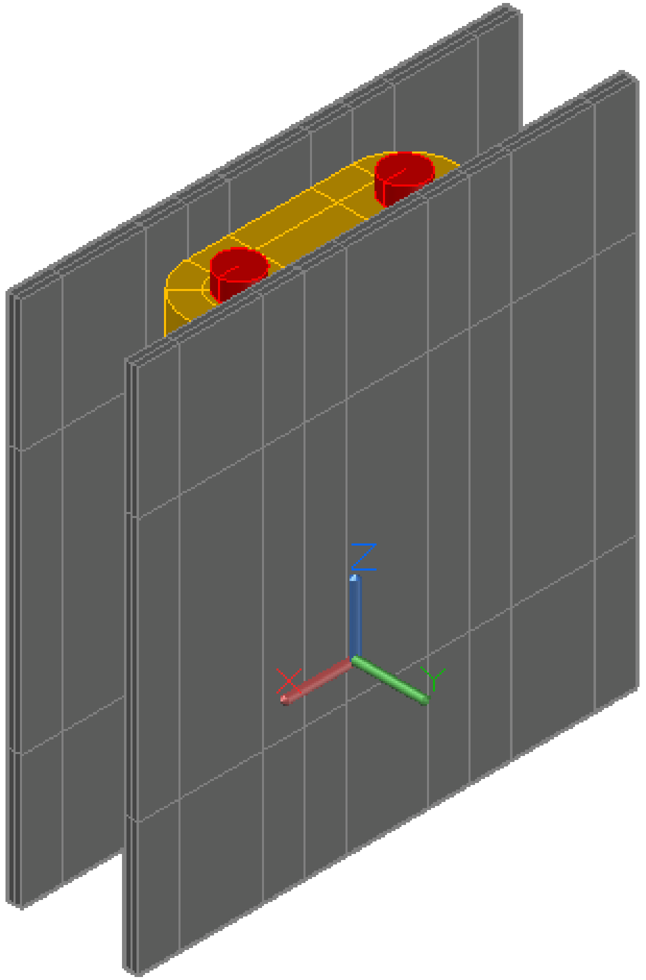
Modeling Methodology

- Single Cell Thermal Model Layout

  A battery assembly level model is only as good as our understanding of the individual cell.

  Developing reduced models to correlate to a single cell in TR can assist later battery assembly design and provide insight based off the thermal responses in a more simplified scenario.

  – Cell Geometry
  – Test Stand
  – Heat Loads
  – Effluent



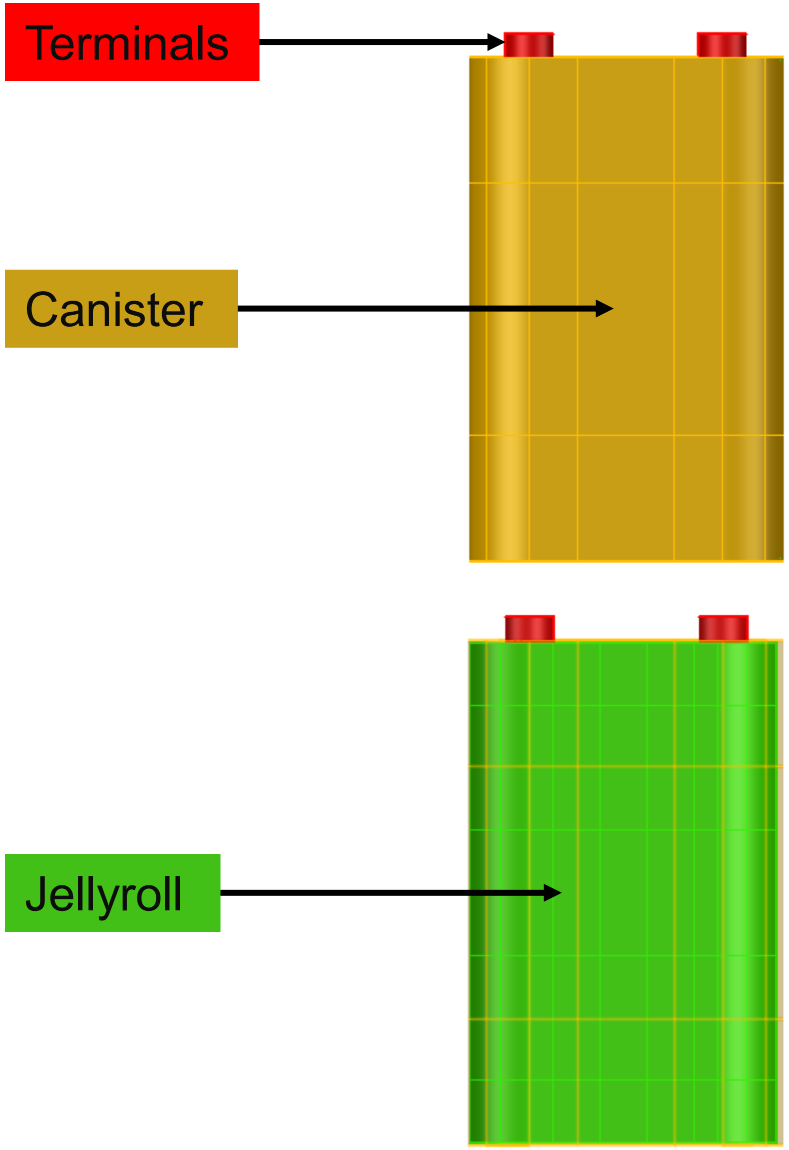
Modeling Methodology

- Single Cell Thermal Model Layout
  - **Cell Geometry**
    - Cell model will consist of the jellyroll, canister, and terminals connected via thermal desktop surface-surface contactors.

      Terminals: Aluminum or Copper Alloy

      Canister: Al 6061 T-6

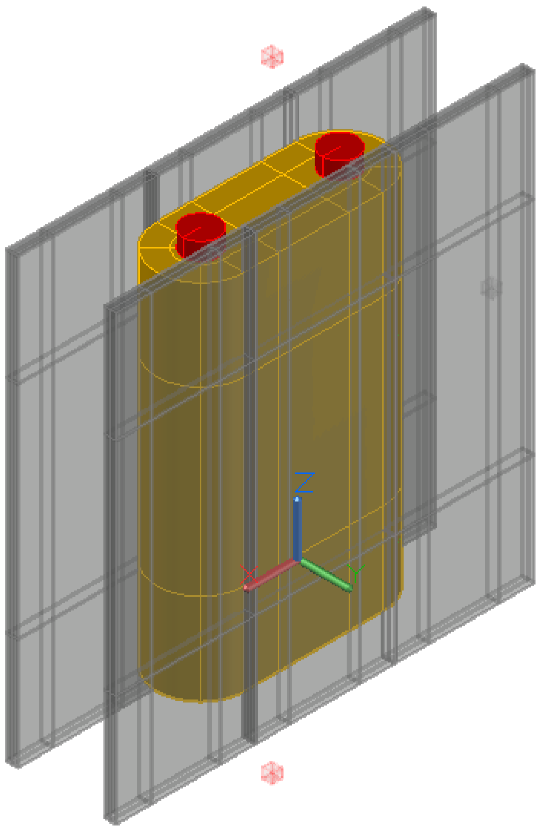
      Jellyroll: typically, a composite of the separator, cathode/anode, and electrolyte, etc. Need properties and accurate Cp and material conductivity characterization.
  - Test Stand
  - Heat Loads
  - Effluent



Modeling Methodology

- Single Cell Thermal Model Layout
  - Cell Geometry
  - **Test Stand**
    - The cell test stand's purpose is to hold the cell rigidly during testing and apply pressure to the cell to encourage venting if battery TR occurs. Consider ambient conditions, as well as similar cases in vacuum for spacecraft applications.

      Test Stand: Stainless Steel, assume high contact conductance from canister to plate.
  - Heat Loads
  - Effluent



Modeling Methodology

- Single Cell Thermal Model Layout

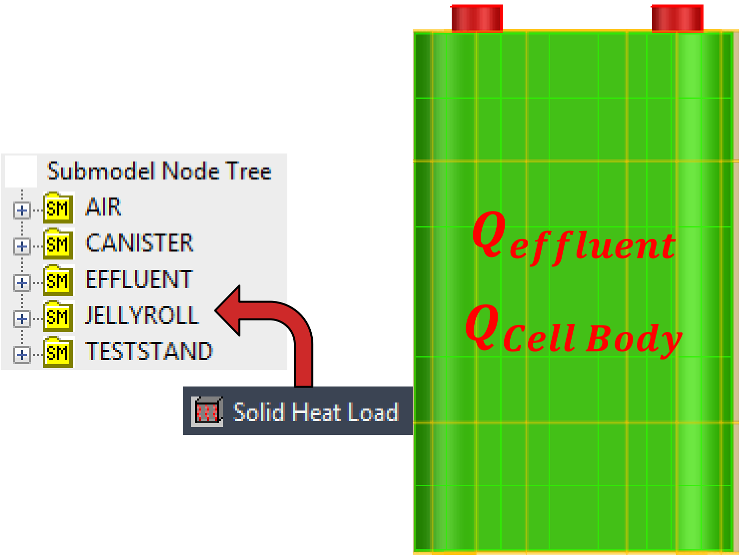
  - Cell Geometry
  - Test Stand
  - **Heat Loads**

    Heat generated inside the canister should represent a total energy release captured from cell calorimetry tests of the specific cell, or a cell of similar geometry and chemistry. Heat release from electrolyte, SEI, cathode/anode decomposition, and electro-chemical energy release are summarized as simple solid heat loads.

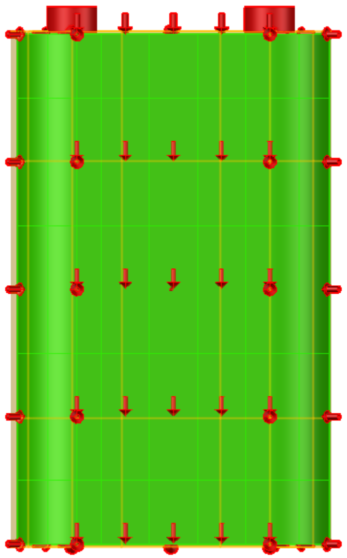
    $Q_{Effluent}$: energy release during effluent heating is rapid

    $Q_{Cell\ Body}$: energy release typically longer (minutes) and can be considered a thermally worst-case scenario.

  - Effluent



Heat loads applied in thermal model as two separate Solid Heat Loads only on the jellyroll



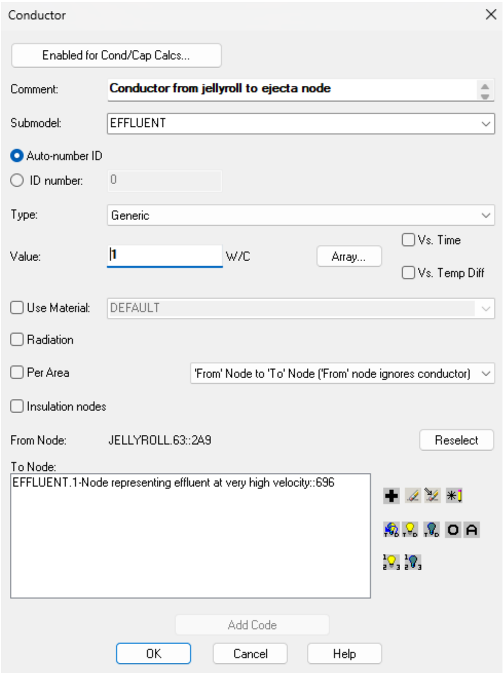
Modeling Methodology

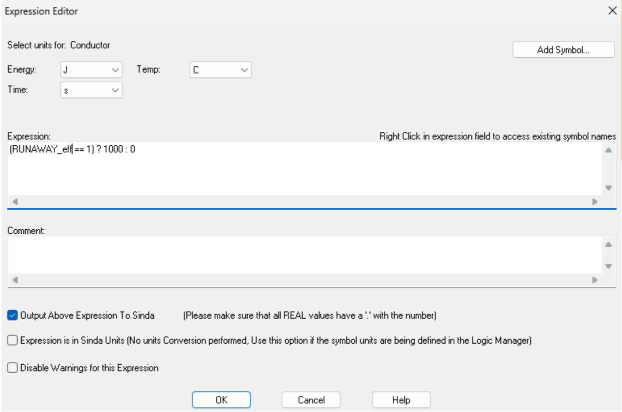
- Single Cell Thermal Model Layout

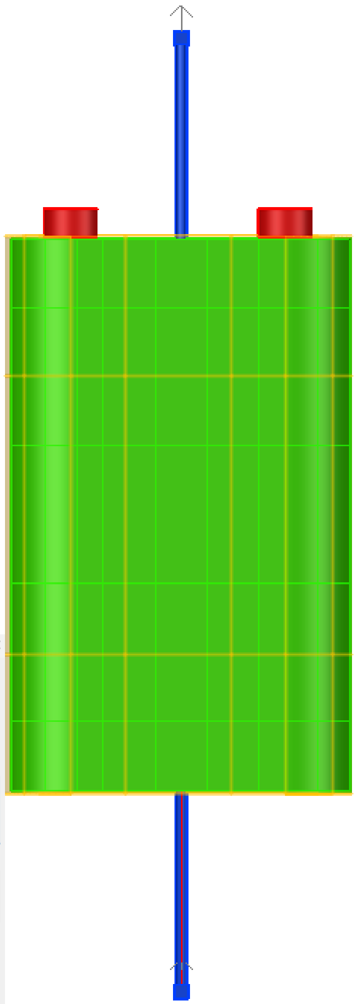
  - Cell Geometry
  - Test Stand
  - Heat Loads
  - **Effluent**

    The effluent/ejecta leaving the cell can be represented as diffusion/arithmetic nodes with one-way node-to-node conductors from the center of the jellyroll.

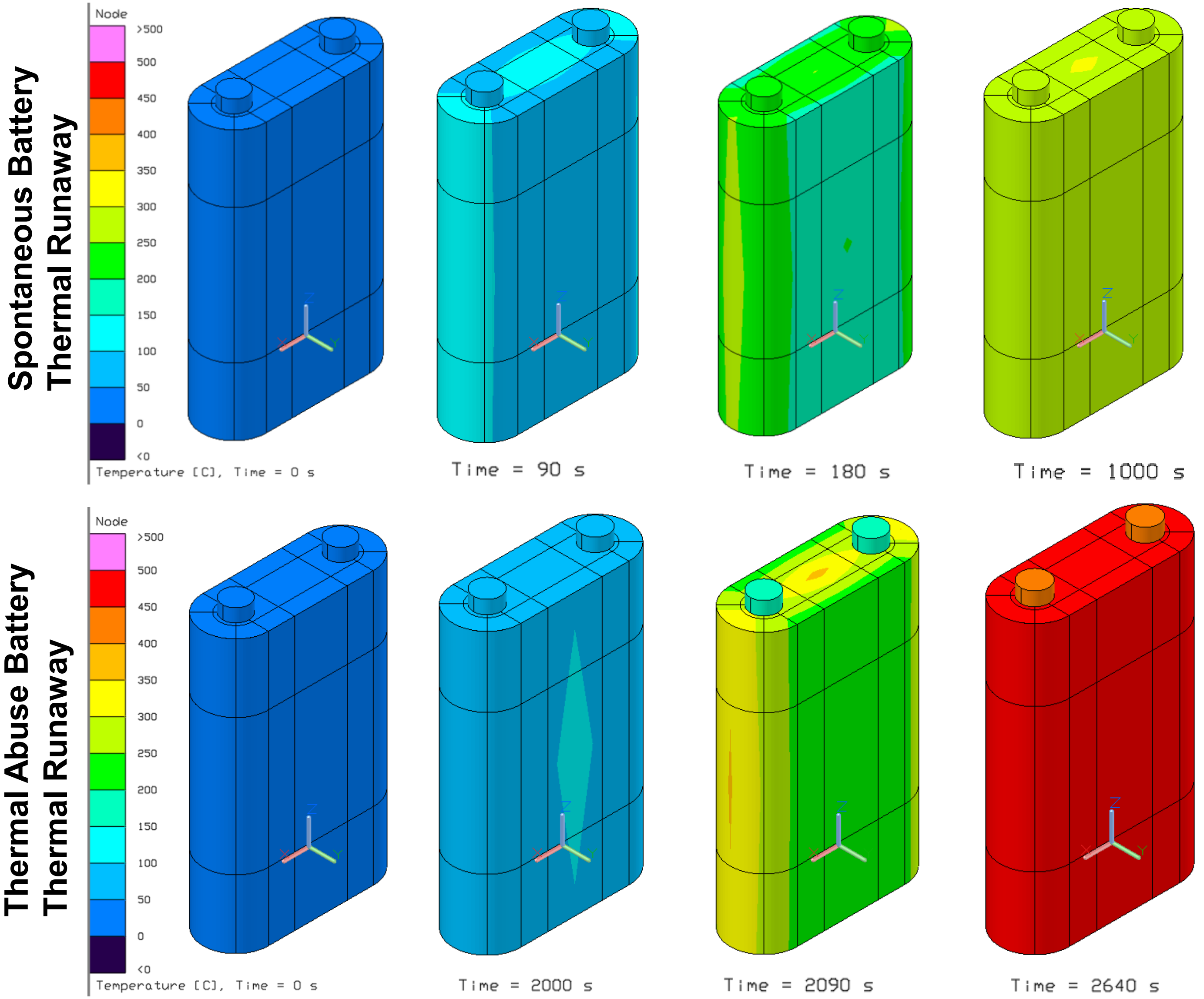
    Vented gasses from the jellyroll to the next node can be assumed to be nearly perfect, as the gasses are moving at high velocities. Mass flow rates and convection over flat plates can be applied for battery pack effects.

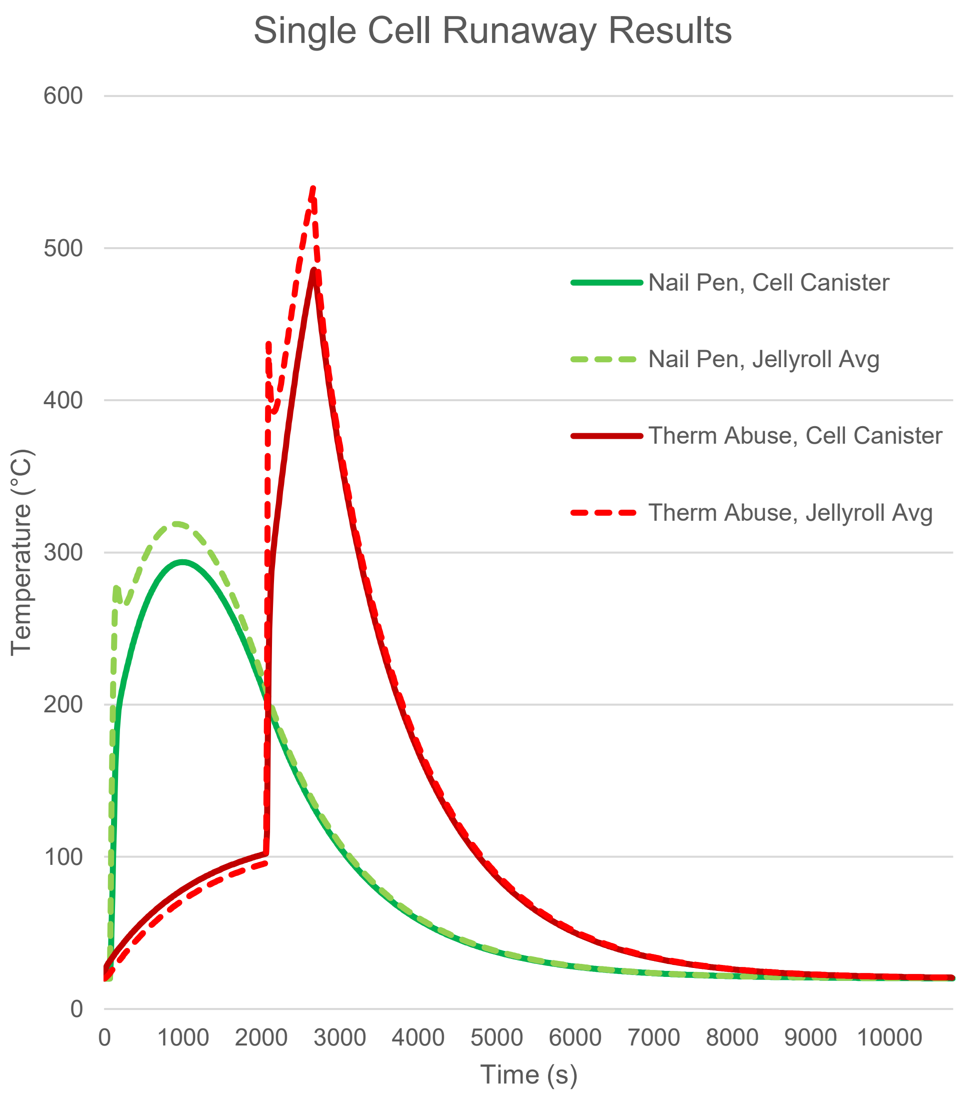






Results, single cell





Modeling Methodology

- Battery Pack Modeling
  - When building a thermal model for battery pack models, similar considerations can be made as the single cell model.
  - Single cells can be XREF'd or inserted as blocks into a battery model.
  - Battery Pack modeling in early design stages can help determine:
    - What insulation material can be used
    - Are heat sinks/heat pipes necessary for thermal control
    - How far should cells be away from each other
    - How much heat needs removed from the system

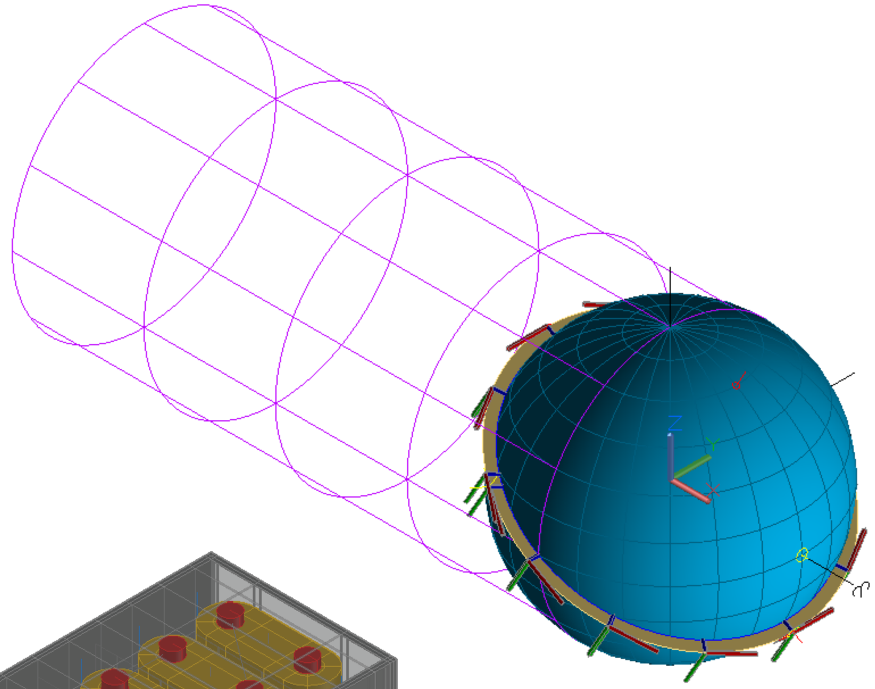
Modeling Methodology

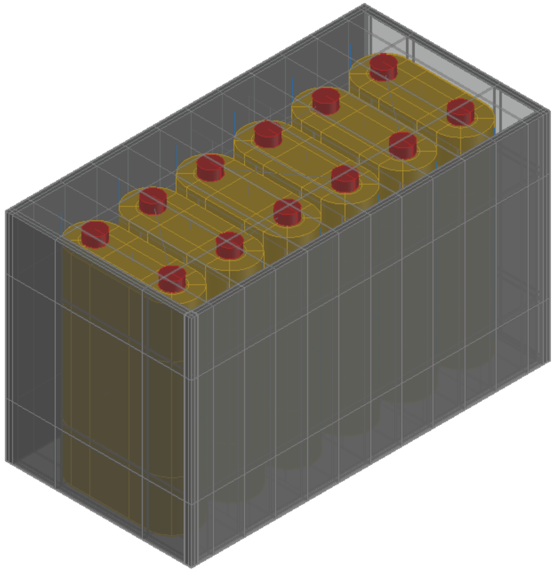
- Battery Thermal Model Layout
  - **Battery Geometry**

    Battery enclosure, bus bars, insulation, test stand/vehicle, and any natural or induced environments should be considered.

    Solver time may vary depending on how many cells are in a battery pack, how many cells propagate (if any), and transient time steps.

    - Large time steps should be avoided, too small of time steps may take too long to solve. Symbol driven time step based on runaway criteria may be applicable.
  - Heat Loads
  - Effluent





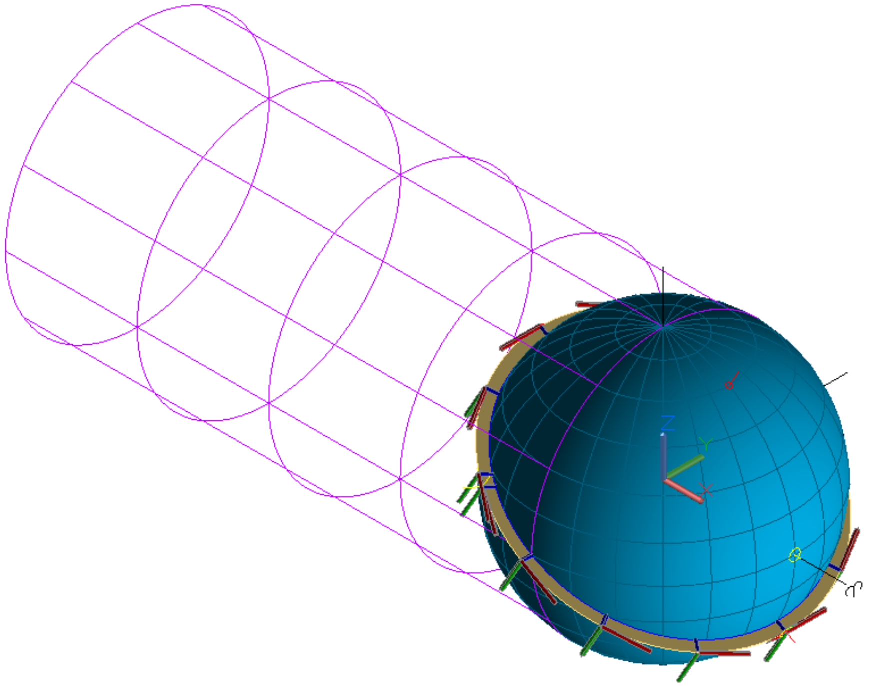
Modeling Methodology

- Battery Thermal Model Layout
  - Battery Geometry
  - **Heat Loads**

Similar heat loads are applied to the first cell in thermal runaway as used in the single cell model. For analysis on battery packs and passive propagation resistance, additional heat loads are applied to each of the remaining cells to determine if a cells internals surpass a trigger temperature. Each cell will have its nodes temperatures recorded at each timestep.

There is no universal value where TR occurs, so assigning a value where onset runaway reactions occur may be difficult. However, a lower temperature than what is observed in calorimetry or other tests can be used to determine if onset runaway reactions occur for the purpose of PPR (Passively Propagation Resistant) analysis.

  - Effluent



Modeling Methodology

Heat Loads Continued

- Thermal Runaway Logic
  - **TTRIG,** determines at what temperature a cell enters TR, and QEVENT is applied
  - **TEVENT,** states the duration of the runway event
  - **QEVENT**, the heat loads associated with TR in the cell
  - **RUNAWAY**, ensures TR can only occur once in a cell. This symbol equals 1 when TTRIG is reached in the cell
  - **END_TRIGGER,** this symbol tell the TR logic when cell TR has ended, setting RUNAWAY to -1

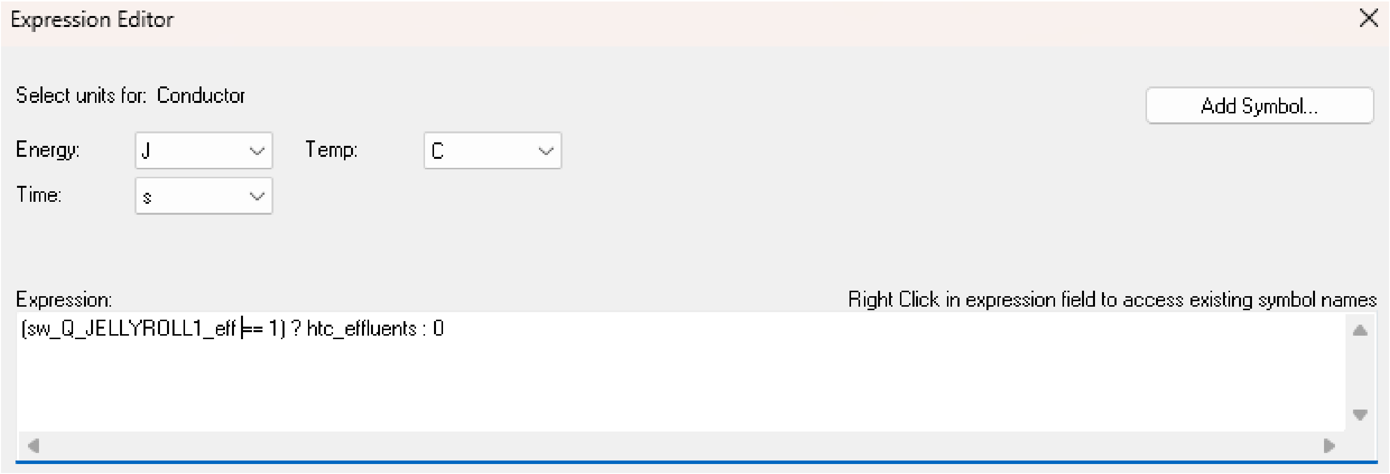
```
FSTART
C find submodel reference ID
        call modtrn('JELLYROLL1',mtest)
C loop through all diffusion nodes in the submodel
C assumes nodes are sequentially numbered
        do itest = 1, nmdif(mtest)
C look up node storage location
        call nodtrn('JELLYROLL1',itest,ntest)
C perform runaway logic
        if((T(ntest).ge.TTRIG).and.(RUNAWAY1.ge.0))then
        if(RUNAWAY1.eq.0.)then
        ENDTRIGGER1=TIMEN+TEVENT
        RUNAWAY1= 1
        endif
        if((T(ntest).ge.TTRIG).and.(RUNAWAY1_eff.ge.0))then
        if(RUNAWAY1_eff.eq.0.)then
        ENDTRIGGER1_eff=TIMEN+TEVENT_eff
        RUNAWAY1_eff = 1
        endif
        endif
        if(TIMEN.ge.ENDTRIGGER1)then
C use capacitance fraction to proportion the heat load
C battery_mCp can be calculated in advance
        RUNAWAY1=-1
        endif
        if(TIMEN.ge.ENDTRIGGER1_eff)then
        RUNAWAY1_eff=-1
        endif
        endif
        end do
FSTOP
```

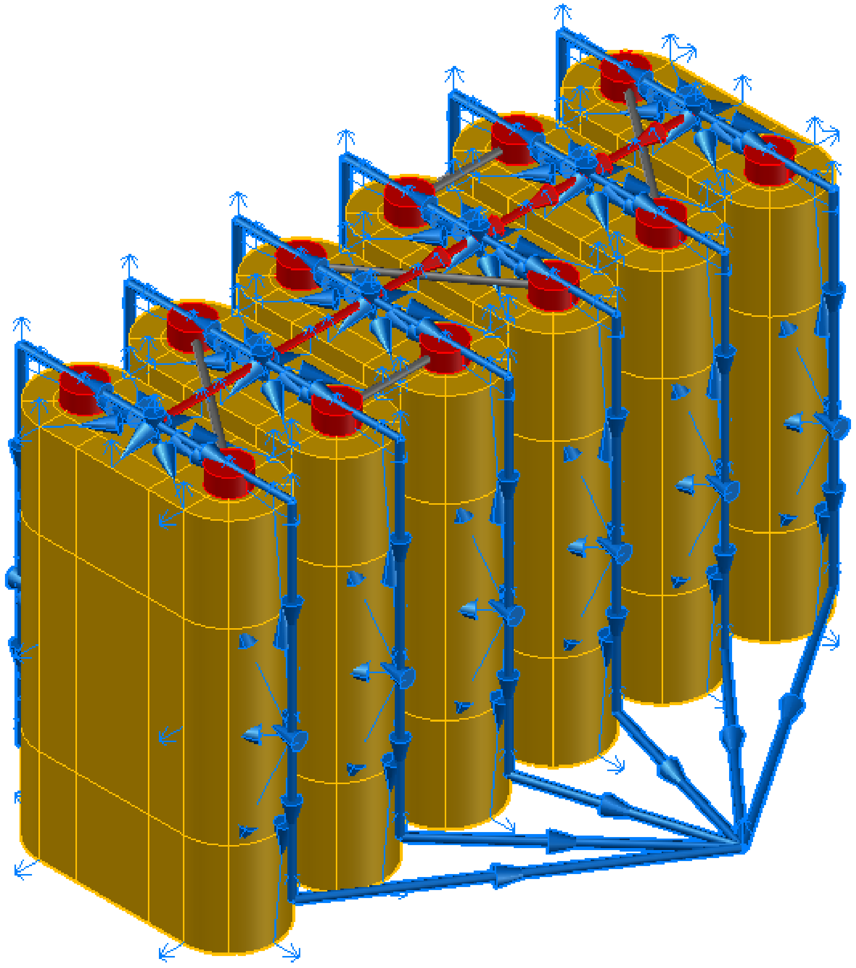
Source: TFAWS 2015 Short Course on Lithium-Ion Batteries (Walker, NASA JSC)

Modeling Methodology

- Battery Thermal Model Layout
  - Battery Geometry
  - Heat Loads
  - **Effluent**

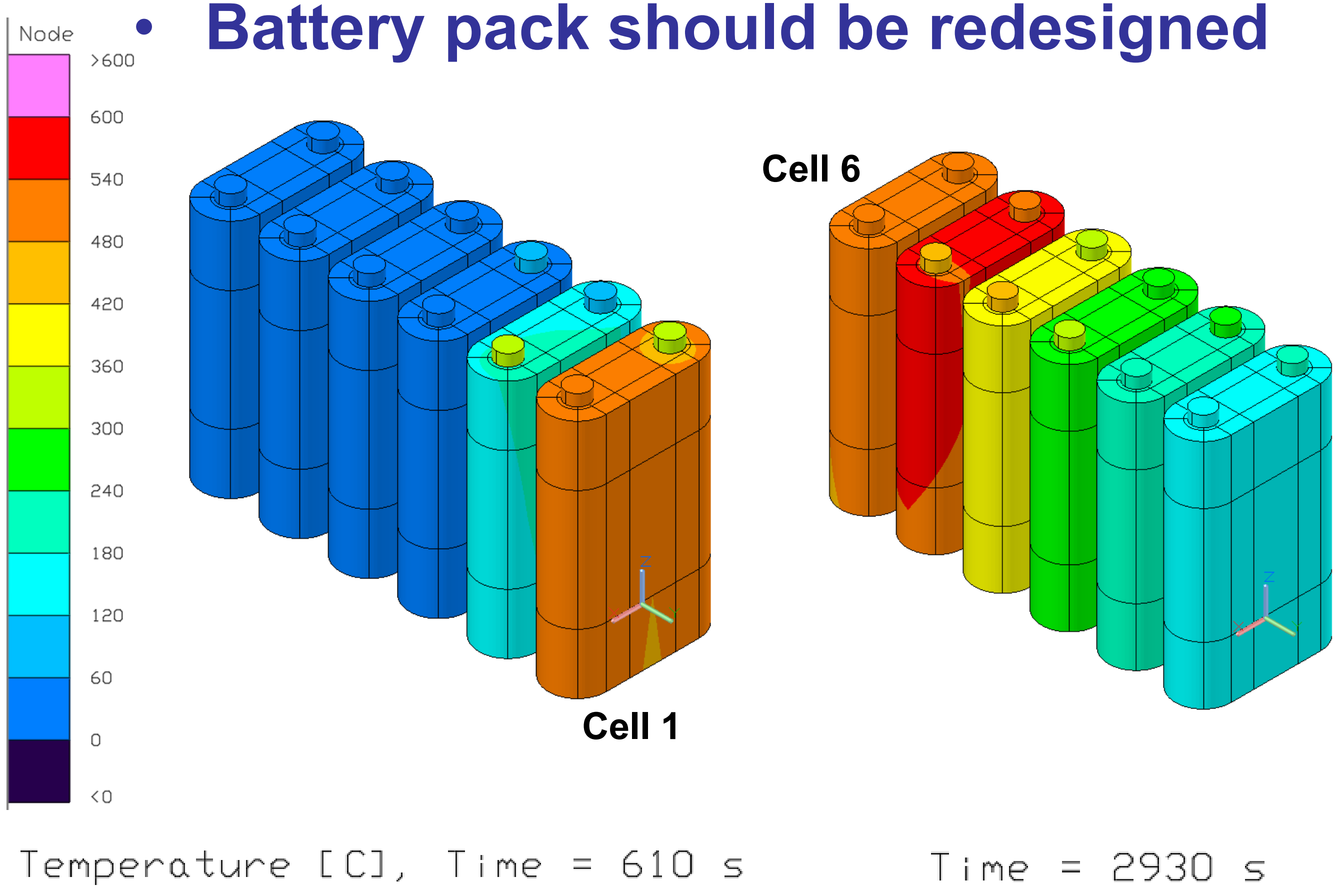
  Vented gasses and other effluents are modeled with one way node-node conductors. Effluent networks for each cell are tied to the RUNAWAY symbol so that the conductor is only enabled when RUNAWAY = 1

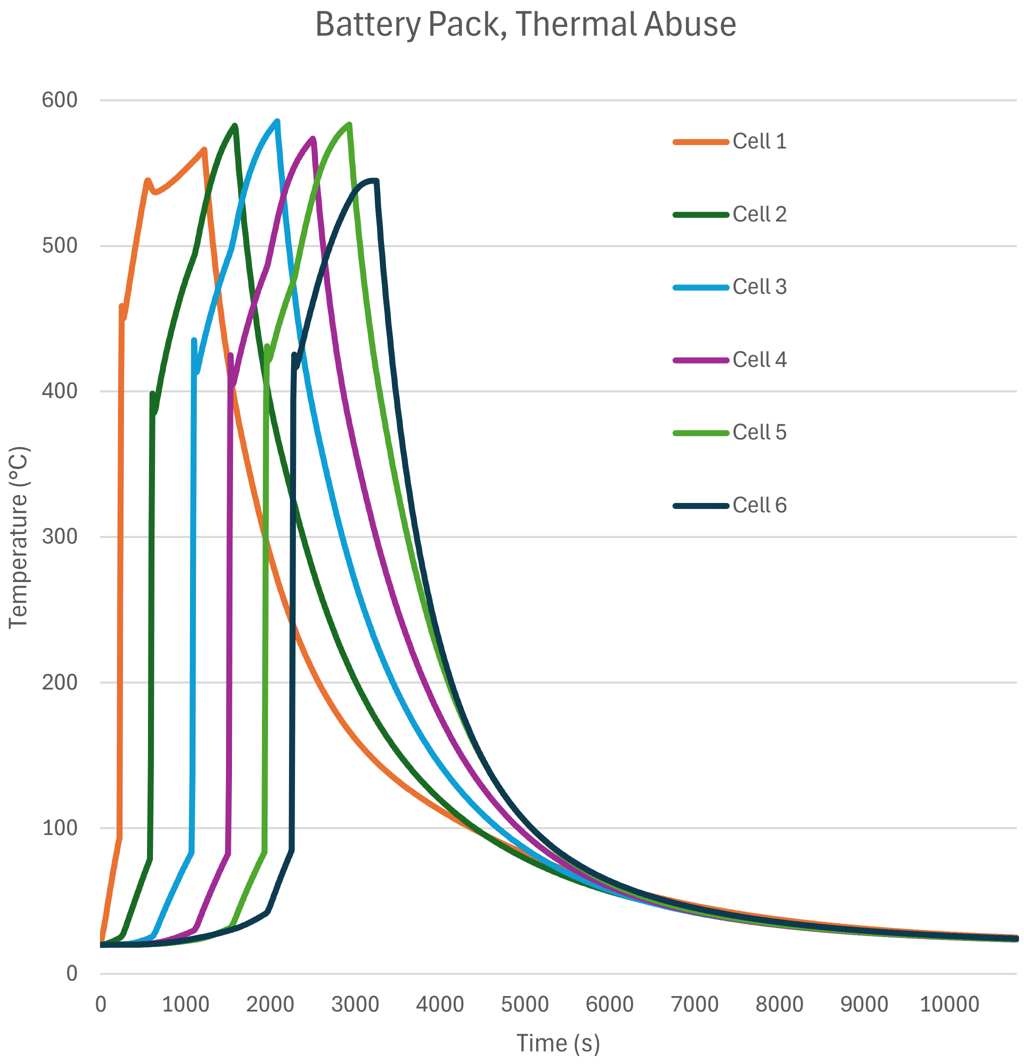




Results, Battery Pack

- Thermal abuse analysis shows propagating cells, resulting in cascading failure within battery pack.
- **Battery pack should be redesigned**





Conclusion

- Large Format Lithium-Ion Batteries offer excellent energy density for lower mass, but their high energy density introduces significant thermal hazards.
- Understanding heat generation, gas production, energy release, and cell-to-cell effects is critical for predicting and mitigating these risks.
- Cell specific characterization is essential, testing multiple cells may be necessary if there is a lack of calorimetry for the analysis.
- While it may not be feasible to prevent all cell thermal runaway, however the goal is to control and prevent any catastrophic consequences if TR occurs.
- For spaceflight, understanding thermal runaway is essential to moving high-energy battery technology hazards into controllable and predictable spaceflight systems.

Questions?