Battery Virtual Cell Module Failure Propagation Thermal Analysis

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Presentation Highlights

- **General assessment to investigate risk of propagation in a multi-cell lithium-ion battery for trigger cells selected by engineering judgement**
  - Determine which of the initially proposed trigger cell locations could propagate to other cells
- **Led to a mathematical characterization of trigger cell placement that gives insight to areas of concern where traditional convention of "engineering judgement" may overlook sensitive areas**
  - Geometric based approach correlated with Thermal Model results
- **Methods facilitate better design, and test planning for battery modules**

Analysis Description

A virtual cell module (VCM) heatsink was redesigned. Subsequent testing and analysis was required to determine the possibility of thermal runaway during battery cell failure

Objectives:

- **Create a thermal model of the Virtual Cell Module (VCM) assembly to simulate failure of individual battery cells and show Passive Propagation Resistance (PPR) to Thermal Runaway.**
- **Goal to determine how cell failure in different locations may propagate to adjacent cells**
  - 80 °C (176°F) warning and 120 °C (248°F) failure condition
- **Analysis was performed, and trigger cell locations were finalized for testing**
- **Model was modified to replicate test setup with the goal of correlating to test results and refining the model (test pending)**

General Assumptions

- Model contains VCM inside housing, including battery cells and bus plate representation
- Initial temperature is 20 °C for failure cases
- External radiation to a 20 °C boundary node for failure cases (assumed environment)
- Convection disabled
- Radiation enabled between internal surfaces
- Cell failure is modeled as 65 kJ of energy (75% cell heat) over a 3 second event
  - Cell heat load = (65kJ*0.75)/3 = 16.25 kW applied for 3 seconds
- Cells nominal heat load of 0.000106 W (0.625 A, 0.036 Ohms, 3% cell heat) used in failure analysis
- Density multipliers are used on solids that have been simplified to match the actual mass

Material Assumptions (Some are changed in nominal analysis cases):

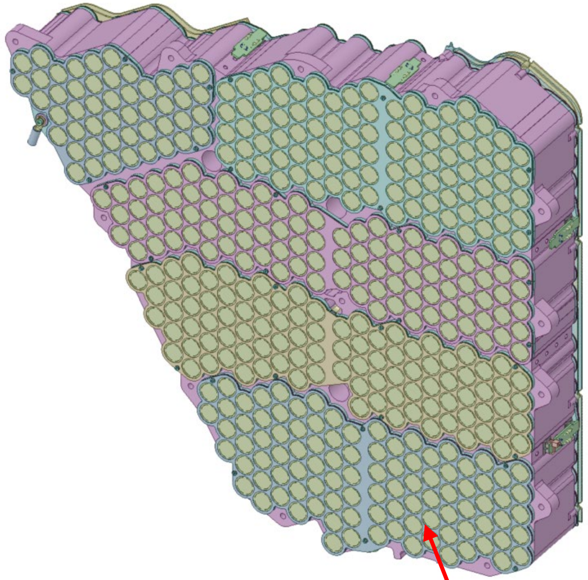
Part	Material	Density (lb/in^3)	Specific Heat (BTU/lb/°F)	Conductivity (BTU/hr/in/°F)
Heatsink/Housing	Al 7050_T7451	0.102	0.205	7.56
Battery Cells	LGM36T(Model)	0.098	0.2	1.45
PCB	Anisotropic PCB Material	0.091	0.241	2.41 lateral, 0.031 thru thickness

Single Cell	
Cell Heat Percent	3%
Current	0.313 A (15 A total)
Cell Resistance	0.036 Ohms
Internal Heat Per Cell	**0.000106 W**

CAD and TD Model

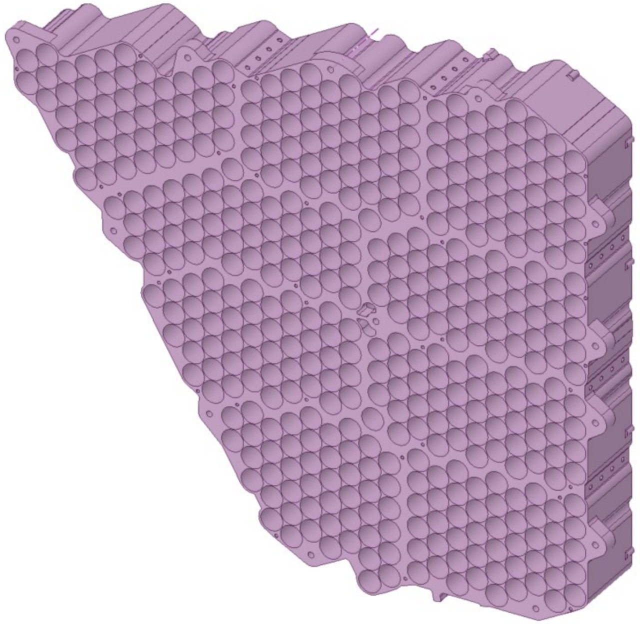
- Thermal model includes heatsink, battery cells, housing, circuit board and lid
- Each virtual cell bus plate is modelled as a single node with bus plate mass

- Battery Assembly

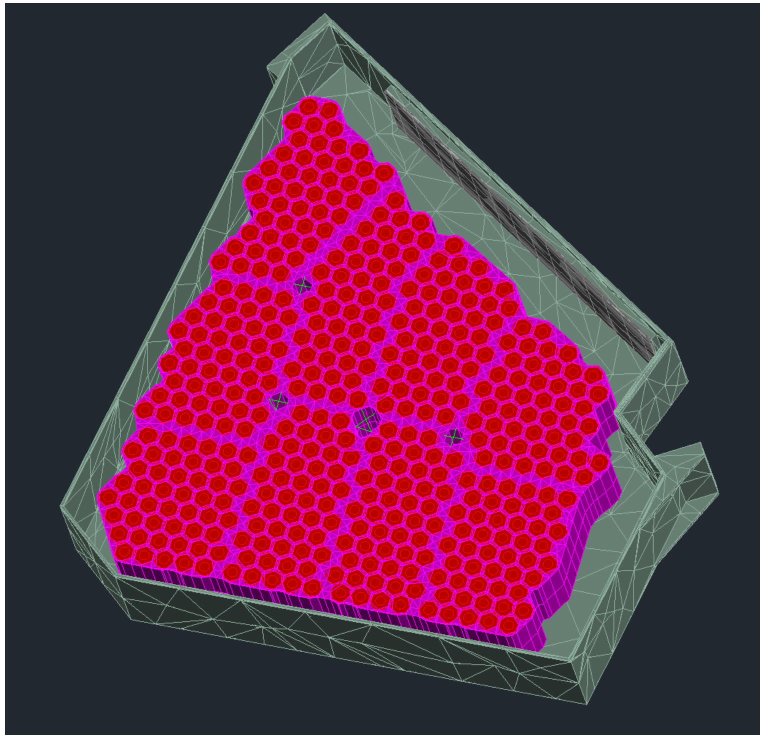


Bus plates and perforation sheets

- Aluminum Heat Sink

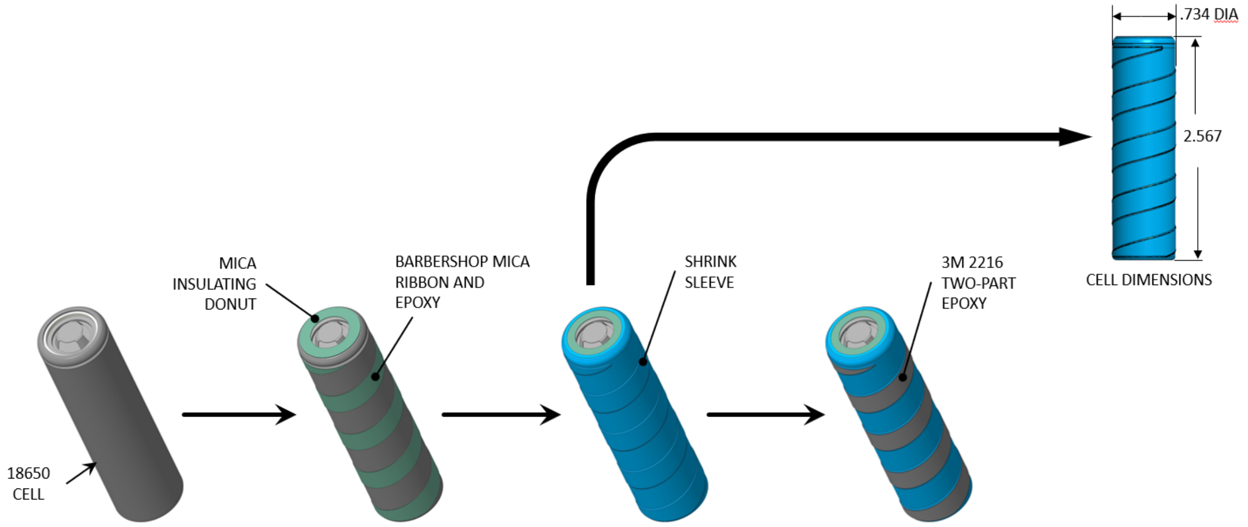


TD Model: Lid and bus plate nodes hidden



Cell Wrap Contact

Items	Material	Conductivity (BTU/hr/ft/F)	Radial Thickness (inches)
Cell to Heatsink	Mica	0.0967	0.012



Step 1: Manufacturer installed shrink tubing removed with particular care taken not to scratch or score cell can.

Step 2: Application of mica ribbon (0.25" x 4 complete rotations), bonded with 3M 2216 epoxy. Installation of insulating donut (0.012" thick).

Step 3: Installation of shrink sleeve immediately following application of epoxy/mica ribbon to provide clamping.

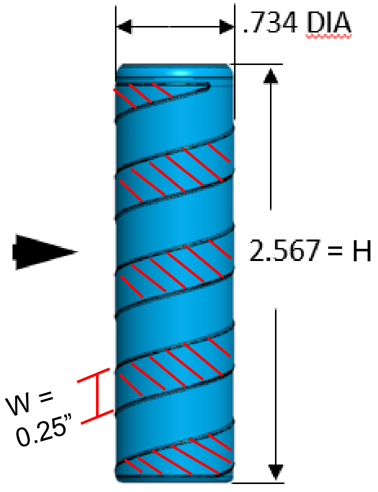
Step 4: Application of epoxy (3M 2216) on mica ribbon spiral for installation into heat sink.

A/L for the Mica wrap is calculated and used in the contact between cell wall and heat sink slot

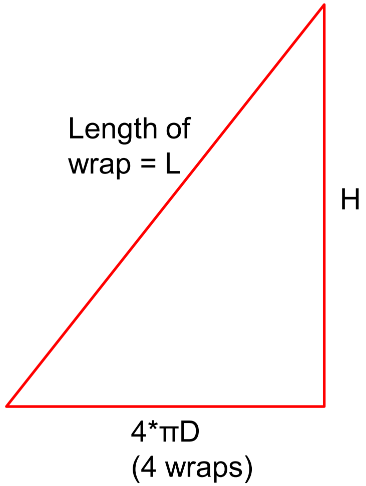
- Thermal resistance through epoxy is ignored

Cell Wrap Contact Calc

Items	Materia l	Conductivity (BTU/hr/ft/F)	Radial Thickness (inches)
Cell to Heatsink	Mica	0.0967	0.012



CELL DIMENSIONS



$$L = \sqrt{H^2 + (4 * \pi D)^2}$$
$$L = 9.574\ in$$
$$A = W * L = 2.394\ in^2$$

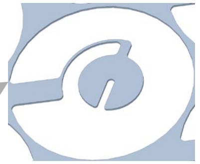
Total Thermal Conductance kA/t:

A/t = (2.394 in^2)/(0.012 in) = 199.5 in

k_mica*(A/t) is then used in the model to connect the cell to heatsink

Bus plate Assumptions

Items	Side	Material	Conductivity (BTU/hr/ft/F)	Thermal Path		
				Thickness (mm)	Width (mm)	Length (mm)
Cell to Cell via fusible links	Negative	Nickel	35.59	0.254	0.254	8.6
Cell to Cell via fusible links	Positive	Nickel	35.59	0.254	3.175	5.9
Heatsink to housing	13 bolts at 100 BTU/(HR FT2 F)					
Heatsink to Lid	3 bolts at 100 BTU/(HR FT2 F)					

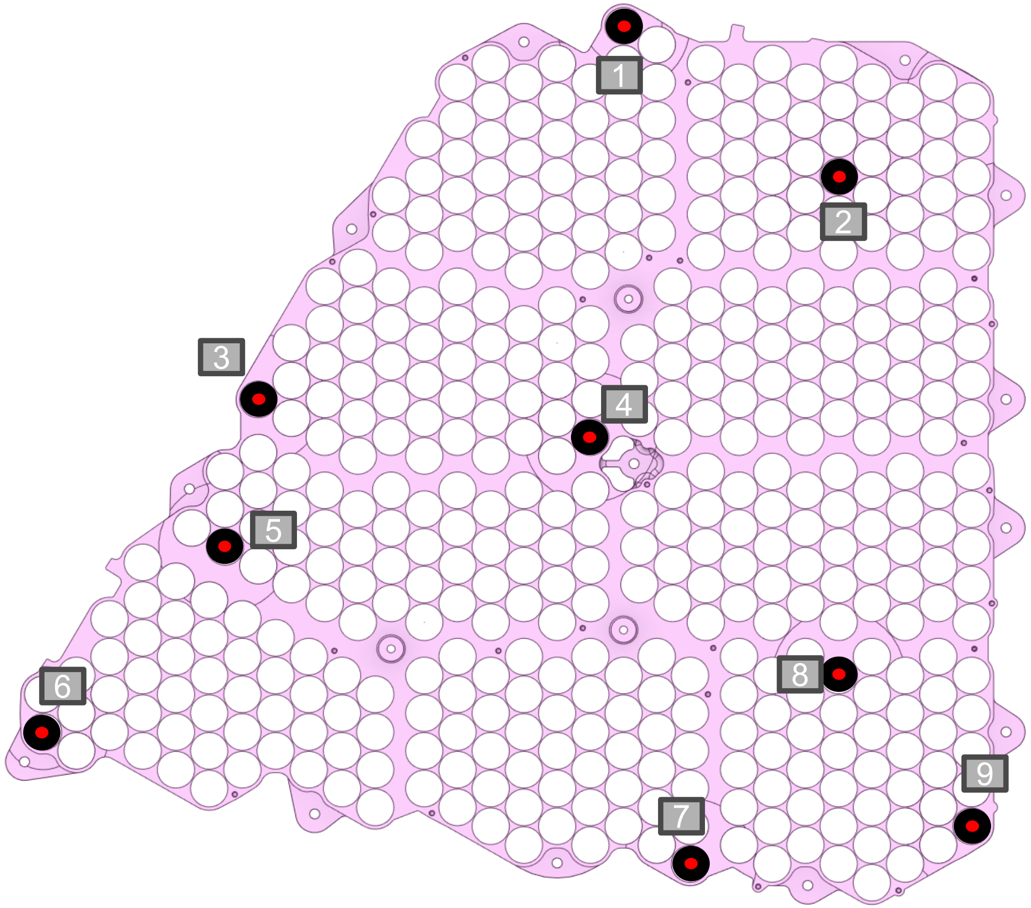


- Cells connected via two bus types using the conductance of the thinnest portion of the thermal path
- One node for each Bus plate is created and connected to each of the cells in the modules that interface to that bus plate.
  - The mass of each bus plate is accounted for within each node
  - This allows the connection of cells via the Bus to be modelled without meshing and connecting the Bus plate geometry.

Cell Failure Propagation Analysis

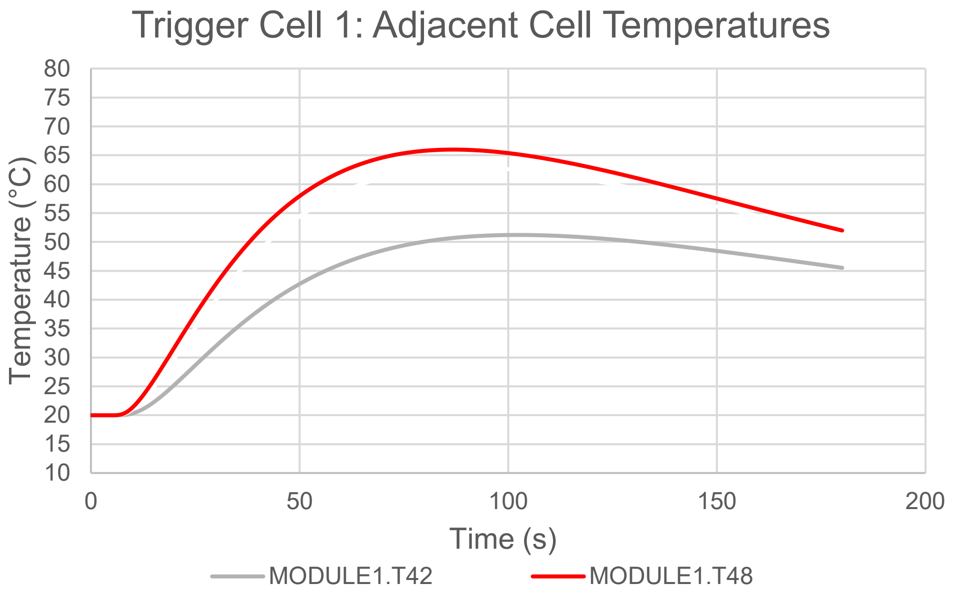
Trigger Cell Layout and Results Overview

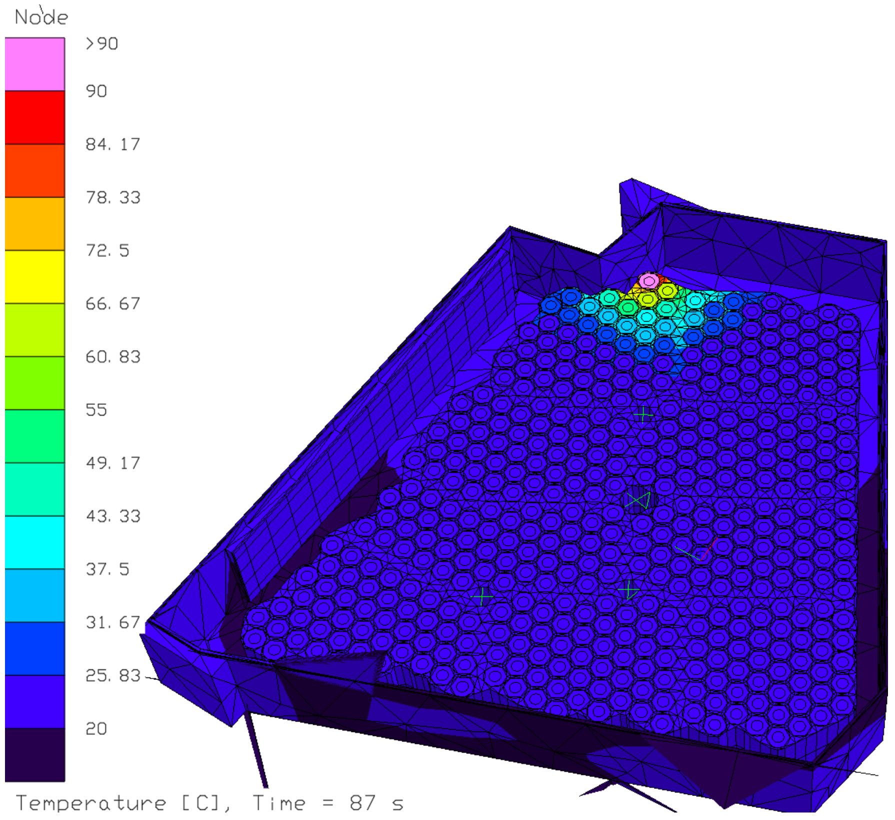
- 9 trigger cell locations given for this analysis
- Maximum Adjacent cell temps found
- Sensitivity study done on case 1



Trigger Cell	Location	Max Adjacent Cell Temp (°C)	ΔT from Initial (°C)
1	Module 1, Top Corner	66.0	46.0
2	Module 2, Center	46.7	26.7
3	Module 3, Left Corner	57.3	37.3
4	Module 3, Right Corner	42.3	22.3
5	Module 5, Bottom	51.2	31.2
6	Module 7, Left Corner	83.7	63.7
7	Module 8, Right Corner	62.4	42.4
8	Module 9, Top	44.2	24.2
9	Module 9, Right Corner	71.0	51.0

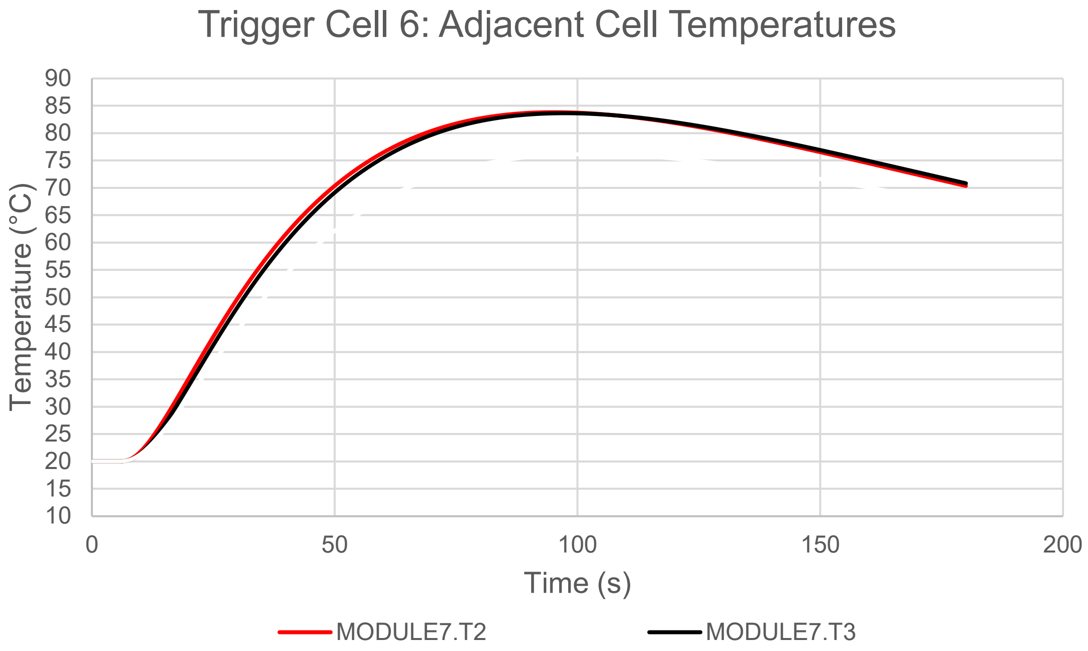
Individual Results and Sensitivity

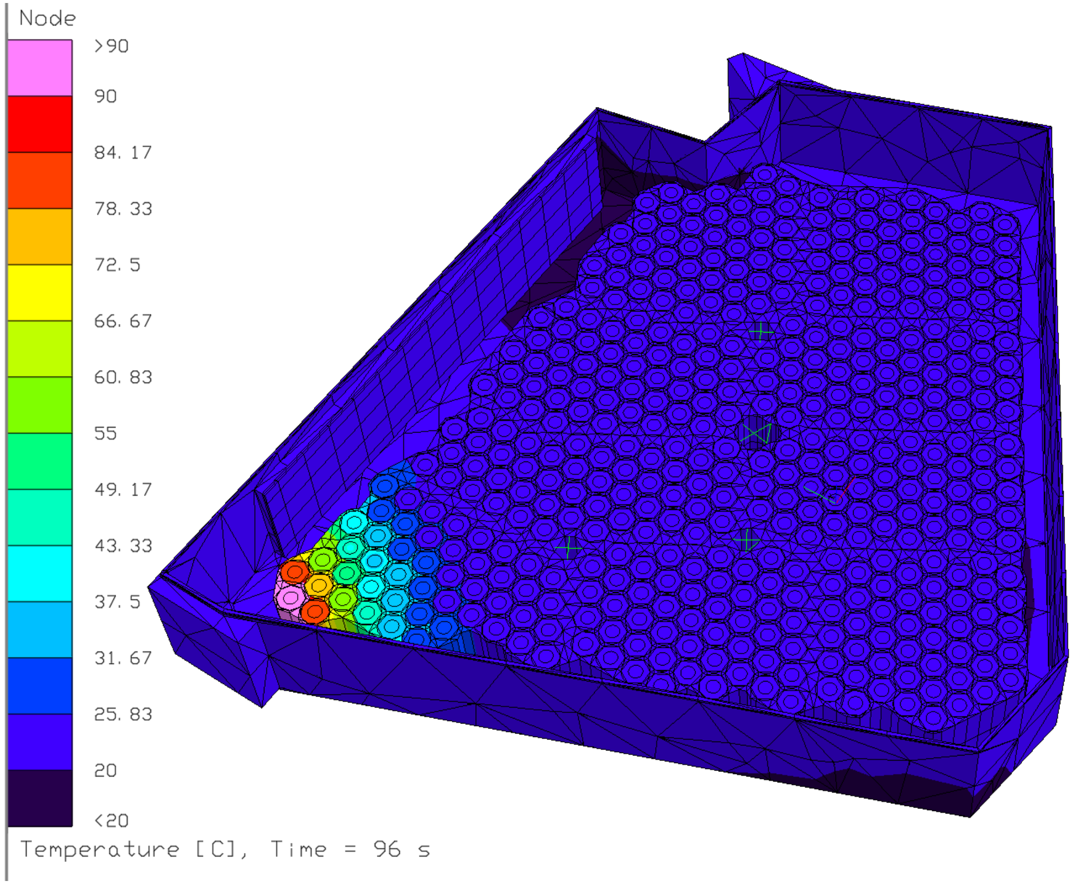




- **Max adjacent cell temp: 66 °C**
- **Sensitivity to contact assumptions also evaluated with this case**
  - Conductance to Bus plate nodes x10 showed 4 °C reduction in adjacent cell temp
  - Conductance to Bus plate nodes x0.1 showed 0.5 °C increase in adjacent cell temp
  - Conductance between cells and heatsink x2.0 showed 20 °C increase in adjacent cell temp
    - This is significant, however the model's current assumption using the KA/L of the mica wrap is conservative since their will be additional thermal resistance at the interface.

Results – Worst case



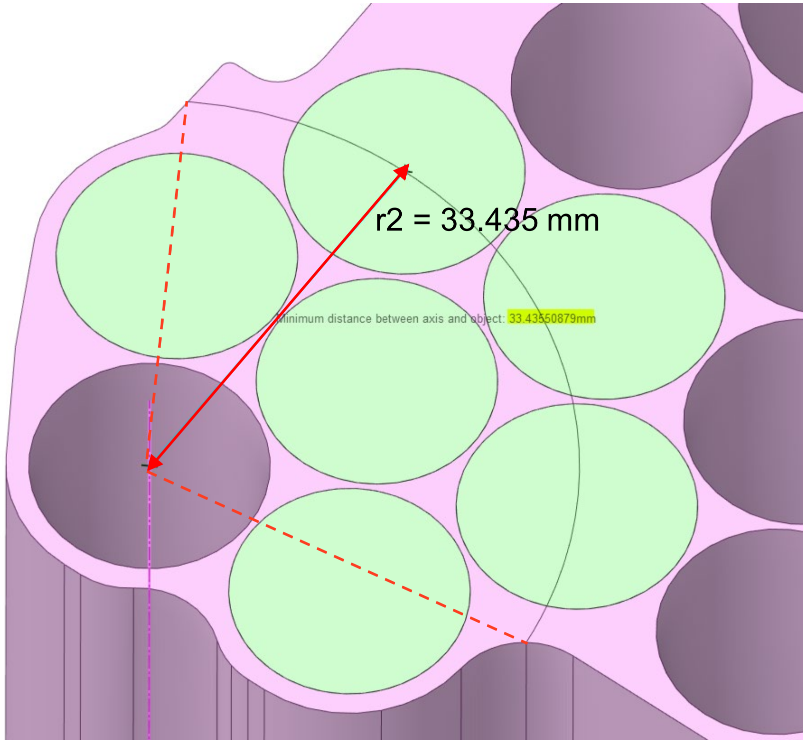


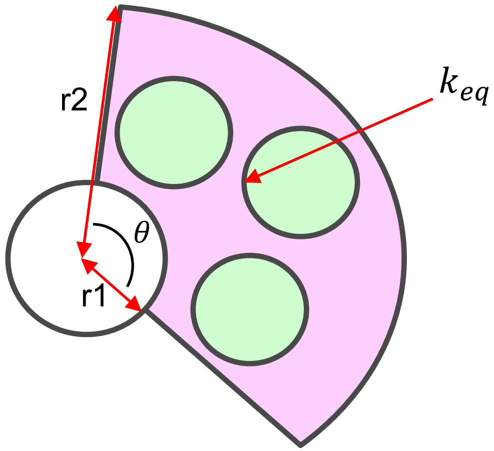
- **Max adjacent cell temp: 83.7 °C**

Results Characterization

A characterization of the results was done in order to map the max temperatures as a function of the trigger cell positioning

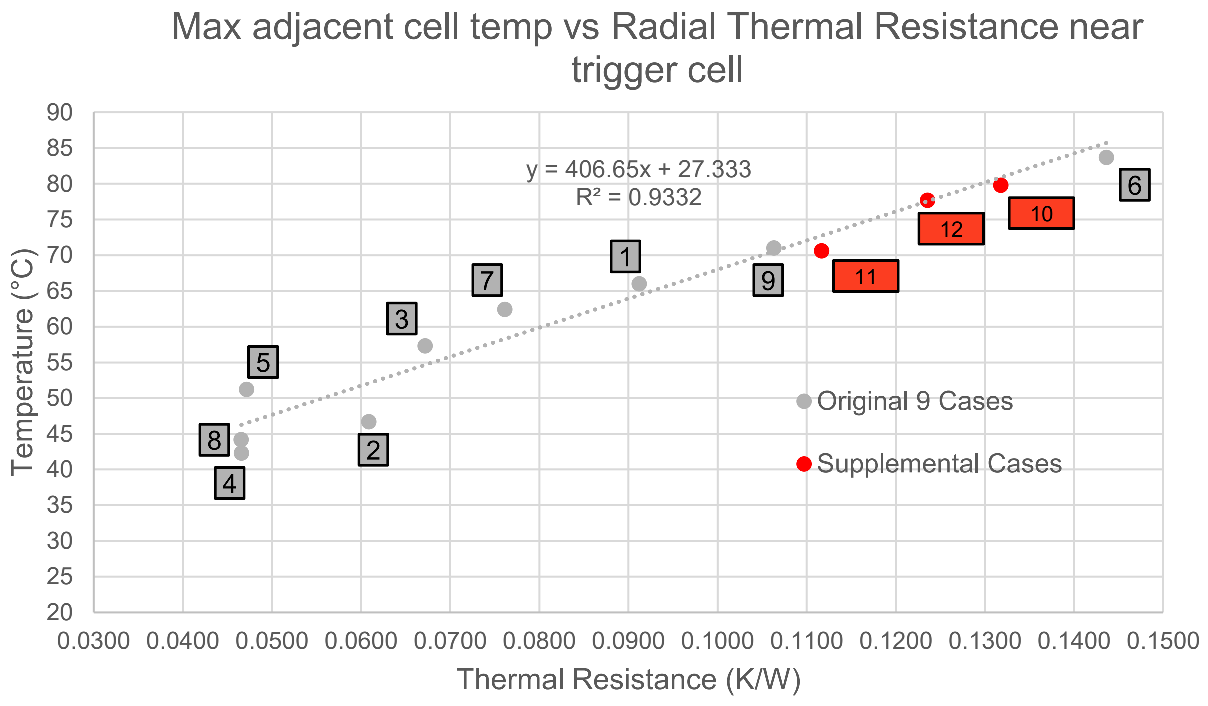
- Equivalent thermal resistance through the solid within some radius of the failed cell
- The thermal resistance through the portion near the failed cell will dictate the max temp of adjacent cells
- Within this radius what is the volume of heatsink and volume of battery cells
  - Find the volume weighted thermal conductivity within this radius
- Radial thermal resistance within this volume
  - $R_{th} = \frac{\ln(\frac{r_2}{r_1})}{\theta L k_{eq}}$
  - r2/r1 is constant ratio of the radius of the volume to the battery cell radius
  - L is the thickness of the heat sink (Length of this cylindrical portion)
  - θ is the radians of this cylindrical portion that contains the solid
  - k is the volume weighted thermal conductivity
- **The thermal resistance (and therefore adjacent cell temperature) is determined by the angle (amount of solid volume near the cell) and equivalent conductivity (how much of this volume is made up of cells vs heatsink)**

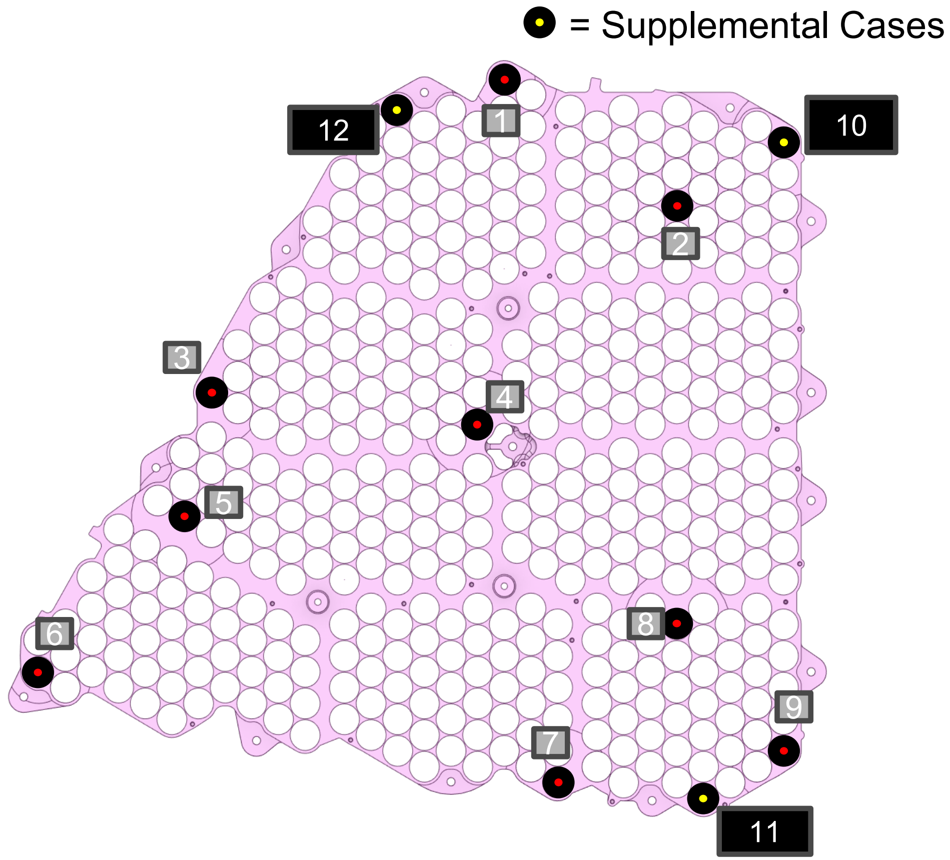




Results Characterization

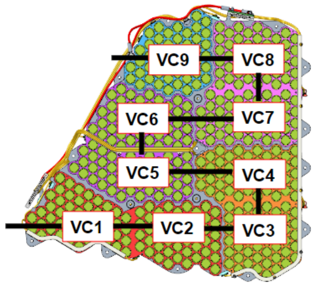
- Adjacent cell max temp vs thermal resistance for the original 9 cases
  - A strong linear trend was seen that can be used to evaluate potential problem cells before running the model
- 3 Supplemental trigger cell cases were added (red) after calculating their thermal resistance
  - Case 10: Upper right corner of Module 2. Had a similar thermal resistance to the worst case (Case 6)
  - Case 11: Lower middle of module 9. Similar thermal resistance to case 9
  - Case 12: Upper left of module 1
- Supplemental case results followed the linear trend



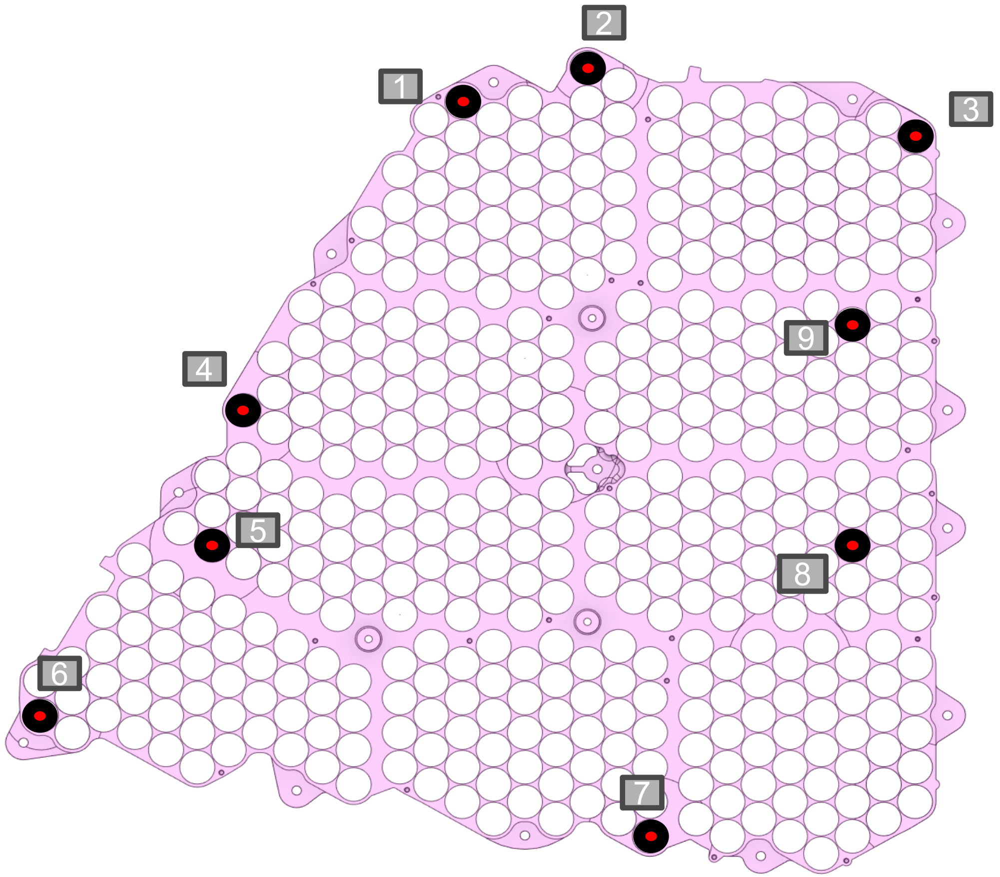


Trigger Cell Layout: Most Important Cases

- For the testing trigger cell layout the lowest temperature cases are removed, and cases renumbered
- Cases 8 and 9 relocated to provide test points with 5 and 6 adjacent cells
- Location naming convention updated to reflect actual cell bussing convention
- **Note: This proposed trigger cell arrangement was later consolidated to a single virtual cell based on the testing apparatus used.**



VIRTUAL CELL BUSSING (TOP)



Trigger Cell (# of adj cells)	Location	Max Adjacent Cell Temp (°C)	∆T from Initial (°C)
1 (3)	VC 9, Top Left	77.7	+57.7
2 (2)	VC 9, Top Corner	66.0	+46.0
3 (3)	VC 8, Top Right	79.8	+59.8
4 (2)	VC 6, Left Corner	57.3	+37.3
5 (4)	VC 5, Bottom	51.2	+31.2
6 (3)	VC 1, Left Corner	83.7	+63.7
7 (2)	VC 2, Right Corner	62.4	+42.4
8 (6)	VC 4, Middle	48.3	+28.3
9 (5)	VC 7, Top Right	46.9	+26.9

Propagation Model Summary

- Failure results were insensitive to bus plate conduction changes, but could be sensitive to contact between cell and heatsink

- Thermal resistance was characterized with a linear relationship to max temperature, and can be used to predict behavior of other possible trigger locations
  - Cells with the same number of adjacent cells and similar positioning showed similar maximum adjacent cell temperatures due to similar thermal resistance

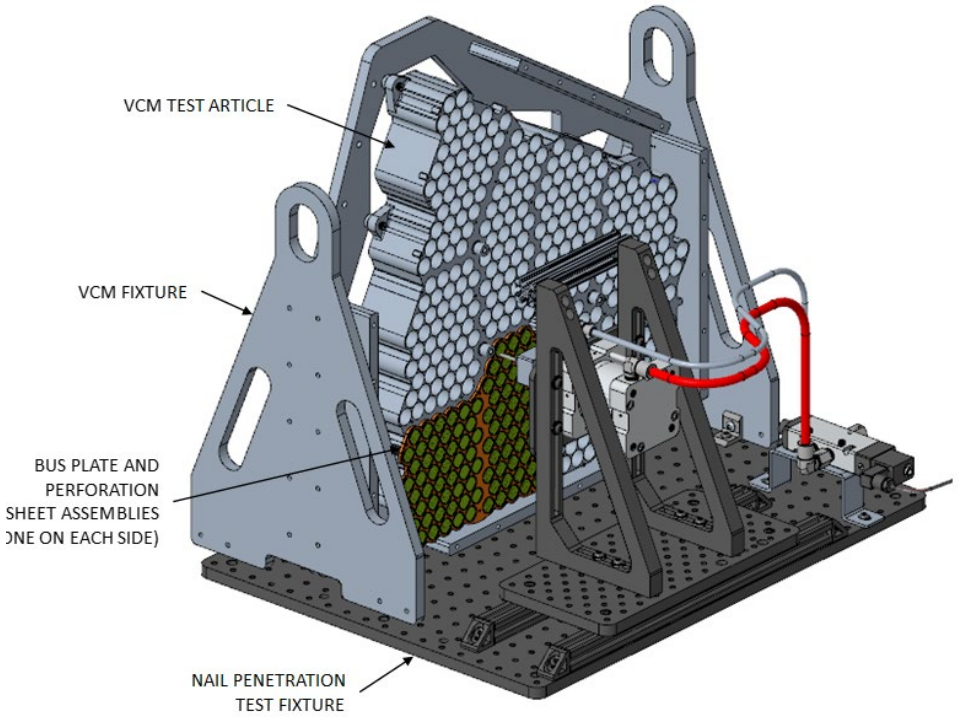
- Only Trigger Cell location 6 showed adjacent cell temperatures increasing above 80 °C
  - Resulted in higher temperatures than Trigger Cell 1, which was originally thought to be the worst location due to having the fewest neighboring cells.
  - Result is backed by thermal resistance characterization, which allows for a more thorough trigger placement strategy

Testing and Correlation Model

Testing Description

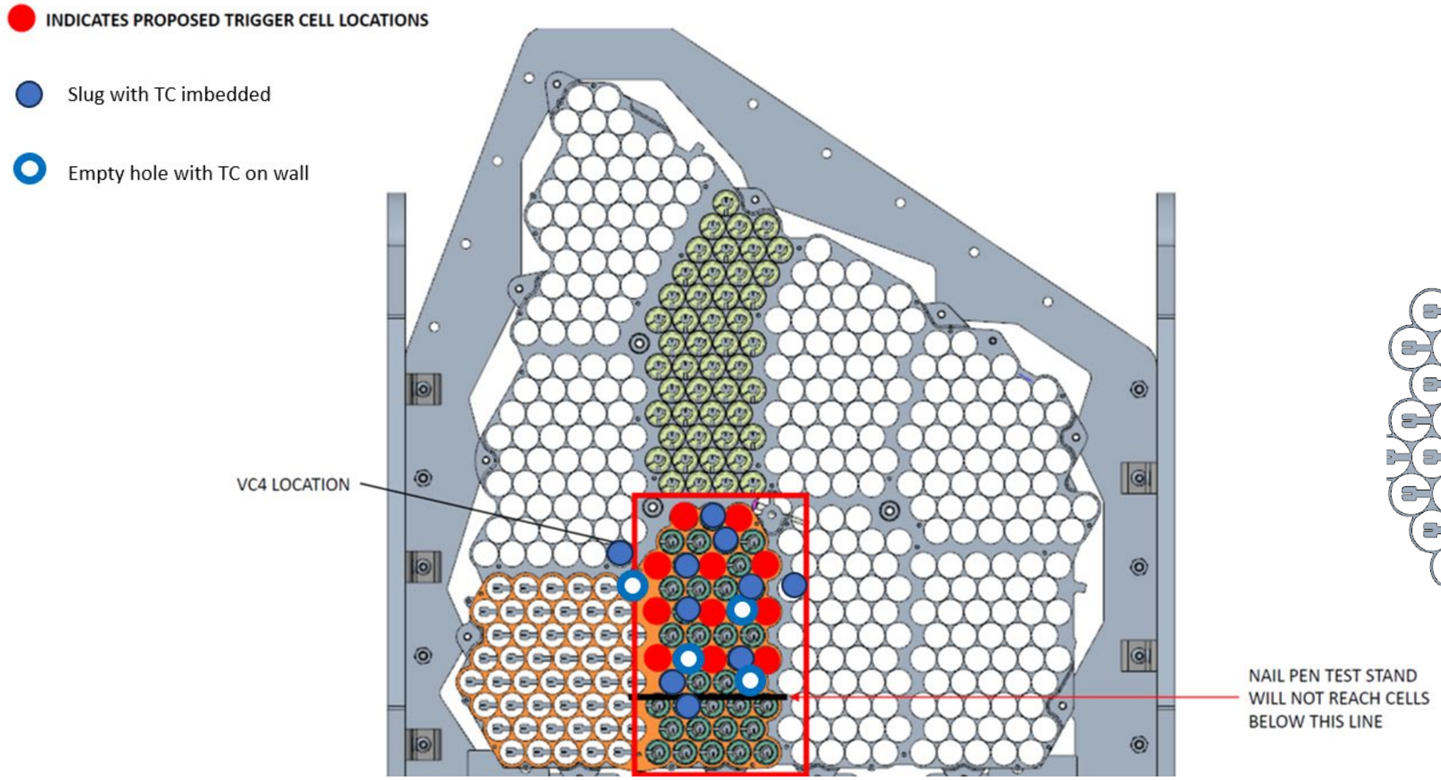
- **A modified version of the previous thermal model has been created to represent the newest proposed test setup simulating cell failure**
  - Nail penetration gives more consistent failure initiation
  - Slugs with embedded TC's give more sensing fidelity to determine thermal response

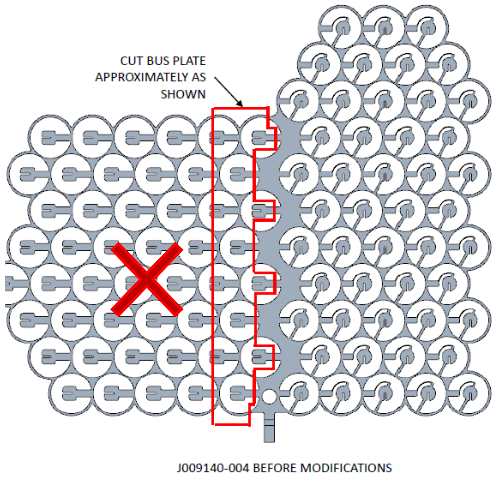
- **This model will be used to correlate results to test data**
  - Cases are run pre-testing with 11 trigger cell locations
  - Updates to failure heat loads contact conductances and material density multipliers can be made to match test data, and carry over to full scale model.

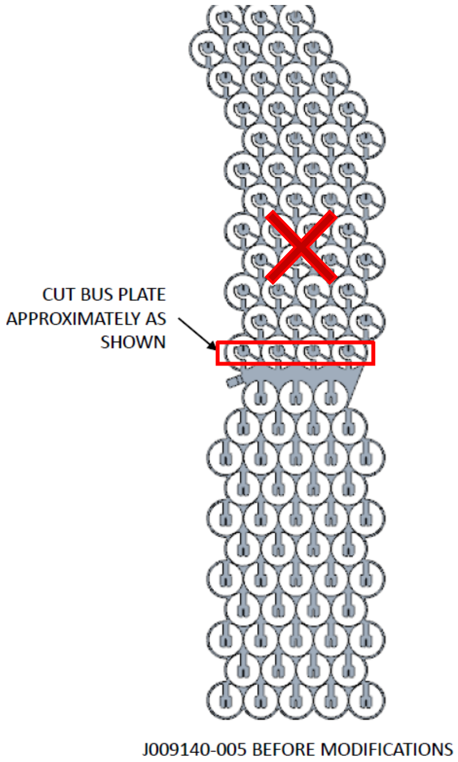


Test Setup

- 11 trigger cell locations are proposed in one module
- TC measurements taken on empty cell walls, and within Aluminum 6061 slugs that replace certain cell locations
  - TC temp profile will be determined by where on the wall TC is placed in test
- Bus plates are cut so that only the portion connecting to the active module are used

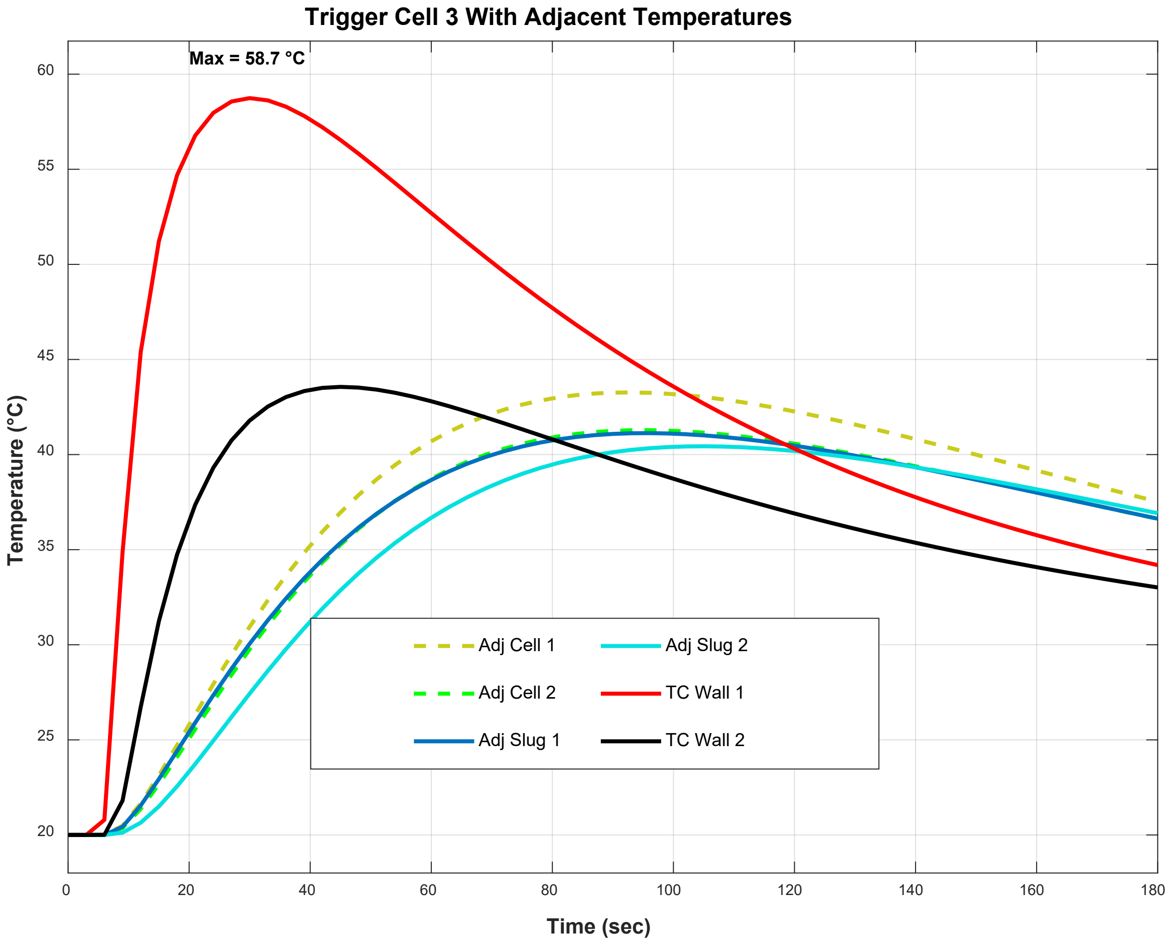


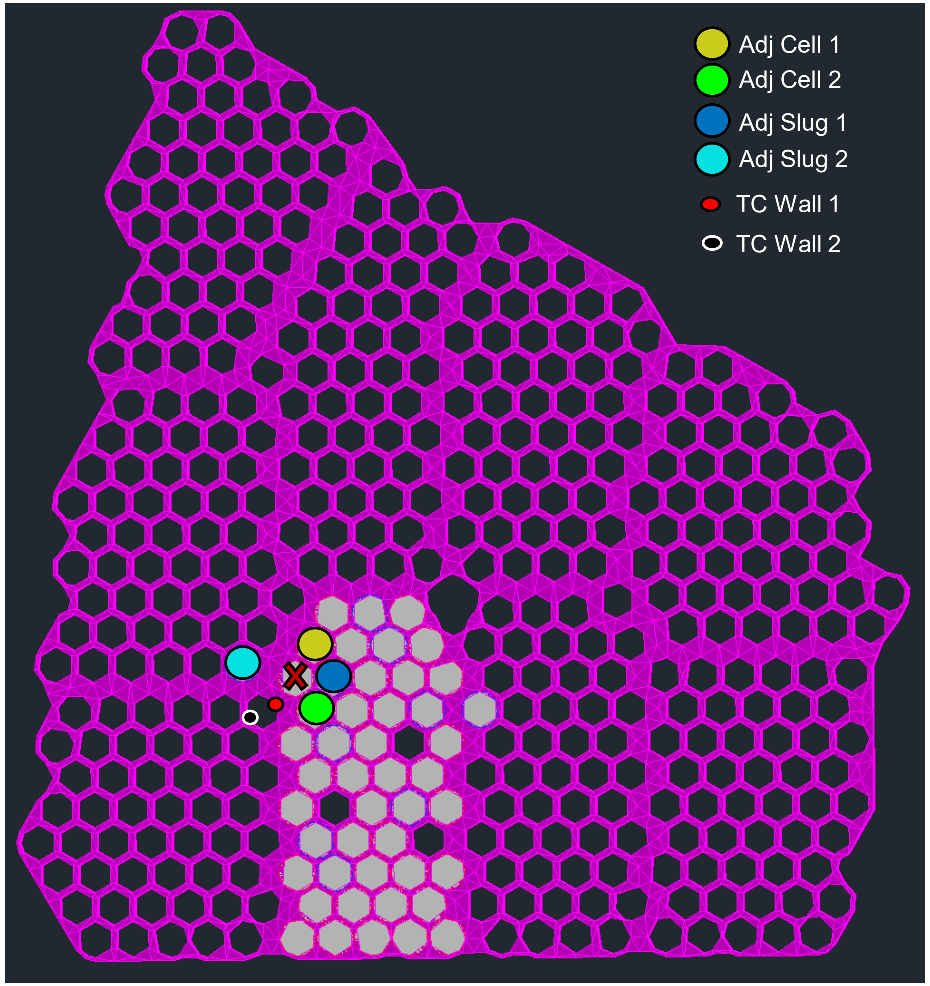




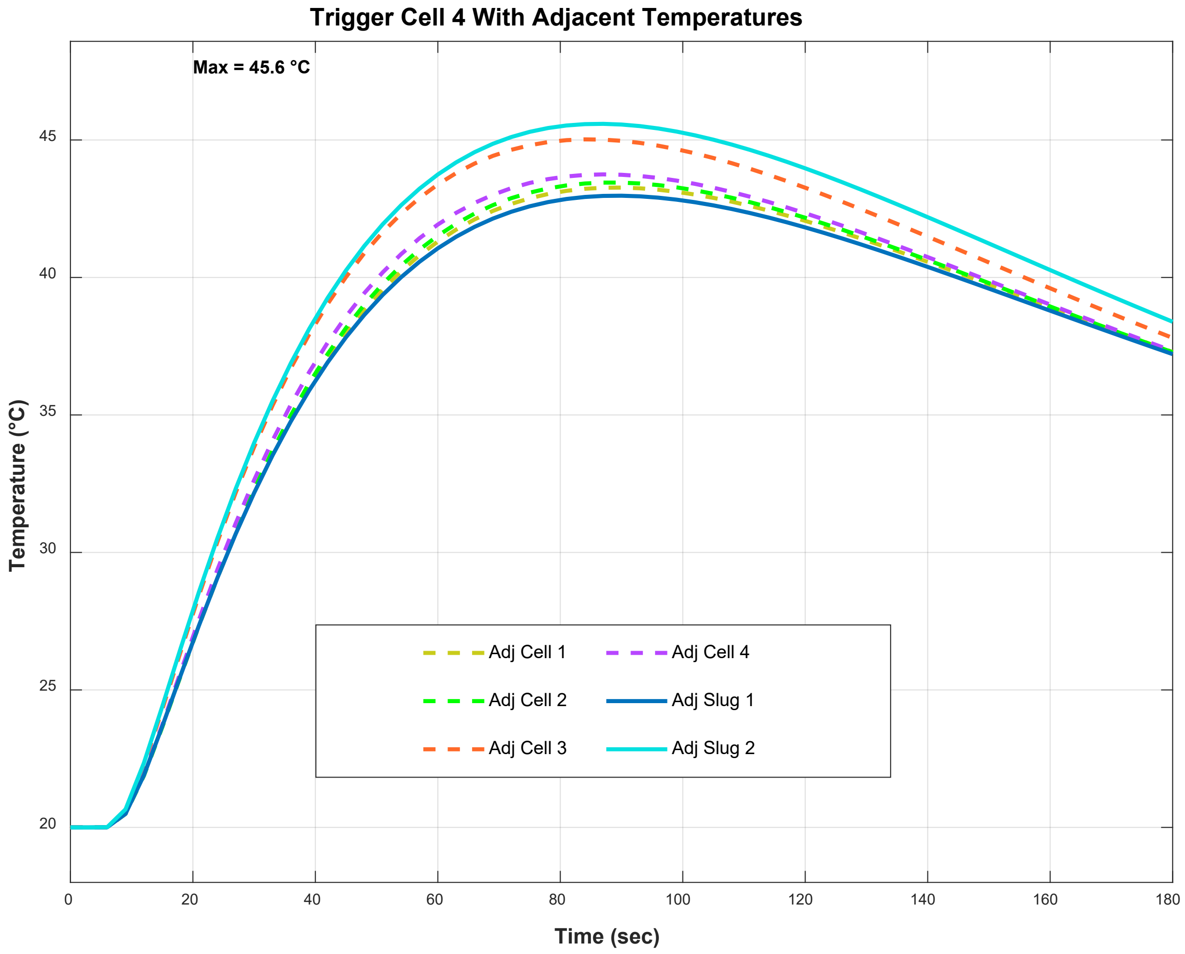
Trigger Cell 3 (Pre-Correlation)

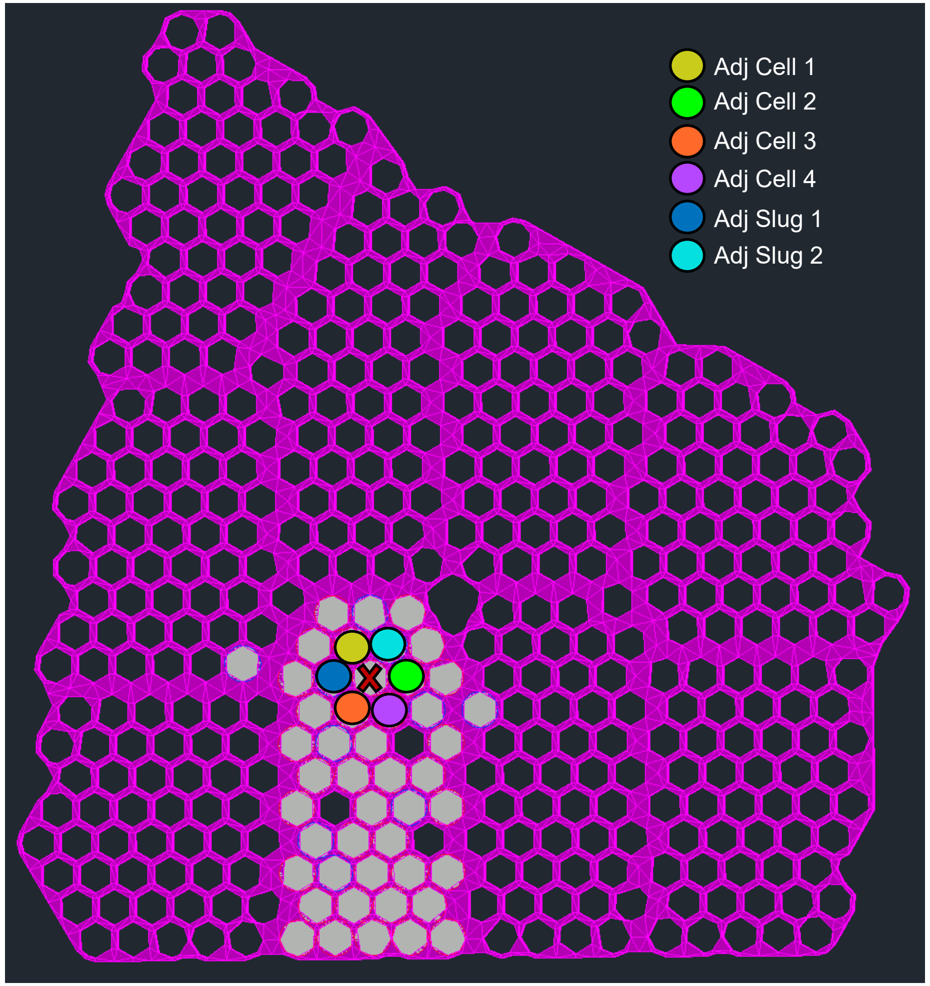
NASA JSC EP



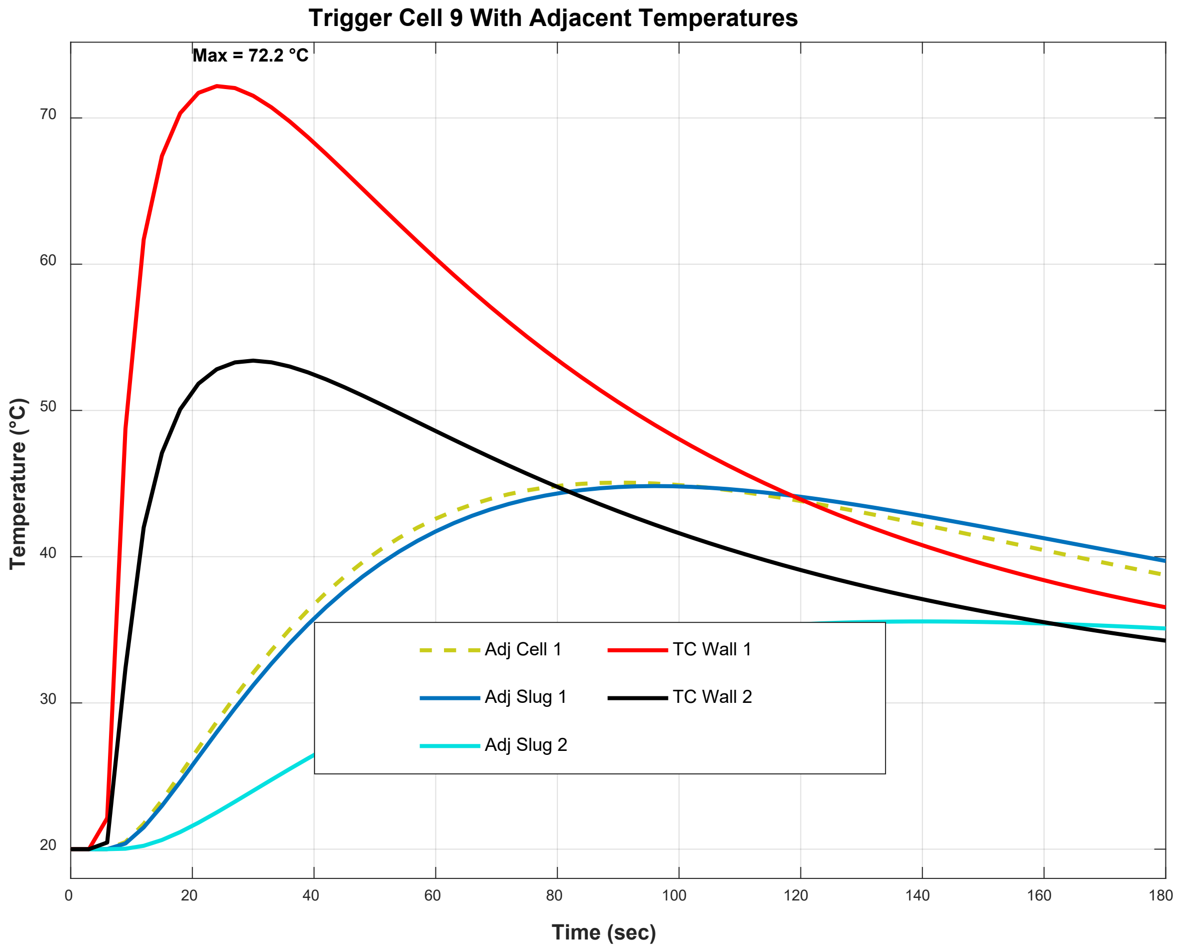


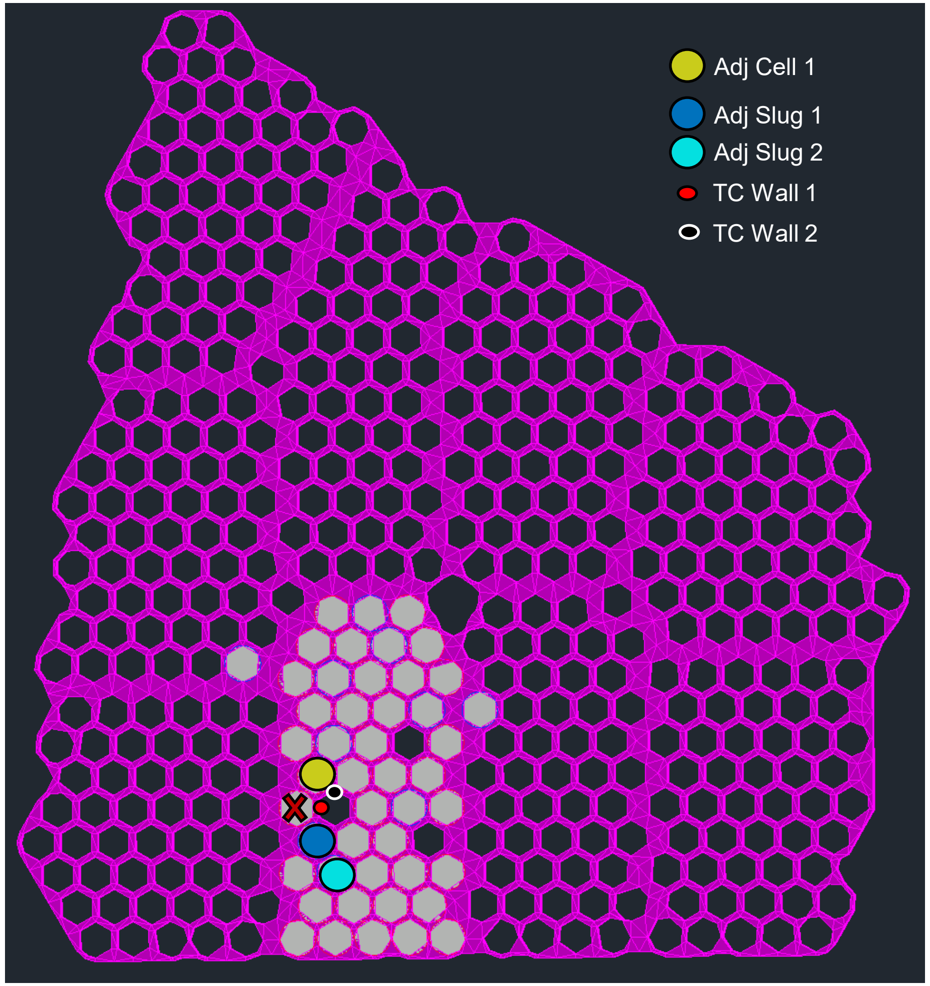
Trigger Cell 4 (Pre-Correlation)





Trigger Cell 9 (Pre-Correlation)



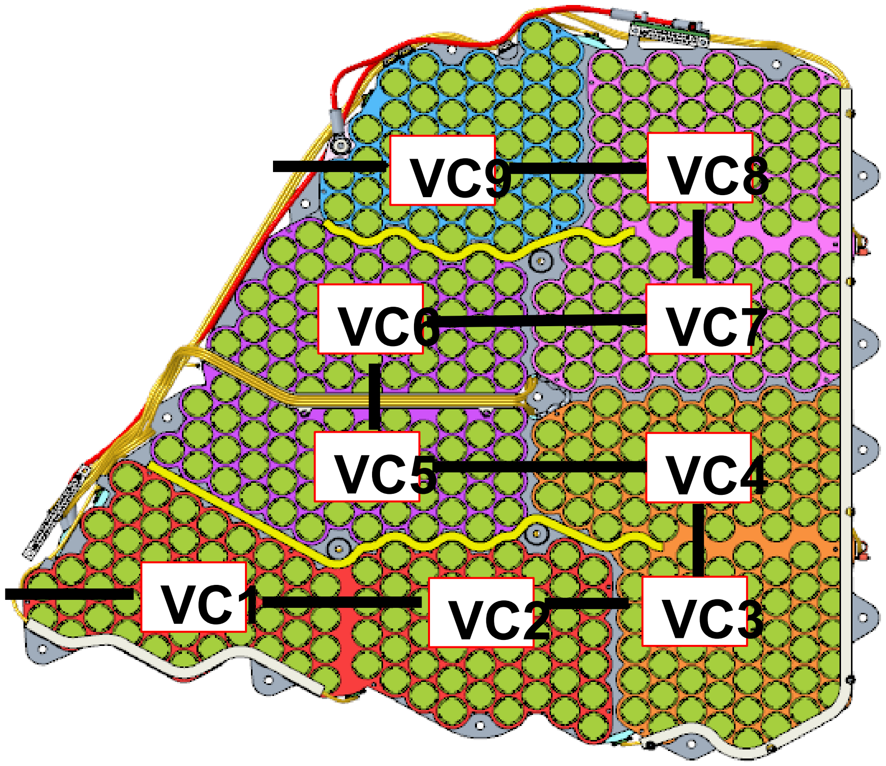


Correlation Model Conclusions

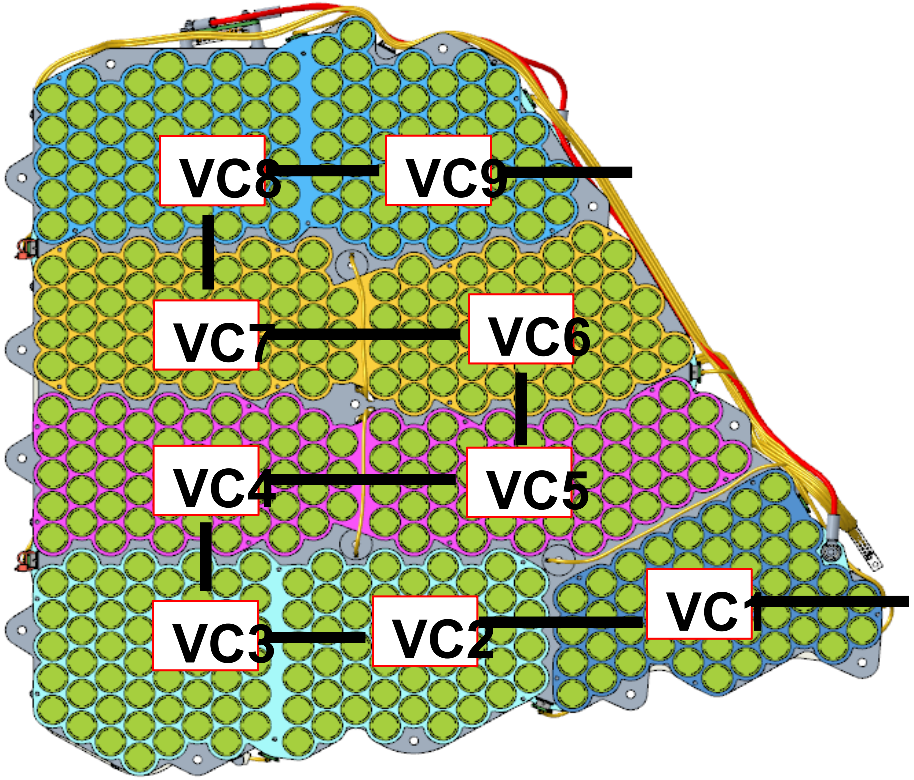
- Initial results for proposed testing setup did not show any indications of failure propagation, and cell temperatures remained around 45 °C
- Thermocouples indicating heatsink wall temperature reach up to 72.0 °C
- The results of this model will be correlated using test result output of slug and wall thermocouple response

Backup/Supplemental

Bus layout



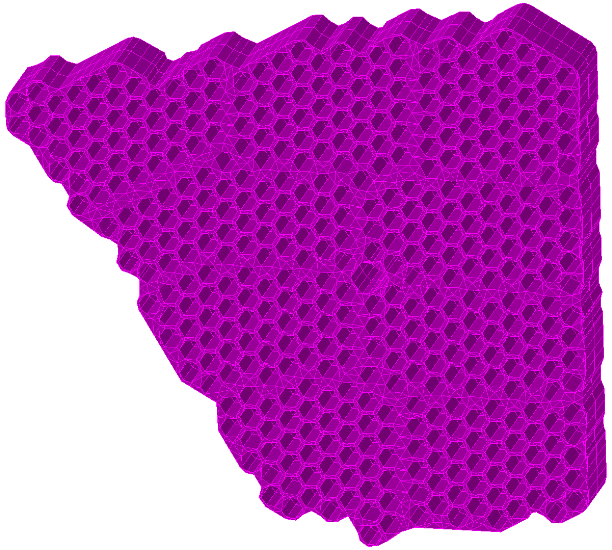
VIRTUAL CELL BUSSING
(FRONT SIDE)

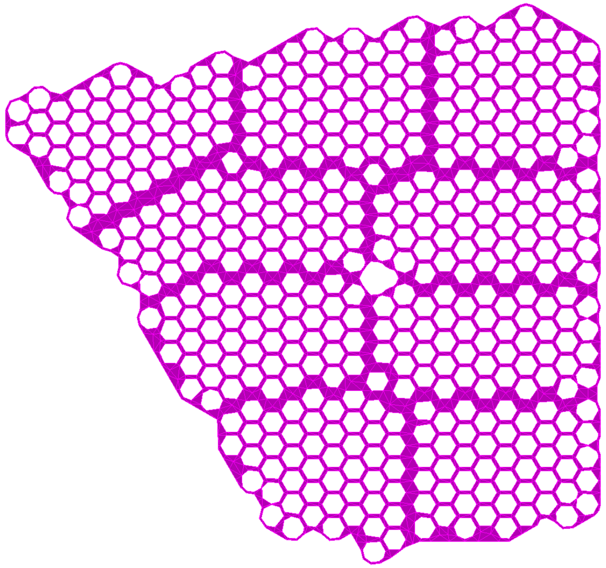


VIRTUAL CELL BUSSING
(REAR SIDE)

Thermal Assumptions of Aluminum Heat Sink

- Aluminum Heat Sink





Item	Material	Mass (lbm)	Conductivity (BTU/hr/in/°F)	Density (lbm/in^3)	Cp (BTU/lb$_m$/°F)	Coating	Emissivity
Heatsink	Al 7050_T7452	15.5	7.56	0.102	0.205	Nickel	0.06