Sandia National Laboratories

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Cross-Lab Comparison of Standardized, Module-Level Propagation

In Collaboration with National Institute of Technology and Evaluation (Japan)

PRESENTED BY

Alex M. Bates

2023 DOE Office of Electricity Peer Review
Session 3: Safety & Reliability
Tuesday, October 24th 2023, 4:00 PM

Objective: Understand Variability in Lab-to-Lab Concurrent Testing of "Identical" Test Conditions

1. How does abuse response compare from test-to-test and from lab-to-lab?
   a) Can we replicate tests internally and achieve the same results?
   b) Can we replicate tests across labs and achieve the same results?
   c) If there is a difference, what is the underlying cause?
2. What do differences in replicate testing outcomes imply with regards to safety standards and pack integration?
   a) Can outcomes be significantly altered by choice of components and materials?
   b) What are the biggest sources of uncertainty and how do we minimize those to inform better standards?

Alignment with Core Mission of DOE OE

To ensure a resilient and reliable grid, it is important to understand the implications of safety standards testing and the variability that will inevitability be present in any Li-ion system. This project is a collaboration with NITE in Japan and all tests are designed to provide validation data for modeling efforts.

NITE Visit to SNL

September 26-27, 2023
Sandia's Burnsite

Previous work:

- Single cell
  - Nail Penetration
  - Thermal Ramp
  - External Short Circuit
- Presented by Loraine Torres-Castro at OE Peer review in 2021

Visit supported by: Emily Kowalchuk, Kayla Gutierrez, Connie Acosta, and Kyle Fenton

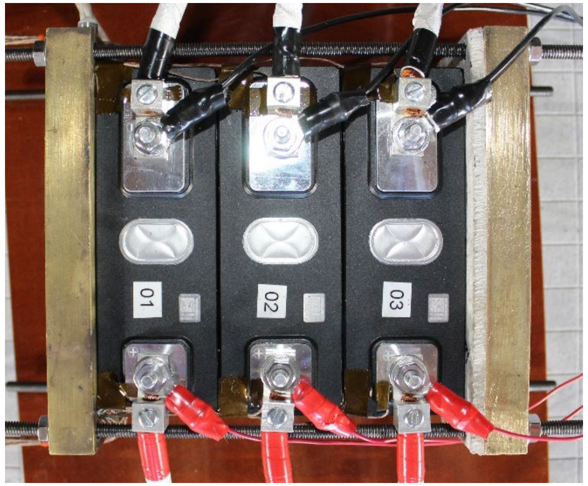
Test Protocols Followed by SNL and NITE

Methodology

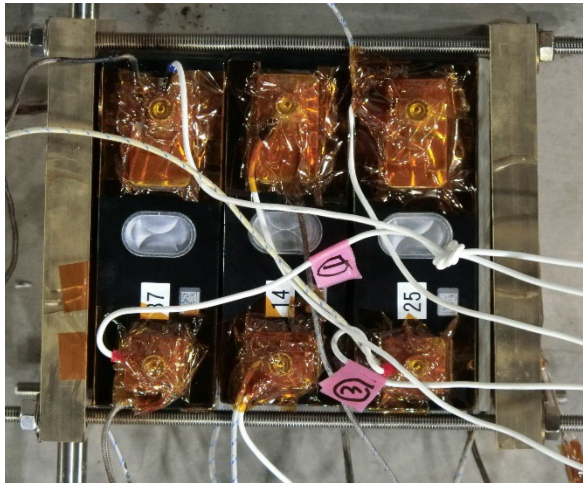
- Replicate test setups for 3-cell pack propagation testing to the extent of each labs capability.

Key Items Replicated

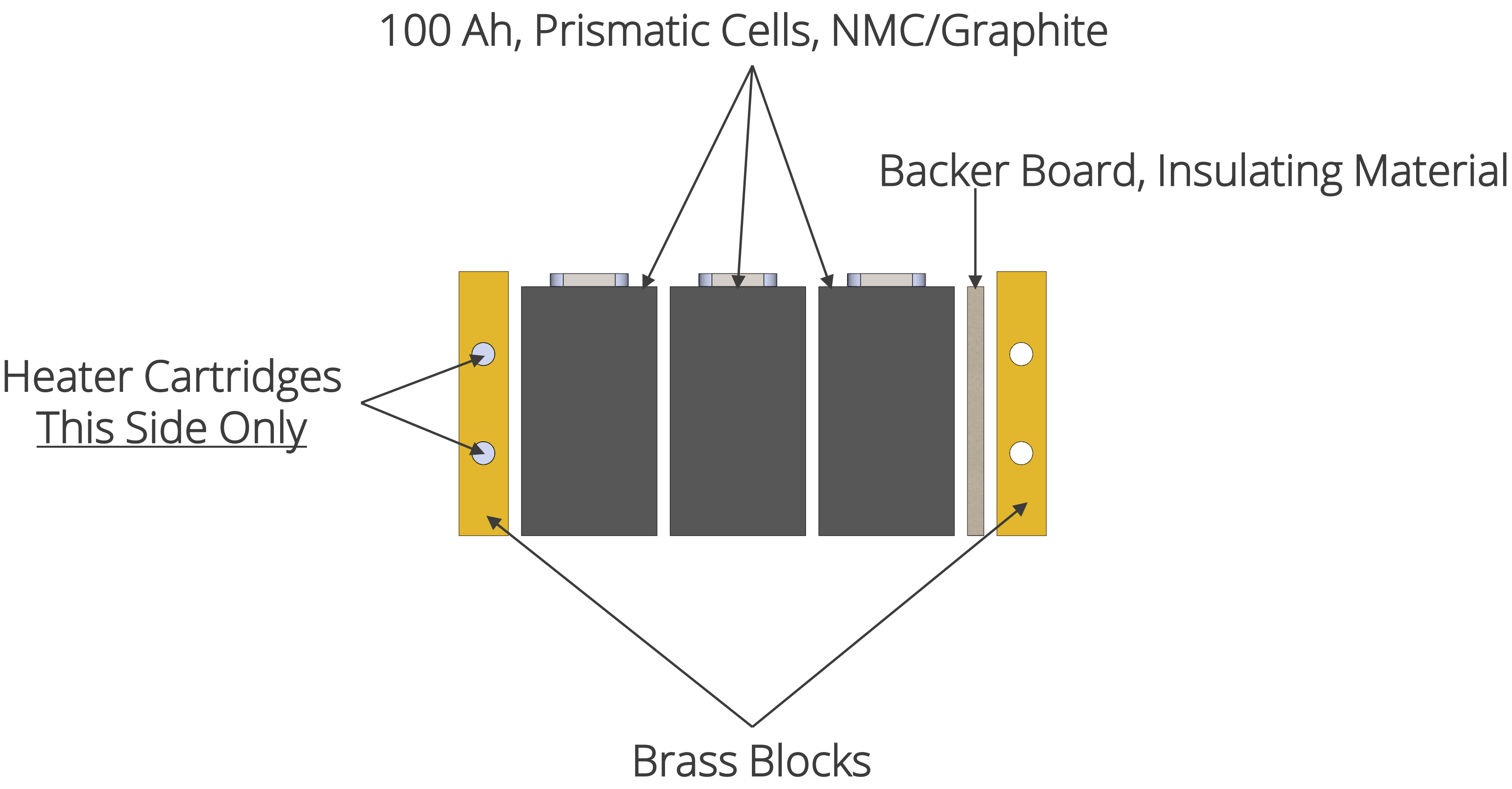
- Thermal ramp rate: 50 °C/min
- 3-cell pack
  - 100 Ah, Prismatic Cells, NMC/Graphite
  - Purchased from the same manufacturer
  - All cells charged to 100% SOC
- Brass block fixturing
  - Identical block dimension
  - Cartridge heaters for heating
  - Insulating backer board between last cell and brass



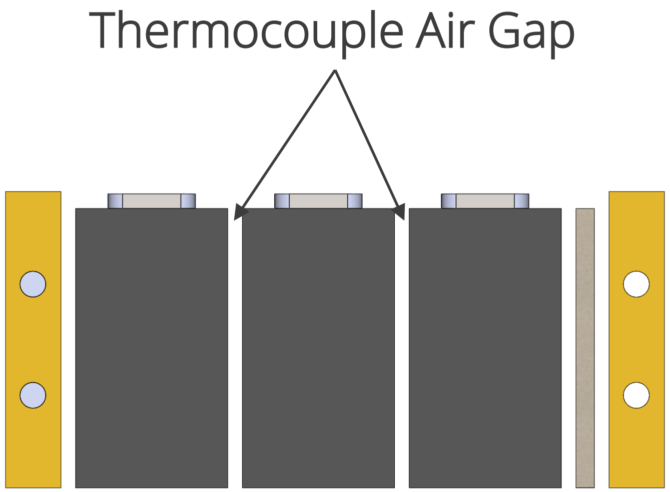
SNL

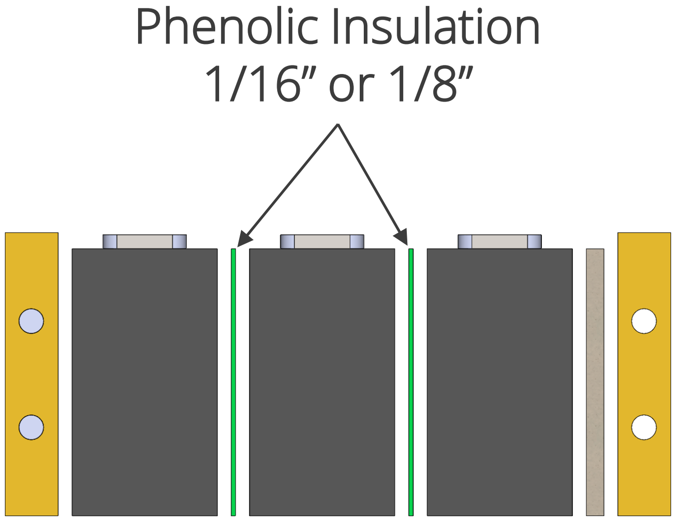

NITE

Schematic of 3-Cell Pack Assembly

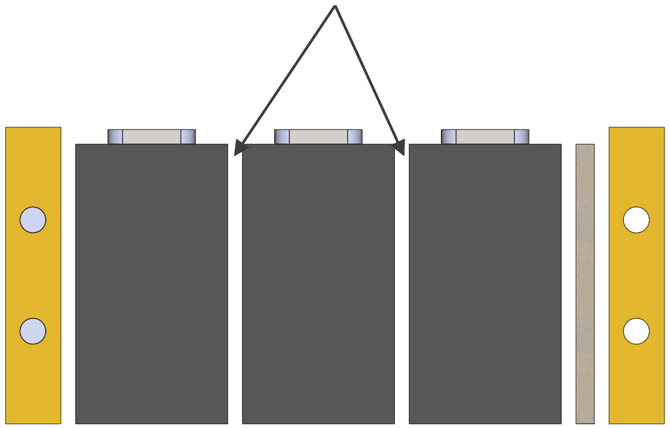


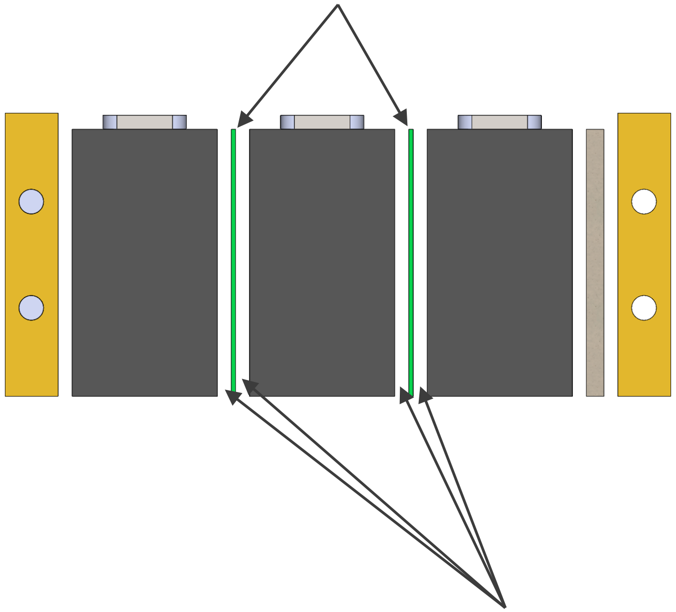
Schematic of 3-Cell Pack Assembly



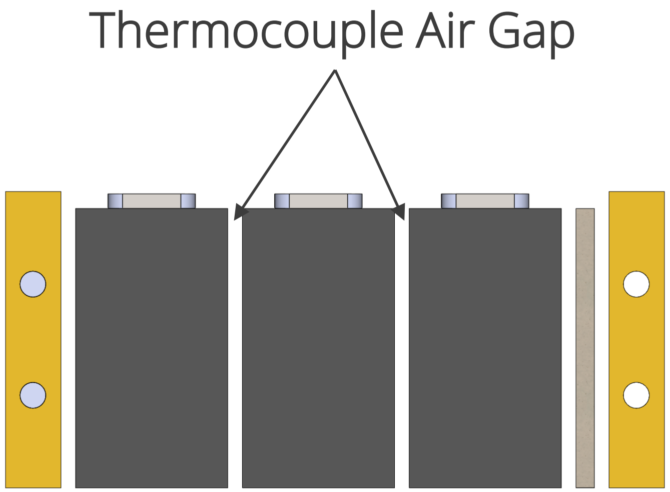


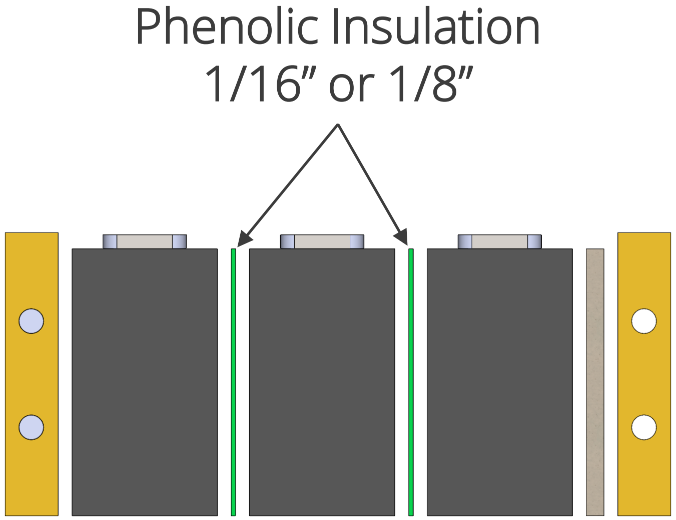
Schematic of 3-Cell Pack Assembly



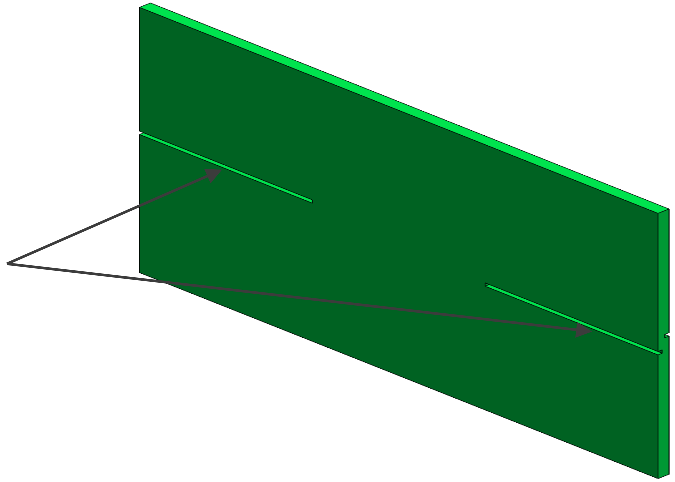


Schematic of 3-Cell Pack Assembly



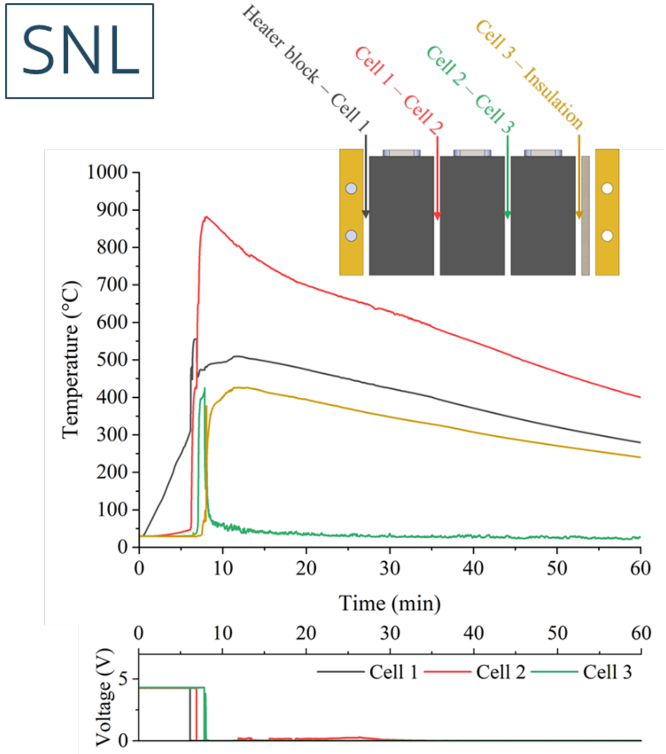


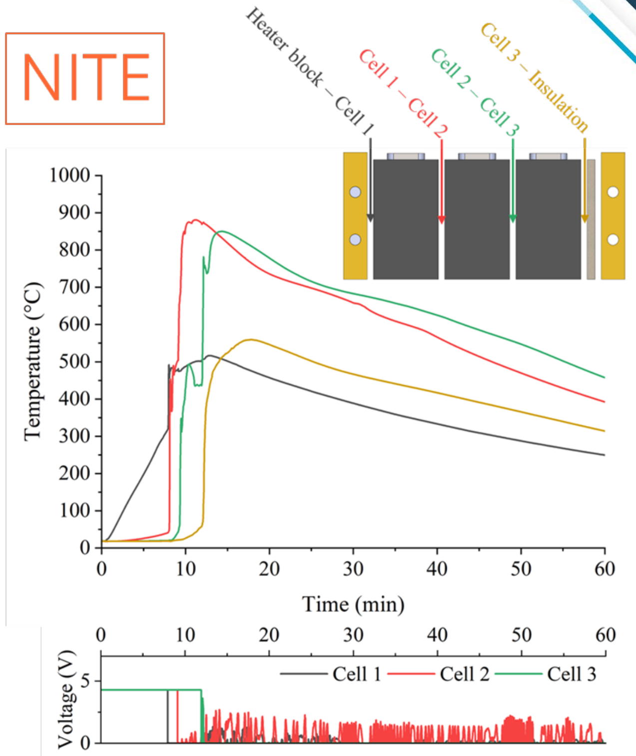
Alternatively, grooves in the phenolic were cut to remove the thermocouple air gap.



Cell-to-Cell Gap Modification, Impact on Propagation Thermocouple Air Gap

	Cell	Thermal Runaway	Voltage Loss
SNL	1	Zero	0 sec
	2	45 sec	41 sec
	3	1 min 46 sec	1 min 38 sec
NITE	1	Zero	12 sec
	2	1 min 15 sec	1 min 23 sec
	3	4 min 5 sec	4 min 12 sec





Similarities

- Full propagation through pack
- Peak temperature ~900 °C

Differences

- Cell-to-cell propagation delay longer for NITE
- Thermocouple sheath thicker in NITE testing

Cell-to-Cell Gap Modification, Impact on Propagation Thermocouple Air Gap

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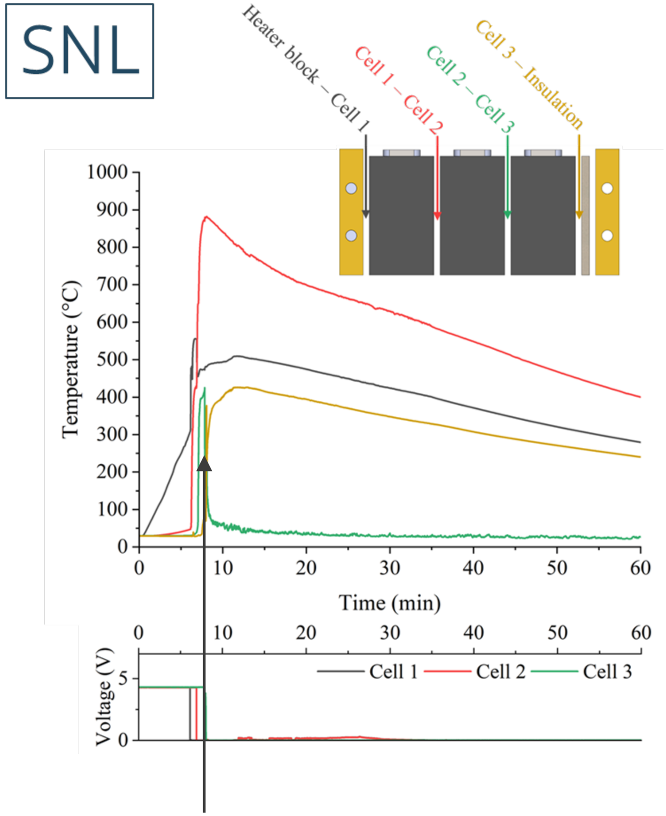

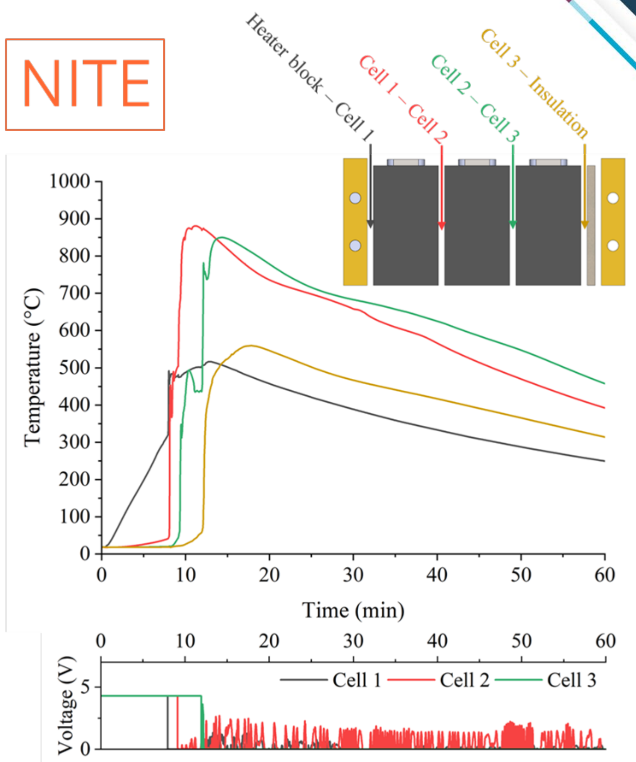

Similarities

- Full propagation through pack
- Peak temperature ~900 °C

Differences

- Cell-to-cell propagation delay longer for NITE
- Thermocouple sheath thicker in NITE testing

Rapid cooling of Cell 3 thermocouple (green) likely a result of jelly roll ejection

Cell-to-Cell Gap Modification, Impact on Propagation Thermocouple Air Gap

	Cell	Thermal Runaway	Voltage Loss
SNL	1	Zero	0 sec
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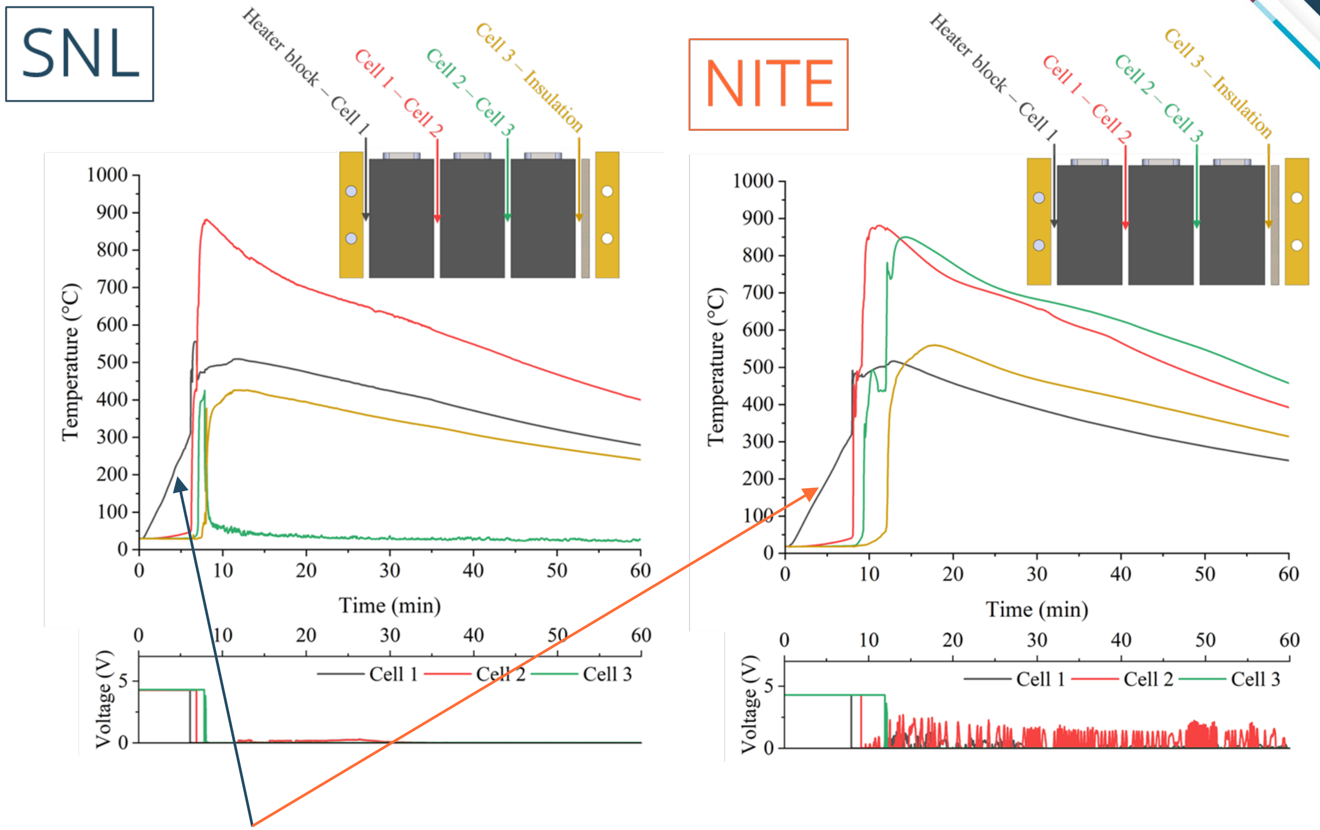

Difference in observable heating rate due to choice of control thermocouple

Similarities

- Full propagation through pack
- Peak temperature ~900 °C

Differences

- Cell-to-cell propagation delay longer for NITE
- Thermocouple sheath thicker in NITE testing

Cell-to-Cell Gap Modification, Impact on Propagation Thermocouple Air Gap

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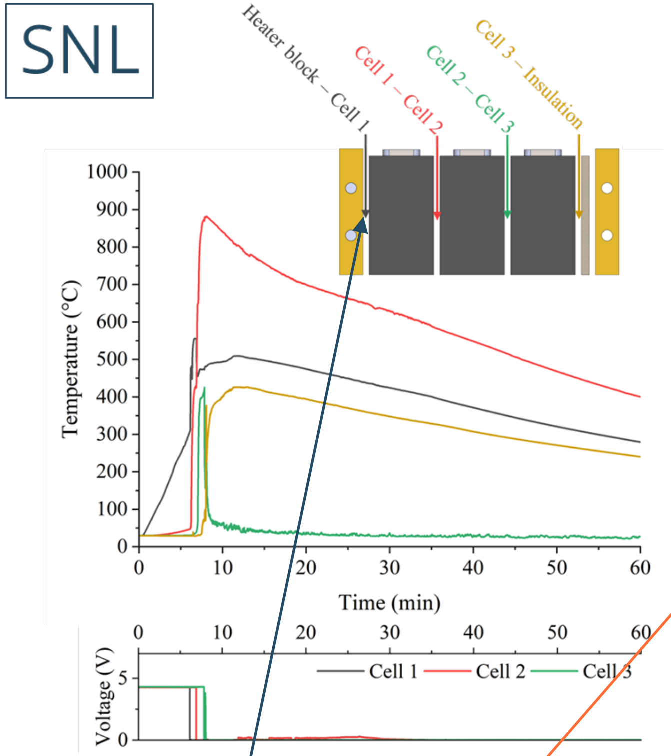
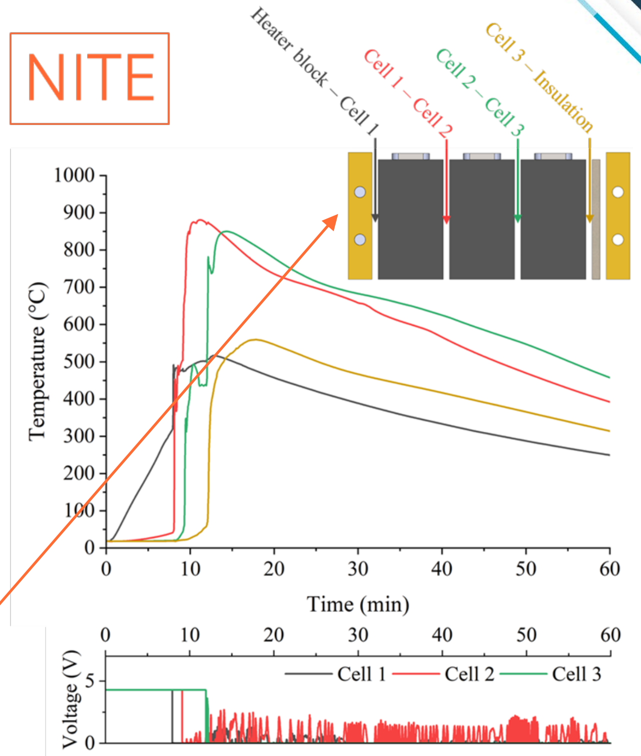




Similarities

- Full propagation through pack
- Peak temperature ~900 °C

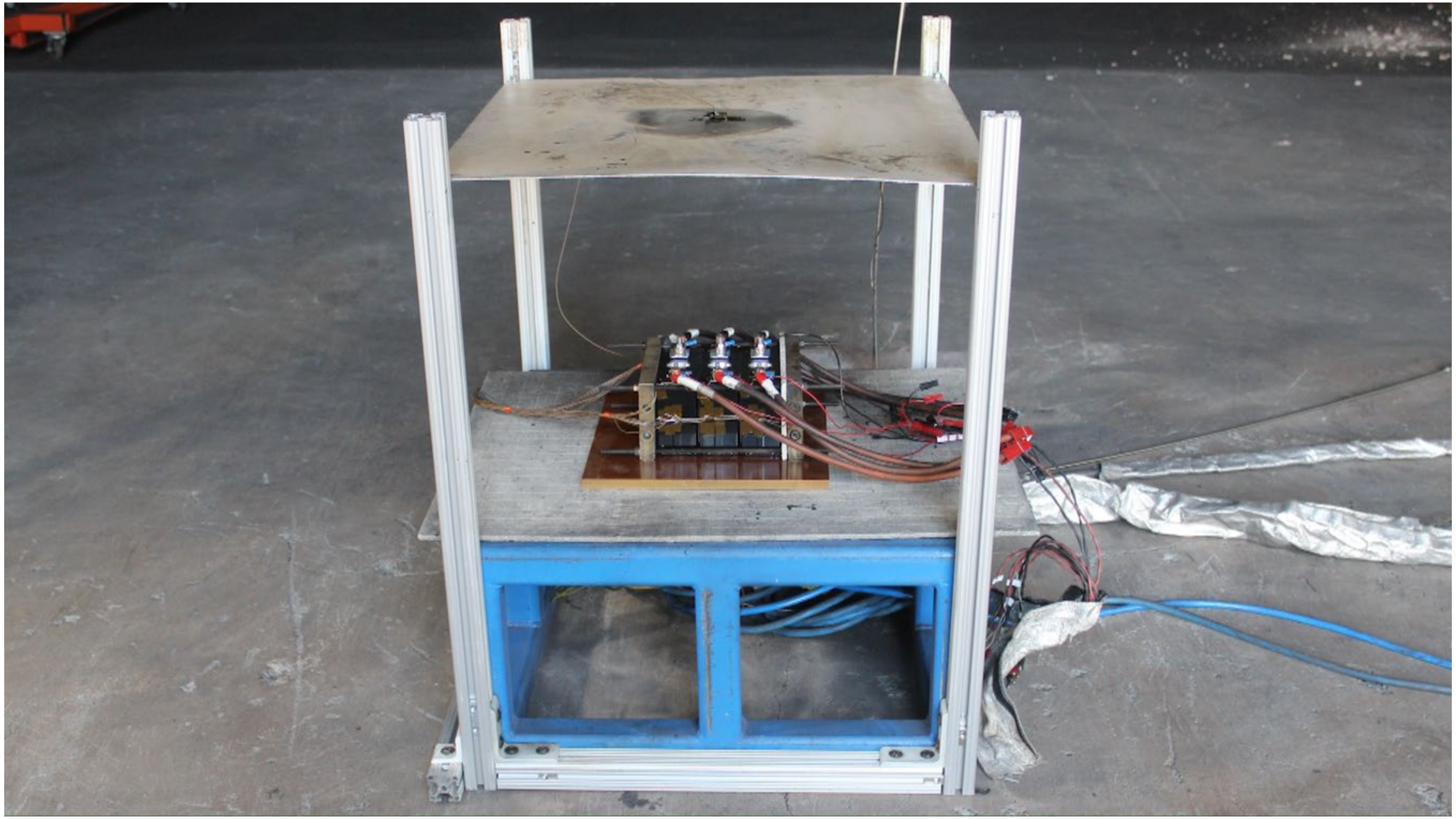
Differences

- Cell-to-cell propagation delay longer for NITE
- Thermocouple sheath thicker in NITE testing

Difference in observable heating rate due to choice of control thermocouple

- SNL – between Heater block and Cell 1
- NITE – outside of Heater block

SNL – Thermocouple Air Gap Test



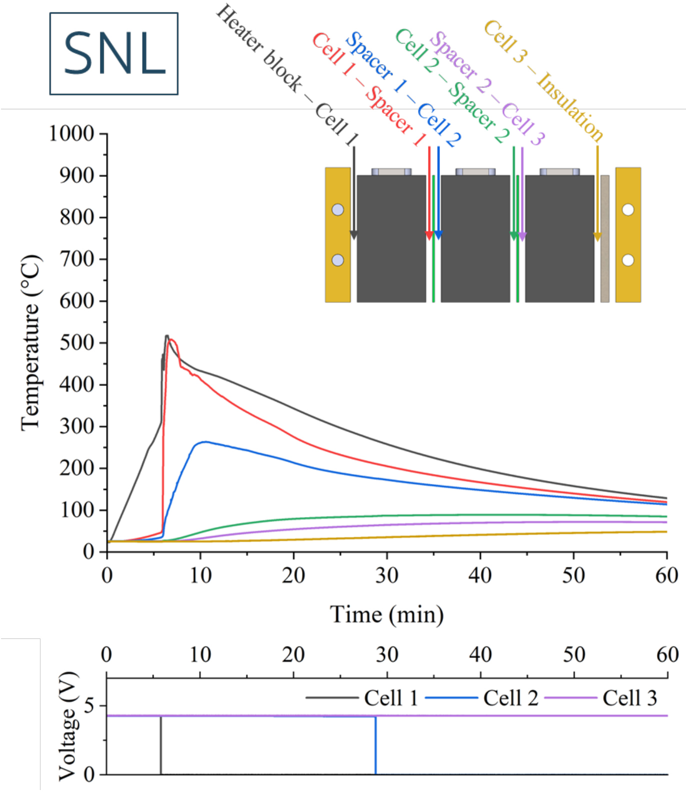
Cell-to-Cell Gap Modification, Impact on Propagation
1/16” Phenolic + Thermocouple Air Gap

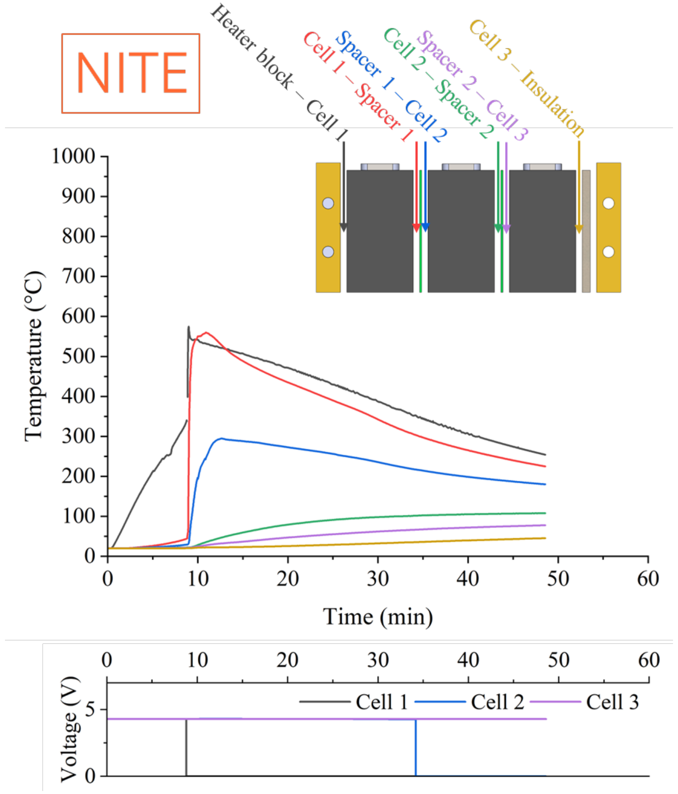
	Cell	Thermal Runaway	Voltage Loss
SNL	1	Zero	-6 sec
	2	No	22 min 51 sec
	3	No	No
NITE	1	Zero	10 sec
	2	No	25 min 23 sec
	3	No	No

Similarities

- No propagation
- Cell 2 voltage loss occurred at similar time intervals

This set of tests contained the most repeatable results between labs.





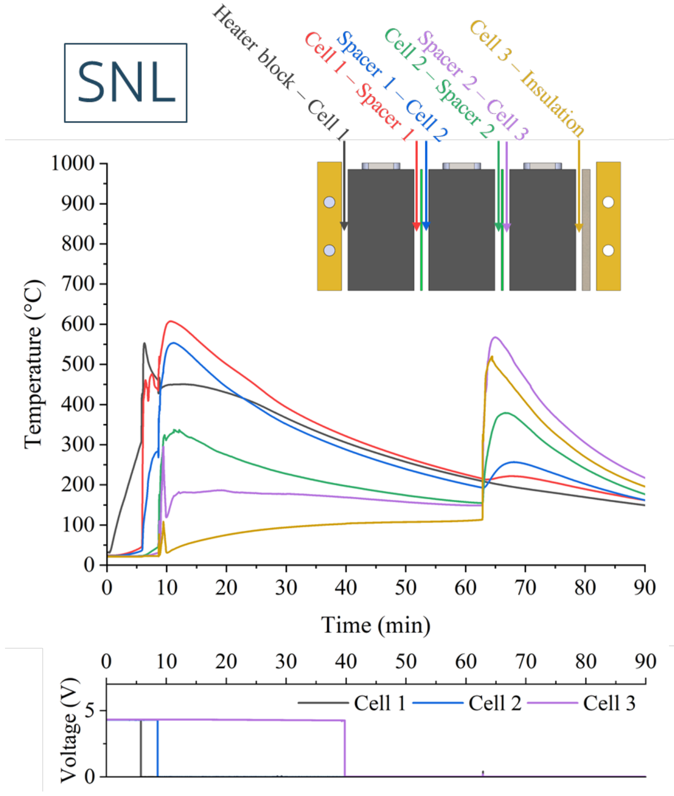
Cell-to-Cell Gap Modification Impact on Propagation
1/16" Phenolic + Thermocouple Grooves

	Cell	Thermal Runaway	Voltage Loss
SNL Test 1	1	Zero	-5 sec
	2	2 min 45 sec	2 min 42 sec
	3	56 min 56 sec	33 min 55 sec
SNL Test 2	1	Zero	-7 sec
	2	2 min 19 sec	2 min 12 sec
	3	7 min 23 sec	7 min 23 sec

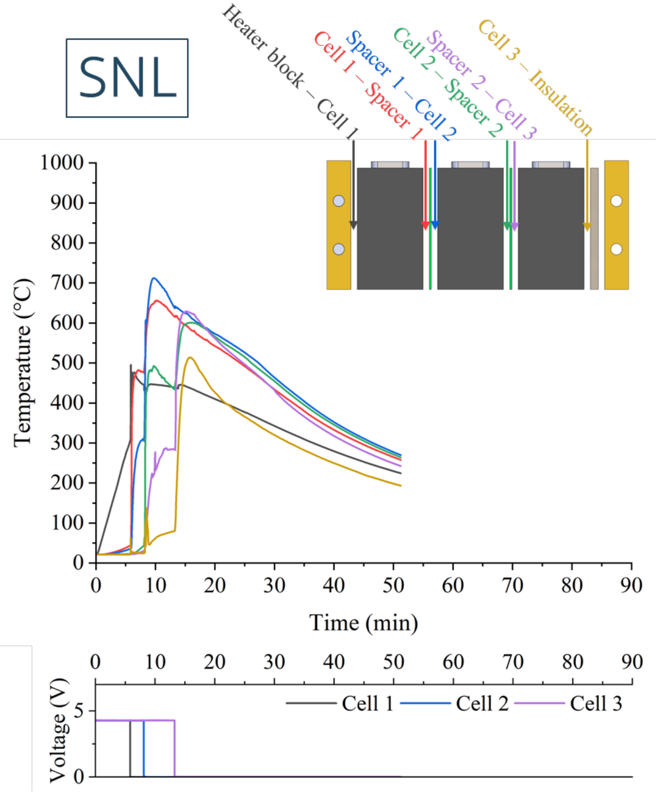
Test 1

- Cell 2 – jellyroll ejected
  - Likely resulting in the delay in propagation, due to removal of heated thermal mass

This set of tests demonstrates the variability of test results, even with identical setups in the same lab.

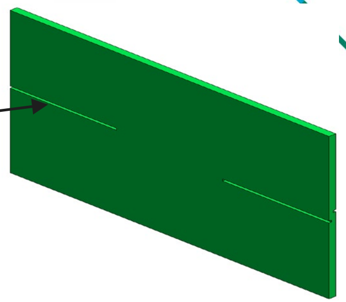


Test 1



Test 2

Cell-to-Cell Gap Modification Impact on Propagation
1/16” Phenolic + Thermocouple Grooves



	Cell	Thermal Runaway	Voltage Loss
SNL Test 1	1	Zero	-5 sec
	2	2 min 45 sec	2 min 42 sec
	3	56 min 56 sec	33 min 55 sec
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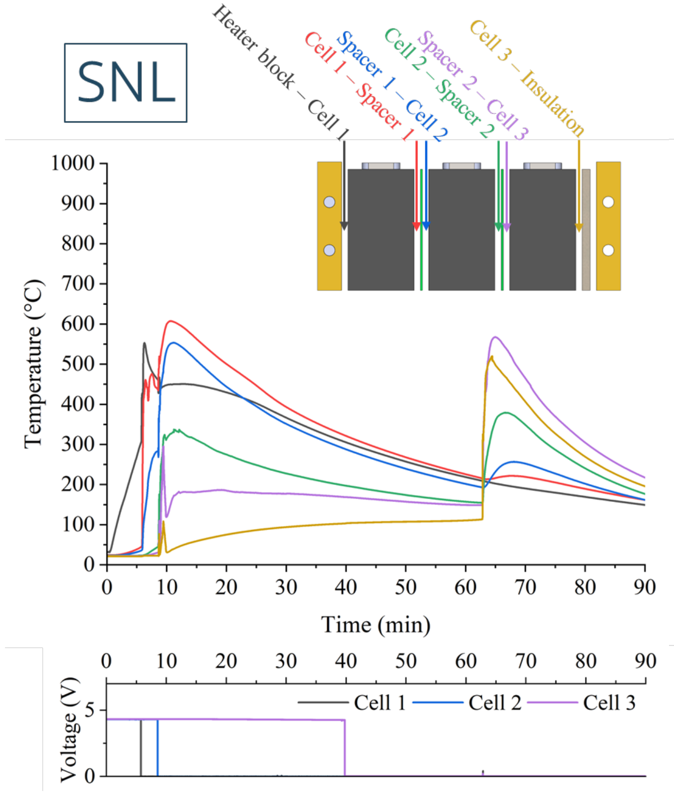
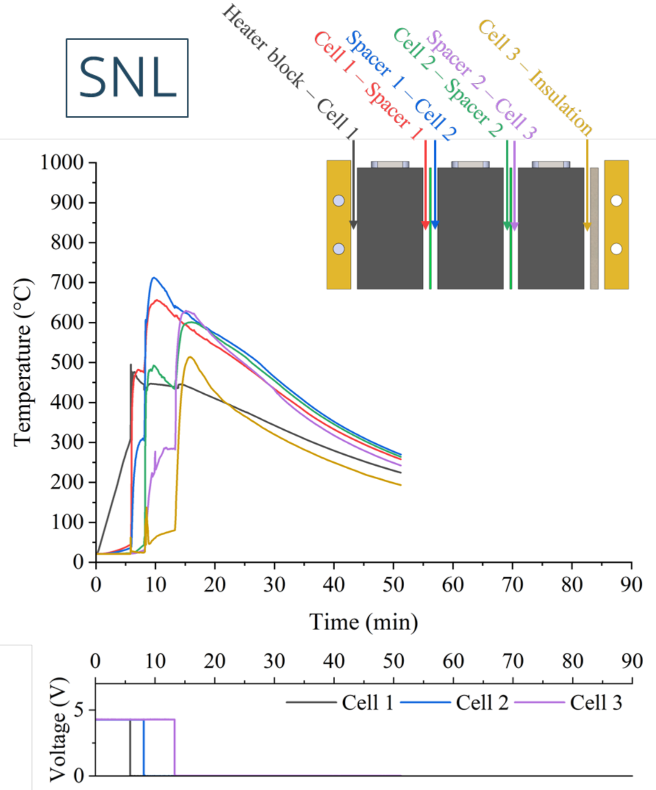
	3	7 min 23 sec	7 min 23 sec



Test 1



Test 2

Test 1

- Cell 2 – jellyroll ejected
  - Likely resulting in the delay in propagation, due to removal of heated thermal mass

This set of tests demonstrates the variability of test results, even with identical setups in the same lab.

Cell-to-Cell Gap Modification Impact on Propagation
1/16" Phenolic, No Thermocouples Between Cells

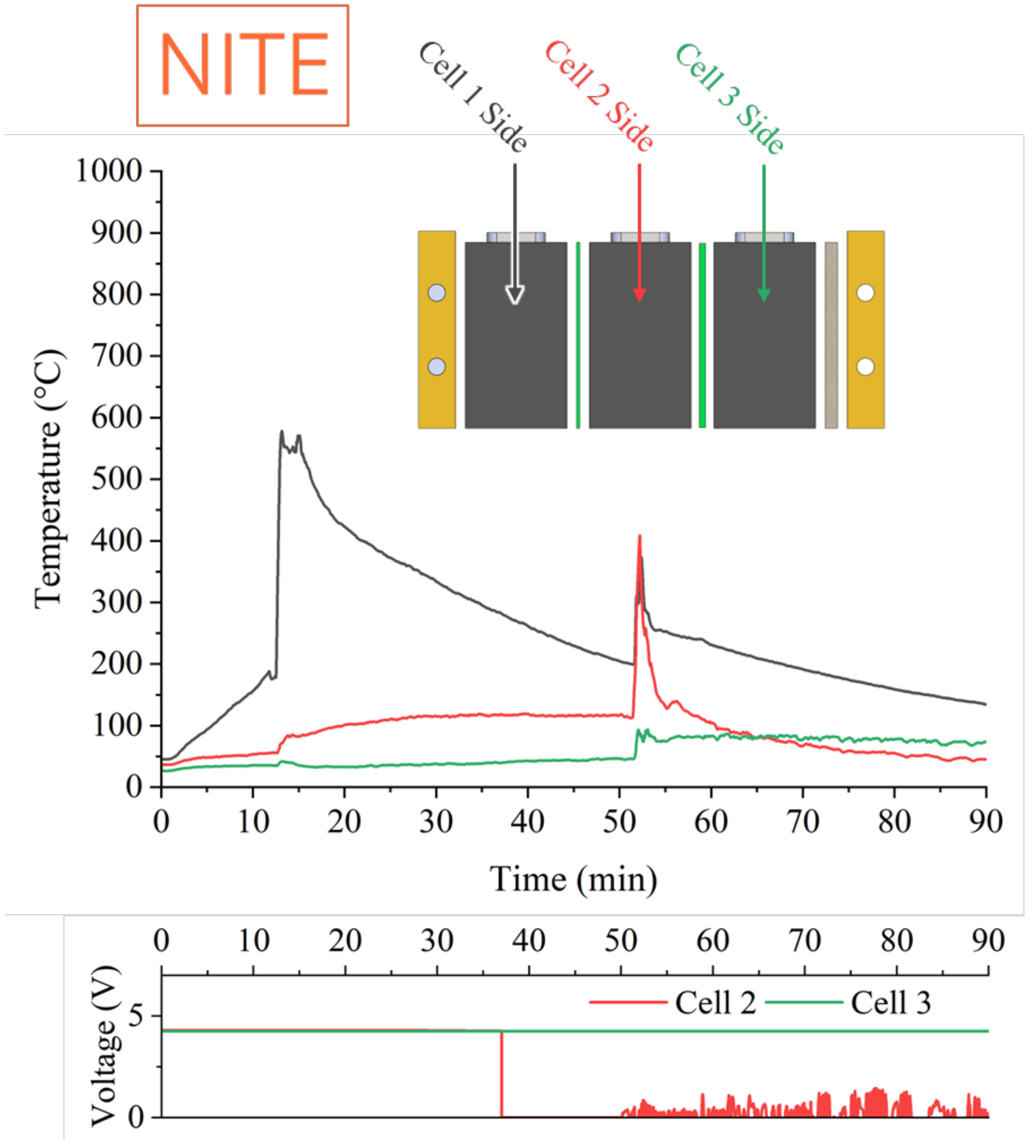
	Cell	Thermal Runaway	Voltage Loss
NITE	1	Zero	N/A
	2	39 min 5 sec	24 min 42 sec
	3	No	No

SNL results shown in previous slide.

	Cell	Thermal Runaway	Voltage Loss
SNL Test 1	1	Zero	-5 sec
	2	2 min 45 sec	2 min 42 sec
SNL Test 2	1	Zero	-7 sec
	2	2 min 19 sec	2 min 12 sec

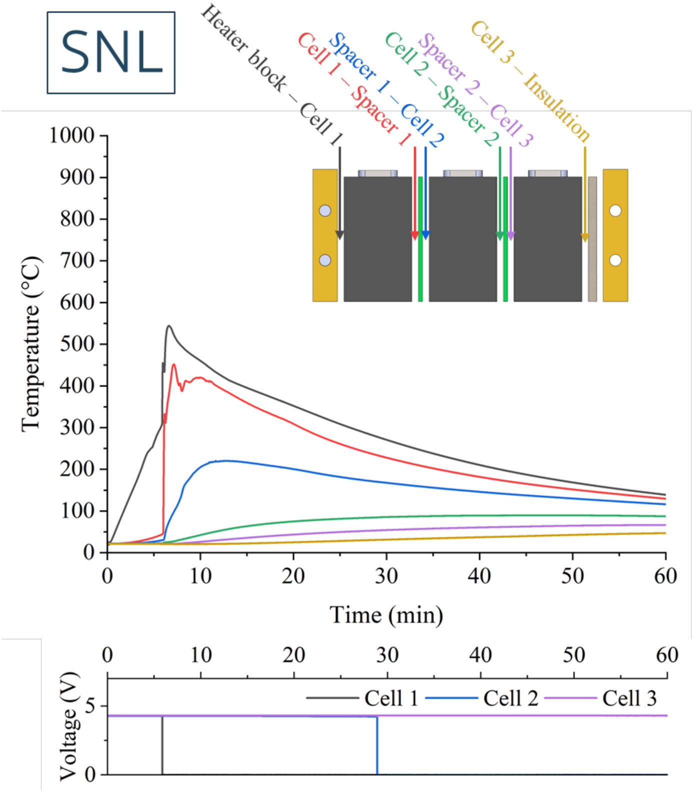
Similarities
- Propagation Cell 1 to Cell 2
- Peak temperature ~600 °C

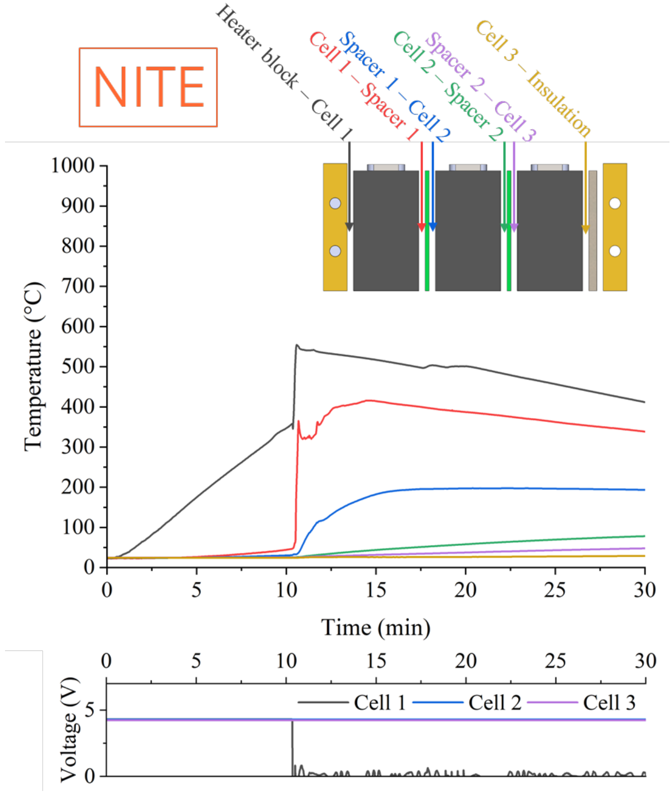
Differences
- Significant difference in time to propagation of Cell 2



Cell-to-Cell Gap Modification Impact on Propagation
1/8” Phenolic + (NITE Only) Thermocouple Air Gap

- Different testing configuration
  - Sandia had grooves for thermocouple placement
- No propagation to Cell 2 or Cell 3





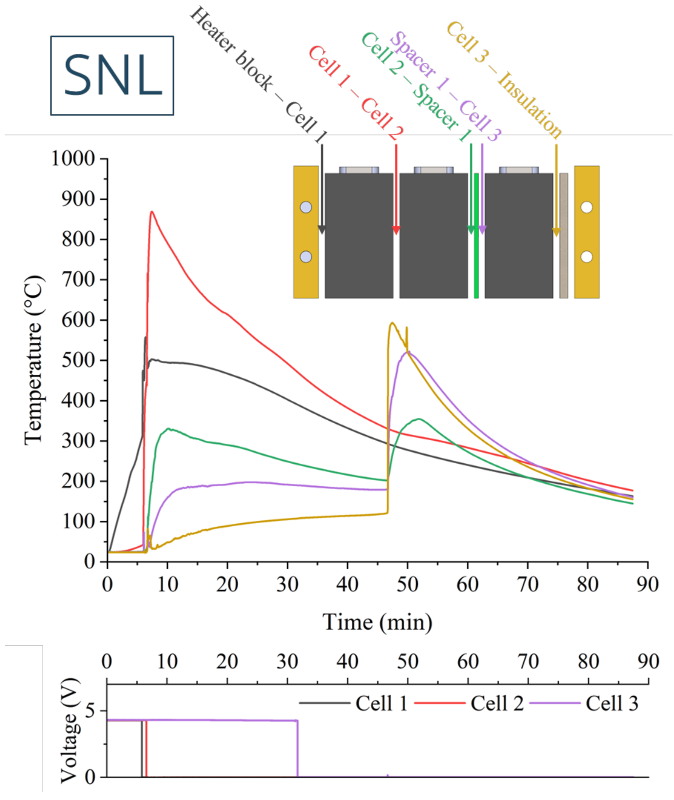
1/8” phenolic separator between cells appears to be sufficient to mitigate propagation within the testing constraints at both SNL and NITE.

Cell-to-Cell Gap Modification Impact on Propagation
Thermocouple Air Gap & 1/8" Phenolic

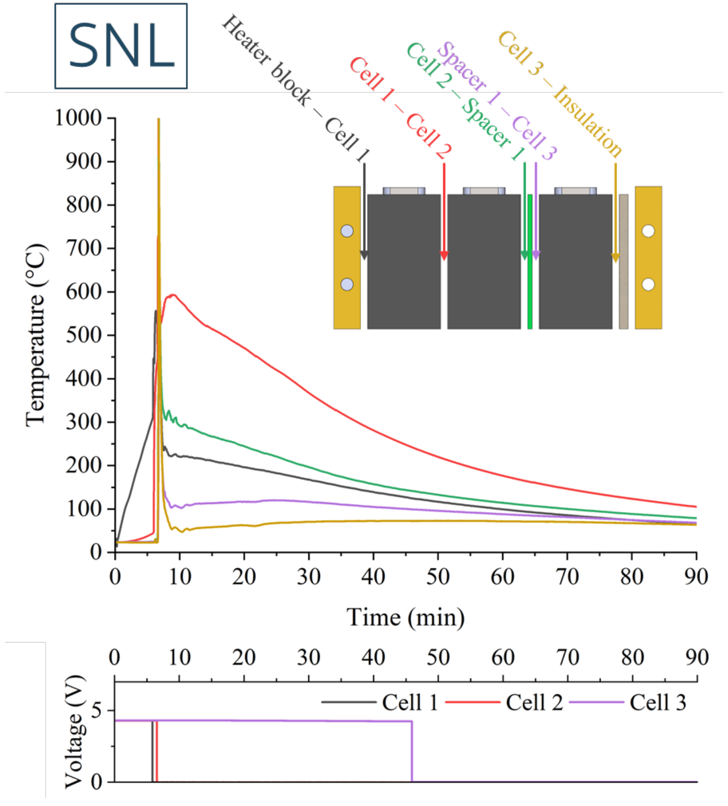
	Cell	Thermal Runaway	Voltage Loss
SNL Test 1	1	Zero	-7 sec
	2	39 sec	37 sec
	3	40 min 42 sec	25 min 44 sec
SNL Test 2	1	Zero	-5 sec
	2	36 sec	37 sec
	3	No	39 min 59 sec

Test 1
- Cell 2 had jellyroll ejection
- Ejected mass resting on Cell 3

Test 2
- Cell 2 appears to have vented out the bottom



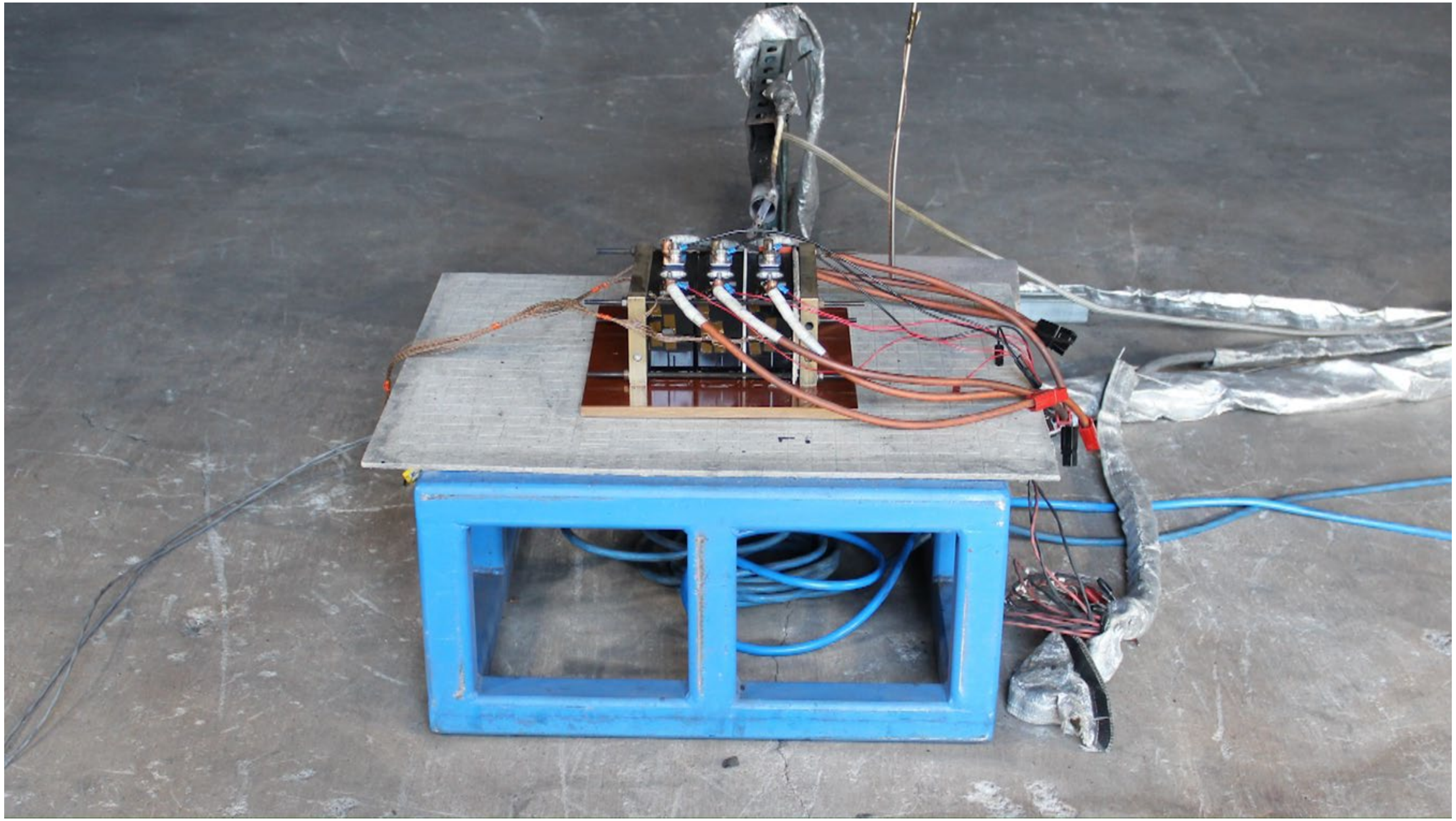
Test 1



Test 2

The movement of internal heated mass and gas outside of the cell is believed to have a significant impact on the occurrence and rate of propagation.

SNL – Thermocouple Air Gap & 1/8” Phenolic Test



Testing Summary

Institution	Condition	Propagation Cell 1 to Cell 2	Propagation Cell 2 to Cell 3
SNL	Thermocouple Air Gap	☑	☑
NITE	Thermocouple Air Gap	☑	☑
SNL	1/16” Phenolic + Thermocouple Air Gap	☒	☒
NITE	1/16” Phenolic + Thermocouple Air Gap	☒	☒
SNL	1/16” Phenolic	☑☑	☑☑
NITE	1/16” Phenolic & 1/8” Phenolic	☑	☒
SNL	1/8” Phenolic	☒	☒
NITE	1/8” Phenolic + Thermocouple Air Gap	☒	☒
SNL	Thermocouple Air Gap & 1/8” Phenolic	☑☑	☑☒

Testing Summary

SNL and NITE testing agreement in thermocouple air gap propagation.
Delay in onset time for cell-to-cell propagation in NITE's testing compared to SNL.

Institution	Condition	Propagation Cell 1 to Cell 2	Propagation Cell 2 to Cell 3
SNL	Thermocouple Air Gap	☑	☑
NITE	Thermocouple Air Gap	☑	☑
SNL	1/16" Phenolic + Thermocouple Air Gap	☒	☒
NITE	1/16" Phenolic + Thermocouple Air Gap	☒	☒
SNL	1/16" Phenolic	☑☑	☑☑
NITE	1/16" Phenolic & 1/8" Phenolic	☑	☒
SNL	1/8" Phenolic	☒	☒
NITE	1/8" Phenolic + Thermocouple Air Gap	☒	☒
SNL	Thermocouple Air Gap & 1/8" Phenolic	☑☑	☑☒

Testing Summary

SNL and NITE testing agreement in 1/16” Phenolic + Thermocouple Air Gap propagation. Cell voltage loss timing and heating profiles highly consistent.

Institution	Condition	Propagation Cell 1 to Cell 2	Propagation Cell 2 to Cell 3
SNL	Thermocouple Air Gap	☑	☑
NITE	Thermocouple Air Gap	☑	☑
SNL	1/16” Phenolic + Thermocouple Air Gap	☒	☒
NITE	1/16” Phenolic + Thermocouple Air Gap	☒	☒
SNL	1/16” Phenolic	☑☑	☑☑
NITE	1/16” Phenolic & 1/8” Phenolic	☑	☒
SNL	1/8” Phenolic	☒	☒
NITE	1/8” Phenolic + Thermocouple Air Gap	☒	☒
SNL	Thermocouple Air Gap & 1/8” Phenolic	☑☑	☑☒

Testing Summary

Both SNL and NITE experienced propagation from Cell 1 to Cell 2 when using 1/16” phenolic and no air gap between cells.

Institution	Condition	Propagation Cell 1 to Cell 2	Propagation Cell 2 to Cell 3
SNL	Thermocouple Air Gap	☑	☑
NITE	Thermocouple Air Gap	☑	☑
SNL	1/16” Phenolic + Thermocouple Air Gap	☒	☒
NITE	1/16” Phenolic + Thermocouple Air Gap	☒	☒
SNL	1/16” Phenolic	☑☑	☑☑
NITE	1/16” Phenolic & 1/8” Phenolic	☑	☒
SNL	1/8” Phenolic	☒	☒
NITE	1/8” Phenolic + Thermocouple Air Gap	☒	☒
SNL	Thermocouple Air Gap & 1/8” Phenolic	☑☑	☑☒

Testing Summary

Both SNL and NITE did not experience propagation between cells when using 1/8″ phenolic and no air gap between cells.

Institution	Condition	Propagation Cell 1 to Cell 2	Propagation Cell 2 to Cell 3
SNL	Thermocouple Air Gap	☑	☑
NITE	Thermocouple Air Gap	☑	☑
SNL	1/16” Phenolic + Thermocouple Air Gap	☒	☒
NITE	1/16” Phenolic + Thermocouple Air Gap	☒	☒
SNL	1/16” Phenolic	☑☑	☑☑
NITE	1/16” Phenolic & 1/8” Phenolic	☑	☒
SNL	1/8” Phenolic	☒	☒
NITE	1/8” Phenolic + Thermocouple Air Gap	☒	☒
SNL	Thermocouple Air Gap & 1/8” Phenolic	☑☑	☑☒

Testing Summary

SNL results showed a difference in propagation outcomes from replicate testing within the same lab.

Institution	Condition	Propagation Cell 1 to Cell 2	Propagation Cell 2 to Cell 3
SNL	Thermocouple Air Gap	☑	☑
NITE	Thermocouple Air Gap	☑	☑
SNL	1/16” Phenolic + Thermocouple Air Gap	☒	☒
NITE	1/16” Phenolic + Thermocouple Air Gap	☒	☒
SNL	1/16” Phenolic	☑☑	☑☑
NITE	1/16” Phenolic & 1/8” Phenolic	☑	☒
SNL	1/8” Phenolic	☒	☒
NITE	1/8” Phenolic + Thermocouple Air Gap	☒	☒
SNL	Thermocouple Air Gap & 1/8” Phenolic	☑☑	☑☒

Objective: Understand Variability in Lab-to-Lab Concurrent Testing of “Identical” Test Conditions

1. How does abuse response compare from test-to-test and from lab-to-lab?
   a) Can we replicate tests internally and achieve the same results?
      i. *Yes and no. It appears we can bound the configuration in terms of onset temperature, peak temperatures, and rate of propagation. But, it is not yet clear the breadth of that boundary.*
   b) Can we replicate tests across labs and achieve the same results?
      i. *Yes and no. In some cases, surprisingly consistent. In others, significant difference in rate of propagation.*
   c) If there is a difference, what is the underlying cause?
      i. *Components and assembly methods can have a significant impact in outcome .*
         - *e.g., thermocouple sheath thickness and gap consistency*
      ii. *The manner in which a cell experiences runaway can have a significant impact on the response of adjacent cells.*
2. What do differences in replicate testing outcomes imply with regards to safety standards and pack integration?
   a) Can outcomes be significantly altered by choice of components and materials?
      i. *It may be possible to push configurations that straddle the boundary of propagation one way or the other.*
   b) What are the biggest sources of uncertainty and how do we minimize those to inform better standards?
      i. *The way in which a cell fails (location of vent, vent direction, ejection of heated mass, etc.) is highly variable*
      ii. *Choice of ancillary equipment, materials, and assembly methods may have a significant impact on testing outcome.*

Key Findings

- Testing between institutions is challenging
  - Difficulty in stipulating parameters which may have an impact on heat flow. The following examples are considering thermocouples alone:
    - Thickness of thermocouple wire
    - Thermocouple sheathing material
    - Placement of thermocouple wire and impact on cell-to-cell air gap
    - The way in which thermocouple wire is fixed to the cell
    - Etc.

- Thermal runaway behavior can be bounded (in terms of peak temperature, propagation rate, etc.) but, not predicted
  - With an identical testing configuration at SNL, variability occurred in propagation
  - Jelly roll ejection occurred in some cells but, not others
  - Flame direction dependence on cell swelling
  - Ejected mass may land in close proximity to adjacent cells

- Implications for safety standards testing
  - During test article assembly, small decisions are required that are not explicitly covered in the test plan (e.g., fixturing materials)
    - These decisions may impact heat flow and can push a boundary condition one way or the other
    - Through this work, these “micro-decisions” are being identified

Future Work

Single and 3-Cell Pack Testing

- Similar testing matrix to work shown in this presentation
  - Adjustments to better connect work to our modeling efforts
    - Venting models
    - Prismatic cell models

- Increased constraints on experimental setup and methodology

- Test cells purchased from a single manufactured lot
  - Eliminate variability in manufacturing
  - Purchase coordinated by NITE

SNL Project Team

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Lucas Gray
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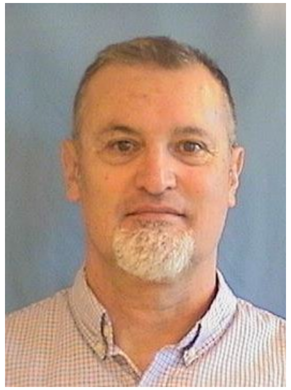
Power Sources R&D



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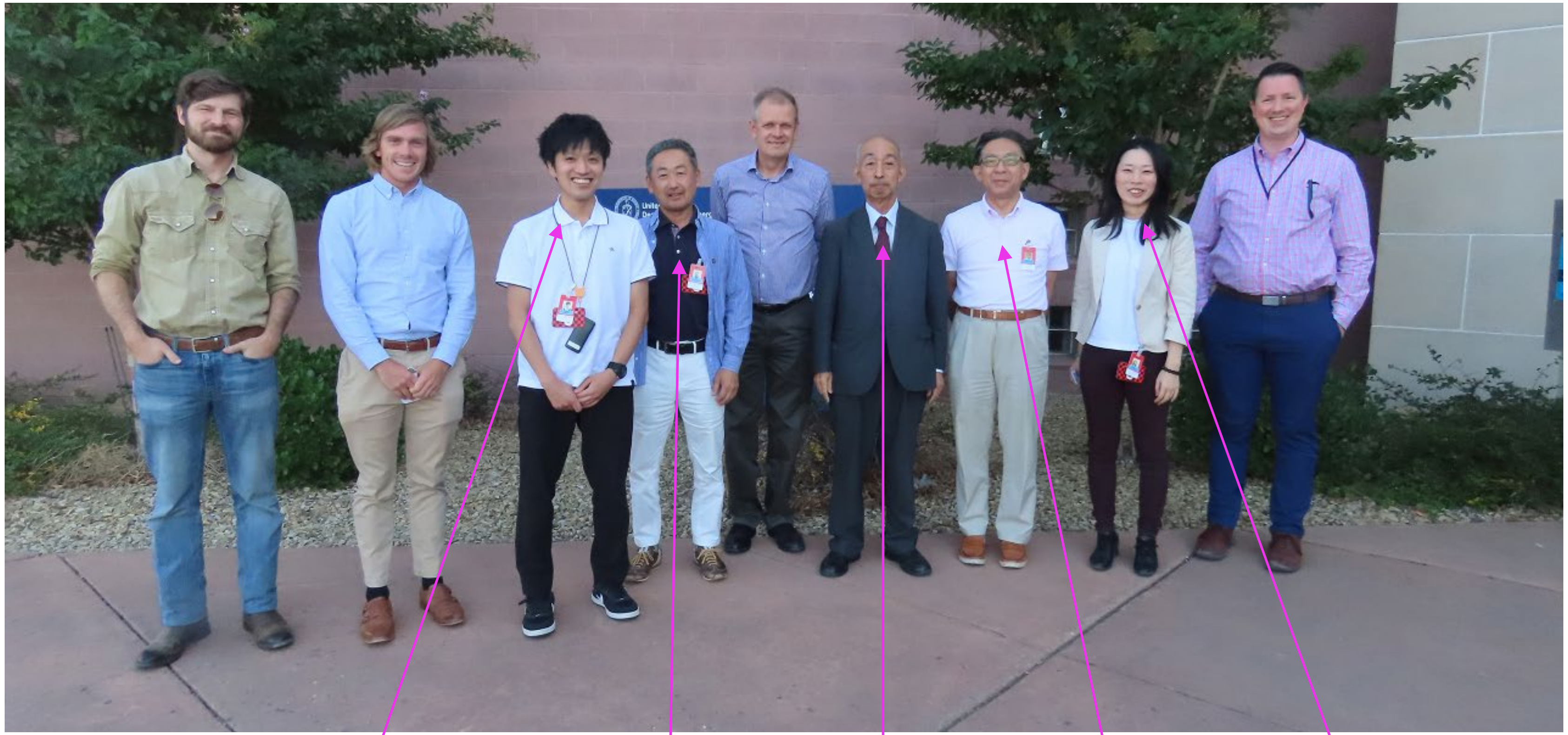
Fire Sciences and Technology

NITE Project Team



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Questions?

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