Insights into Fire Propagation in NMC 21700 Cell Modules with and without Immersive Cooling

SOUTHWEST RESEARCH INSTITUTE®

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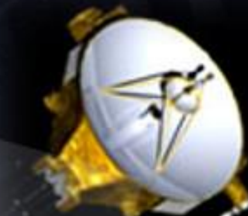
Presented at the International Battery Seminar
07302020

Deep Sea to Deep Space[SM]

Southwest Research Institute (SwRI®)

Independent.
Advanced Science.
Applied Technology.
From *Deep Sea*
To Deep Space.



- New Horizons
  - SwRI-lead
  - Launched: January 19, 2006
  - Closest approach to Pluto: July 14, 2015

- Alvin
  - Tested at SwRI before first (1964) record-setting dives > 8,000 ft.
  - Redesigned (2013) *new* Alvin (3" titanium sphere) capable of > 21,000 ft.

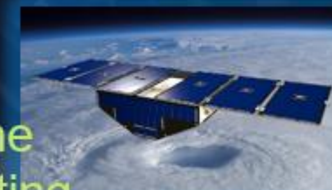
Deep Sea to Deep Space
And Everything Between

Water and Geological Engineering

Robotics, Automation, and Simulations

Drug Discovery and Chemistry

Energy



Cyclone Forecasting

Homeland Security, Defense, and Intelligence

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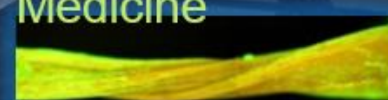
Regenerative Medicine

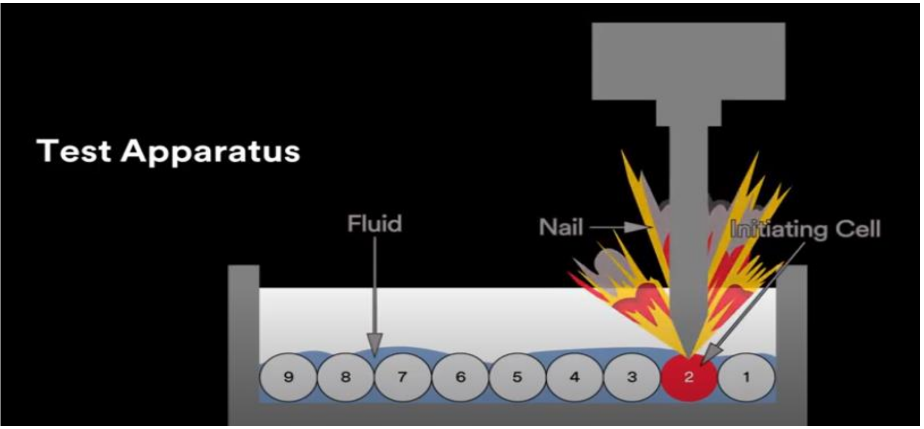


Engine Design and Optimization

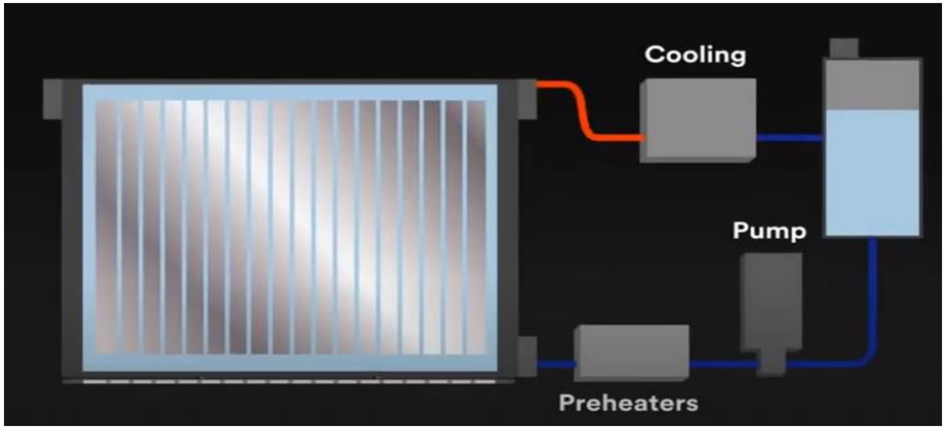
Overview

- With effective removal of heat from cells, a lithium ion battery pack can deliver high power, be charged quickly and minimize balancing activity due to lower temperature differentials across the pack
- Passive and active thermal management of lithium ion cells determines not only the performance envelope but also the fire propagation patterns
- The effectiveness of immersive cooling is demonstrated in this work using AmpCool™ from Engineered Fluids as an example
- 9PS1 modules were tested when a single cell was subjected to nail penetration
- The propagation of fire and thresholds of inception and end were flagged by analyzing the voltage and temperature patterns with and without the presence of the immersive coolant

Sample of Similar Work with Novec™ fluid from 3M



Nail Penetration Test



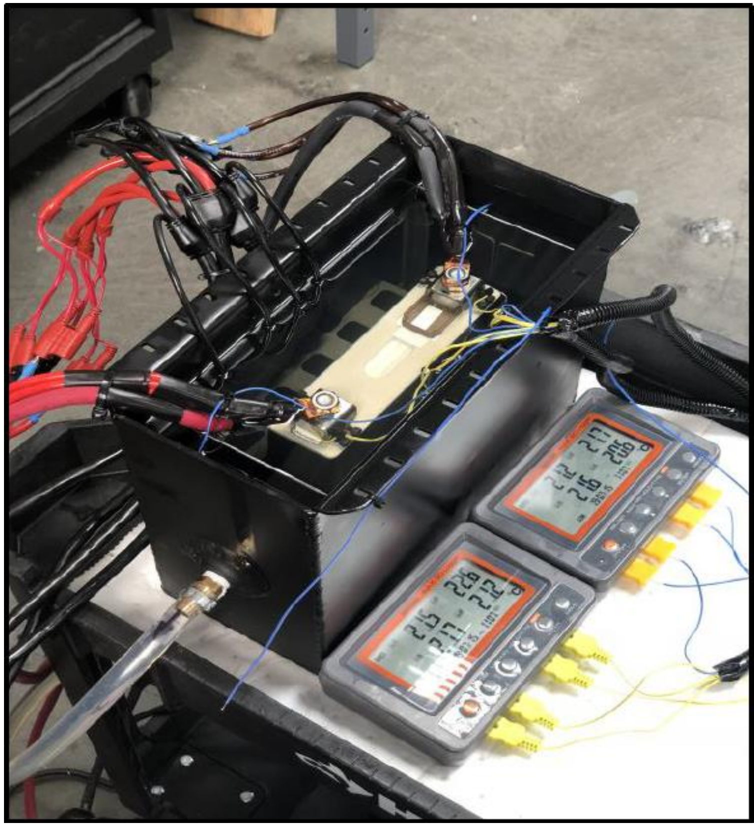
Immersion System Setup

NOVEC™ fluid prevented fire propagation

Courtesy 3M Corporation

Sample Work with AmpCool™ AC-100 from Engineered Fluids

- Immersed test cells maintained average cell temperature of 22.5 ˚C with low deviation from the mean.
  - Using air, the average temperature was 28.7 ˚C with high variation.
- Immersion cooling can maintain a cell's temperature within a desired band even under high thermal stress brought about by accelerated discharge

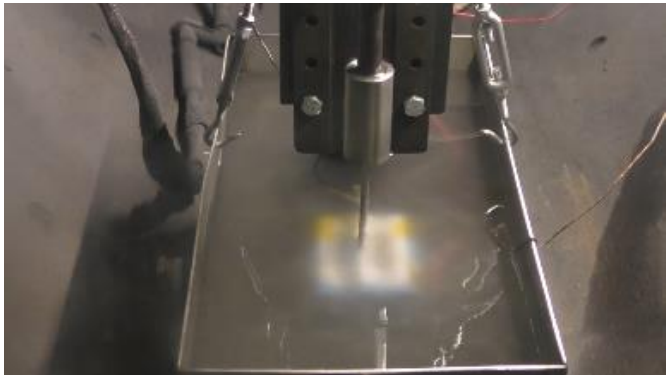


Courtesy: David Sundin and Sebastian Sponholtz, "Thermal Management of Li-Ion Batteries with Single-phase Liquid Immersion Cooling", www.engineeredfluids.com, 2019

SwRI Test Setup

Item	Specification
3.1 Standard discharge capacity	Min. 4,000mAh - Charge: 0.5C(2A), 4.20V, 0.05C(200mA) cut-off @ RT - Discharge: 0.2C(800mA), 2.5V cut-off @ RT
3.2 Rated discharge capacity	Min. 3,900 mAh - Charge:1.5C(6A), 4.20V, 0.025C(100mA)cut-off @RT - Discharge: 10A, 2.5V cut-off @ RT
3.3 Nominal voltage	3.6V
3.4 Standard charge	CCCV, 2A, 4.20 V, 200mA cut-off
3.5 Rated charge	CCCV, 6A, 4.20 V, 100mA cut-off
3.6 Charging time	Standard charge : 180min / 200mA cut-off(@ RT) Rated charge: 70min / 100mA cut-off(@ RT)
3.7 Max. continuous discharge (Surface temperature)	35A(Without temperature cut) 45A(With 80℃ temperature cut)
3.8 Discharge cut-off voltage	2.5V (End of discharge)
3.9 Cycle life	Capacity ≥ 2,400mAh @ after 250cycles (60% of the standard capacity @ RT) - Charge : 6A, 4.20V, CCCV 100mA cut-off @ RT - Discharge: 35A , 2.5V cut-off @ RT
3.10 Retention characteristics	Capacity recovery(after the storage) ≥ 3,510 mAh (90% of the rated capacity @ RT) - Charge : 6A, 4.20V, CCCV 100mA cut-off @ RT - Storage : 30 days (@ 60℃) - Discharge : 10A , 2.5V cut-off @ RT
3.11 Cell weight	70.0g max
3.12 Cell dimension	Height : Max 70.30mm Diameter : Max 21.22mm
3.13 Operating temperature (Ambient)	Charge : 0 to 45℃ Discharge: -20 to 60℃
3.14 Operating temperature(*2) (Surface)	Charge : 0 to 50℃ (recommended recharge release < 45℃) Discharge: -20 to 80℃ (must re-discharge release < 60℃)
3.15 Storage temperature(*3) (Recovery 90% after storage)	1 year 0~25℃ 3 months 0~45℃ 1 month 0~60℃

Specification of the Samsung 40T 21700 Cell

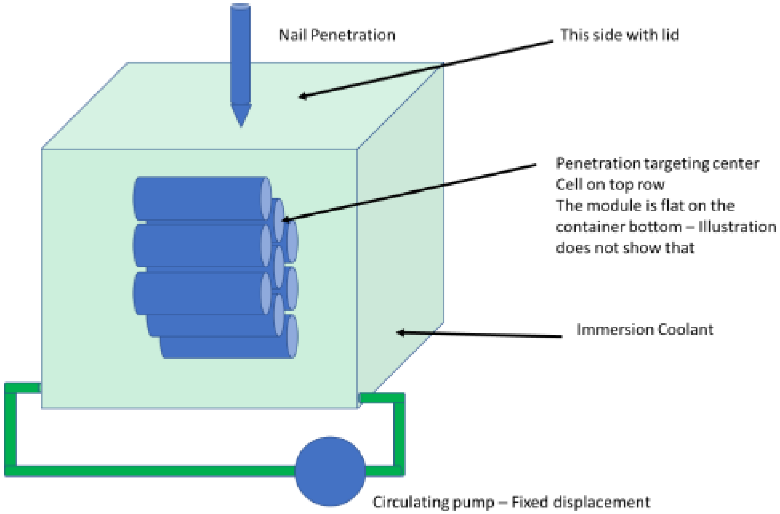


Coolant Container and Pneumatic Nail Penetration Rig

9PS1 Module with 0.5 mm Cell Spacing

SwRI Test Chamber

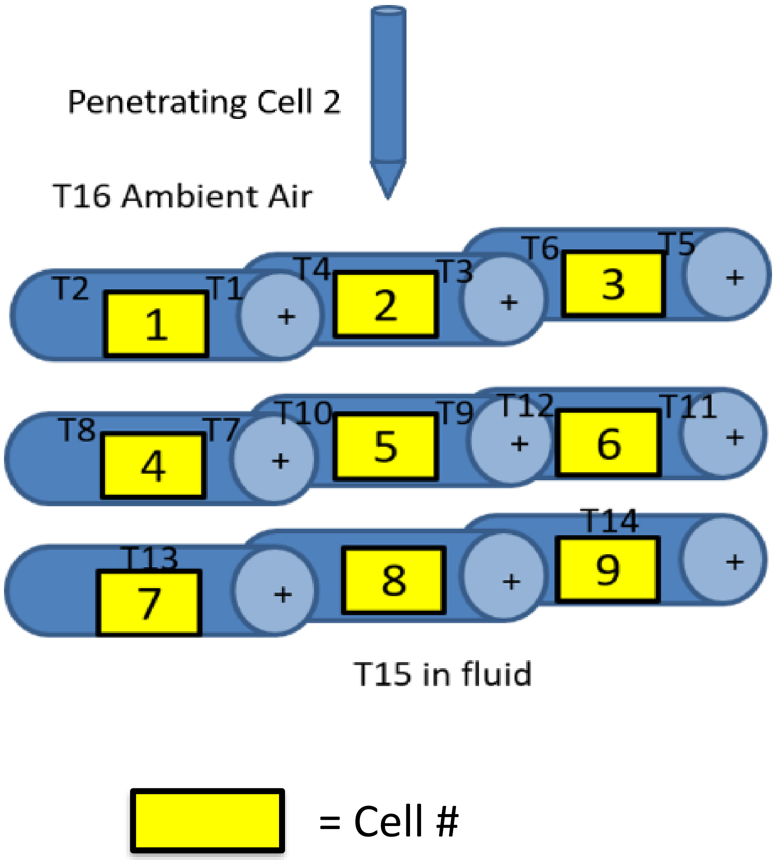
Blast Chamber to Contain Gases and Effluents



Nail Penetration of One Cell in a Module to Study Propagation with and without Immersion Coolant

Visual and thermal video cameras were focused on the test article through a glass window of the blast chamber. All charge conditioning of modules was performed using power cyclers and thermal chambers located outside the test chamber.

Module Configuration



- Cell form factor is 21700
- Cell cathode is an NMC
- Module is in 9PS1 configuration
- 16 K-type thermocouples on cells as shown
- Module was conditioned to 100% SOC at 25 °C

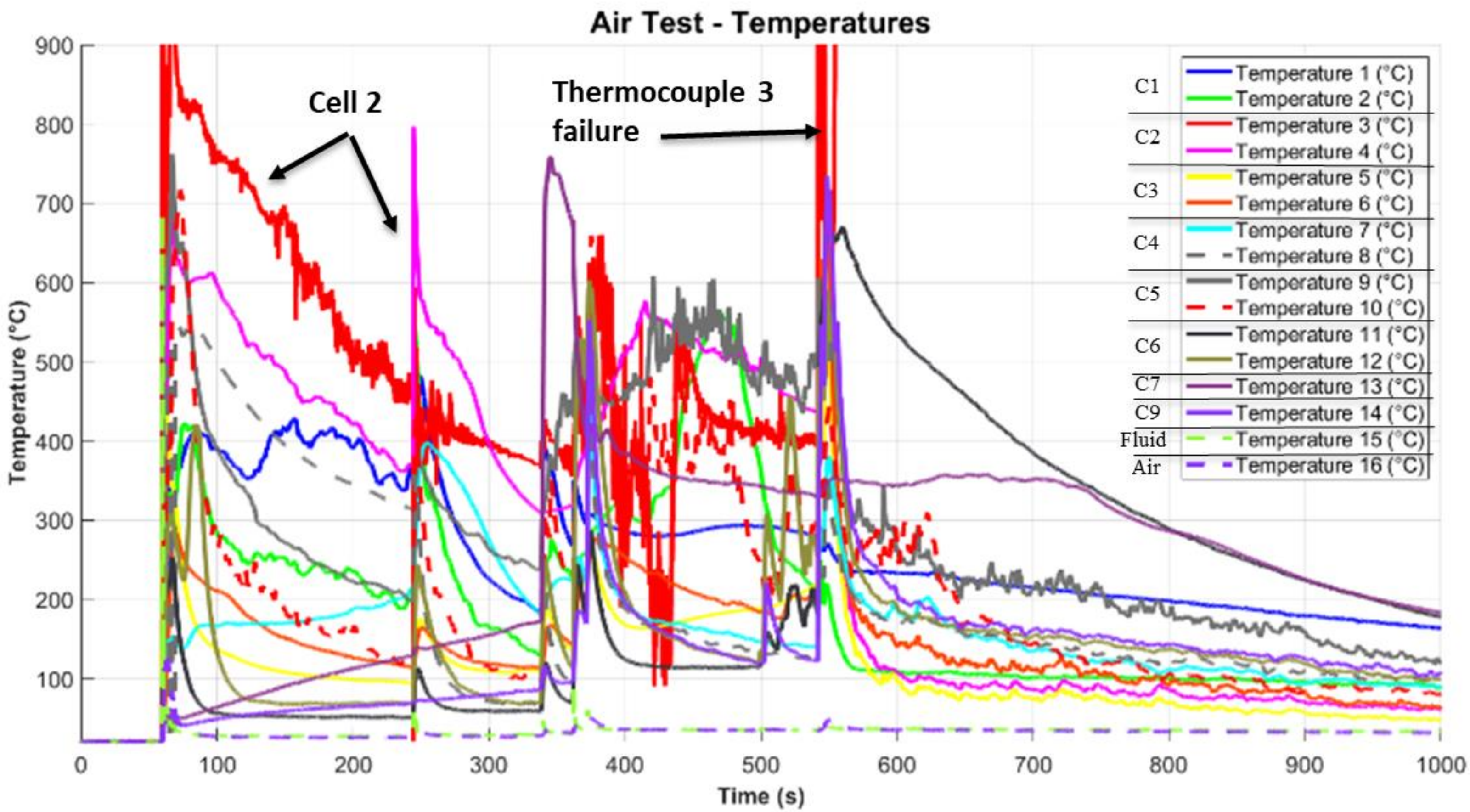
Penetration without Immersive Coolant

(a) Module Before Failure

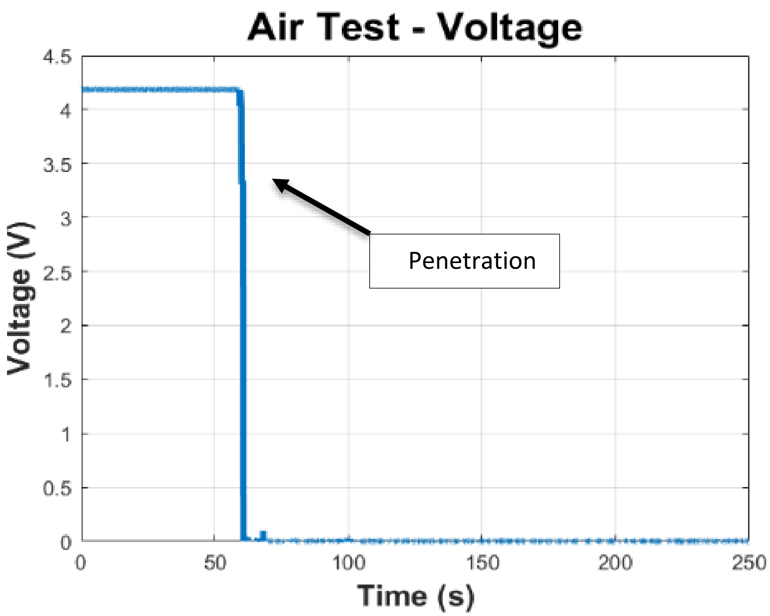
(b) Module Immediately Following Penetration

Data logging is started before commanding the pneumatic penetration rig to allow for clear contrast of measurements before and after penetration. After penetration, the data continued to be logged until all temperatures reached a quasi-steady state.

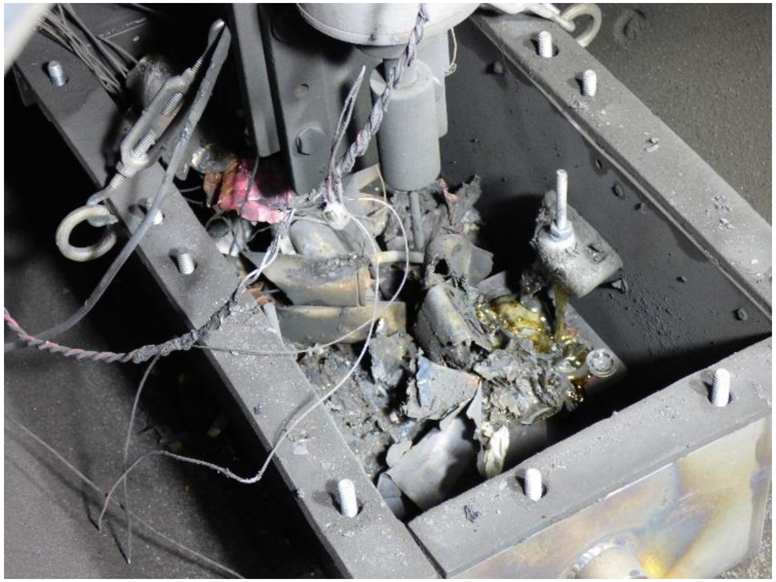
Thermocouple Readings for Baseline Test without Coolant



State of Module Failure after Baseline Test

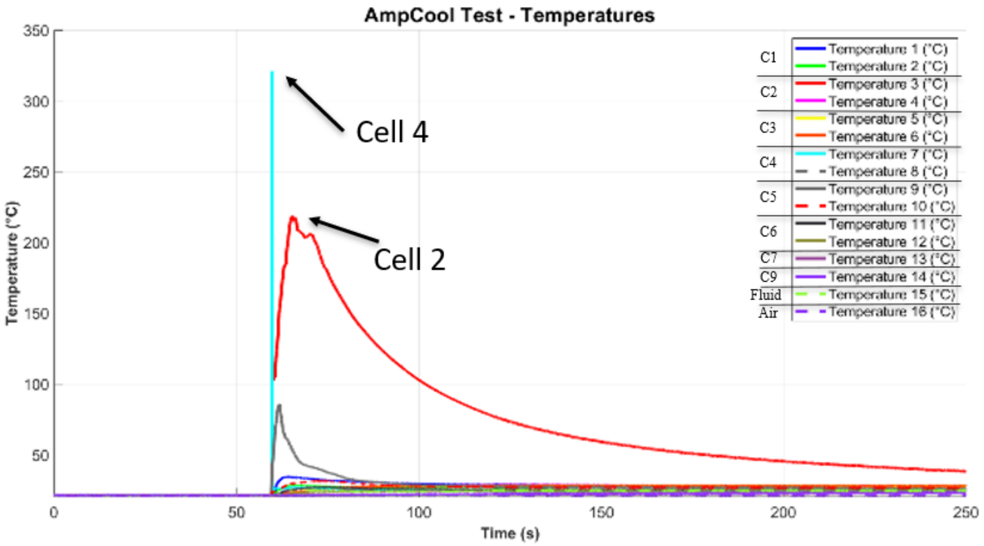


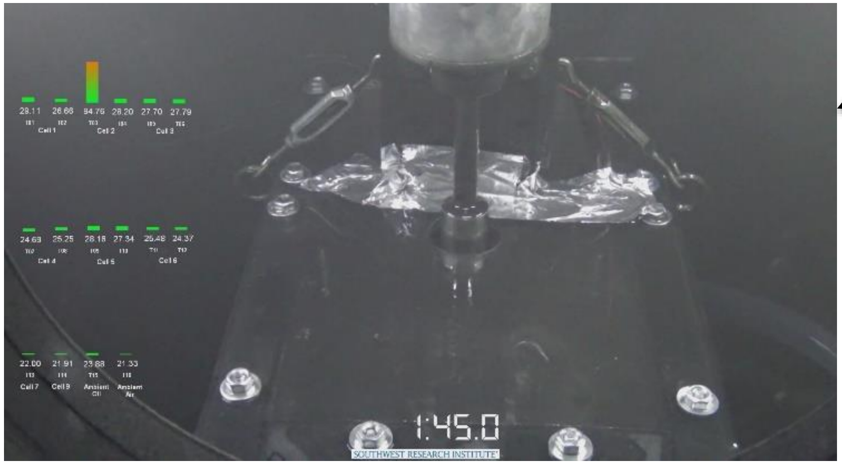
a) Module Voltage Over Time



b) Posttest Module

Penetration with Immersive Coolant

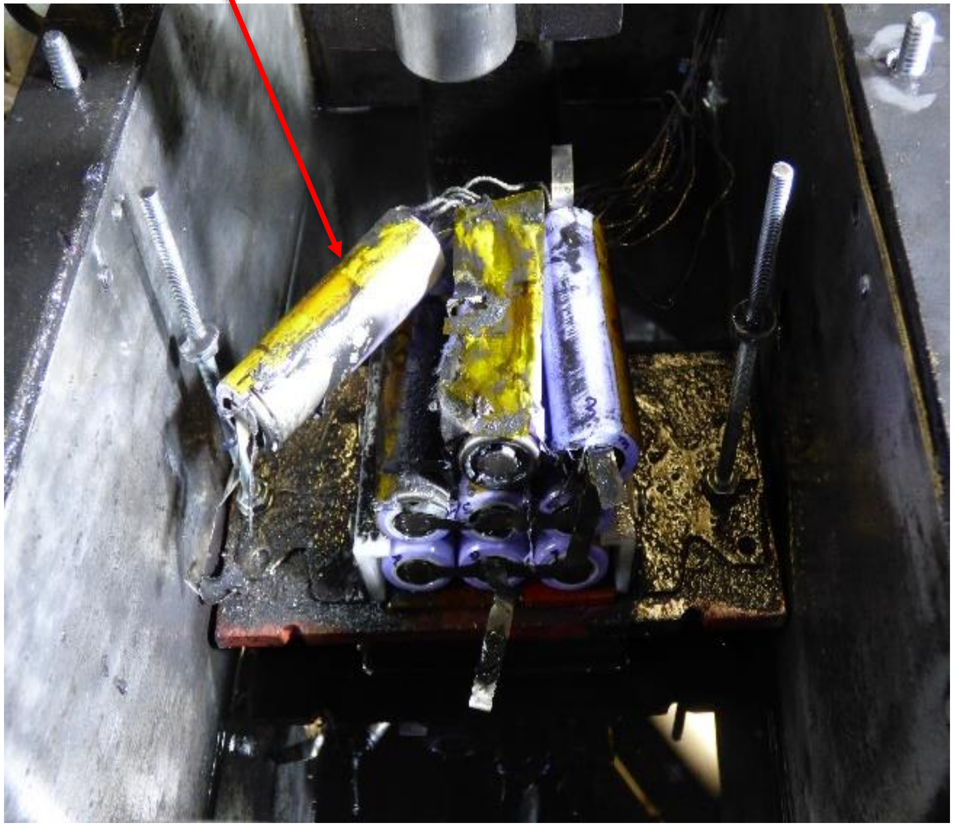




- Immediate smoke cloud upon penetration
- No visible fire
- Smoke remained trapped in container but dispersed over time.

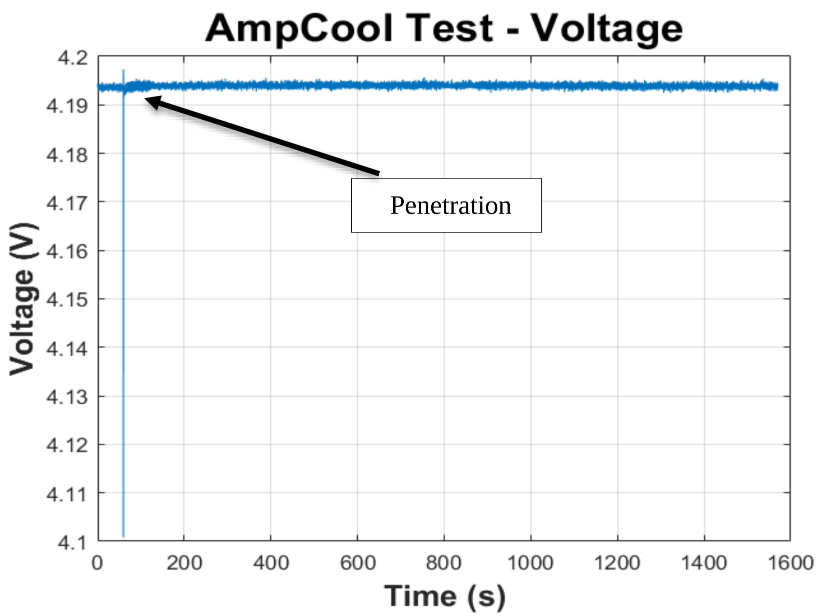
State of Module After Immersion Test

Cell 1

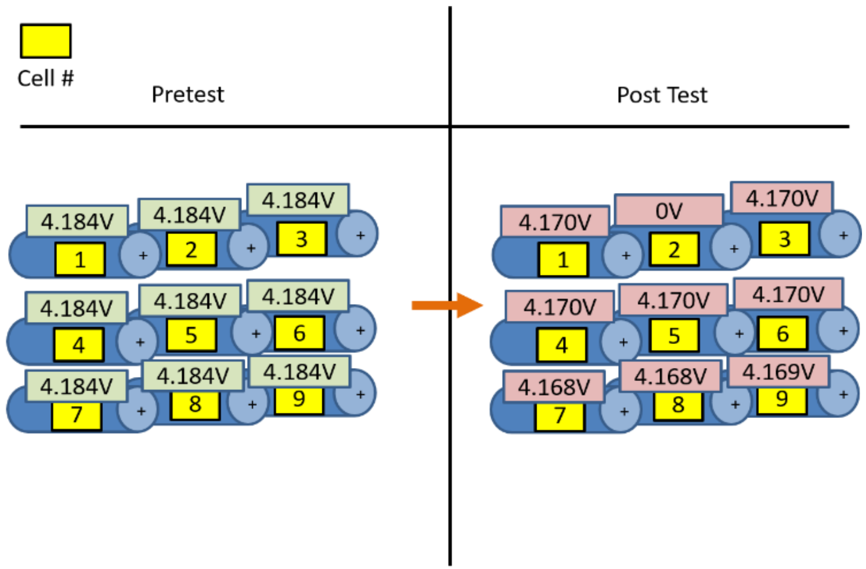


- Initial penetration caused Cell 1 to separate from the module
- Damage corresponds with temperature results, as T3 and T7 were adjacent to the location of damage.

State of the Module After Immersion Test …

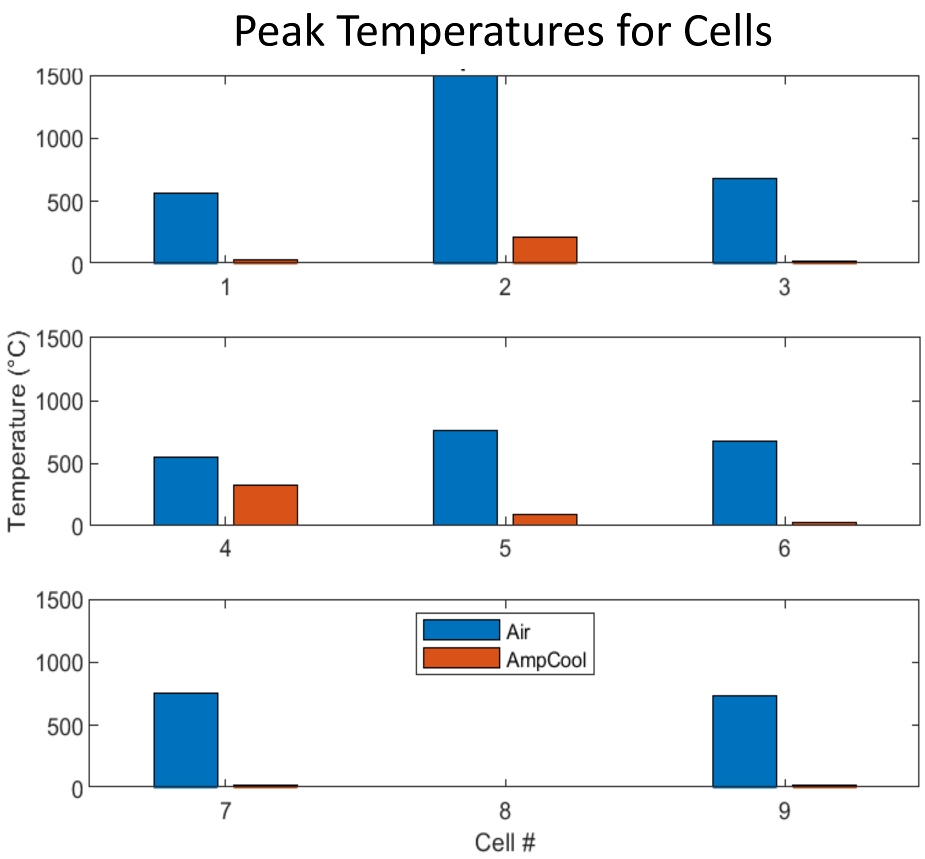


a) Module Voltage Over Time



b) Posttest Cell Voltages

Immersion (Cooled) vs. Baseline (Uncooled) Comparison



The use of coolant resulted in:

- No fire
- Lower thermal propagation
- Increased posttest cell health
- Less damage to module and surrounding structures

Note: Cell 8 had no thermocouple's and hence is unobserved

Conclusion

- An immersive coolant, in this case AmpCool™, was successful in preventing fire propagation to neighboring cells. By carrying heat away from target cells, a clear increase in failure thresholds, localization and mitigation of fire propagation is demonstrated with the immersed module in comparison to the baseline test
- Extrapolating from safety to performance, with effective removal of heat from cells, battery packs can deliver high power, can be charged quickly, and passive cell balancing activity can be minimized due to lower temperature differentials across the pack. Indirectly, these traits also enhance life and reduce warranty costs