PASSIVE PREVENTION OF THERMAL RUNAWAY AND FIRE PROPAGATION IN LI ION BATTERIES

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2023 NASA AEROSPACE BATTERY WORKSHOP

HUNTSVILLE, AL

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OUTLINE

- Introduction to battery fires
- Safety measures used in current batteries
- ASP's multi-functional technology
  - Thermal Management
  - Thermal Runaway (TR) Detection
  - TR Prevention in Trigger Cell
  - TR and Fire Propagation Prevention
- Applications

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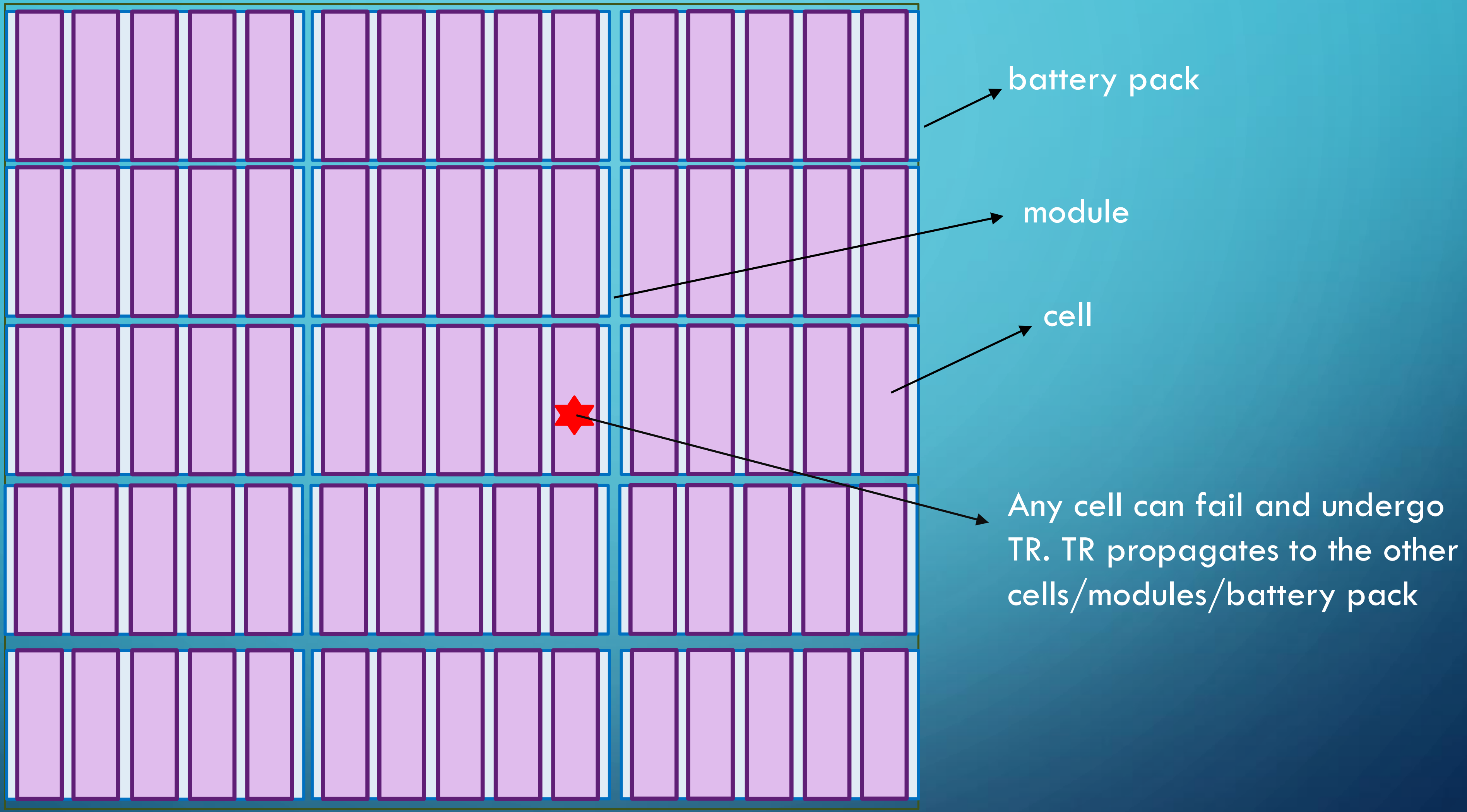
INTRODUCTION

- Li ion cells may fail due to manufacturing defects, abnormal use, and abuse
- Some failures develop slowly, while others occur very rapidly
- Irrespective of what causes failure, the cells undergo a series of chemical reactions that start at different temperatures
- Most reactions are exothermic, and the reaction rates increase with *T*: Heat release rate increases with *T*
- The positive feedback between reaction rate and heat release can cause the cell to self-heat and reach TR
- TR in one cell releases enough energy, flammable content and debris to propagate to the nearby cells eventually burning down even very large battery packs


battery pack
module
cell
Any cell can fail and undergo TR. TR propagates to the other cells/modules/battery pack

SAFETY MEASURES

- Intra-cell mechanisms
  - Positive Temperature Coefficient (PTC) & Current Interrupt Device (CID) – address specific types of failures
  - Shutdown separators & vents – delay, but cannot prevent TR
  - Low energy density materials – increase the $T_{threshold}$ for failure, but cannot prevent it
- Extra-cell mechanisms
  - Electrical (fuses, circuit breakers, etc.) – prevent electrical propagation, but do not address the source
  - Thermal (intumescent coating, phase change materials, thermal separators, etc.) – weight & volume penalties, effective mainly for slowly developing failures due to slow conduction time scales, possible interference with Thermal Management System (TMS)
  - Fire suppression (aqueous solutions) – need activation with concepts like heat plugs, too slow to prevent TR propagation within the module

Battery fires continue to occur despite these, suggesting that they are either not used (cost, weight, volume, logistics issues) or are inadequate

SUPPRESSION OF BATTERY FIRES

- “Best way to extinguish a flaming electric vehicle? Let it burn.” [J. Keilman, WSJ Article, Nov. 8, 2023]
- Fire suppression typically starts after a visible fire is noticed – may be too late to save the battery, so the focus is on limiting damage to nearby receptors
- Battery fires are commonly fought by discharging a lot of water from outside
  - Water must penetrate various barriers/clutter to reach the hot cells and quench them to prevent TR
  - 1000s of L of water are commonly used to fight an EV fire – suppressing fire alone is not enough due to the possible re-ignition
- Technologies to discharge water into the battery pack are being developed. These are more efficient than discharging water from outside the system
  - They still rely on fire detection systems which delays the response
  - Water must still penetrate various barriers to reach the hot cells
  - They flood the entire pack with water, so the battery cannot be salvaged

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ASP'S MULTI-FUNCTIONAL TECHNOLOGY

Our technology improves battery performance, cycle life, and safety

1. Active Thermal Management: maintains individual cells within an acceptable temperature range during routine operation
2. Passive Detection: detects cell overheat, a precursor to TR
3. Passive TR Prevention: uses the energy from overheating cell to activate TR prevention system
4. Passive TR and Fire Propagation Prevention: prevents thermal propagation of TR and fire from the failed cell to the surrounding cells

1. THERMAL MANAGEMENT

- Objective: maintain individual cells within an optimal *T* range and minimize *T* gradients to improve battery efficiency and minimize degradation
- High thermal capacity liquid coolant flows through channels adjacent to the cells – similar in principle and operation to the current liquid coolant based thermal management systems (TMS)
- Indirect Contact Sensible Heat Transfer: as the liquid flows through the channels, it extracts heat from cells across the thermally conductive channel walls
- Liquid coolant undergoes sensible heat gain

$$q_{convection} = \text{f(liquid flow rate, } T_{cell} - T_{coolant})$$

- Active system that draws energy from the battery for refrigeration and pumping

CFD Simulations to Examine the Effect of Coolant Flow on T_{CELL} During Routine Operation: Inputs

- 18650 cells arranged in 4x4 configuration in an enclosure
- Coolant flows through channels above and below the cells exchanging heat
- Heat generation rate: 0.6 W/cell (2500 mAh cell, R_{int} = 100 mΩ, 1C discharge)
- Coolant channel dimensions: 8.1 cm × 8.1 cm × 0.5 cm
- Coolant flow rate = 0.0004 m^3/s (to generate a local velocity of 1 m/s near the cells)
- Counter-current coolant flow through top and bottom channels
- Initial conditions
  - T_{cell} = 20°C (293 K)
  - $T_{coolant,inlet}$ = 20°C (293 K)

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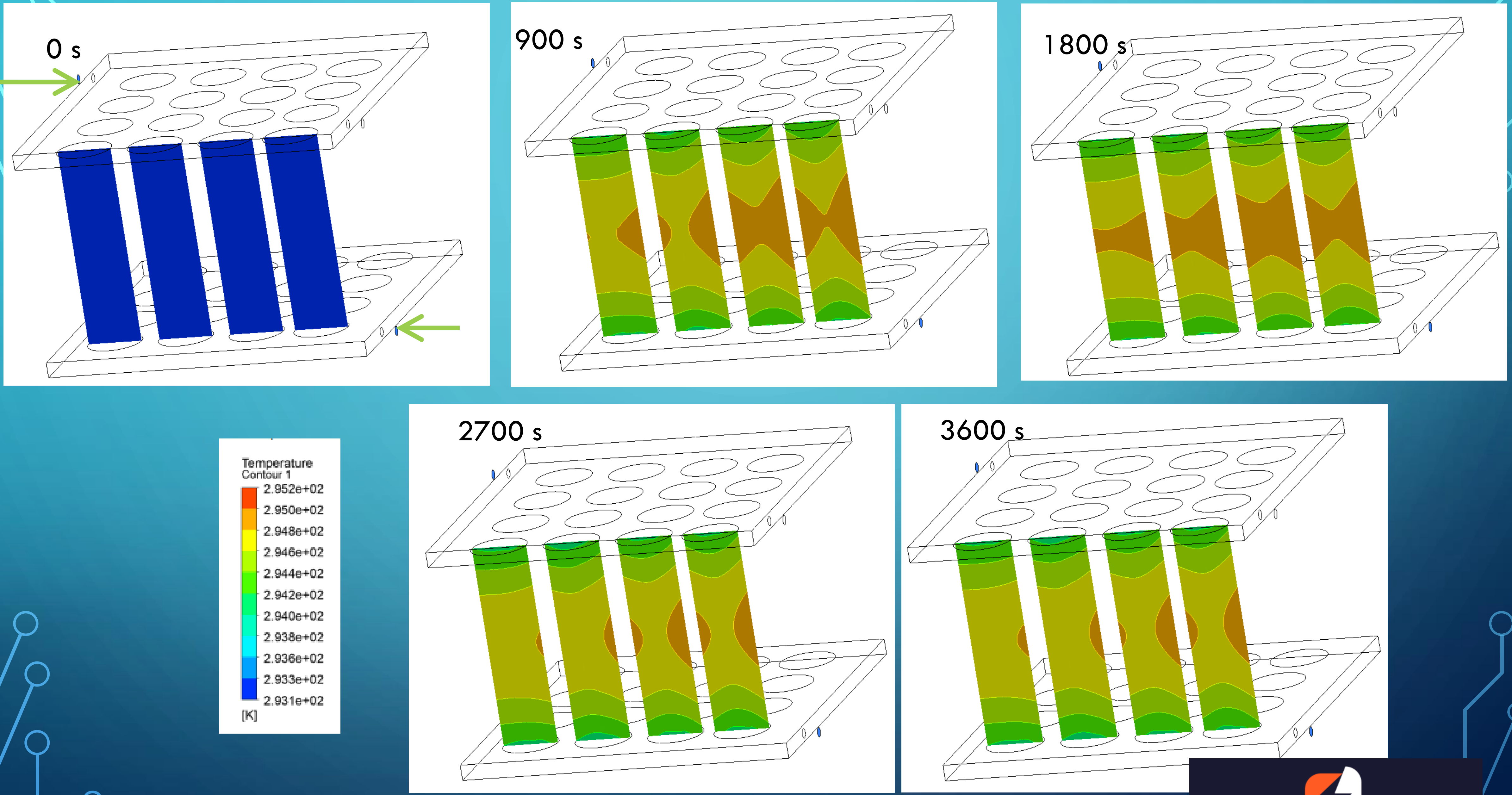

CFD simulations performed by Dr. Ankur Jain from the University of Texas at Arlington using ANSYS

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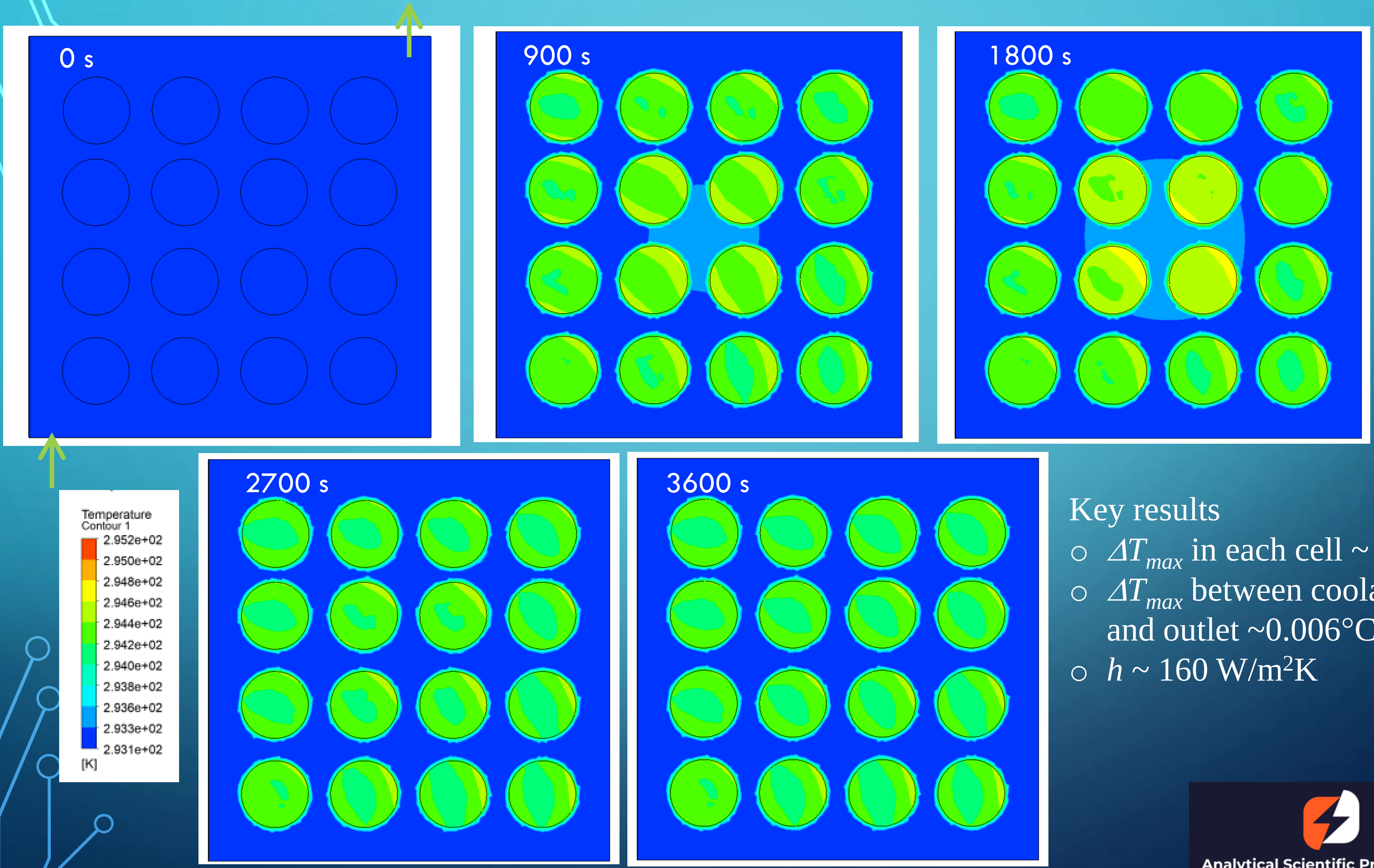

Key results

- ΔT_{max} in each cell ~ 1°C
- ΔT_{max} between coolant inlet and outlet ~0.006°C
- h ~ 160 W/m^{2}K

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2. THERMAL RUNAWAY DETECTION

- Detection is based on sensing cell overheat above the normal operating range
- Detection occurs passively via mechanical processes – does not depend on battery power and remains functional even when the battery is not in use
- Detection is independent of cell design/chemistry and failure trigger
- Provides early detection of both the occurrence of overheat as well as the location of hot cell
- Detection can be used to
  - Alert the operator
  - Electrically isolate the failed cell module from the rest of the battery pack
  - Start or increase coolant flow to the failed module to potentially avert failure
  - Remove stranded energy from the failed module
  - Collect data for analytics

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3. THERMAL RUNAWAY PREVENTION

- Our TR prevention concept is based on “Direct Contact Boiling Heat Transfer”
- When a cell overheats significantly, our technology passively discharges the coolant from the liquid channels used for TMS on the surface of the hot cell to quench it
  - Direct contact of coolant with the hot cell increases heat transfer rate (compared to the indirect contact heat transfer across the channel wall)
  - When the cold liquid contacts the superheated cell, local boiling occurs increasing the *h* by several orders of magnitude
  - Boiling heat flux between a hot surface and “stagnant” liquid is can be calculated using Rohsenow’s correlation [J.P. Holman, *Heat Transfer*, Seventh Edition, McGraw Hill Publishers, 1990]

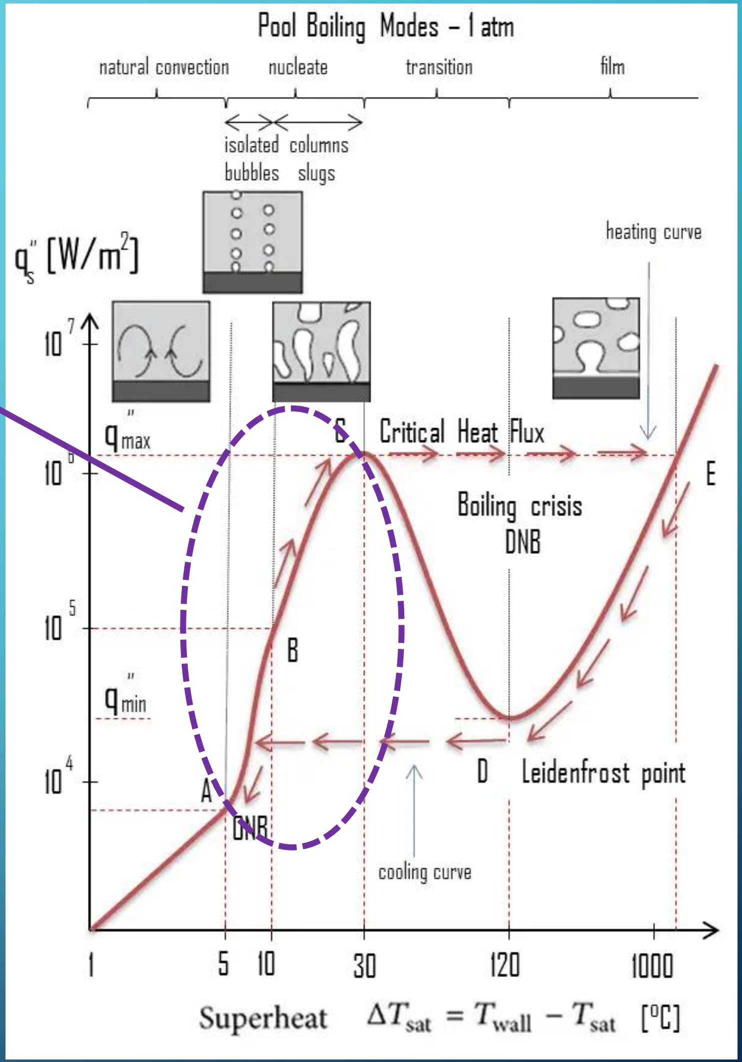
$$\frac{q}{A} = \mu_L h_{vap} \left(\frac{C_p (T_{cell} - T_{BP})}{h_{vap}\, Pr_L^s\, C_{sf}} \right)^3 \sqrt{\frac{g(\rho_L - \rho_v)}{\sigma}}$$

  - This expression yields *h* of 140,000 W/m^{2}K for a T_{cell} of 125°C: heat transfer is ~875× faster than the liquid based TMS
  - Our activation mechanism discharges the liquid at high speed on the cell which increases the *h* even further

BOILING HEAT TRANSFER

- T_{cell} < ~107°C: h is low (natural convection driven)
- **107°C < T_{cell} < ~130°C: h increases exponentially with ΔT (nucleate boiling)**
- 130°C < T_{cell} < ~220°C: h decreases with ΔT (transition regime)
- T_{cell} >~220°C: h increases exponentially with ΔT (film boiling)
- Our concept harnesses the extremely high heat transfer flux ($10^4 – 10^6$ W/m^2) within the nucleate boiling regime to rapidly quench the overheated cell and prevent TR

Region of Interest



Source: https://www.nuclear-power.com/nuclear-engineering/heat-transfer/boiling-and-condensation/boiling-heat-transfer/

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ABILITY TO REMOVE ENERGY RELEASED DURING TR

Calculated the amount of coolant by equating the heat release from TR to the sensible + latent heat gain by the coolant assuming perfect thermal contact. We neglected the sensible heat gain by the vapor.

Cell Size	Cumulative Energy (kJ/cell)	Coolant Needed to Remove Energy Released During TR (mL)*	No. of Cells Undergoing TR That Can Be Cooled With a Gallon of Coolant#
18650	36	13.7	276
21700	53	20.3	187
26650	42	16.2	233
4680	351	135.3	28

* In reality, we need to remove only ~85% of the energy to cool the failed cell adequately to prevent TR propagation
# EV battery packs that rely on liquid coolant for TMS typically use 3 gallons of coolant

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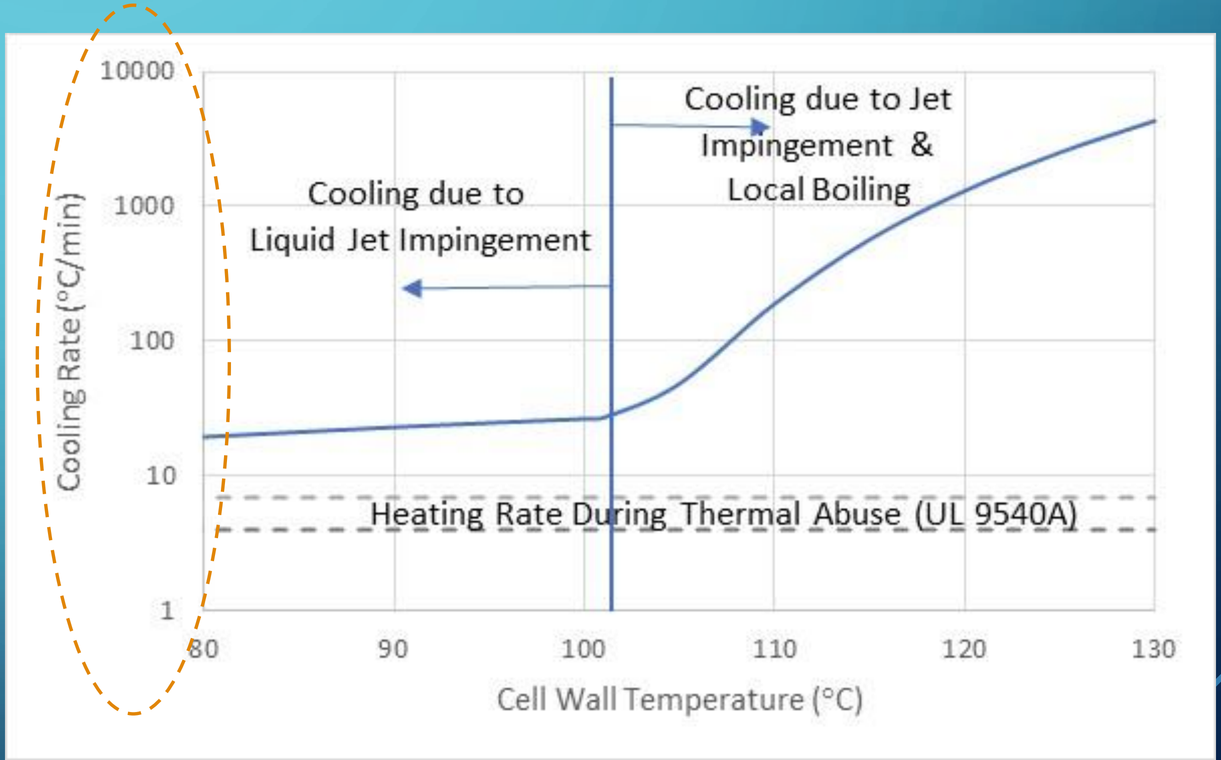
COOLING RATE PROVIDED BY LIQUID IMPINGEMENT ON HOT CELL: COMPUTED

- 18650 cell heated to different *T* before the start of liquid coolant discharge
- T_{cell} < ~105°C: heat transfer is governed by liquid impingement
- T_{cell} >~105°C: heat transfer is governed by nucleate boiling
- Cooling rate increases significantly as T_{cell} increases: timely coolant discharge prevents TR
- Cooling rate with our technology is much faster than the heating rate required by the UL 9540A: Battery packs equipped with our technology should easily satisfy the thermal abuse standard



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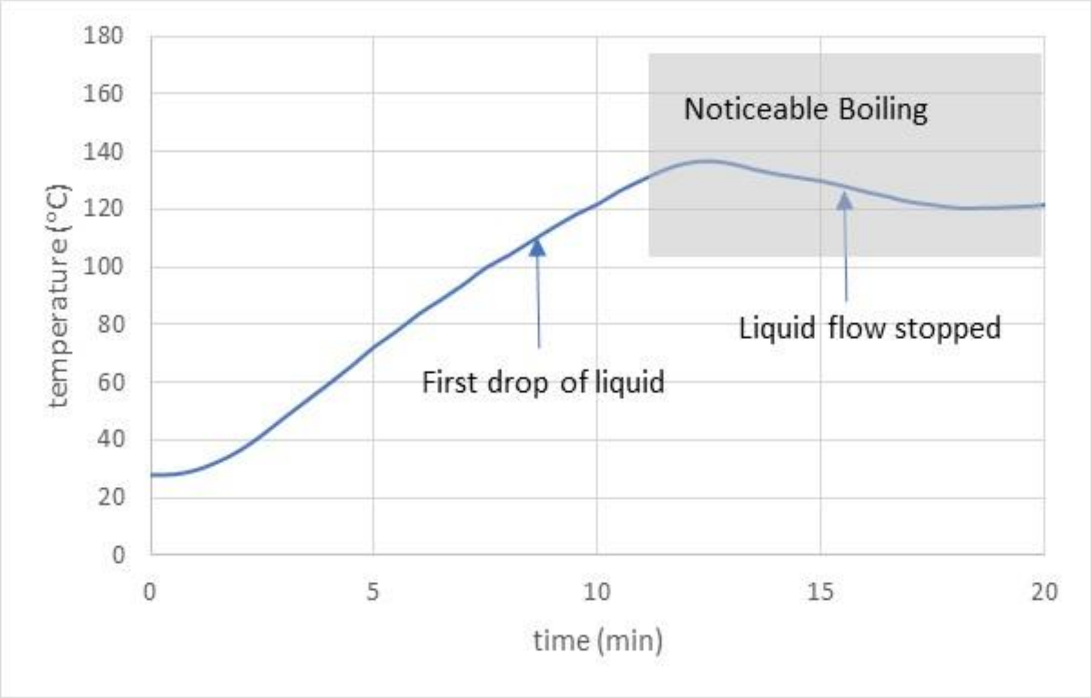
COOLING RATE PROVIDED BY LIQUID DISCHARGE ON HOT CELL: DATA FROM PRELIMINARY TESTS

- Constructed a 16-cell battery pack with 18650 cells equipped with TR detection & prevention system. One cell is heated at ~11.3°C/min
- Measured T_{cell} with a thermocouple located away from the wetted region
- Passive discharge of coolant started at T_{cell} ~108°C
- Observed a cooling rate of 13.7°C/min that caused the cell to reach a T_{peak} of 132°C. We noticed significant nucleate boiling at T_{cell} of ~125°C.
- Our "test" system quenched the overheated cell. Improvements are underway to further increase the heat transfer rate by:
  - Increasing the pressure in liquid line
  - Increasing the amount of liquid available to cool the cell
  - Providing confinement for the coolant to ensure that it does not disperse away from the hot cell module



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4. TR PROPAGATION PREVENTION

- Coolant discharge directed towards the failing cell prevents TR in that cell
- If the trigger cell somehow manages to still reach TR, the coolant prevents TR propagation to the neighboring cells
    - It cools the trigger cell reducing its peak temperature and radiative heat flux. For example, lowering the T_{peak} from 800°C to 500°C reduces the radiative heat flux from the cell by 75%
    - The liquid acts as radiative barrier to reduce the heat transfer from the trigger cell to the nearby cells
    - Splashing of liquid when it hits the trigger cell creates droplets that deposit on and preemptively cool nearby cells
    - Evaporation of the liquid dilutes any flammable gas released by the trigger cell reducing its flammability

IMPLEMENTATION STRATEGY

We envision three different implementation options for our technology depending on the TMS used currently in the battery pack

1. Battery pack currently has no TMS: our implementation consists of an integrated solution that provides thermal management, TR detection, TR prevention and fire propagation prevention
2. Battery pack currently has a liquid coolant based TMS: we can anchor our system to the existing TMS to provide TR detection, TR prevention and fire propagation prevention
3. Battery pack currently has an alternate TMS (like forced air, phase change material, etc.): integrate a liquid line into the battery pack to provide TR detection, TR prevention and fire propagation prevention

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UNIQUENESS OF ASP TECHNOLOGY

- Non-intrusive to cells since all components are external to the cells: chemistry & cell-agnostic
- Early TR detection without sensors, monitoring and reliance on battery power
- Prevention of TR in trigger cell due to various types of failures
- Prevention of TR propagation to the rest of the pack

PASSIVE

- Isolation of hot cell module during failure
  - Prevents electrical propagation of failure
  - Ensures that the rest of the battery pack functions normally
- Low size, weight, power consumption and cost (SWAP-C)
- Ability to customize the implementation depending on battery system design and needs

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POTENTIAL APPLICATIONS

- Our technology can improve the performance, cycle life and safety of Li ion batteries used in any application
- Example applications include
  - Air transport: eVTOL, aircraft, drones
  - Ground transport: Electric Vehicles, Electric Trucks and Electric Buses
  - eMobility systems: Ebikes and scooters
  - Battery Energy Storage Systems (BESS) for residential applications and power grids
  - Power tools
  - Medical devices

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