ENGINEERING AND SCIENTIFIC CONSULTING

Exponent®

Prepared for:

NAATBatt 14th Annual Meeting & Conference

February 20th – 23rd

Litchfield Park , Arizona

Sergio Mendoza, Ph.D.
Manager
508-654-8196
smendoza@exponent.com

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Resolve your toughest problems, move forward

HOLISTIC FAILURE ANALYSIS, BEYOND STANDARD TECHNIQUES

SPECIALIZING IN NOVEL FAILURES PRODUCED BY NEW TECHNOLOGIES

INFORMING FUTURE DIRECTIONS FROM TODAY'S FAILURES

Exponent®

Polymers & Biomedical
- Biomedical Engineering
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Environmental Sciences
- Ecological & Biological Sciences
- Environmental & Earth Sciences

Mechanical & Thermal
- Thermal Sciences
- Mechanical Engineering

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- Human Factors
- Vehicle Engineering

Infrastructure & Materials
- Buildings and Structures
- Civil Engineering
- Construction Consulting
- Material & Corrosion

Electrical & Data Sciences
- Electrical Engineering & Computer Science
- Statistics & Data Sciences

- ❖ 90+ science and engineering disciplines
- ❖ 900+ consultants
- ❖ Global reach

Battery Work Across Product Lifecycle

- **Design review**
  - FMEA's for design, manufacturing, and product
  - Fault tree analysis
- **Qualify prototype batteries**
  - Standardized tests (e.g. UL 1642)
  - Factory audit(s)
  - Cell qualification

- **Monitor product quality during all stages of ramp**
  - Periodic battery quality checks
  - Periodic factory audits
- **Functional testing and analysis**
  - Study long term effects of functional tests on passing units
- **Failure analysis**
  - Analyze units which fail quality or reliability testing

- **Reliability studies with finalized product**
  - Subject cells to reasonable but severe stresses and long term cycling
- **Initial field data analysis**
- **Perform effects analysis**
  - Update DFMEA and PFMEA documents when new failure modes are discovered

- **Continue to monitor battery production**
  - Periodic follow up audits
  - Periodic quality and reliability assessments
- **Analyze RMA units**
  - Failure analysis of units which experienced battery related complaints

- **Update internal processes & protocols**
  - Incorporate lessons learned
  - Account for problems observed during ramp, failures from the field, and any other field use data collected

Lithium-ion cell failure ranges from benign performance degradation to catastrophic evolution of heat

Thermal Event

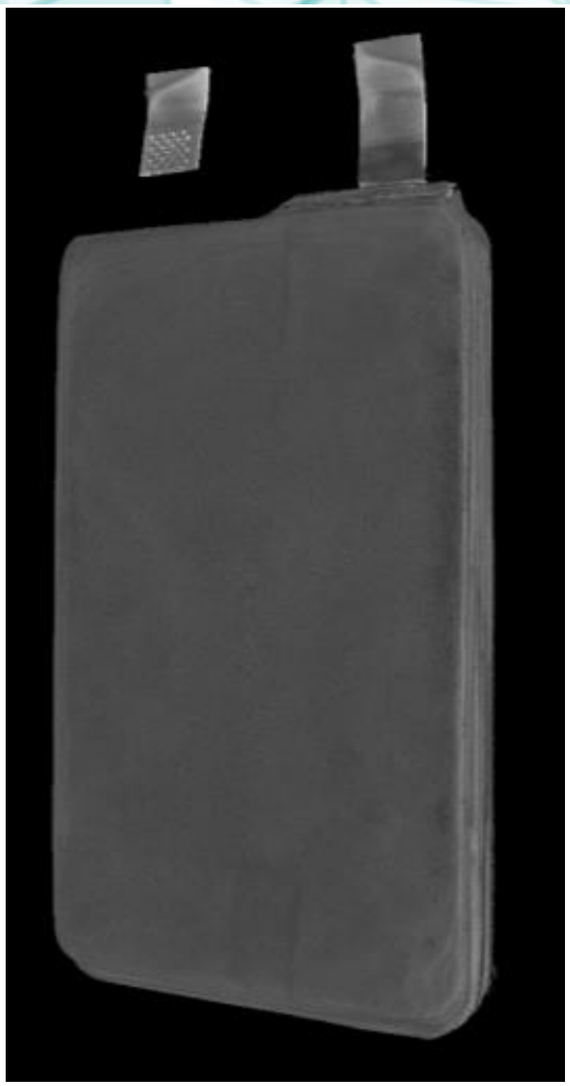
Cell Swelling

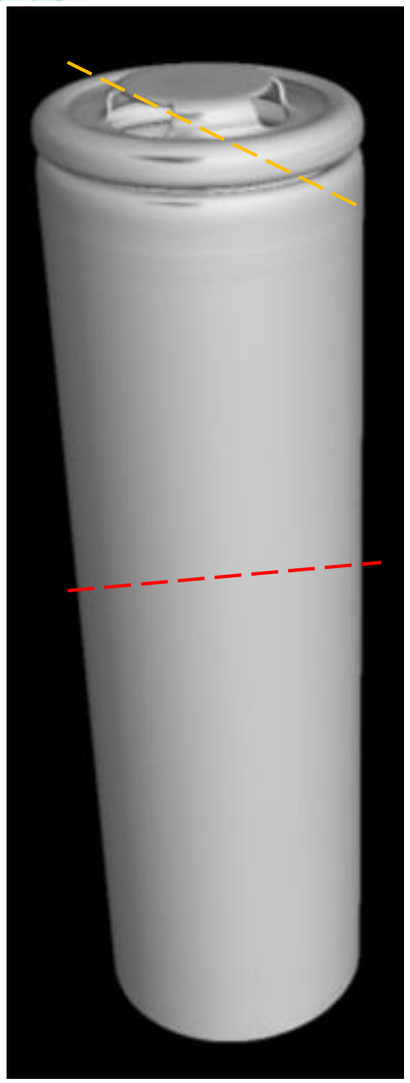
Impedance Increase

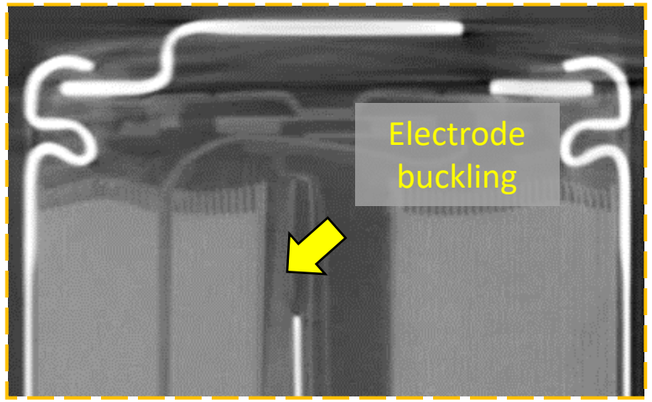
Capacity Fade

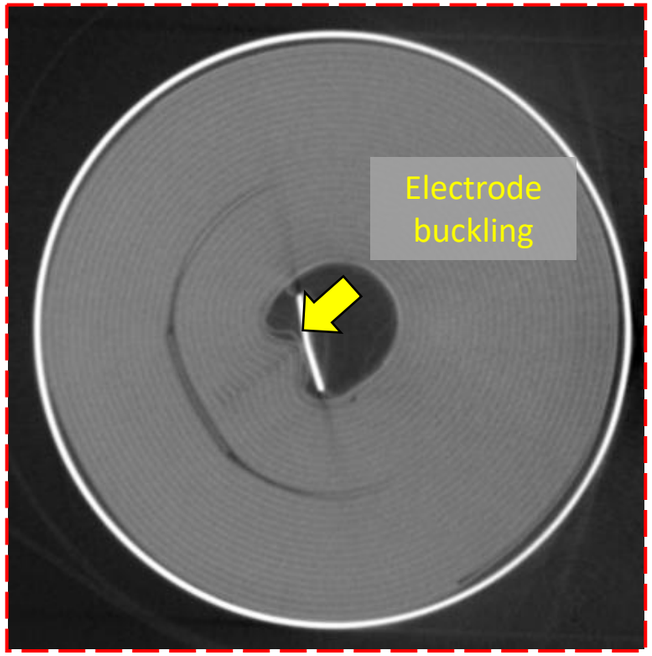
Won’t charge

Non-Destructive Battery Cell Evaluation





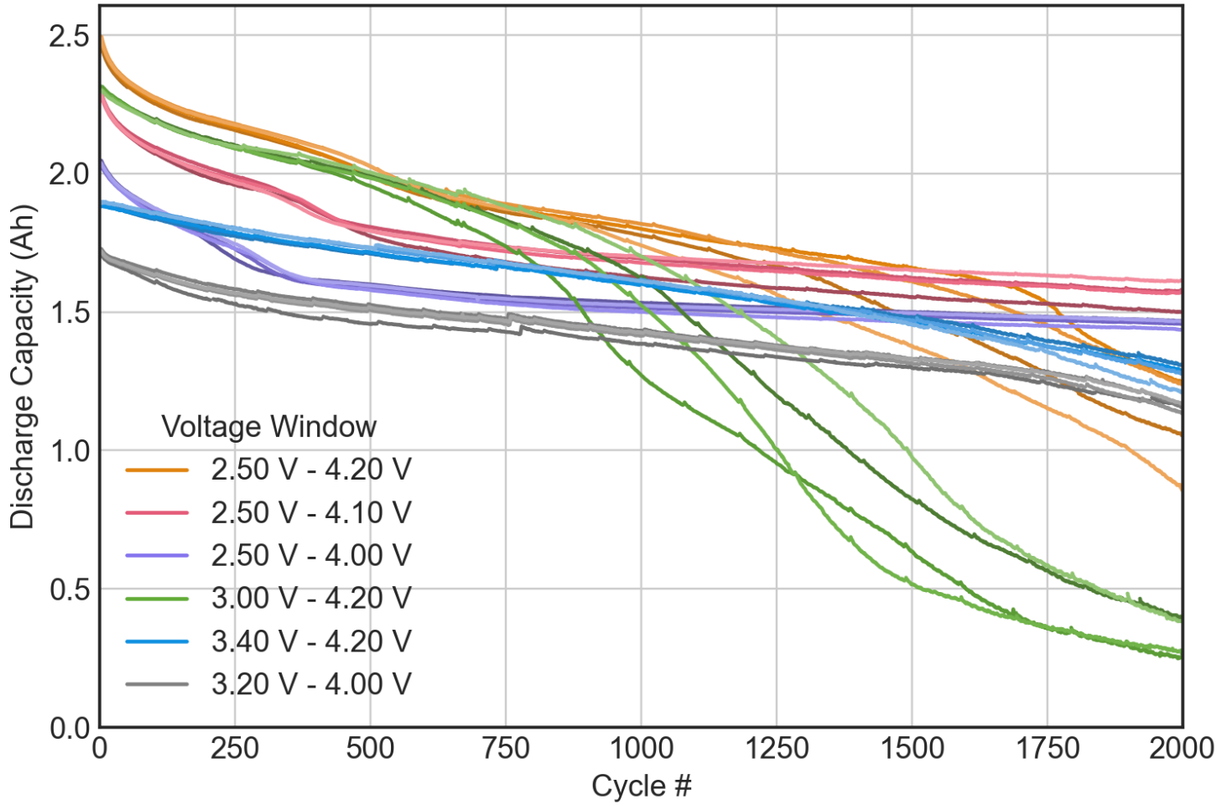


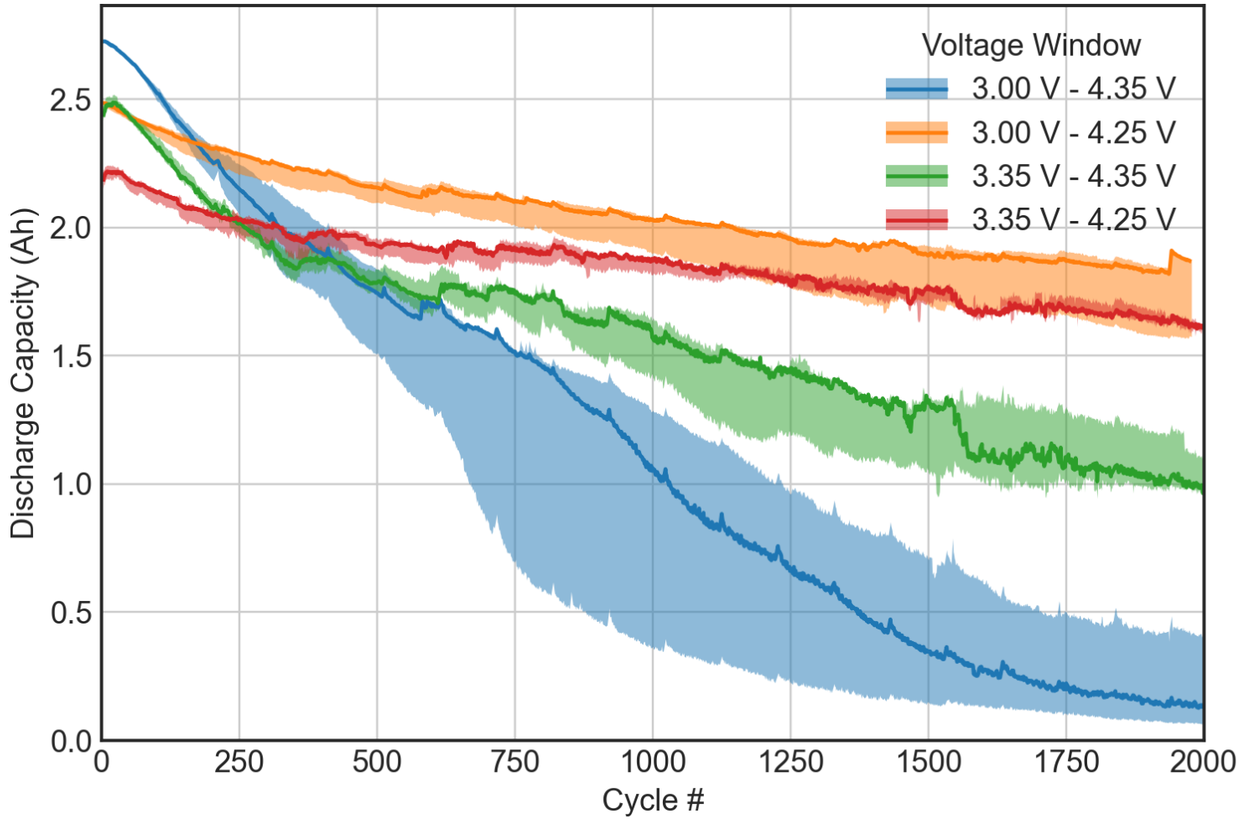


CT analysis allows for non-destructive evaluation of cell construction and quality

Electrochemical Characterization

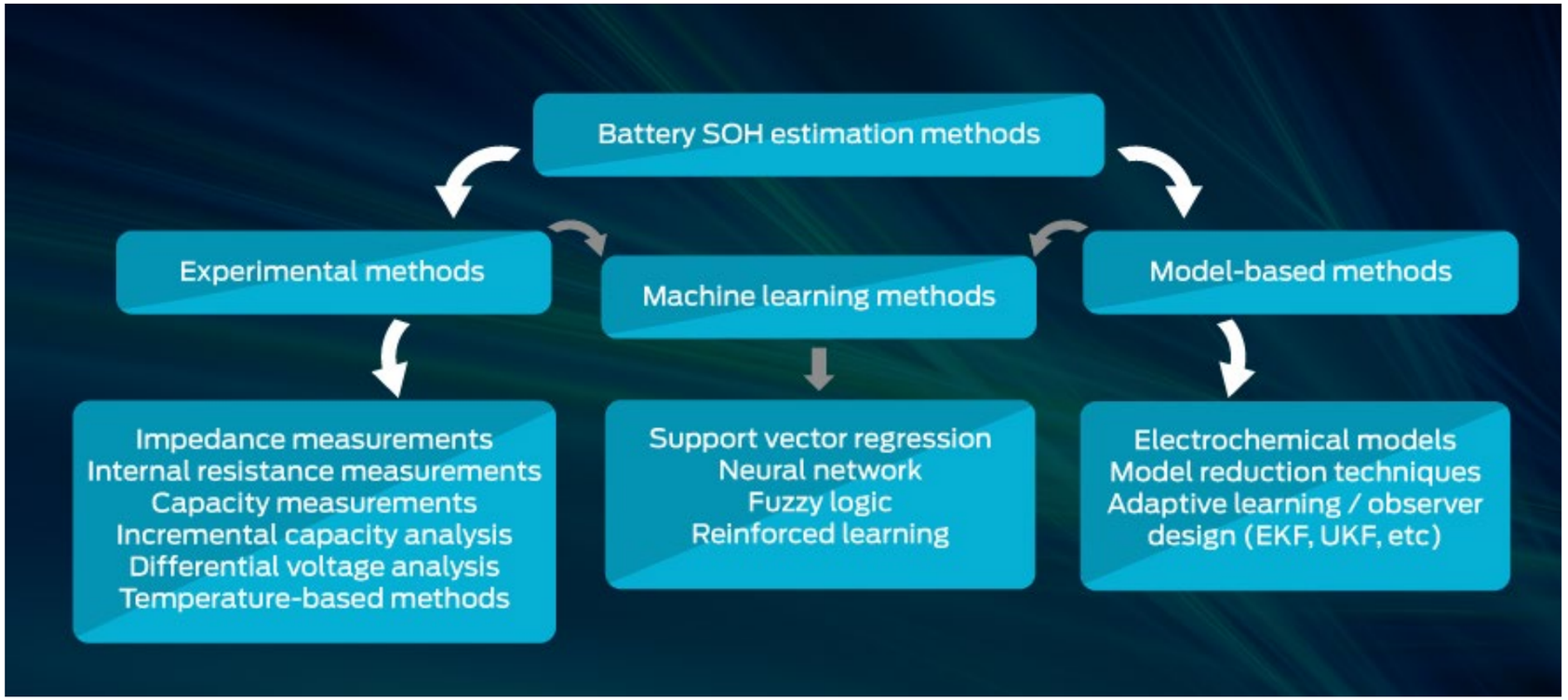
Battery performance and safety varies with voltage, current, temperature and cycle count. Different battery chemistries also perform differently through their lifetime.





State of Health (SOH) Estimation and Modeling

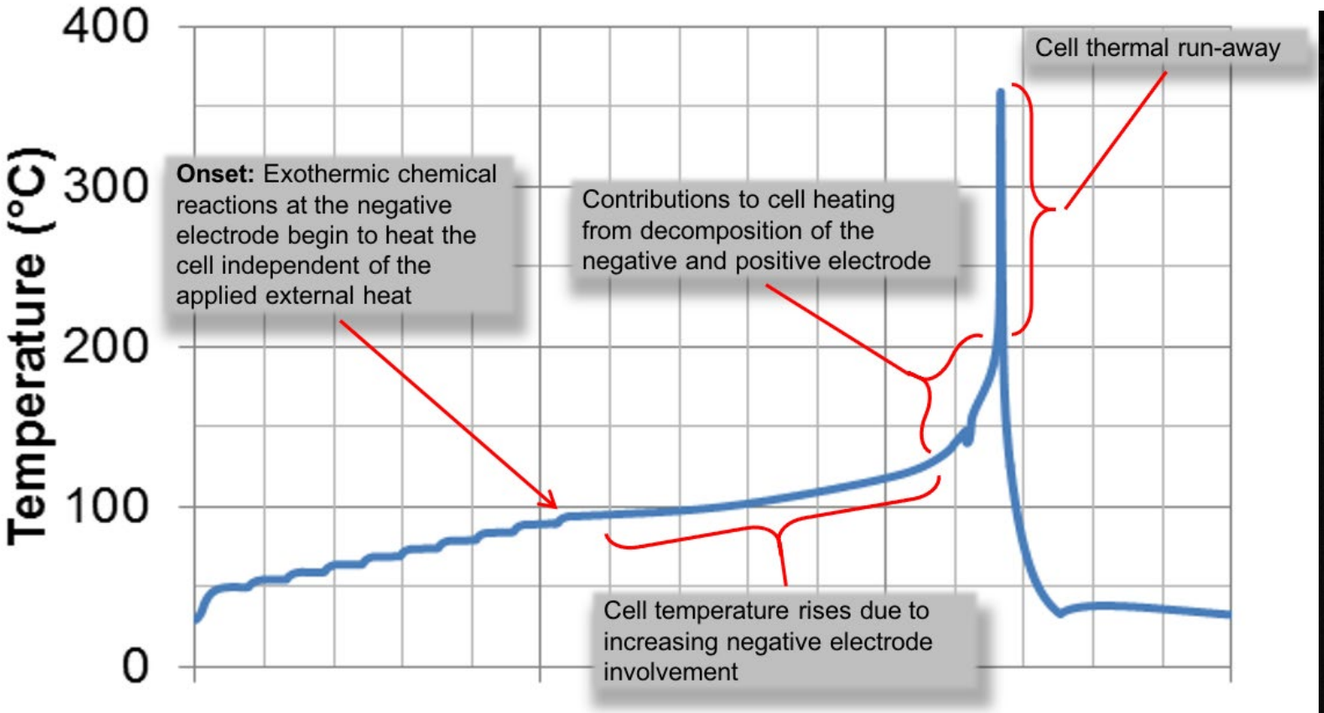
General SOH and cell modeling theories, techniques, and relationships

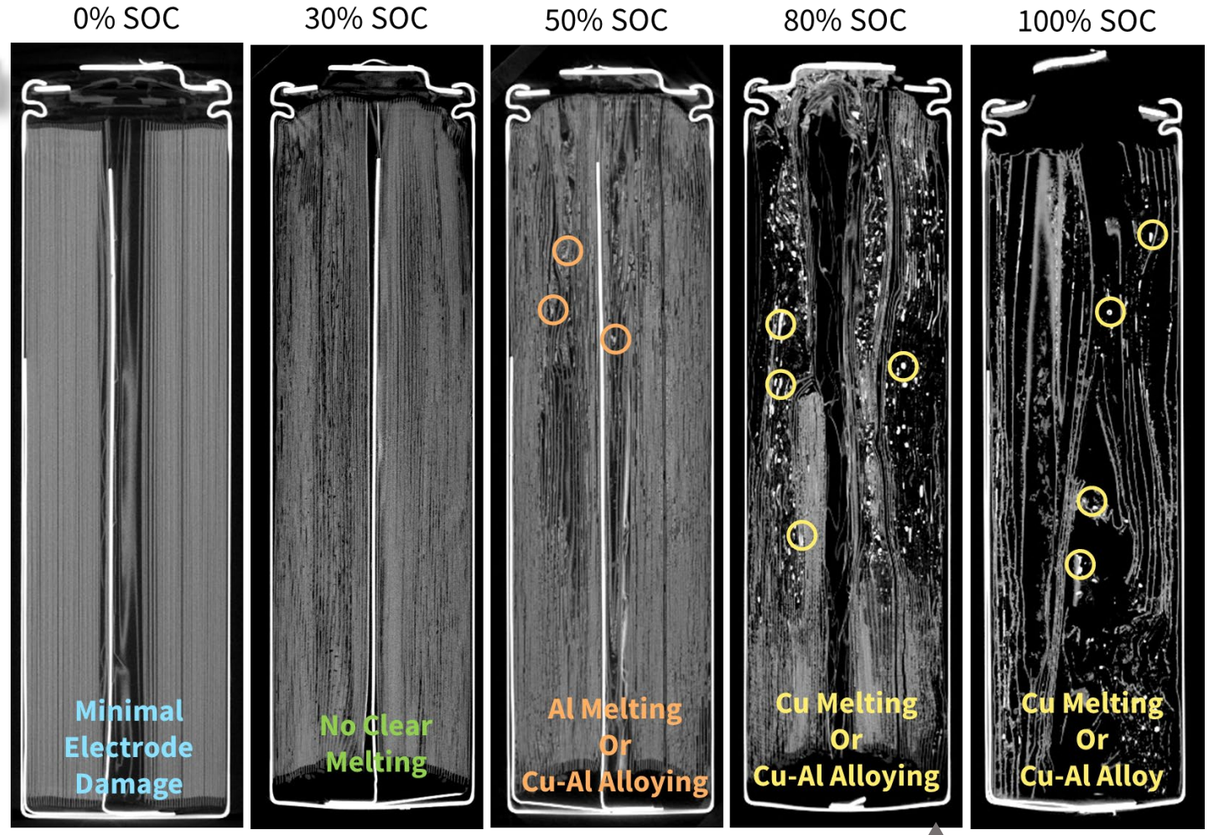


SOH can be used for individual cell analysis or fed into larger modeling and simulation tools for population analysis

Thermal Characterization

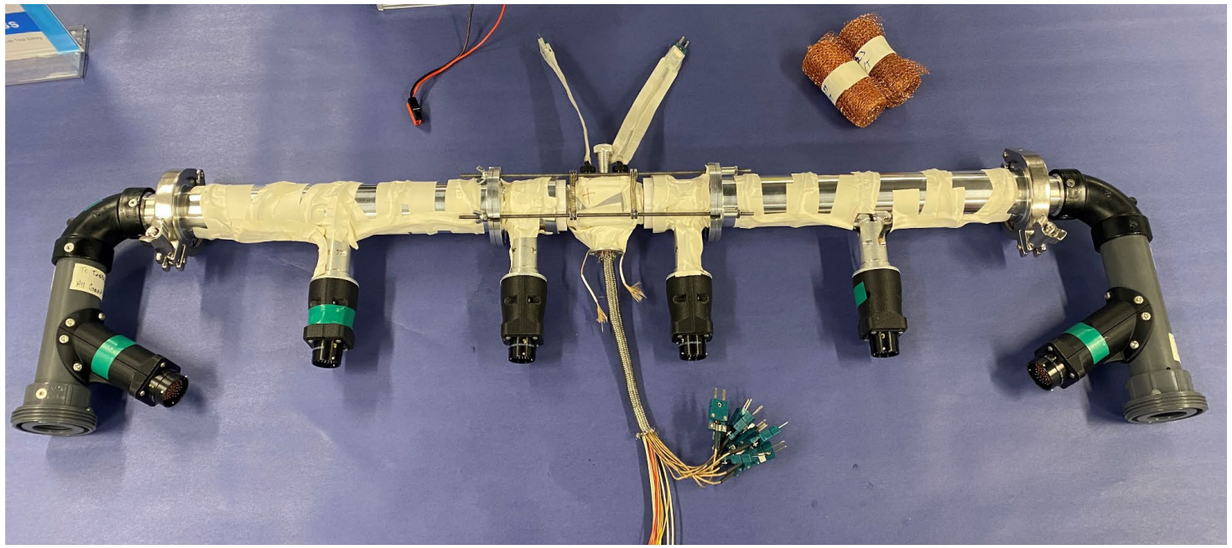
Five Different Cells Were Tested

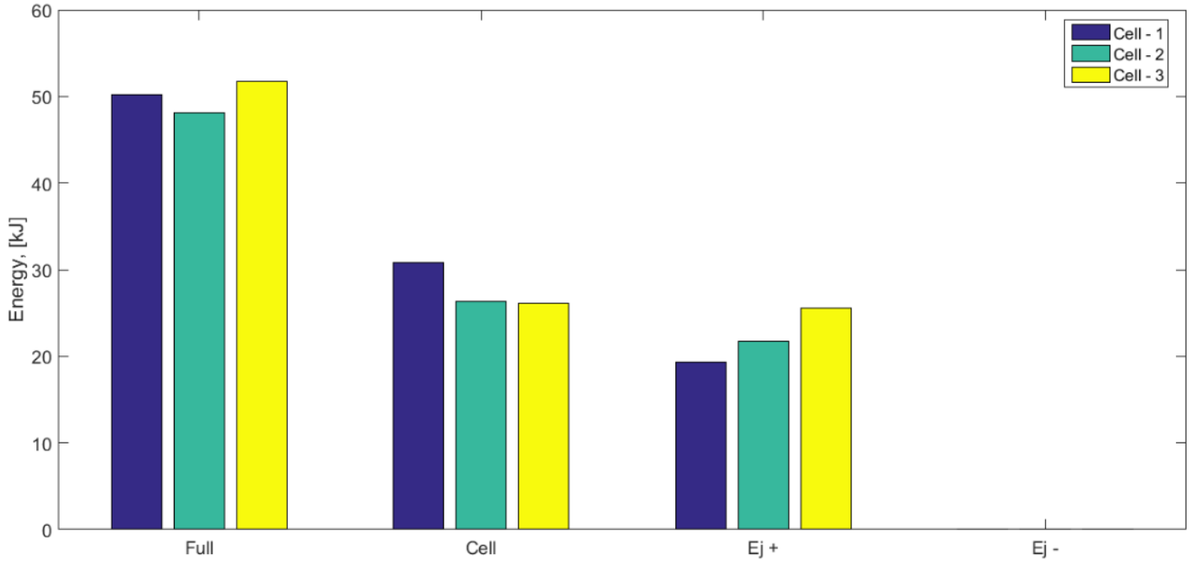




Self-heating rate as a function of temperature and post-thermal-runaway CT cross-sections for cells with different SOCs

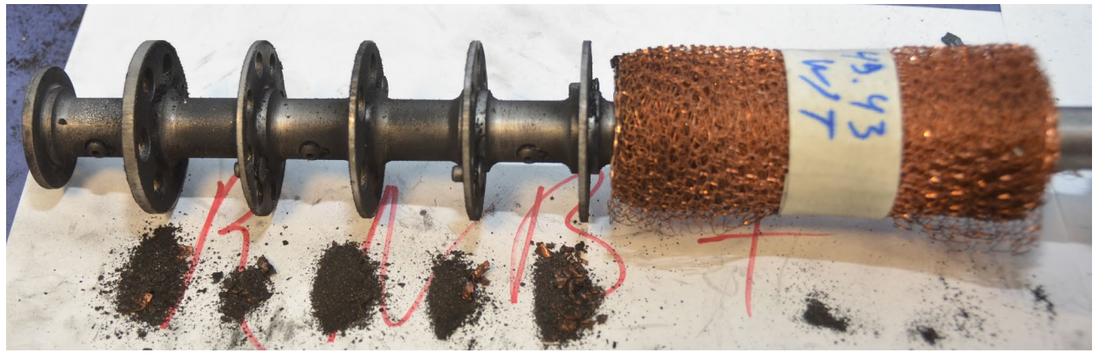
2.6 Ah 18650 Data from Exponent's FTRC





Ejecta - enclosure

Rod and baffle and copper mesh



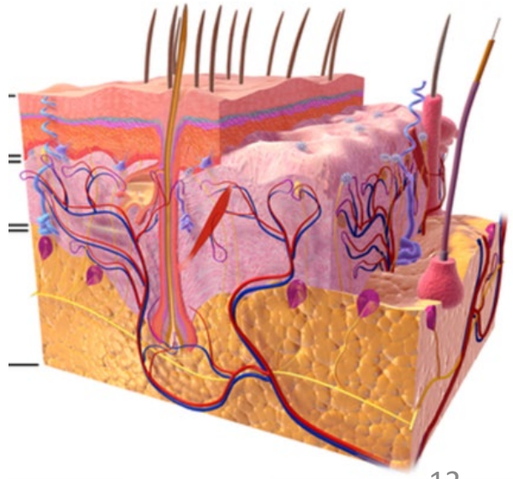
- Exponent's FTRC comprises hundreds of individual components.
- All component masses and heat capacities are quantified.
- Ejecta and debris deposited within each calorimeter subassembly are collected and weighed to determine the contribution to the total energy of the system

Thermal Characterization, Modeling and Control

- Consumer electronics safety requirements demand the characterization of touch temperature limits for safe operations.
  - The current regulatory framework has limited applicability for long term and non-contact exposure scenarios.
- The proposed model-based methods can be used to determine thermal damage criteria through the following steps:
  - Determination of the time-temperature exposure of the tissue.
  - Determination of tissue-specific injurious conditions.
  - Statistical assessment of the variability associated with the expected population of users.

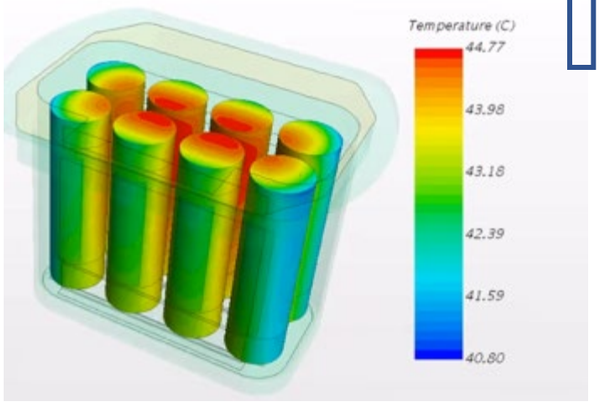
- Exponent has experience helping clients assessing the risk of tissue thermal damage associated with various products.
- Exponent performed several assessments including but not limited to:
  - Short term/long term exposures
  - Thermal interaction with complex tissue structures (i.e. ocular tissues)
  - Multitude of devices (phones, VR goggles, ear buds, etc.)

Skin Layer Structure

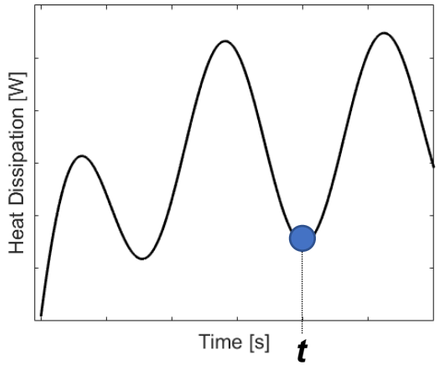


Reduced Order Models – Workflow

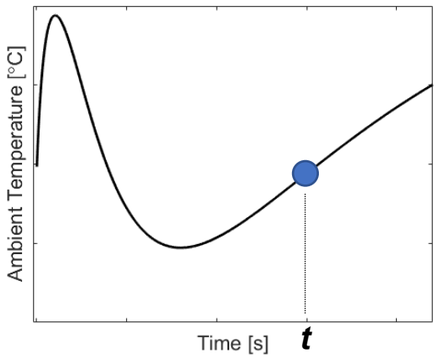
Pack geometry



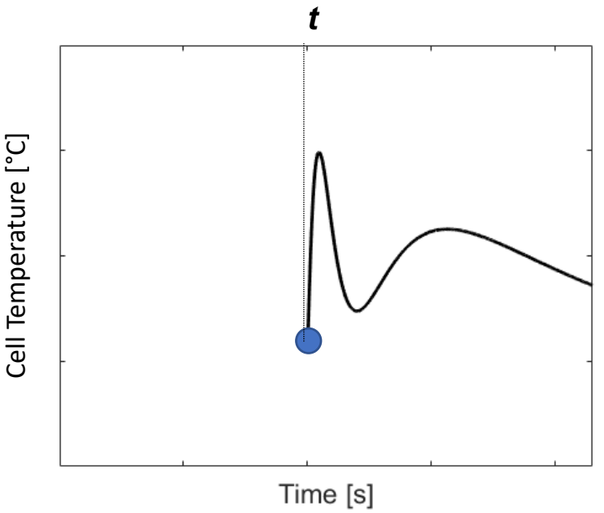
Reduced Order Models



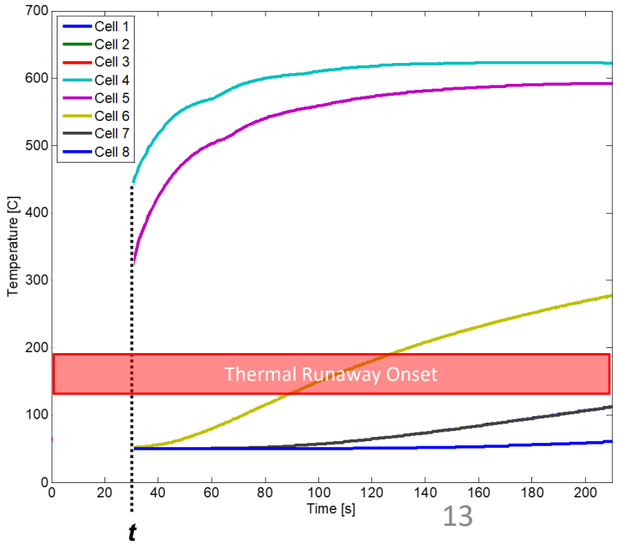
Control Algorithm



Normal Operation Example



Upset Conditions Example



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