Thermal Runaway Risks for Li-ion Batteries in Energy Storage Systems

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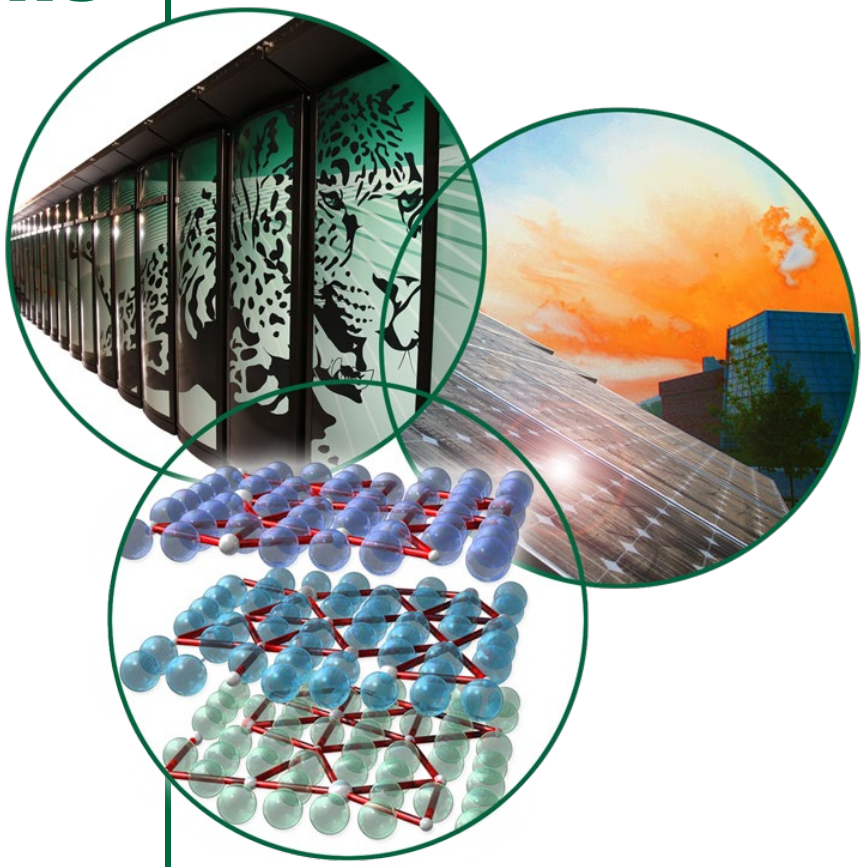

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U.S. DEPARTMENT OF ENERGY

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MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Project Overview

- To develop a Li-ion battery thermal runaway risk database for energy storage systems
- It is important to understand and manage the safety risks of Li-ion batteries in energy storage systems, especially for thermal runaway
- This work fits specifically into OE efforts to ensure a resilient, reliable, and flexible electricity system

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Project Team

- **Project Lead: Oak Ridge National Laboratory**
  - **Hsin Wang, Srikanth Allu and X. Zhu (battery testing, modeling and database development)**
- **University of Tennessee:**
  - **Prof. Yanfei Gao and Xue Wang (thermomechanical modeling)**
- **Sandia National Laboratory**
  - **Loraine Torres-Castro, June Stanley, Eric J. Deichmann and Joshua Lamb (large format battery testing)**

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Project Objectives

1. Develop a simple indentation-based test protocol to induce internal short circuit in Li-ion cells
2. Analyze cells responses and other parameters to assign a thermal runaway risk score and rank the cells in terms of risks
3. Utilize machine learning (ML) to identify the most sensitive parameters for thermal runaway
4. <u>Ultimate goal:</u> A user can perform a single indentation test at low a SOC and use the database and ML tools to correctly rank the cell for thermal runaway risk

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Project Metrics and Milestones

- The 3-year project started in July 2018
- The performance metrics are test standard developed, number of Li-ion cells tested, data analysis software, papers and reports generated
- Major Milestones:
  1. Development of test protocol with Sandia - completed December 2018
  2. Testing of small Li-ion cells (0.5 Ah, 1.5 Ah and 2.0 Ah and over 60 tests) – completed April 2019
  3. Testing large format cells at ORNL and Sandia (25 Ah and 32 Ah cells) – on-going
  4. Database development and ML tools – on-going

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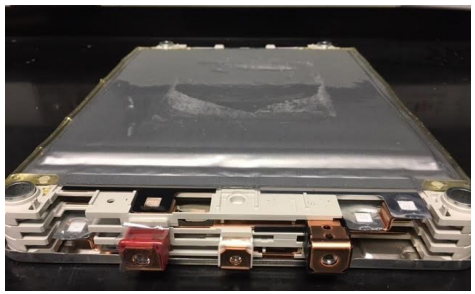
Project Challenges

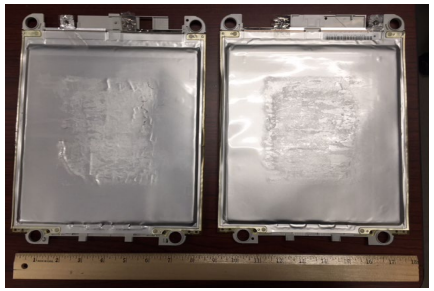
- Identify the most sensitive indentation tests
  - Joint protocol developed: 6 mm diameter indenter, 0.05 inch/min loading and 100 mV Voltage drop
- Certified Test Facilities for Thermal Runaway Tests:
  - Sandia cell safety testing facility utilized and ORNL test chamber for large format cells certified
- Sources for Li-ion batteries:
  - Commercially available Li-ion cells were purchased
  - Large format cells obtained from disassembled electric vehicle (EV) battery packs

Nissan Leaf Battery Pack

Battery Modules



Disassembled Module



Individual Cells (32 Ah)

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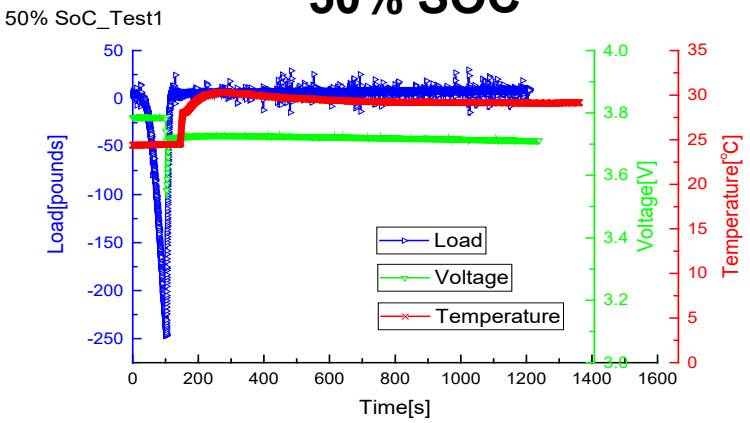
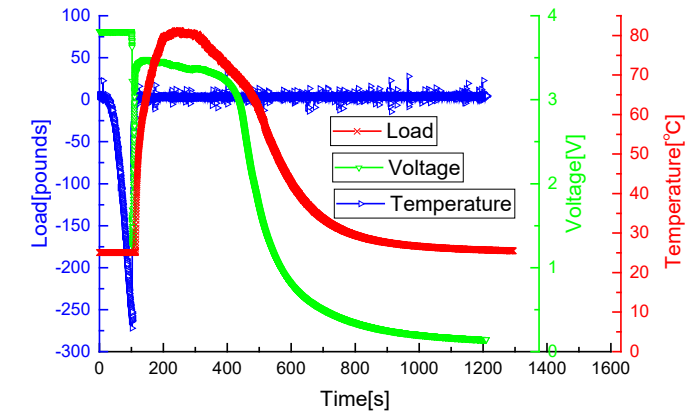
Project Results

Characteristic Responses from 500 mAh Li-ion Cells as Function of SOC

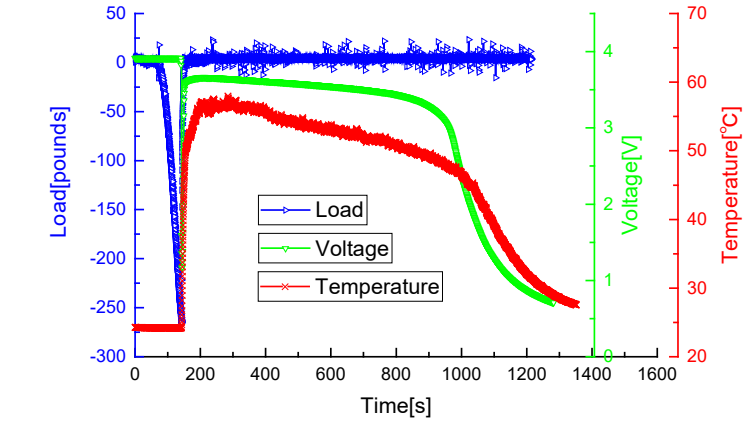
50% SOC



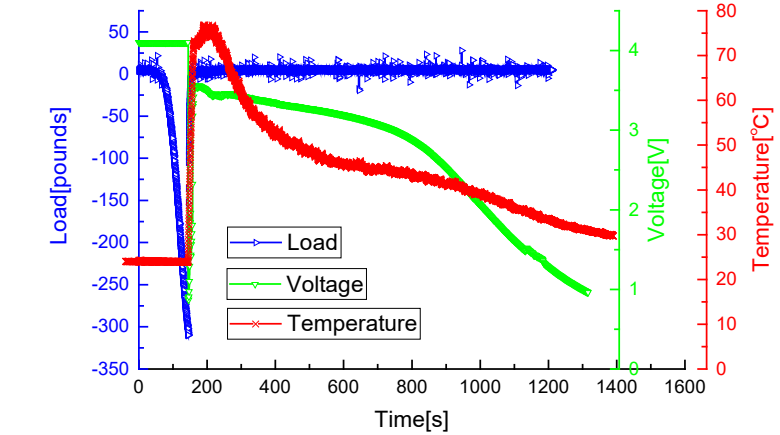
60% SOC



70% SOC



100% SOC



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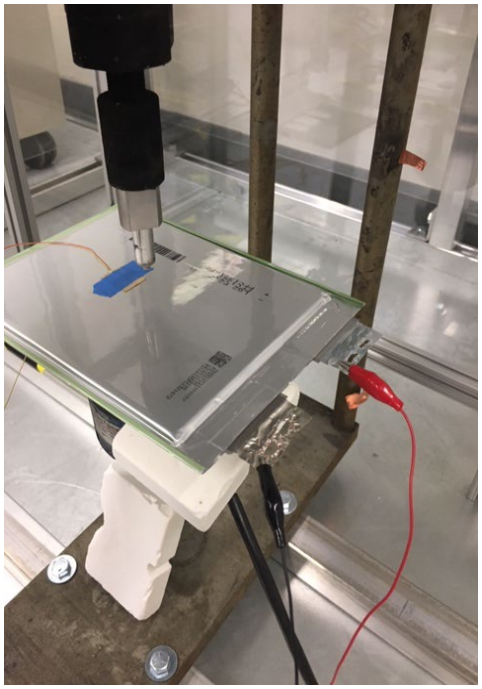
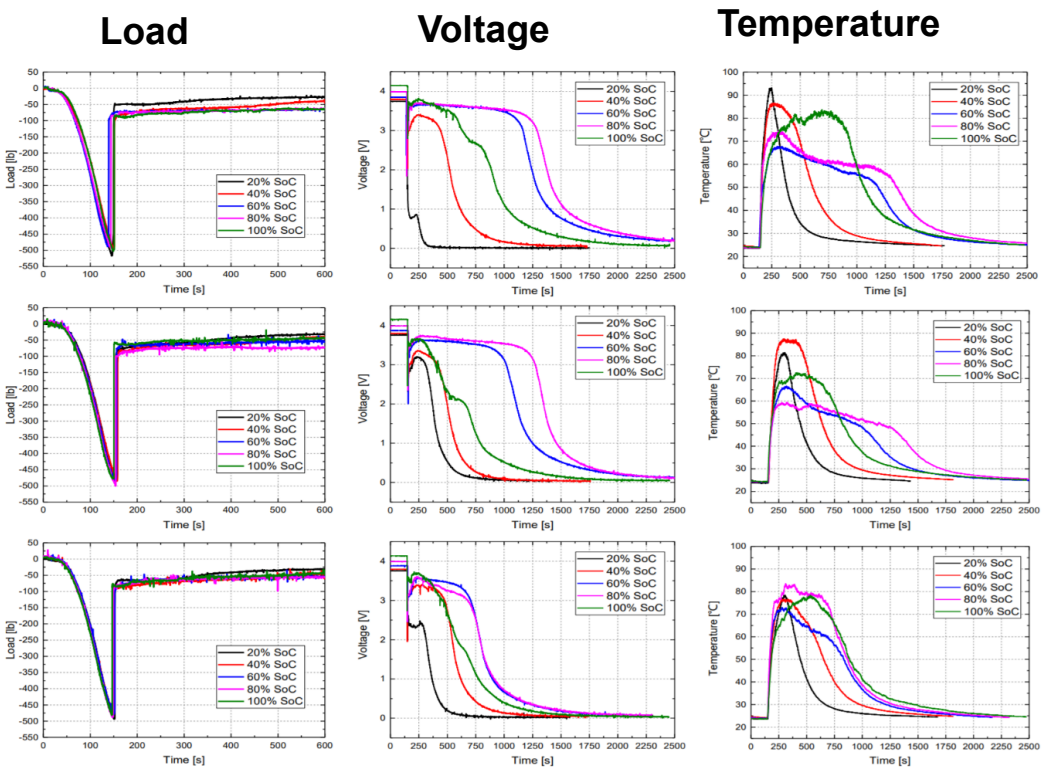
ORNL Efforts: Small and Large Cells Testing, Data Analysis

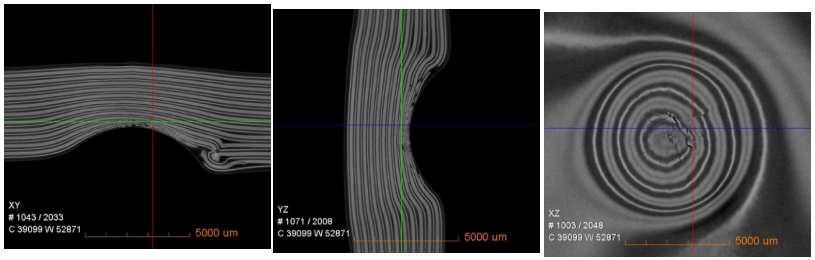


Nissan Leaf Cells Testing

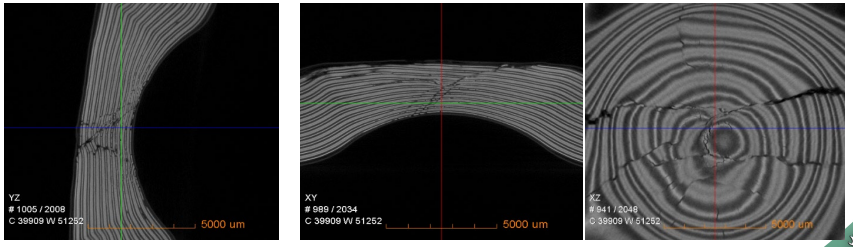


Capacity: 500 mAr, 1500 mAr, 2000 mAr; SOC: 20%, 40%, 60%, 80%, 100%

X-Ray Tomography
6mm Diameter Indenter



X-Ray Tomography
12 mm Diameter Indenter



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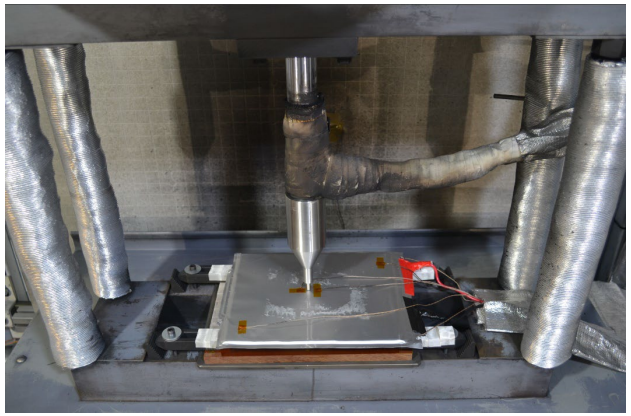
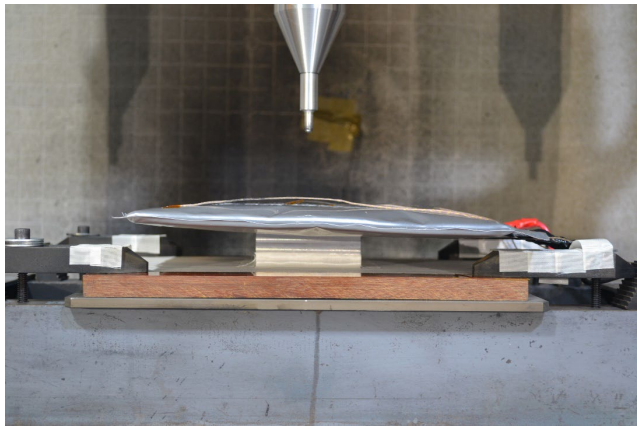
Sandia Efforts: Large Format Cells Testing, Data Analysis

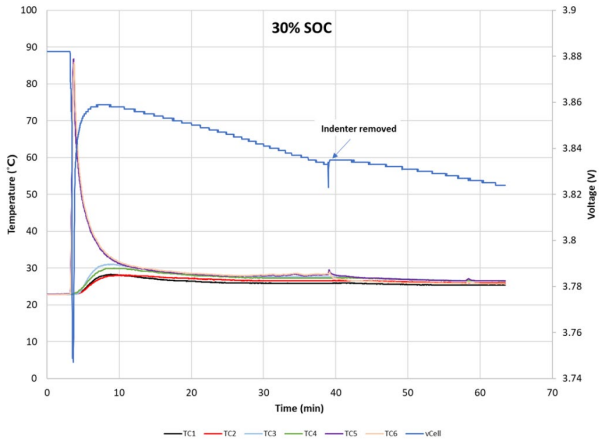
Nissan Leaf Cell in Sandia Test Chamber



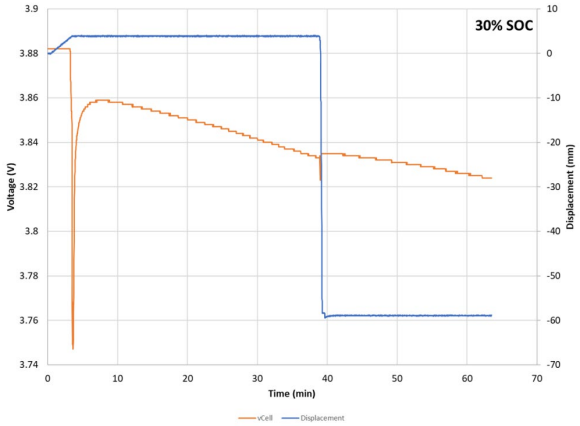
Nissan Leaf Cell After Indentation



Voltage and Temperature vs. Time



Voltage and Displacement vs. Time



Battery Tests at Various SOCs:

Sandia: 30%, 50%, 75%, 100%

ORNL: 20%, 40%, 60% 80%,100%

Sandia Poster: Wednesday, September 25

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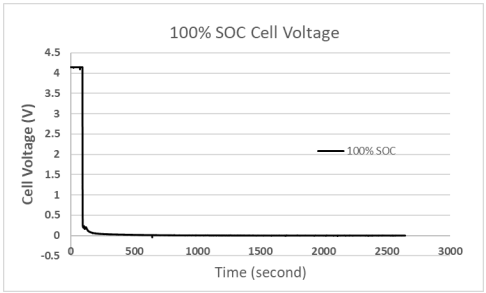
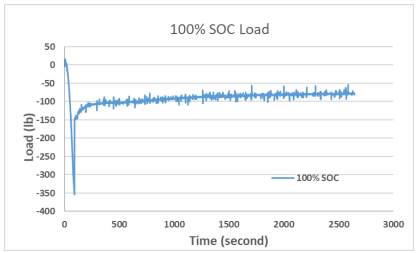
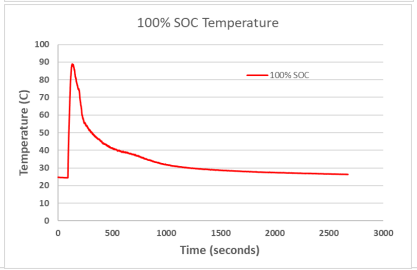
Data Analysis: Test Parameters and Results

Test Data

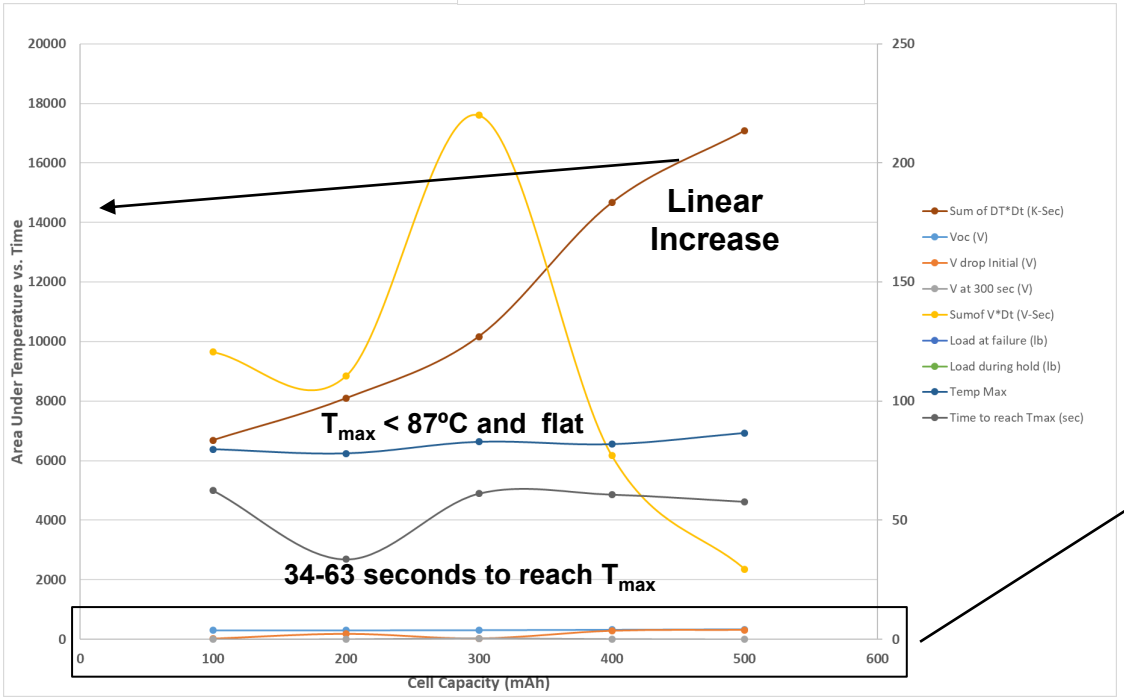


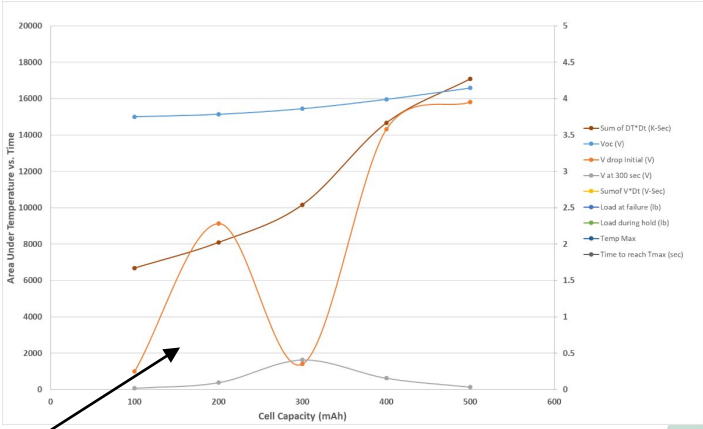




Sample test set of five 500 mAh cells

Cell Capacity (mAh)	500	500	500	500	500
SOC %	20%	40%	60%	80%	100%
Test Cell Capacity (mAh)	100	200	300	400	500
Voc (V)	3.75	3.784	3.861	3.991	4.147
V drop Initial (V)	0.25	2.284	0.351	3.581	3.955
V at 300 sec (V)	0.0183	0.095	0.407	0.15595	0.033569
Sumof V*Δt (V-Sec)	120.63	110.47	220.09	77.176	29.462
Load at failure (lb)	-338	-337.52	-345.7	-355.16	-353.82
Load during hold (lb)	-81.79	-88	-131.6	-170.04	-147.09
Temp Max	79.83	78.055	82.93	81.913	86.655
Sum of ΔT*Δt (K-Sec)	6685.3	8093.482	10168.27	14668.71	17089.57
Time to reach Tmax (sec)	62.57	33.6	61.2	60.8	57.8





Traditional data analysis:

- Plots
- Correlations
- Trends

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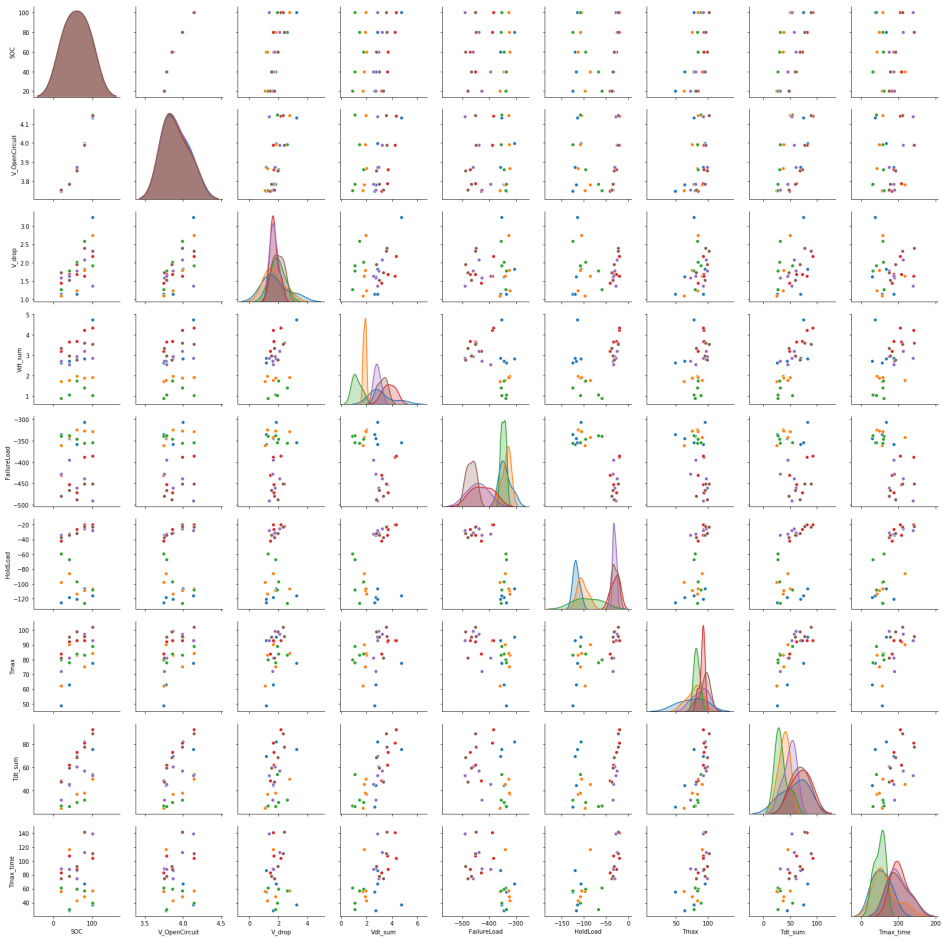
Data Set Processed From the Experiments

Machine Learning Data analysis



Test Data Table

SOC	TestedCapacity	V_OpenCircuit	V_drop	Vdt_sum	FailureLoad	HoldLoad	Tmax	Tdt_sum	Tmax_time
20	100	3.745728	1.147461	2.648559	-335.571680	-125.267985	48.749	26.3770	55.7
40	200	3.781433	1.621094	2.716705	-345.080566	-117.699707	63.111	44.5640	28.9
60	300	3.872986	1.150818	2.863648	-358.065820	-120.303061	92.944	69.6976	86.7
80	400	3.998108	1.834412	2.842712	-306.482666	-106.499088	95.381	82.2172	66.9
100	500	4.132080	3.233032	4.733307	-354.538330	-115.336545	77.753	75.3942	37.3
20	100	3.750610	1.092529	1.729156	-361.388818	-97.893185	62.223	25.2136	56.5
40	200	3.781128	1.636047	1.777618	-342.013184	-85.957838	90.343	45.6836	116.6
60	300	3.866882	1.236877	1.992035	-324.120117	-113.315894	83.152	36.9226	42.6
80	400	3.991394	1.799622	1.891968	-326.318408	-108.862092	75.258	38.3880	49.0
100	500	4.143677	2.741394	1.926453	-327.443115	-106.135606	84.331	50.1312	57.5
20	100	3.750916	1.278687	0.893341	-338.378906	-59.318439	79.900	27.0004	61.0
40	200	3.784485	1.784668	1.079346	-337.524414	-66.991820	78.071	26.6582	30.7
60	300	3.860779	2.014160	1.760529	-346.252441	-97.149743	83.985	30.2422	59.7
80	400	3.991089	2.581177	1.420196	-355.773926	-125.970826	82.976	32.0020	57.5
100	500	4.147034	1.920471	1.046448	-353.820801	-107.910288	88.944	54.2370	39.8

Example: ML Analysis Open Source Software

ML Data Analysis Features:

- Analyze parameters correlation
- Identify sensitive parameters
- Training data sets: test data
- Prediction and Ranking

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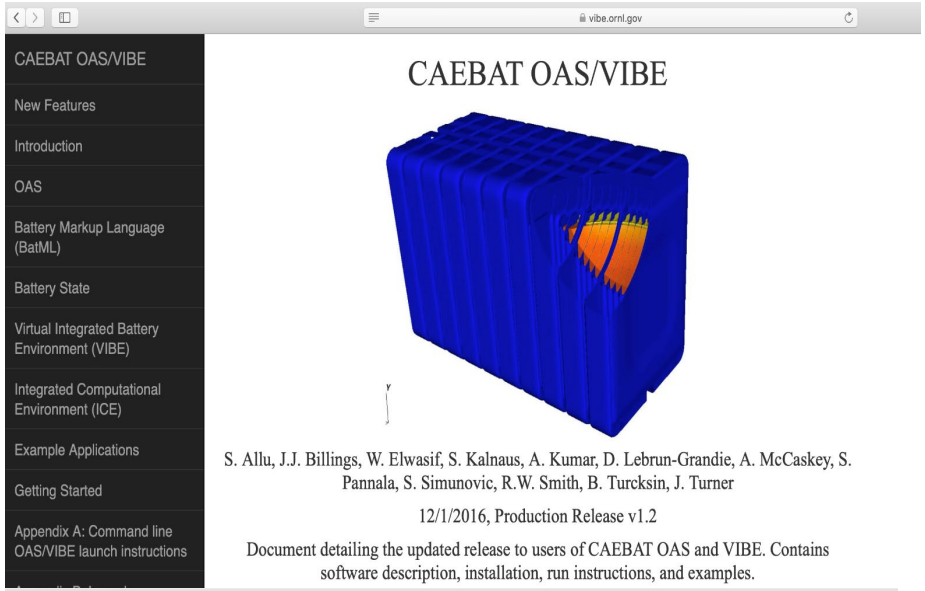
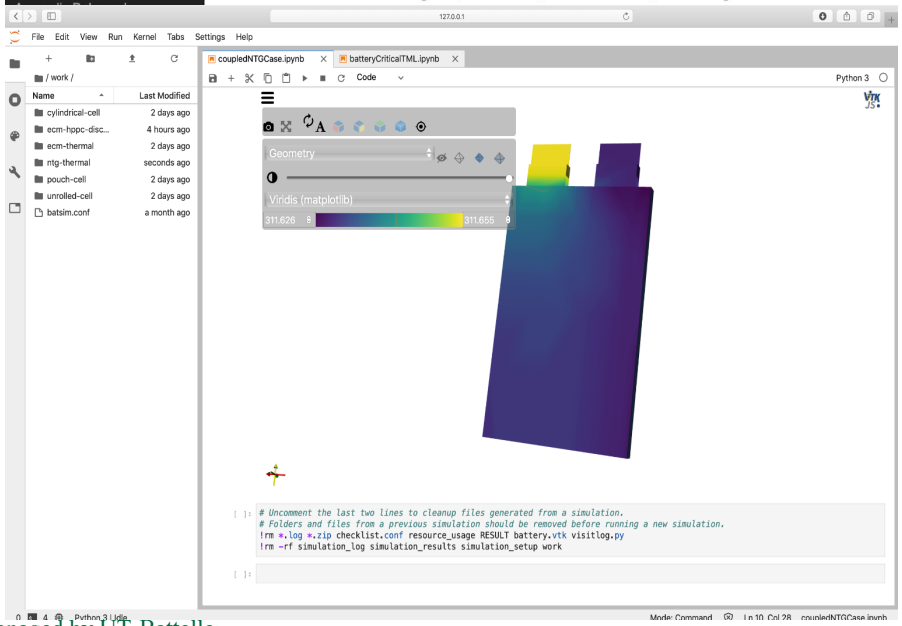
Additional Tools: New Virtual Integrated Battery Environment (VIBE) Deployment and Safety Test Simulation





- VIBE was packaged and deployed at https://vibe.ornl.gov
- Framework allows for users to upload experimental data on cloud
- Using this data we can parametrize the electrochemical model variables.
- Allows to populate battery safety database and run complex data analytics
- Compute numerical solutions based on simulations and predict behavior under various scenarios.
- Conduct post-processing and analysis within the browser.

For users with more battery design and performance information

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Project Results

- **Major Results:**
  - **Thermal runaway risk test protocol has been developed by ORNL and Sandia**
  - **Testing of small Li-ion cells has been completed and the data are being used to develop ML analysis software**
  - **Large format testing are on-going at ORNL and Sandia. We expect to expend the database and make it ready for user inputs**
- **Publications:**
  - **Xiaoqing Zhu, Zhenpo Wang,Yituo Wang, Hsin Wang, Cong Wang, Lei Tong and Mi Yi, "Overcharge investigation of large format lithium-ion pouch cells with $Li(Ni_{0.6}Co_{0.2}Mn_{0.2})O_2$ cathode for electric vehicles: Thermal runaway features and safety management method", *Energy*, doi.org/10.1016/j.energy.2018.12.041, Vol. 169, pp868-880 2019**
  - **Xiaoqing Zhu, Hsin Wang, , Xue Wang, Yanfei Gao, Srikanth Allu, Ercan Cakmak and Zhenpo Wang, "Internal short circuit and failure mechanisms of lithium-ion pouch cells under mechanical indentation abuse conditions: An experimental study", *Journal of Power Sources*, Submitted September 2019**
- **Invention Disclosure:**
  - **Title: "Temperature sensitive paint with gas and chemical release functions", with Beth Armstrong and Katie Burdette, ORNL No. 81912952, Filed May 2019**

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Looking Forward

- Testing more Li-ion cells to populate the database
- Data analysis will be updated to make better predictions of thermal runaway risks
- Working with standards and codes developers to better utilize the test data
- Develop education plan so battery manufacturers, users and first responders can all benefit from the information

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Project Contacts

Thank You!

- We'd like to thank DOE and Dr. Irme Gyuk for supporting this project
- This project is managed at ORNL by Dr. Michael Starke
- Presenter: Dr. Hsin Wang, Materials Science and Technology Division, Oak Ridge National Laboratory
- Corresponding Email: wangh2@ornl.gov

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