Energy Storage Safety and Reliability

Thermal Runaway Database Development

Hsin Wang[1], Lianshan Lin[1], Srikath Allu[1]

Loraine Torres-Castro[2], Yuliya Preger[2], Valerio De Angelis[2]

Development of Thermally Sensitive Paint

Hsin Wang[1], Beth Armstrong[1], Chanaka Gamalalaralage[1] Michael Starke[1]

[1]Oak Ridge National Laboratory

[2]Sandia National Laboratories

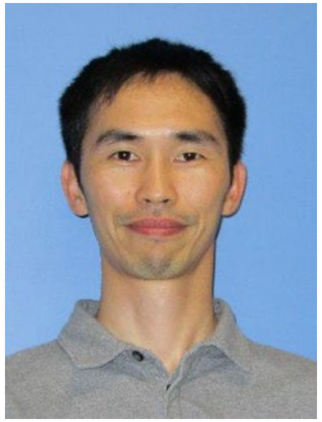
Team Members - ORNL

Hsin Wang

Material Science and Technology Division
Material Scientist, Testing

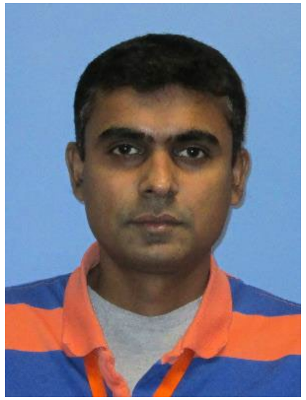
Beth Armstrong

MSTD
Ceramist, Paint Development



Lianshan Lin

MSTD
Mechanical, Database

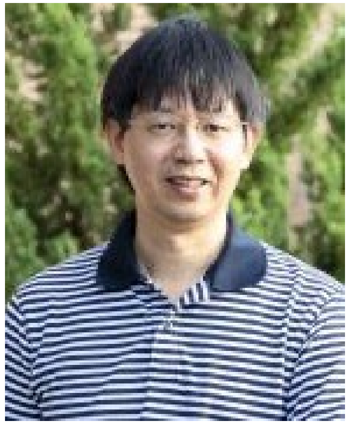


Chanaka Gamaralalage

MSTD
Chemist, Paint Development

Srikanth Allu

Computational Science & Engineering
Modeling & Simulation



Jianlin Li

Electrification & Energy Infrastructure
Battery Research

Michael Starke

Electrification & Energy Infrastructure
Battery Management System

Isabella Fishman

Northwestern University
DOE SULI Student, Battery Testing

Collaboration: Sandia Laboratories and Others

Sandia Laboratories: Protocols development, parallel testing database development

Collaborators: Loraine Torres-Castro, Josh Lamb, Yuliya Preger and Valerio De Angelis

University of Tennessee: Accelerating Rate Calorimetry (ARC), thermal runaway reactions and propagation

Collaborator: Professor Peng Zhang @ UT Space Institute Tullahoma TN

LG&E KU: Technology Research and Analysis Department, Kentucky's first and largest utility-scale energy storage system. On-site lithium-ion battery temperature monitoring directly supports the E.W. Brown Solar facility

Project History and Progression

Energy Safety Reliability

2019

Safety Database

Accomplishments
- ORNL-Sandia test protocol
- Large format EV battery testing at both labs

2020

Safety Database

Accomplishments
- Battery testing from 500 mAh to 33 Ah
- Journal of Power Sources:
  1. Thermal runaway
  2. Capacity fade

2021

Safety Database

New Detection Methods

Accomplishments
- Database development with Sandia
- Temperature sensitive paint developed (patent)

2022 ->

Safety Database

New Detection Methods

Accomplishments
- Thermal runaway severity scores
- Metal particle-based paint: 60-80°C thiol release

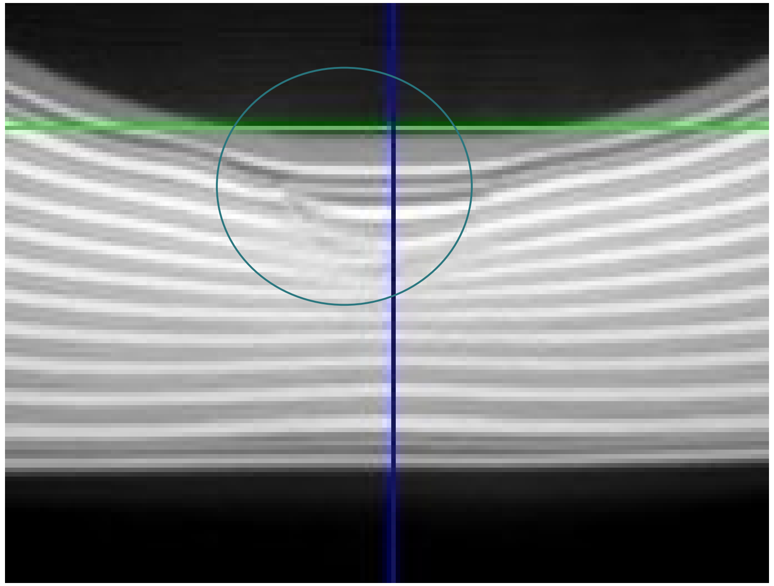
Safety Database

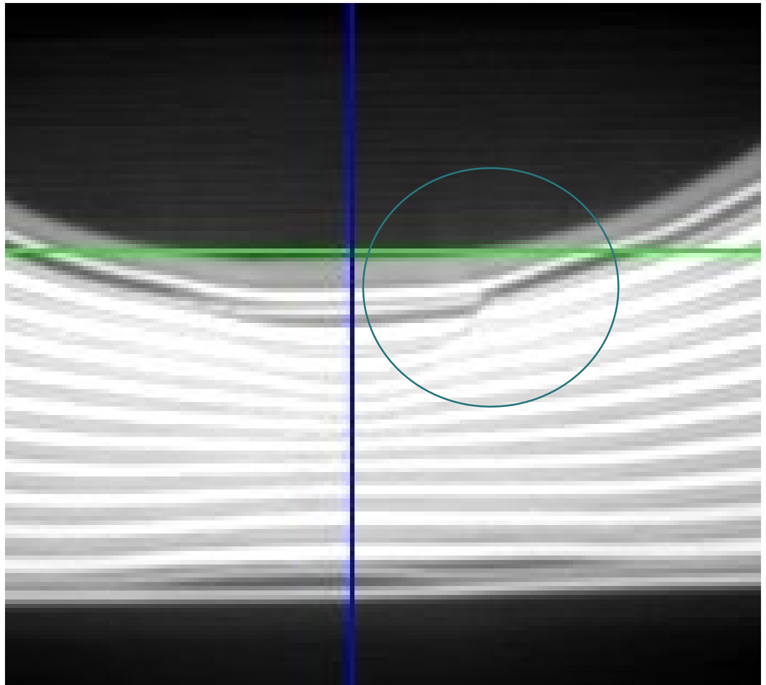
Thermal Runaway Severity

Project Goal: Develop a thermal runaway database to rank/predict hazard severity

Mechanical Induced Short Circuit

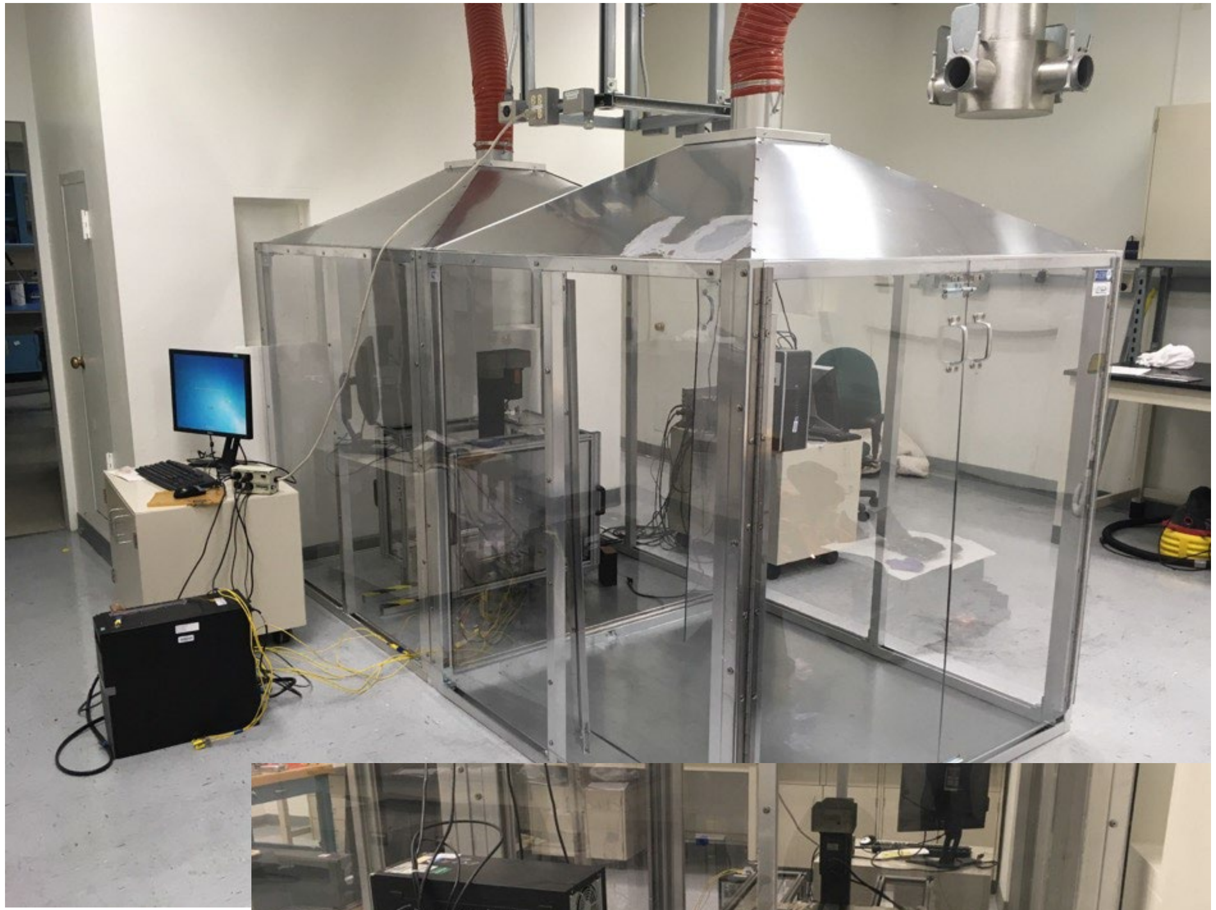
- **Mechanically induced internal short circuit**
  - Nail penetration
  - ➢ **Single-side indentation**
  - Pinch test (two indenters)
  - Pinch-torsion, indent-torsion
- **Real-time Monitoring:**
  - Load, displacement, V_{OC} and temperature
- **Post-mortem Examination:**
  - X-ray computed tomography (XCT)
  - Open cell examination

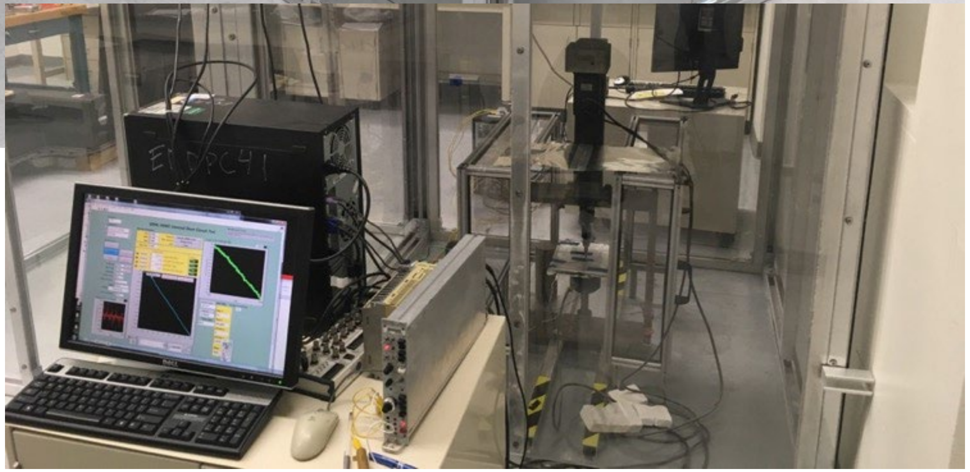




Oak Ridge National Laboratory

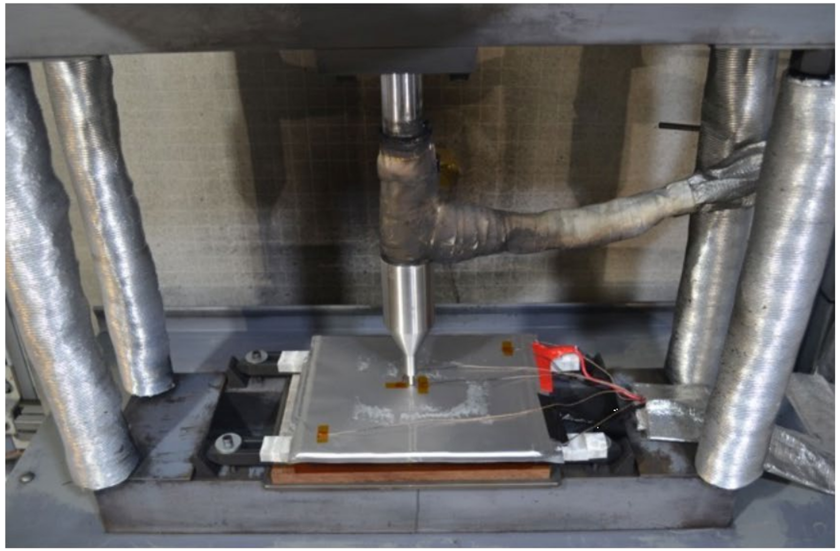
ORNL and Sandia Testing Facility: Large Format Cells



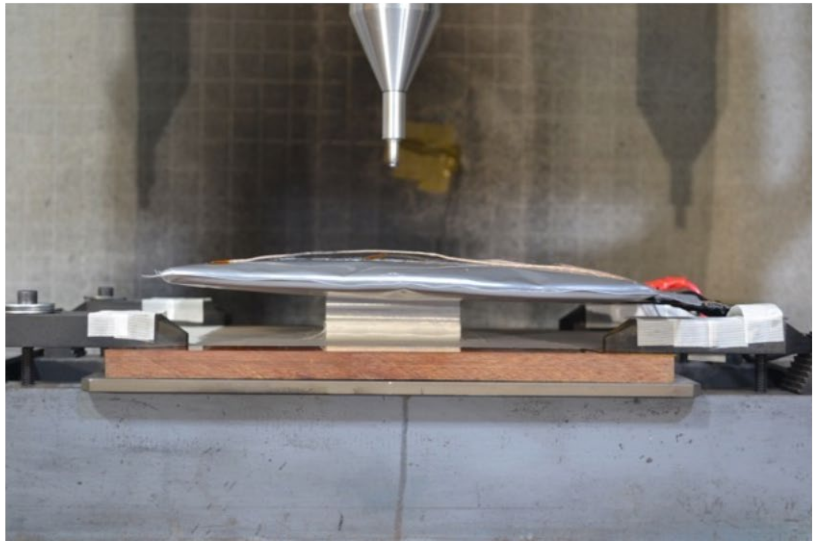


2014-2022
DOE
VTO/NHTSA
DOE OE

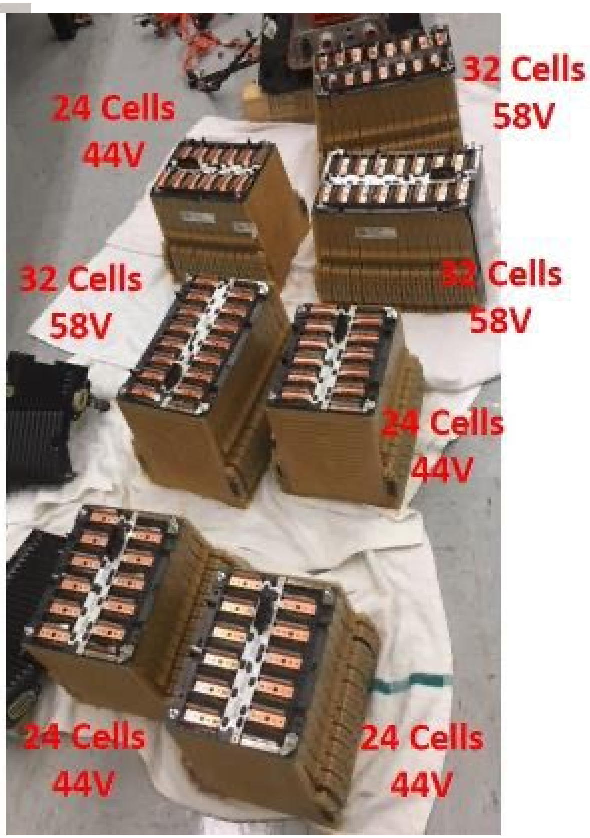
Nissan Leaf Cell in Sandia Test Chamber



Nissan Leaf Cell After Indentation



Extracting Li-ion Cells from Electrical Vehicles at ORNL (Chevy VOLT, Nissan Leaf and FORD Focus EV)



Li-ion Cells: Disassembled EVs and Commercial Sources

Large-format Prismatic Cells Tested at ORNL and Sandia

2017 Chevy VOLT (26 Ah)

2013 Nissan Leaf (33 Ah)

Commercial NMC Cells (10 Ah)

Commercial LFP Cells (10 Ah)

10 NMC Cells (5 SOC x 2) after Testing
Left to right: 0% SOC -> 100% SOC

10 LFP Cells (5 SOC x 2) after Testing
Left to right: 0% SOC -> 100% SOC

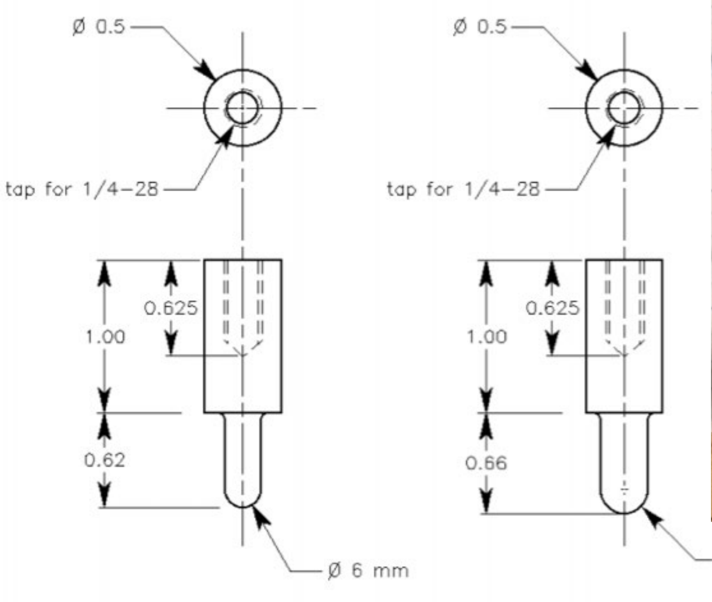
Updated ORNL-Sandia Test Procedures and Standards

Internal Short-ciruit Induced Thermal Runaway

- Mechanical abuse (indentation)

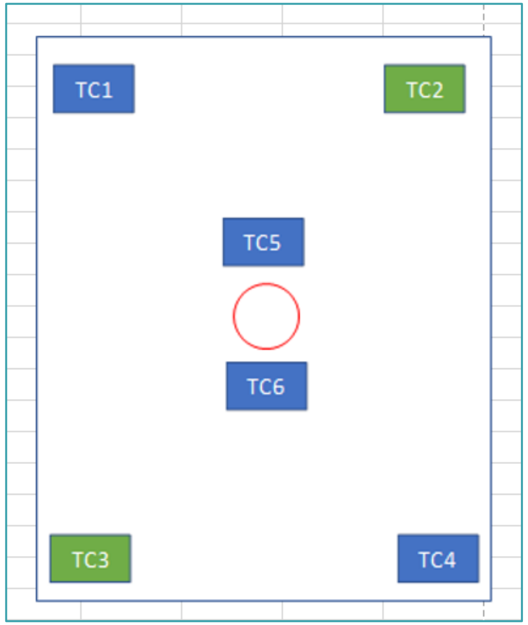
Updated Test Protocols:

- Cycle cell 3-5 times at C/2 between 3.0-4.2V to determine SOC and discharge to test SOC
- Hydraulic or servo-motor driven load frame
- 6 mm punch (most sensitive, small contact)
- 0.05 inch per minute compressive loading
- 25 mV V_{oc} drop
- Hold the punch after short circuit
- Temperature measurement:
  - 5 mm from the indenter
  - At cell corners when possible



Punches for Battery Testing		
ELC-2019.03.001		Scale: 1.5:1
Dimensions: inches (unless otherwise specified)		Material: stainless steel
Make four (4) pieces of each		
Edgar Lara-Curzio	ORNL	March 2019

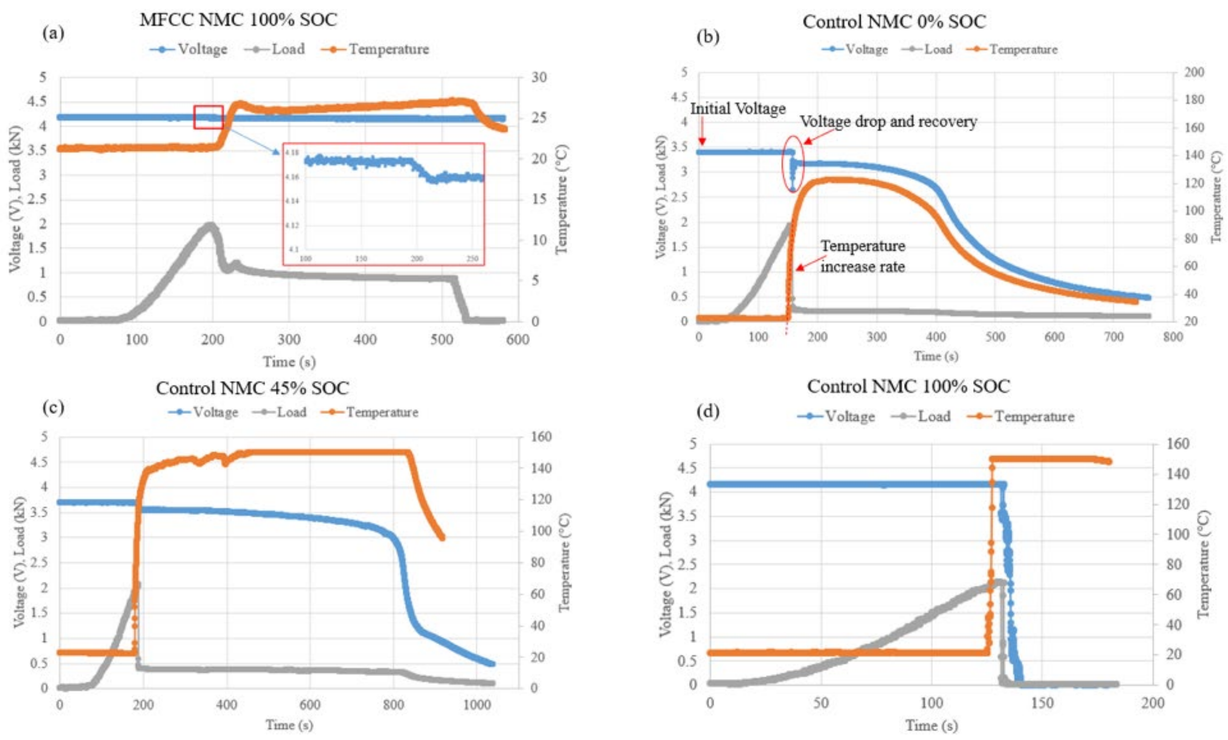
Thermocouple Locations on Large-format Cells



Select the most sensitive test to allow safety risk ranking

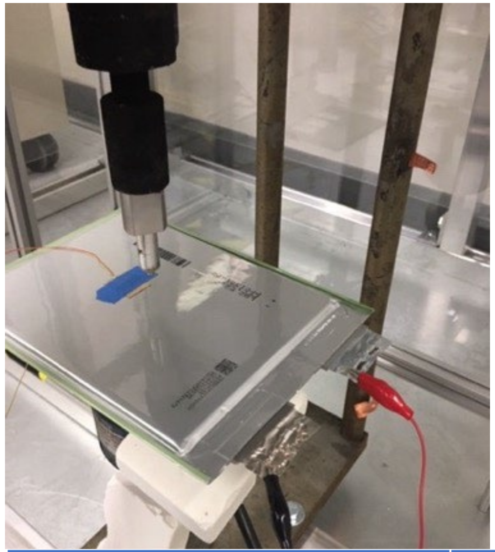
Thermal Runaway Risks for Li-ion Batteries (ORNL-Sandia)

Load **Voltage** **Temperature**



Small Cells Testing at ORNL:
SOC: 20%, 40%,60% 80%,100%
Capacity at 500, 1500, 200 mAhr
Number of Cells: 4 cells/condition

ESS Batteries at Various SOCs:
Sandia: 30%, 50%, 75%, 100%
ORNL: 20%, 40%,60% 80%,100%



Test Data and Cell Information:
- Cell Capacity
- Loading curve: before & after short
- Cell Voltage: drop and response
- Cell Temperature vs. Time
- Open cell voltage
- Anode thickness
- Cathode thickness
- Separator thickness
- C/2 Charge curve
- 1C discharge curve

Cell Name	Chemistry	Capacity (mAH)	Sample Number
Commercial LCO	$LiCoO_2$	500	15
Commercial LCO	$LiCoO_2$	1500	10
Commercial LCO	$LiCoO_2$	2000	15
Commercial LCO	$LiCoO_2$	6400	13
Control NMC	$LiNiMnCoO_2$ (811)	5200	12
Metallized Film Current Collector (MFCC) NMC	$LiNiMnCoO_2$ (811)	5200	10
Commercial LFP	$LiFePO_4$	10000	16
Commercial NMC	$LiNiMnCoO_2$	10000	14

Acronyms for cathode chemistry: lithium cobalt oxide (LCO); lithium nickel manganese cobalt oxide (NMC); lithium iron phosphate (LFP)

Thermal Runaway Severity: EUCAR vs Test Data-driven Severity Levels

EUCAR Severity Levels

Hazard Level	Description	Classification Criteria & Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/Damage	No leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δmass < 50%	No venting, fire, or flame; no rupture; no explosion. Weight loss < 50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting Δmass ≥ 50%	No fire or flame; no rupture; no explosion. Weight loss ≥ 50% of electrolyte weight (electrolyte = solvent + salt).
5	Fire or Flame	No rupture; no explosion (i.e., no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (i.e., disintegration of the cell).

ORNL-Sandia Test Data Based Severity Levels

Hazard Severity Level	Description
1 (VL, 0-10)	Very low, instant local Joule heating, detectable voltage drops
2 (L, 10-25)	Low, localized heating, small voltage drops and recovery
3 (M, 25-75)	Moderate, localized heating spread, significant voltage drops, continued discharge after recovery
4 (H, 75-90)	High, heating due to chemical reactions, cell puff and gas release, voltage drop to close zero
5 (VH, 90-100)	Very high, heating spread to the cell, heavy smoke and possible fire, voltage drops to zero

Calculation of Thermal Runaway Severity Score

Severity Score Calculation Based on Temperature and Voltage

$$\begin{cases} 5, \ if\ Max\ Temperature < 40\ ^{\circ}C \\ \min\{ wA * \left(\frac{Max\ Temperature}{160}\right)^{0.25} + wB * \left(\frac{Temperature\ Increase\ Rate}{200}\right) + wC * wCap * wSOC * Voltage\ Drop\ Score + cOffset,\ 100\} \\ 100,\ if\ Max\ Temperature > 160\ ^{\circ}C \end{cases} \quad (1)$$

Voltage Drop Score=

$$\begin{cases} 1,\ if\ (Voltage\ Range)/(Initial\ Voltage) < 0.2 \\ 2, if\ \frac{Voltage\ Range}{Initial\ Voltage} > 0.5\ and\ \frac{Final\ Voltage\ Change}{Initial\ Voltage} < 0.2 \\ 3,\ if\ \frac{Voltage\ Drop\ in\ 2\ Seconds}{Initial\ Voltage} < 0.4\ and\ \frac{Final\ Voltage\ Change}{Initial\ Voltage} > 0.7 \\ 4,\ if\ \frac{Voltage\ Drop\ in\ 2\ Seconds}{Initial\ Voltage} \geq 0.4\ and\ \frac{Final\ Voltage\ Change}{Initial\ Voltage} > 0.7 \\ 5,\ if\ \frac{Voltage\ Range}{Initial\ Voltage} > 0.7\ and\ \frac{Final\ Voltage\ Change}{Initial\ Voltage} > 0.7\ and\ \frac{Voltage\ Drop\ in\ 5\ Seconds}{Initial\ Voltage} > 0.7 \end{cases} \quad (2)$$

$$wA = 2.0*cScale,\ wB = 3.0*cScale,\ wC = 2.0*cScale \quad (3)$$

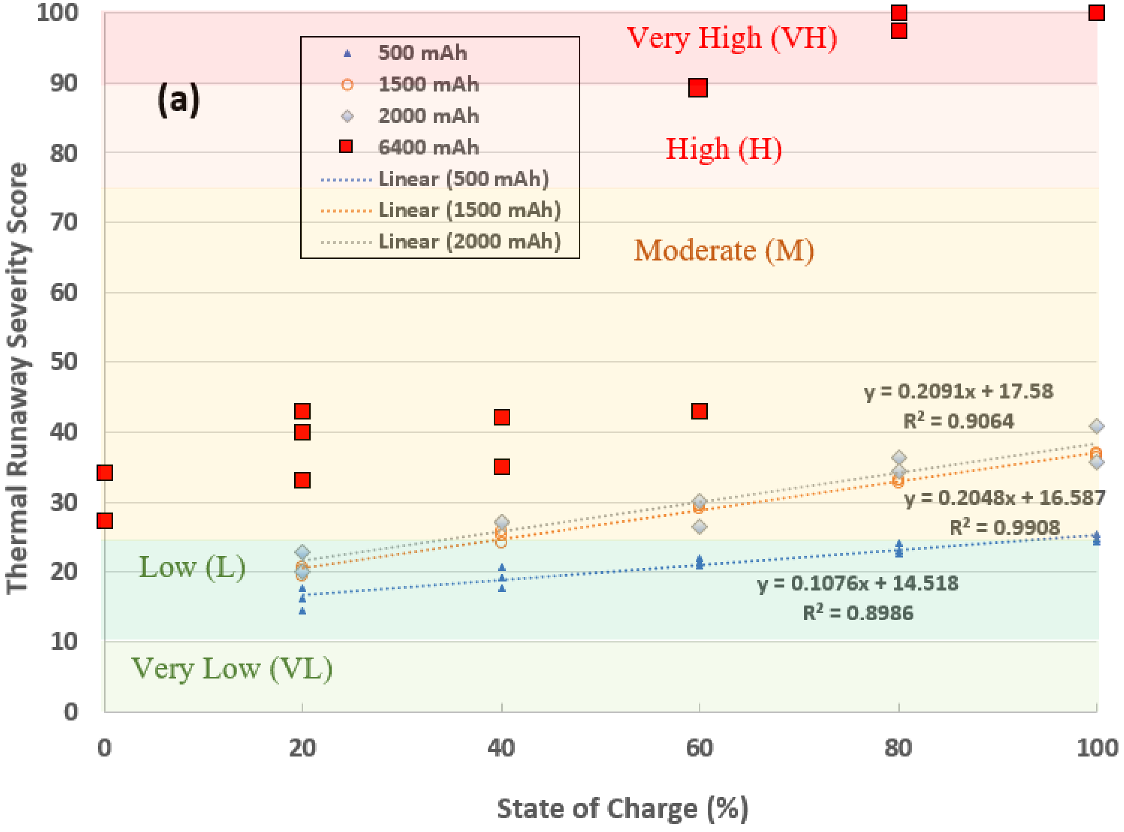
$$wCap = Battery\ Capacity/10000 \quad (4)$$

$$wSOC = Battery\ SOC/100 \quad (5)$$

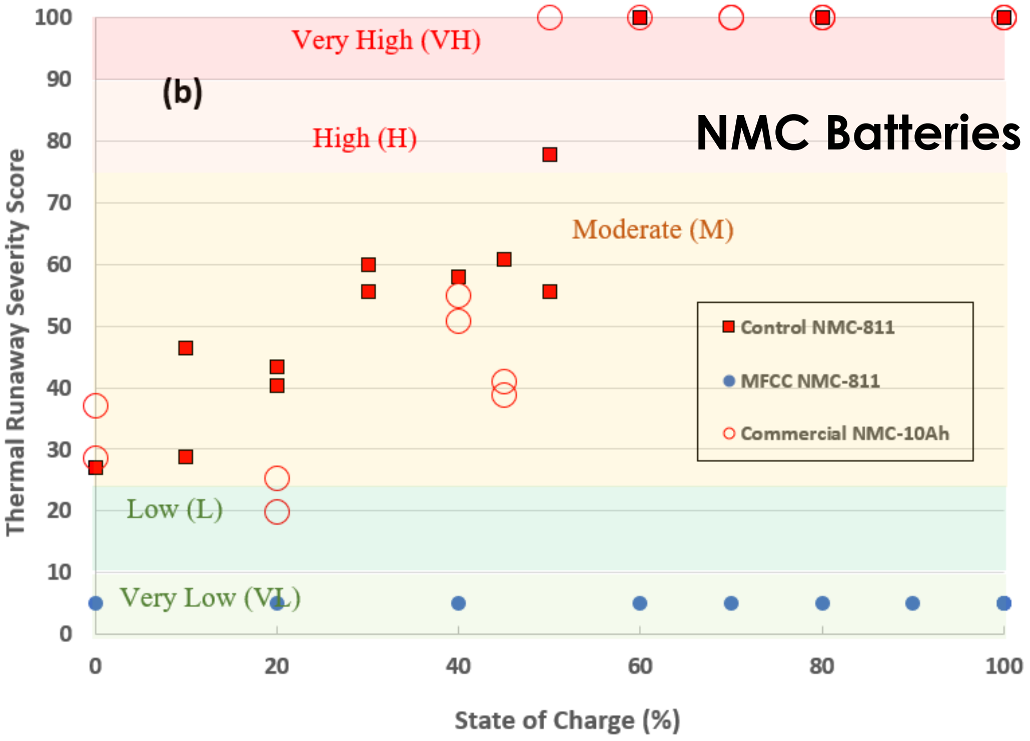
$$cScale = 95/6,\ cOffset = 5\text{-}cScale \quad (6)$$

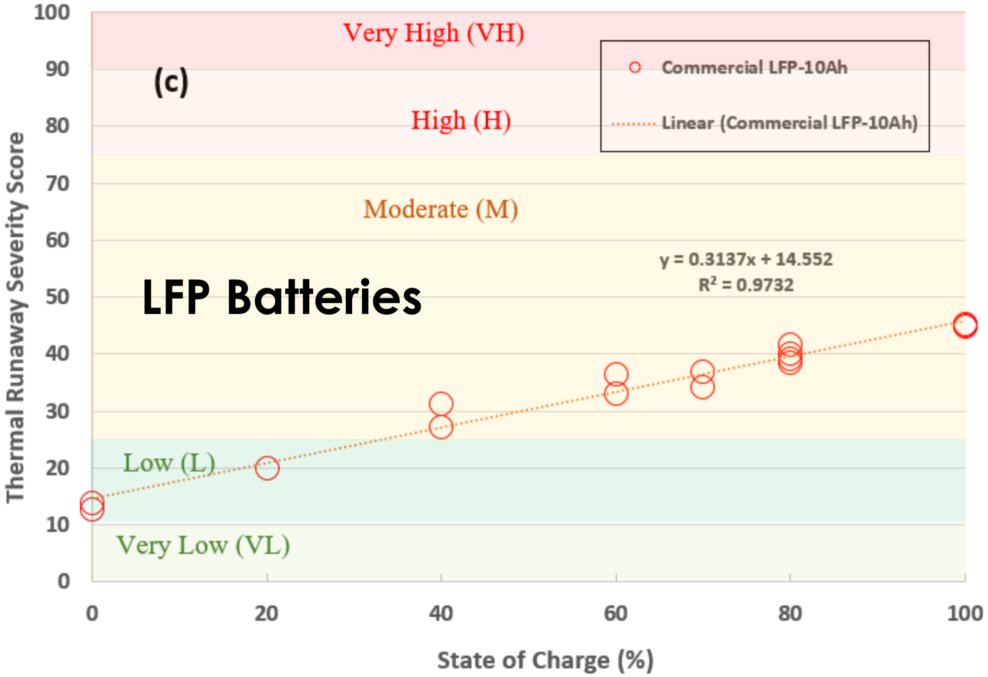
Test Name	Calculated Severity Level (CHS 5-100)	Battery Capacity (mAH)	SOC (%)	Observed Severity Level (OHS)
LCO 500mAh1-20SOC	14.4	500	20	Low
LCO 500mAh1-40SOC	17.6	500	40	Low
LCO 500mAh1-60SOC	22.0	500	60	Low
LCO 500mAh1-80SOC	24.2	500	80	Low
LCO 500mAh1-100SOC	24.3	500	100	Low
LCO 1500mAh1-20SOC	20.7	1500	20	Low
LCO 1500mAh1-40SOC	25.2	1500	40	Moderate
LCO 1500mAh1-60SOC	29.0	1500	60	Moderate
LCO 1500mAh1-80SOC	32.8	1500	80	Moderate
LCO 1500mAh1-100SOC	36.7	1500	100	Moderate
LCO 2000mAh1-20SOC	22.8	2000	20	Low
LCO 2000mAh1-40SOC	27.1	2000	40	Moderate
LCO 2000mAh1-60SOC	26.6	2000	60	Moderate
LCO 2000mAh1-80SOC	36.3	2000	80	Moderate
LCO 2000mAh1-100SOC	35.7	2000	100	Moderate
Soteria-Control-100SOC	100.0	5190	100	Very High
Soteria-Control-80SOC	100.0	4960	80	Very High
Soteria-Control-60SOC	100.0	5190	60	Very High
Soteria-Control-40SOC	57.9	5190	40	Moderate
Soteria-Control-20SOC	40.3	5190	20	Moderate
Soteria-Control-10SOC	46.4	5190	10	Moderate
Soteria-Control-0SOC	27.1	5190	0	Moderate
Soteria-MFCC-100SOC	5.0	4960	100	Very Low
Soteria-MFCC-80SOC	5.0	5180	80	Very Low
Soteria-MFCC-60SOC	5.0	5180	60	Very Low
Soteria-MFCC-40SOC	5.0	4720	40	Very Low
Soteria-MFCC-20SOC	5.0	5180	20	Very Low
LCO- 6400mAh-100SOC	100.0	6400	100	Very High
LCO- 6400mAh-80SOC	100.0	6400	80	Very High
LCO-6470mAh-60SOC	89.1	6470	60	High
LCO-6270mAh-40SOC	35.1	6270	40	Moderate
LCO-6500mAh-20SOC	43.0	6500	20	Moderate
LCO-6560mAh-0SOC	34.3	6560	0	Moderate
LFP 10Ah-0SOC	13.8	10000	0	Low
LFP 10Ah-40SOC	27.1	10000	40	Moderate
LFP 10Ah-60SOC	33.2	10000	60	Moderate
LFP 10Ah-80SOC	39.2	10000	80	Moderate
LFP 10Ah-100SOC	44.8	10000	100	Moderate
NMC 10Ahr-0SOC	37.1	10000	0	Moderate
NMC 10Ah-20SOC	25.3	10000	20	Moderate
NMC 10Ahr-40SOC	55.0	10000	40	Moderate

Results: Linear Change vs ”Step Change”



LCO Batteries: 500 mAh to 6400 mAh





Thermal Runaway Severity Calculation Workflow

Formatted data file in 'excel' folder

Soteria-control-10SOC-cell1.xlsx

Necessary columns

Time Load Voltage Time Temperature

	Time (sec)	Penetrator Force (N)	Cell Voltage (V)	Displacement (mm)	Time (sec)	TC1 (°C)	TC2 (°C)	TC3 (°C)	TC4 (°C)
2	0	-4.19911968	3.452		0	22.8256			
3	0.046	-4.17687858	3.448		0.099	22.82095			
4	0.103	-4.50159864	3.448		0.2	22.81805			
5	0.158	-4.37704848	3.448		0.299	22.77973			
6	0.219	-5.3823462	3.448		0.433	22.77625			
7	0.264	-4.09681062	3.448		0.499	22.77102			
8	0.31	-4.47490932	3.448		0.598	22.76464			
9	0.355	-4.07456952	3.449		0.7	22.79483			
10	0.4	-4.17687858	3.45		0.799	22.78554			
11	0.446	-4.26139476	3.449		0.899	22.78264			
12	0.503	-3.77653878	3.448		1	22.75069			
13	0.55	-3.73205658	3.448		1.1	22.7716			
14	0.66	-2.31752262	3.448		1.2	22.78147			
15	0.744	-3.4251294	3.448		1.299	22.82618			
16	0.84	-3.30947568	3.448		1.4	22.84184			
17	1.017	-4.50604686	3.448		1.499	22.83546			
18	1.063	-4.4704611	3.448		1.599	22.82211			
19	1.121	-4.05232842	3.448		1.699	22.80528			
20	1.167	-4.37260026	3.449		1.798	22.83256			
21	1.214	-3.37175076	3.447		1.899	22.85287			
22	1.259	-4.19911968	3.452		1.999	22.86563			
23	1.304	-4.17687858	3.448		2.132	22.80817			

Code behind the worksheet

```
Private Sub CommandButton3_Click()
Dim oFSO As Object
Dim oFolder As Object
Dim oFile As Object
Dim i As Integer

'Physical effect, rupture of pouch, smoke, gas release, fire - 7
'Physical effect (pouch swelling), rupture of pouch, gas release - 6
'Physical effect (pouch swelling), extended joule heating, local reactions - 5
'Moderate effect, extended joule heating, local reactions (limited spread) - 4
'Moderate effect, extended joule heating, local reactions (no spread) - 3
'No effect, local heating, internal discharge - 2
'No effect, instant local Joule heating, no internal discharge - 1

'clear all existing content
sheetname = "Sheet1"
strPath = Application.ActiveWorkbook.Path
Set oFSO = CreateObject("Scripting.FileSystemObject")
Set oFolder = oFSO.GetFolder(strPath)
i = 0
strFolderExists = Dir(strPath + "\excel\", vbDirectory)
If strFolderExists = "" Then
    MsgBox "data file doesn't exist!"
    Exit Sub
    'MkDir strPath + "\excel\"
End If

Dim strFileName As String
'n = oFolder.Files.Count
n = Cells(Rows.Count, 1).End(xlUp).Row + 10 'rows of first column

For i = 1 To n
'For i = 13 To 25
    strFileName = Cells(i, 1)
    If strFileName <> "" Then
        'addTemperature
        strExcelFile = strPath + "\excel\" + strFileName + ".xlsx"
        strState = Cells(i, 3)
        'If Dir(strExcelFile) <> "" And Dir(strTempFile) <> "" Then
        If Dir(strExcelFile) <> "" And strState = "Processing" Then
            Dim app As New Excel.Application
            app.Visible = False 'Visible is False by default, so this isn't necessary
            Dim book As Excel.Workbook
            Set book = app.Workbooks.Open(strExcelFile)

            Set wsheet = book.Worksheets(sheetname)
            'calculate risk score
            iRow = wsheet.Cells(Rows.Count, 6).End(xlUp).Row 'upbound of voltage column
```

Calculation file

formatData-2022-newscript&5-100.xlsm

Capacity SOC

	A	B	C	D	E	F	G
1	Sorteria-100SOC-cell1		Processing		No effect, instant local Joule heating, no internal discharge – 1	4960	100
2	Sorteria-100SOC-cell2		Processing		No effect, instant local Joule heating, no internal discharge – 1	4960	100
3	Sorteria-Control-100SOC-cell1		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	5190	100
4	Sorteria-Control-100SOC-cell2		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	5190	100
5	LCO-LP-6400mAh-100SOC-cell1		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	6400	100
6	LCO-LP-6400mAh-100SOC-cell2		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	6400	100
7	LCO-LP-6400mAh-80SOC-Cell3		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	6400	80
8	LCO-LP6400mAh-80SOC-cell4		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	6400	80
9	Soetria-80SOC-cell3		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	4960	80
10	Sorteria-Control-60SOC-cell1		Processing		Physical effect, rupture of pouch, smoke, gas release, fire – 7	5190	60
11	Soetria-Control-45SOC-cell1		Processing		Physical effect (pouch swelling), rupture of pouch, gas release – 6	5190	45
12	Sorteria-control-40SOC-cell2		Processing		Physical effect (pouch swelling), rupture of pouch, gas release – 6	5190	40
13	Sorteria-control-20SOC-cell1		Processing		Physical effect (pouch swelling), extended joule heating, local reactions –	5190	20
14	Soteria-control-30SOC-cell2		Processing		Physical effect (pouch swelling), extended joule heating, local reactions –	5190	30
15	Soteria-control-30SOC-cell1		Processing		Physical effect (pouch swelling), extended joule heating, local reactions –	5190	30
16	Soteria-control-10SOC-cell1		Processing		Moderate effect, extended joule heating, local reactions (limited spread)	5190	10
17	Soteria-Control-0SOC-cell1		Processing		Moderate effect, extended joule heating, local reactions (no spread) – 3	5190	0
18	Soteria-SCC-90SOC-cell1		Processing		No effect, instant local Joule heating, no internal discharge – 1	5180	90
19	Soteria-SCC-80SOC-cell1		Processing		No effect, instant local Joule heating, no internal discharge – 1	5180	80
20	Soteria-SCC-60SOC-cell1		Processing		No effect, instant local Joule heating, no internal discharge – 1	5180	60
21	Soteria-SCC-20SOC-5180mAh		Processing		No effect, instant local Joule heating, no internal discharge – 1	5180	20
22	OE-LCO-6490mAh-60SOC		Processing		Moderate effect, extended joule heating, local reactions (limited spread)	6490	60

Sheet1 | Summary

Risk Analysis

Run code

Result worksheet

formatData-2022-newscript&5-100.xlsm

Severity score

	FileName	Observed Score	Observed Score	Calculated Score	Capacity	SOC			
2	Sorteria-100SOC-cell1	No effect, instant local Joule heating, no internal discharge – 1	1.00	5.00	4960	100	20.3214	0.22156	15.7067
3	Sorteria-100SOC-cell2	No effect, instant local Joule heating, no internal discharge – 1	1.00	5.00	4960	100	20.1898	0.18107	15.7067
4	Sorteria-Control-100SOC-cell1	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	100.00	5190	100	31.1724	37.6766	49.305
5	Sorteria-Control-100SOC-cell2	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	100.00	5190	100	31.1724	40.3477	49.305
6	LCO-LP-6400mAh-100SOC-cell1	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	100.00	6400	100	31.1724	53.6488	101.333
7	LCO-LP-6400mAh-100SOC-cell2	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	100.00	6400	100	31.1724	29.8941	101.333
8	LCO-LP-6400mAh-80SOC-Cell3	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	100.00	6400	80	31.1724	29.5352	81.0667
9	LCO-LP6400mAh-80SOC-cell4	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	97.48	6400	80	31.1724	28.5057	48.64
10	Soetria-80SOC-cell3	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	100.00	4960	80	31.1724	29.5128	62.8267
11	Sorteria-Control-60SOC-cell1	Physical effect, rupture of pouch, smoke, gas release, fire – 7	7.00	100.00	5190	60	31.1724	30.7138	49.305
12	Soetria-Control-45SOC-cell1	Physical effect (pouch swelling), rupture of pouch, gas release – 6	6.00	60.73	5190	45	31.1724	18.1999	22.1873
13	Sorteria-control-40SOC-cell2	Physical effect (pouch swelling), rupture of pouch, gas release – 6	6.00	57.93	5190	40	31.1724	17.8647	19.722
14	Sorteria-control-20SOC-cell1	Physical effect (pouch swelling), extended joule heating, local reactions	5.00	40.28	5190	20	30.8922	10.359	9.861
15	Soteria-control-30SOC-cell2	Physical effect (pouch swelling), extended joule heating, local reactions	5.00	55.53	5190	30	30.2916	21.2789	14.7915
16	Soteria-control-30SOC-cell1	Physical effect (pouch swelling), extended joule heating, local reactions	5.00	59.89	5190	30	30.96	24.971	14.7915
17	Soteria-control-10SOC-cell1	Moderate effect, extended joule heating, local reactions (limited spread	4.00	46.36	5190	10	30.345	21.9142	4.9305
18	Soteria-Control-0SOC-cell1	Moderate effect, extended joule heating, local reactions (no spread) – 3	3.00	27.10	5190	0	29.6537	7.78384	0.49305
19	Soteria-SCC-90SOC-cell1	No effect, instant local Joule heating, no internal discharge – 1	1.00	5.00	5180	90	20.9707	0.28818	14.763
20	Soteria-SCC-80SOC-cell1	No effect, instant local Joule heating, no internal discharge – 1	1.00	5.00	5180	80	20.8322	0.21012	13.1227
21	Soteria-SCC-60SOC-cell1	No effect, instant local Joule heating, no internal discharge – 1	1.00	5.00	5180	60	20.5409	0.22226	9.842
22	Soteria-SCC-20SOC-5180mAh	No effect, instant local Joule heating, no internal discharge – 1	1.00	5.00	5180	20	19.9489	0.14925	3.28067
23	OE-LCO-6470mAh-60SOC	Physical effect (pouch swelling), rupture of pouch, gas release – 6	6.00	89.10	6470	60	31.1724	31.8859	36.879

Sheet1 | Summary

OAK RI[dge] National Labo[ratory]

Search Database by Battery and Abuse Test Metadata (Host: Sandia Labs)

Oak Ridge National Laboratory

New Detection Methods

Thermally Sensitive Paint Development

(Seedling)

Project Goal:
Thermal runaway avoidance. Early detection of thermal runaway on every cell and large surface area

Indirect Large Area Temperature Monitoring

Temperature-Sensitive Paint for $T_{Threshold}$ Monitoring

Carriers for paint need to have the following features:

- ✓ Stay normal within battery operation temperature
- ✓ Release chemical/gas $T > T_{Threshold}$
- ✓ Non-line-of-sight (change of color is not an option)
- ✓ Detection via “smell” and gas detector

Thermal Runaway

Heating

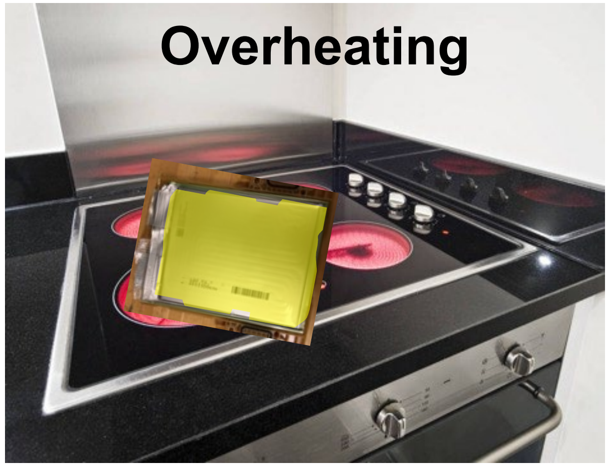
Special Gas Release for Overheating

Li-ion Battery

Brush or Spray Paint

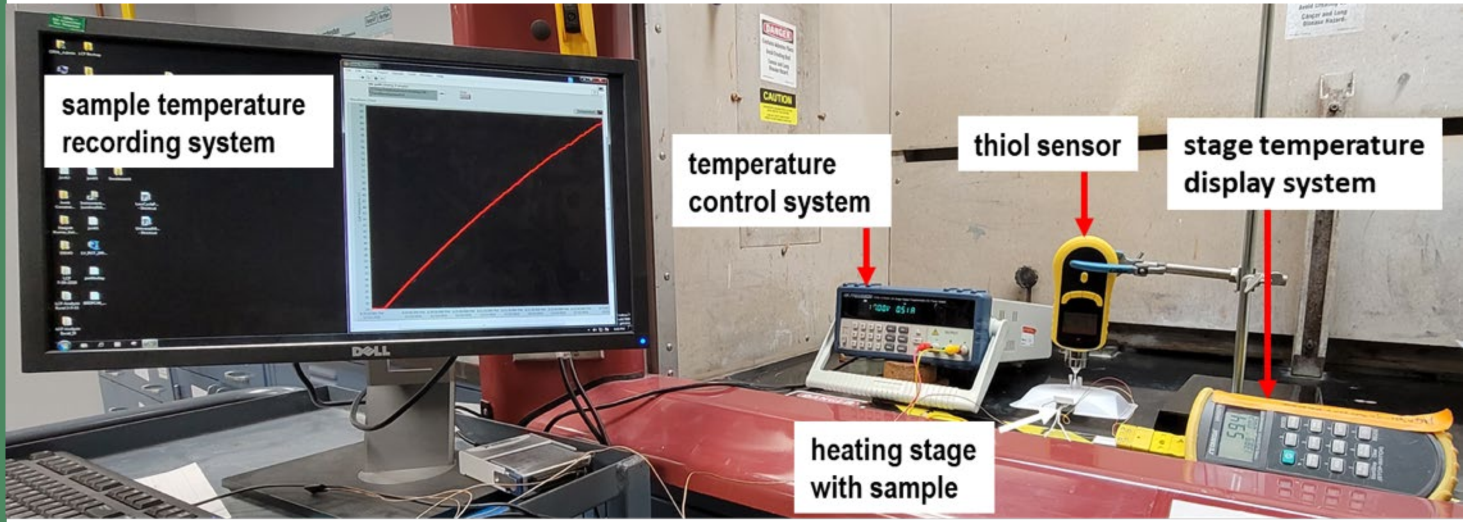
Smoke Alarm

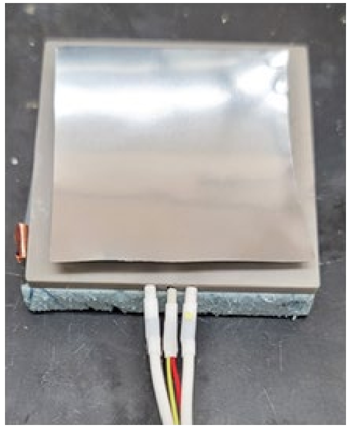
Mercapton Detector



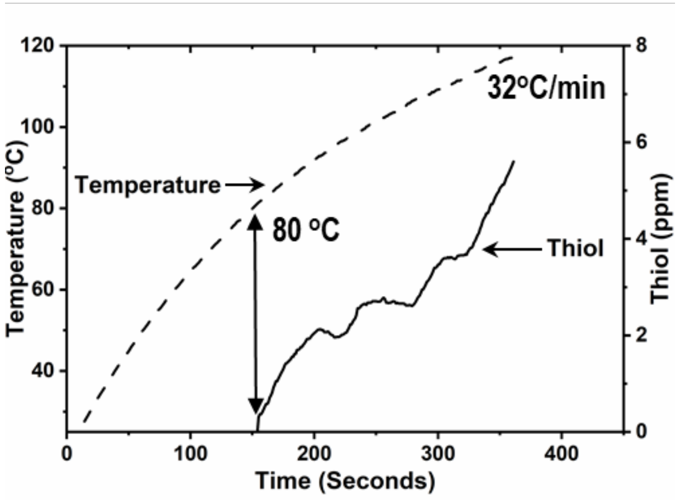
(Web image)

Experimental Setup and Demonstration of Thiol Release

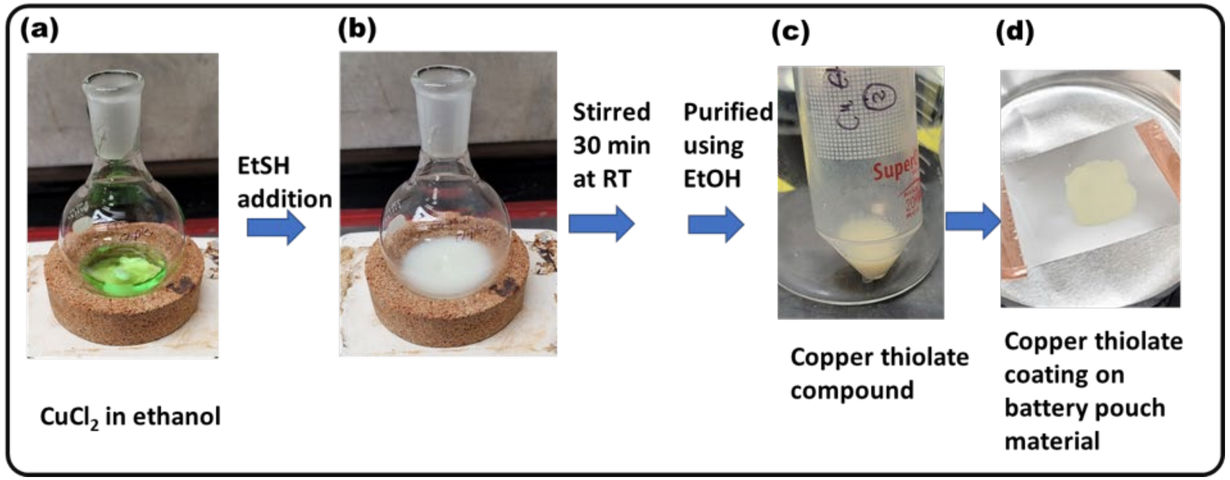




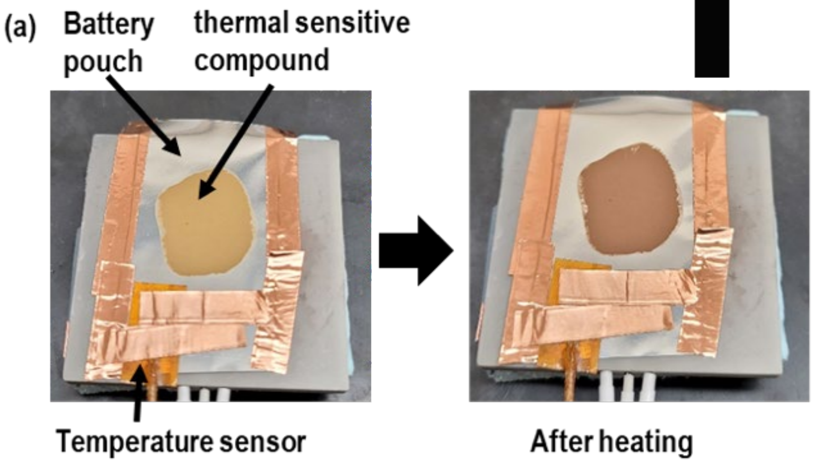
Battery pouch foil on the heating stage



Over-temperature Detection



Paint Development



Coated Pouch on Hot Plate

Future Plan: ESS Reliability Safety Testing and Analysis Facility

Single Cells Database (ORNL-Sandia):

- **UL Standard, end-user upload**
- **Machining learning, prediction of hazard severity**

NHTSA Electrical Vehicles -> battery Packs, module and cell:

- **Thermal runaway testing**
- **Thermal runaway propagation studies**
- **Modeling and Simulations of battery failure**

Battery Safety Technology Development and Demonstration:

- **Thermal runaway warning system (paint development)**
- **Gas detection, BMS/TMS control, prevention mechanisms (isolation, lowering SOC, discharge)**

Acknowledgements and Outputs

Project Supported by DOE EERE Office of Electricity (OE) (Dr. Imre Gyuk)

Publications, Patent, Presentation:

1. Tongxin Shan, Zhenpo Wang, Xiaoqing Zhu, Hsin Wang, Yangjie Zhou, Yituo Wang, Jinghan Zhang and Zhiwei Sun, “Explosion behavior investigation and safety assessment of large-format lithium-ion pouch cells”, ***Journal of Energy Chemistry***, doi.org/10.1016/j.jechem.2022.04.018, April 19, 2022 **Impact factor =11.62**

2. Wei Li, Bobing Xin, Thomas R. Watkins, Yong Xia, Hsin Wang, Juner Zhu, “Mechanical damage of prismatic Lithium-ion cells subject to bending: tests, model, and detection”, ***EcoMat***, revised, doi.org/10.1002/eom2.12257, pp1-16, 2022 **Impact factor =12.213**

3. Srikanth Allu, Jean-Luc Fattebert, Hsin Wang, Srdjan Simunovic,Sreekanth Pannala, and John Turner, **Book Chapter**: “Accelerating Battery Simulations by using High Performance Computing and Opportunities with Machine Learning”, in ***Modern Aspects in Electrochemistry Book Series***, Editor: Shriram Santhanagopalan, Springer, UK (2022)

4. L.S. Lin, J.L. Li, I. Fishman L. Torres-Castro, Y. Preger, V. De Angelis, J. Lamb, X.Q. Zhu, S. Allu and H. Wang, “Mechanically Induced Thermal Runaway Severity Analysis for Li-ion Batteries”, ***Journal of Energy Storage***, Submitted September 2022

5. Joshua Lamb, Sergiy Kalnaus and Hsin Wang, **Book Chapter**: “Experimental Simulations of Field Induced Mechanical Abuse Conditions”, in ***Modern Aspects in Electrochemistry Book Series***, Editor: Shriram Santhanagopalan, Springer, UK (2022)

One Provisional Patent Filed: ID 4373 “Temperature sensitive paint with gas and chemical release functions” by, BL Armstrong, CI Gamalarage, K. Buddett-Trofimov, GM Veith, H Wang

Invited talk: Battery & EV Congress 2022 (June 8-9, 2022 at the MSU Management Education Center, Troy, Michigan), Title: Thermal Runaway Risk of Li-ion Batteries Used in Electric Vehicles: Testing and Analysis by Hsin Wang et al