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Determining the internal pressure in 18650 format lithium ion batteries under thermal abuse

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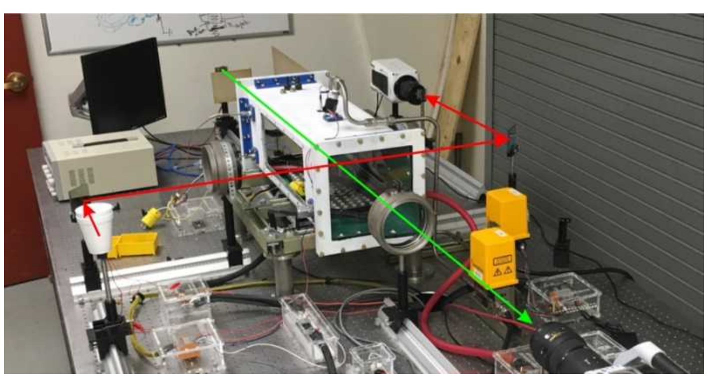
Battery venting under abuse conditions

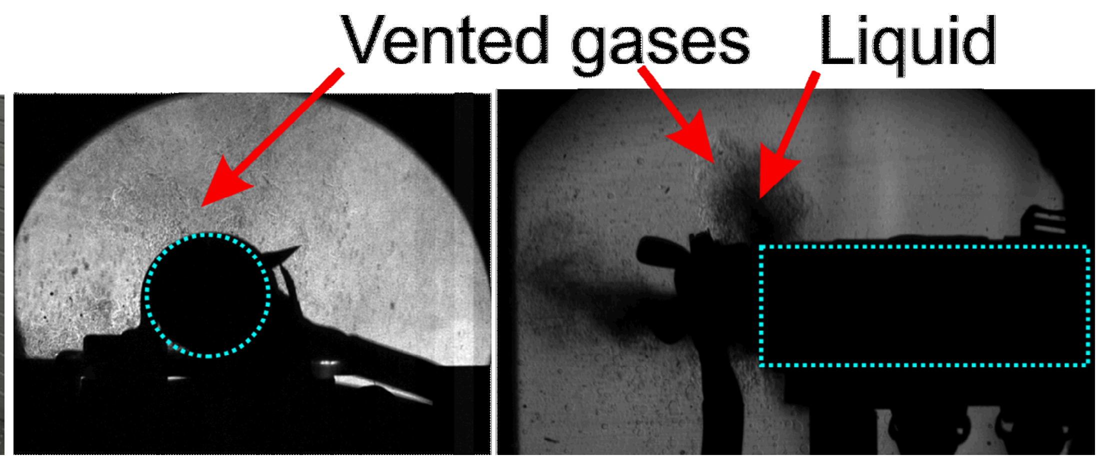
- Most cells have a vent to relieve pressure during thermal runaway
  - Positive terminal of 18650
- Venting avoids case rupture but still presents safety concerns including flammability
- Describing these events can aid in understanding risks and smart design

- LG MG1 (NMC)
- Overcharge and heating
- Elapsed time: 160 ms
- Frame rate: 5 kHz

Previous destructive testing at NMT

- High speed schlieren allowed imaging of venting gasses and liquid droplets
- F. A. Mier, R. Morales. C. A. Coultas-McKenney, M. J. Hargather, J. Ostanek, Overcharge and thermal destructive testing of lithium metal oxide and lithium metal phosphate batteries incorporating optical diagnostics, J. of Energy Storage 13C (2017) pp. 378-386.





Describing the external dynamics of venting starts with quantifying internal pressure

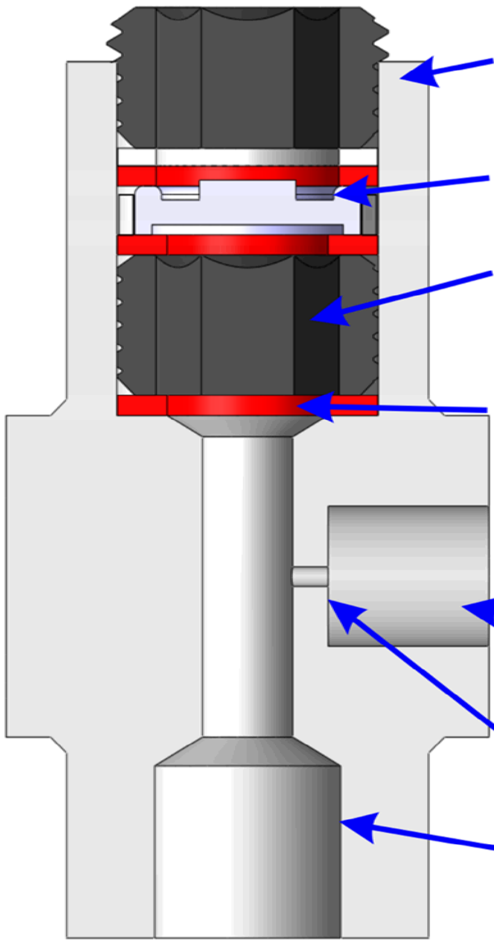
- Current research focuses on the development of two experiments:
  - Pressurization of battery caps and precise direct measurement of burst pressure for comparison to strain-pressure curve.
  - Measurement of case strain under thermal abuse conditions for calculation of to internal pressure before and after venting onset.
- Tests are intended to be performed on 18650 format batteries from any manufacturer and with various chemistries.

Directly measurements with vent caps removed from 18650 cells

- Pipe cutter separates cap from cell at crimp
- Foil tab is cut to separate from cathode
- Experiments can be performed on vent caps from any 18650 format battery
- Measurements include burst pressure and opening area

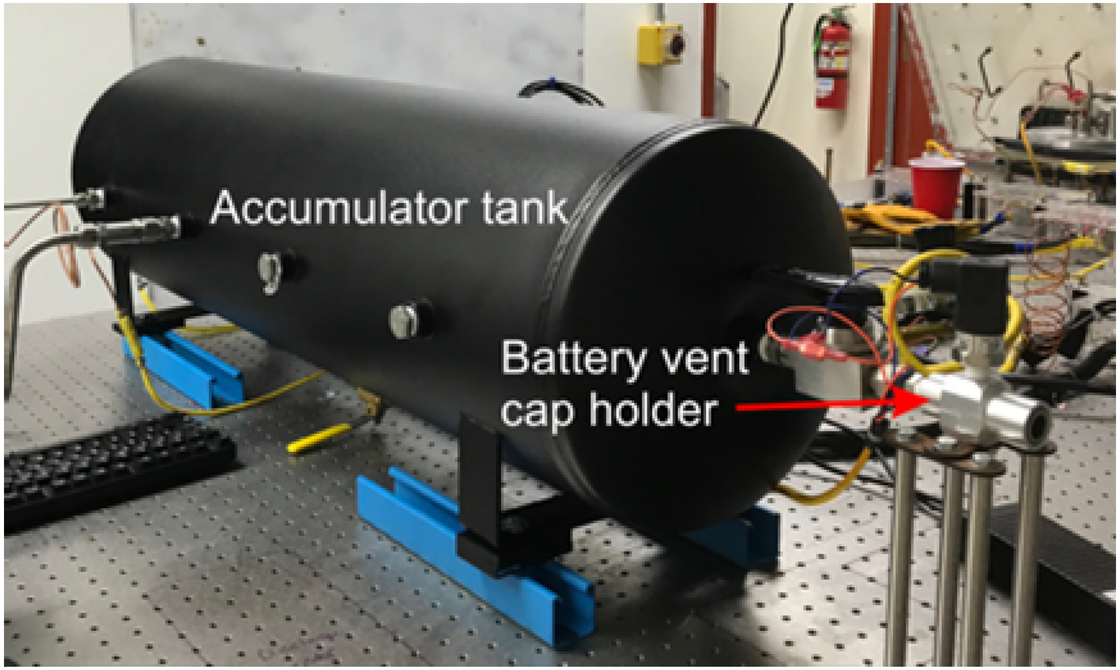
Battery vent cap holder for direct pressurization tests

- Sealed mounting of battery caps
  - Adjustability for size variance
- Designed to choke flow at vent cap
  - Minimum cross section
- Known cross sectional area at pressure tap



Development of a direct pressurization test apparatus

- Pressure gradually increased in 76 L tank with compressed dry air
- National Instruments cDAQ system monitoring
  - Static and stagnation pressures (1 kHz)
  - Stagnation and ambient temperatures (100 Hz)



Investigation into determining vent opening area

- Maximum opening area of vents varies widely between manufacturers
  - A123: 11.2 mm^2
  - LG: 12.7 mm^2
  - Panasonic: 34.3 mm^2
- Determining actual opening area helps describe venting characteristics of gases and liquids
- This measurement can be combined with direct pressure tests
  - Opening area measurement is made after vents open
  - Requires no additional vent caps

Opening area calculation from isentropic flow relationships

- Mach number at the flow constriction via pressure ratio:

$$\frac{P_t}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

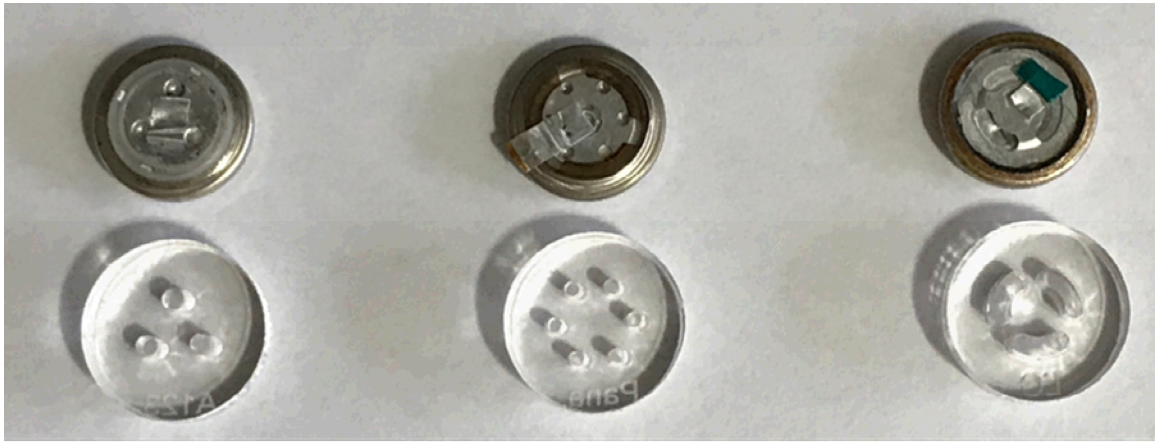
- Vent area is the sonic condition (A^*) for choked flow:
  – Area (A) and Mach number (M) reference constriction

$$\frac{A}{A^*} = \frac{1}{M}\left(\frac{\frac{\gamma + 1}{2}}{1 + \frac{\gamma - 1}{2} M^2}\right)^{\frac{\gamma + 1}{2 - 2\gamma}}$$

- Similar calculation made when flow is not choked
  – Define an arbitrary sonic cross section (A^*)
  – Assume static pressure at the vent is atmospheric

Opening area validation tests with known orifices

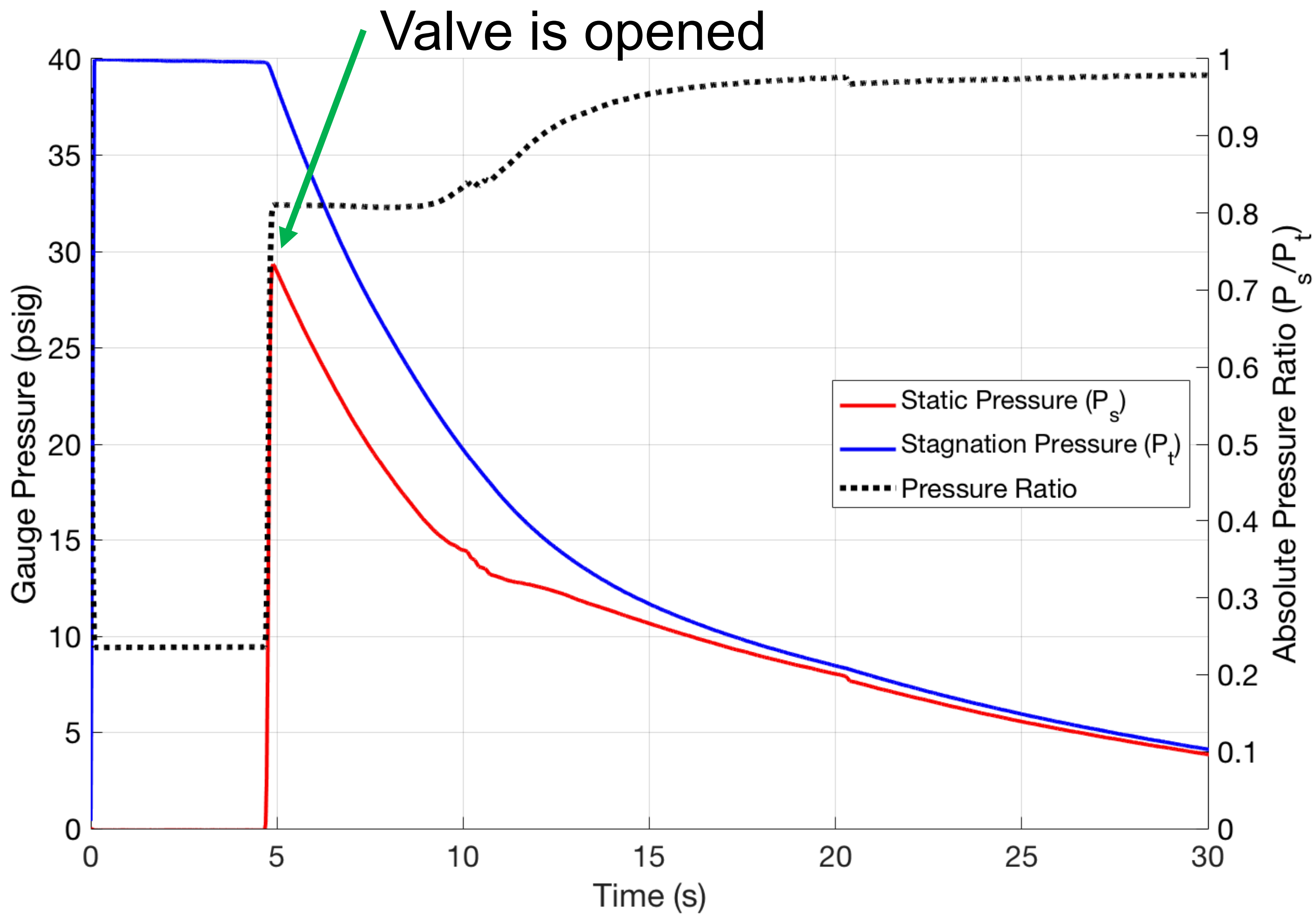
- Laser cut acrylic orifice plates to replace battery cap
  - Twenty individual circular orifices plates
  - Three mock 18650 vent caps



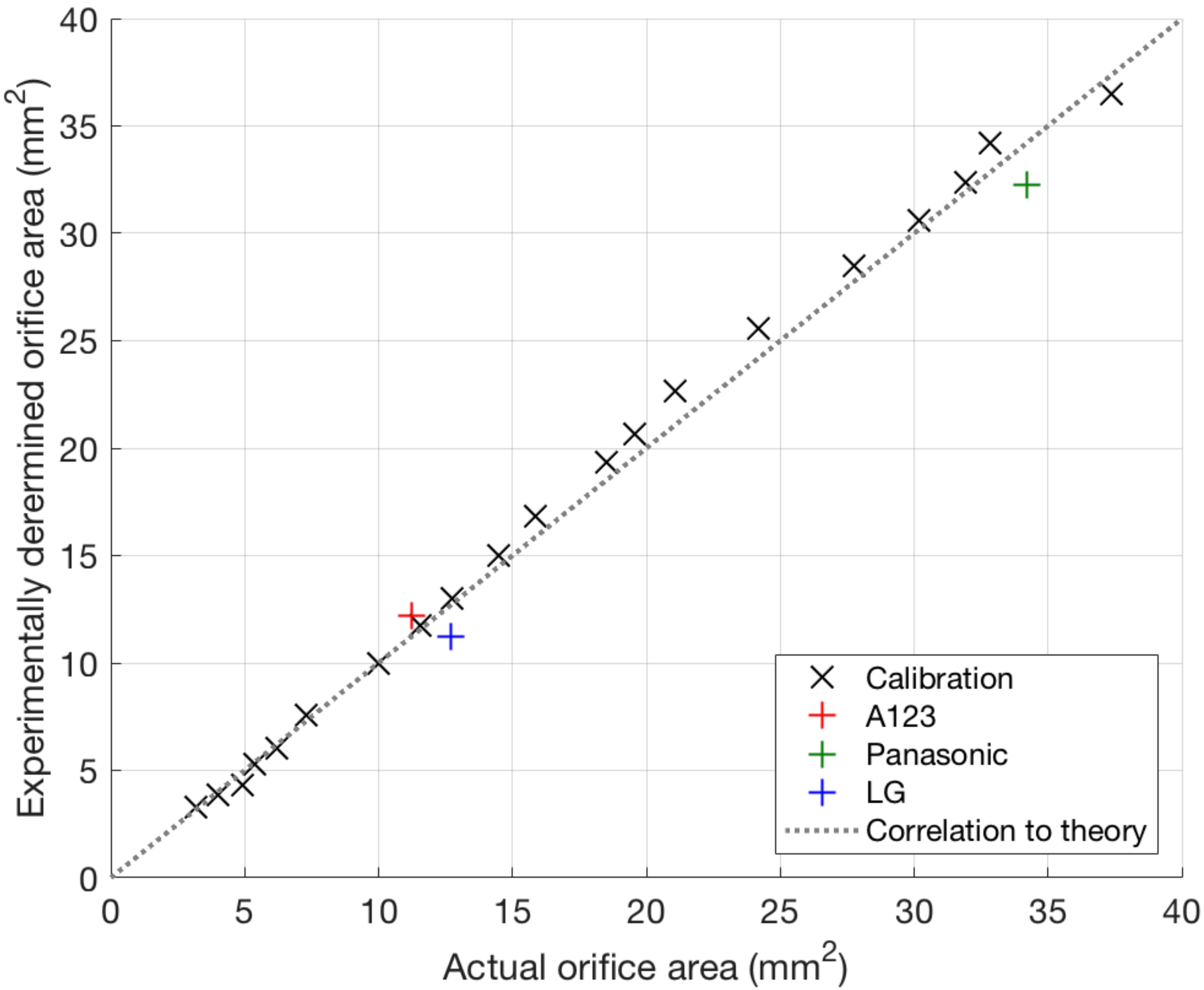
A123 LG Panasonic

- Accumulator tank pressurized to 40 psig for each test
- Manually operated ball valve to simulate vent opening

Sample of data recorded during a single validation test (mock Panasonic)



Validation test results with orifice plates

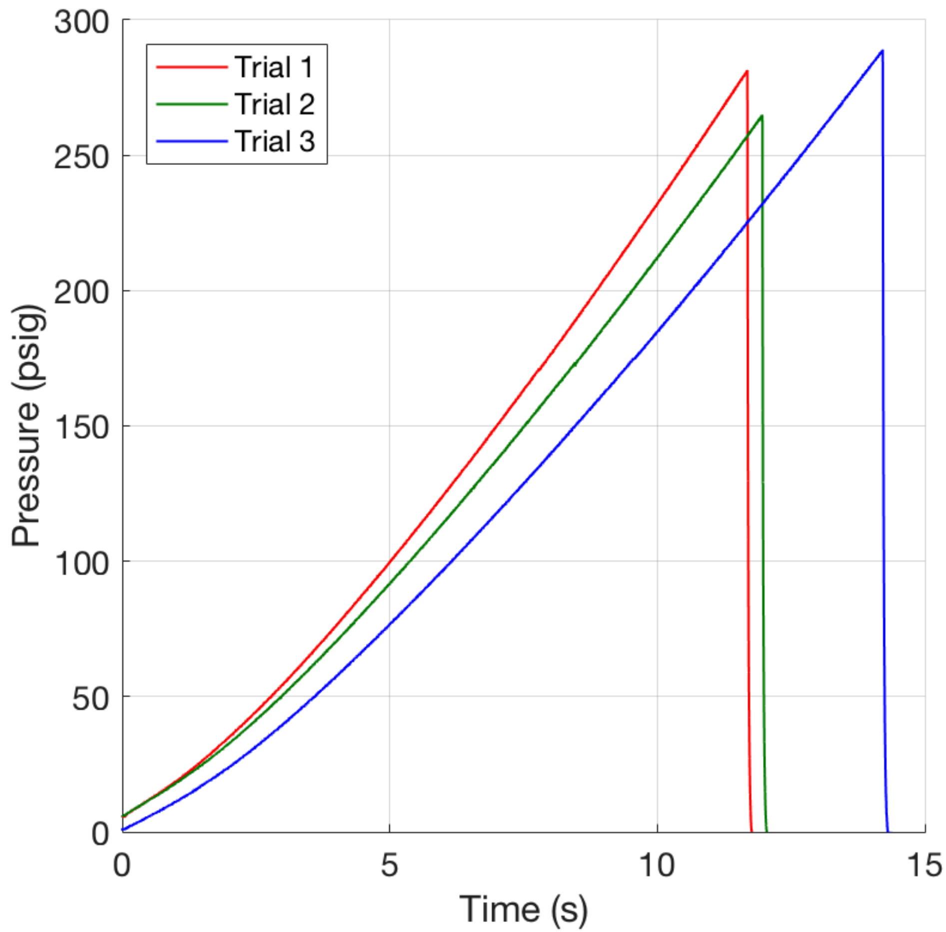


Repeated trials with orifice plates

Test	Actual area (mm^2)	Calculated area (mm^2)	Error (%)
11 Drill, Run 1	18.5	19.4	5.1
11 Drill, Run 2	18.5	19.5	5.3
11 Drill, Run 3	18.5	19.5	5.3
11 Drill, Run 4	18.5	19.6	5.9
11 Drill, Run 5	18.5	19.7	6.3
A Drill, Run 1	27.7	28.2	1.6
A Drill, Run 2	27.7	28.3	1.9
A Drill, Run 3	27.7	28.3	1.9
A Drill, Run 4	27.7	28.4	2.2
A Drill, Run 5	27.7	28.4	2.2
G Drill, Run 1	34.5	34.4	0.4
G Drill, Run 2	34.5	34.4	0.4
G Drill, Run 3	34.5	34.4	0.4
G Drill, Run 4	34.5	34.4	0.4
G Drill, Run 5	34.5	34.4	0.4

Initial testing attempts with vent caps from LG HE2 (LCO) cells

- Reached accumulator tank pressure rating of 150 psig without burst
- Connected caps directly to 1,400 psig
  - Minimized flow rate with needle valves
- Caps burst at:
  1. 281.5 psig
  2. 264.5 psig
  3. 289.0 psig



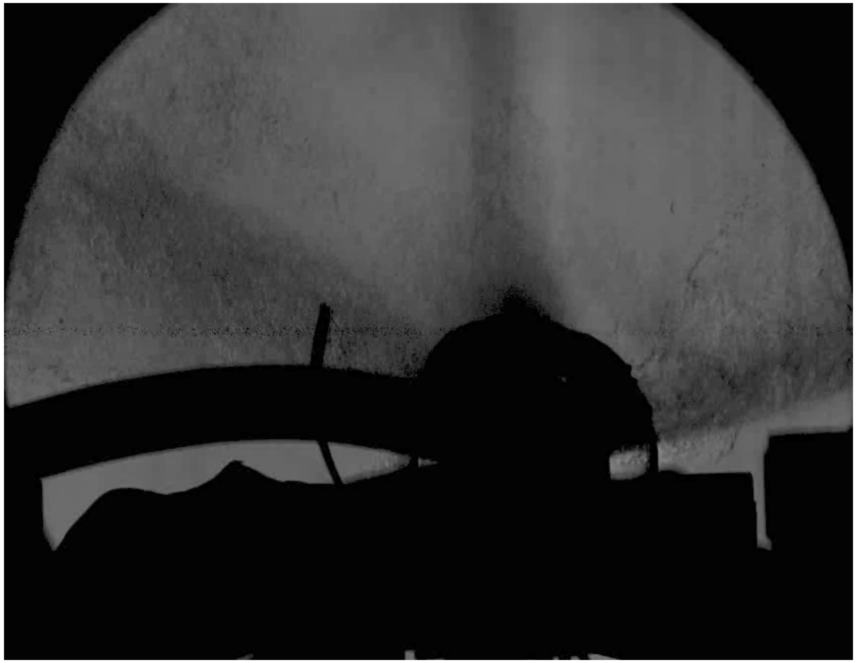
Burst vent caps remain open and are retested to calculate area

- Maximum possible opening area: 12.7 mm^2
- Calculated area of burst vents:
  1. 7.3 mm^2
  2. 7.1 mm^2
  3. 6.5 mm^2
- Not enough data to suggest trends between opening area and burst pressure

Vent opening

Quantifying internal pressure during thermal abuse tests to describe venting

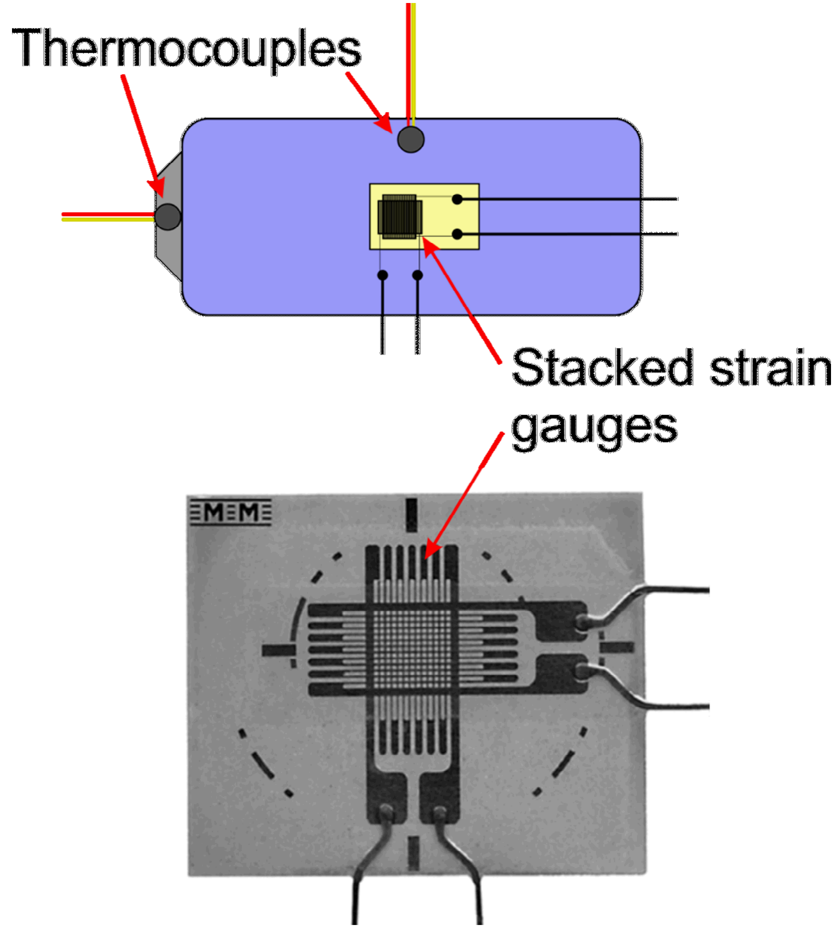
- Pressure is an important parameter in explaining gas and liquid flows
- Strain provides a non-invasive approach for pressure calculation
- Able to perform tests on live cells with various:
  - Heating rates
  - Manufacturers
  - Chemistries
  - States of charge



- LG MG1 (NMC)
- Thermal abuse
- Elapsed time: 30 ms
- Frame rate: 20 kHz

Pressure will also be inferred from two measurements of strain on the cell case

- Measuring hoop and longitudinal strain
  - Functions of temperature and pressure
- No modifications are necessary to cells which could skew results
- Can test on 18650 cells with different chemistries and manufacturers



Calculating internal pressure from strain measurements

- Strain measurements will be the sum of stress due to internal pressure and linear thermal expansion of the battery case:
  - Circumferential component:

$$\varepsilon_{\mathrm{H}} = E\frac{PD}{2t} + \alpha dT$$

  - Longitudinal component:

$$\varepsilon_{\mathrm{L}} = E\frac{PD}{4t} + \alpha dT$$

- Since ε_H and ε_L are both measured, internal pressure (P) can be solved for:

$$P = \frac{t}{4ED}(\varepsilon_H - \varepsilon_L)$$

Considerations for internal pressure calculation

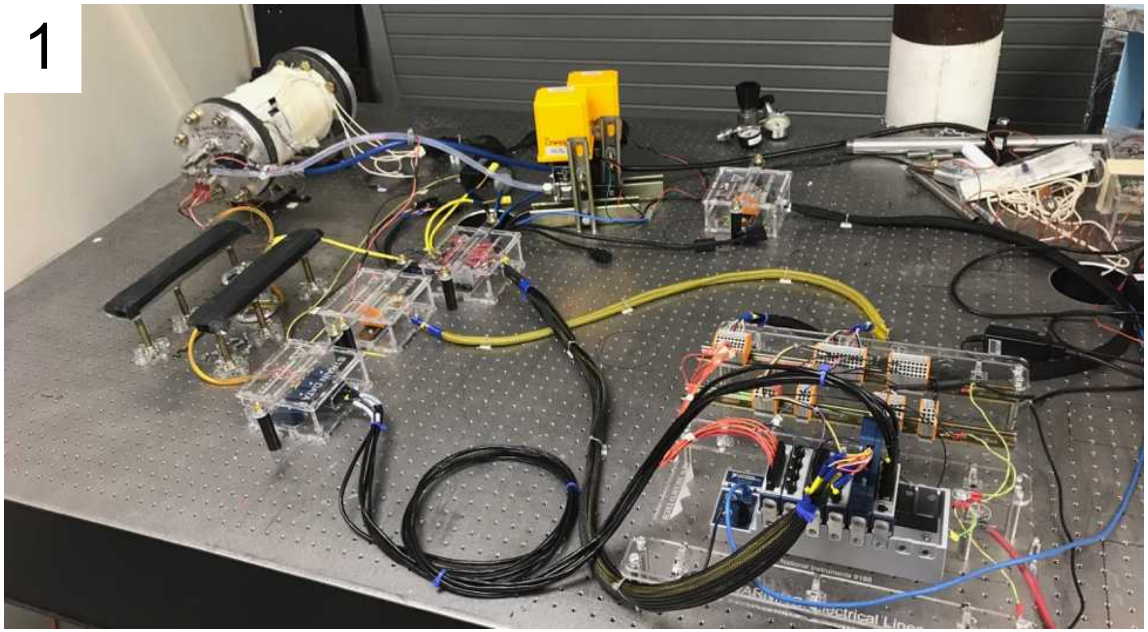
- Pressure equation:

$$P = \frac{t}{4ED}(\varepsilon_H - \varepsilon_L)$$

- Young's modulus (*E*) and case thickness (*t*) are not precisely known without further testing
- Maximum case strain and internal pressure can be assumed to occur at vent burst
  - Strain-pressure curve can be calibrated with directly measured burst pressures
- Potentially non-uniform pressure inside cells due to localized internal failure locations
  - To be addressed by measuring multiple pairs of strain gauges located in different locations on the battery

Laboratory setup installed at NMT

1



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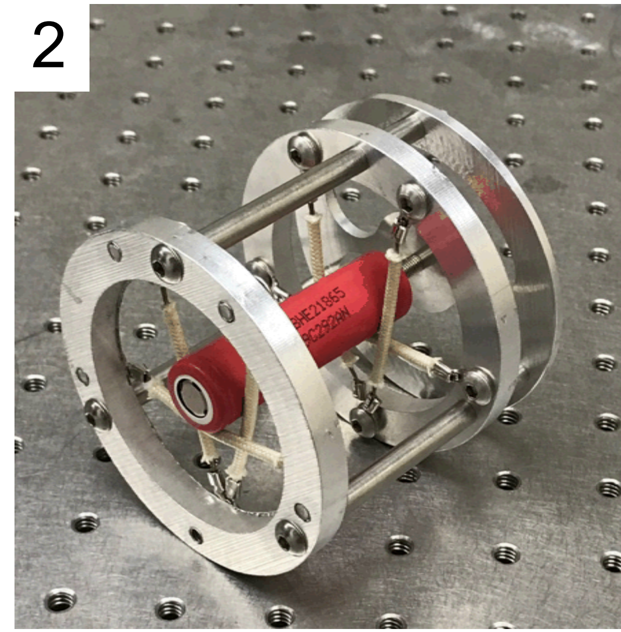

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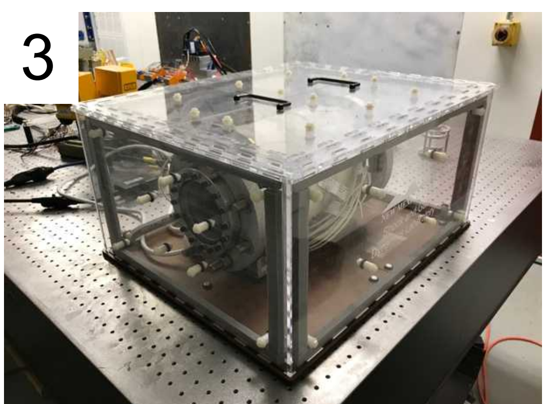

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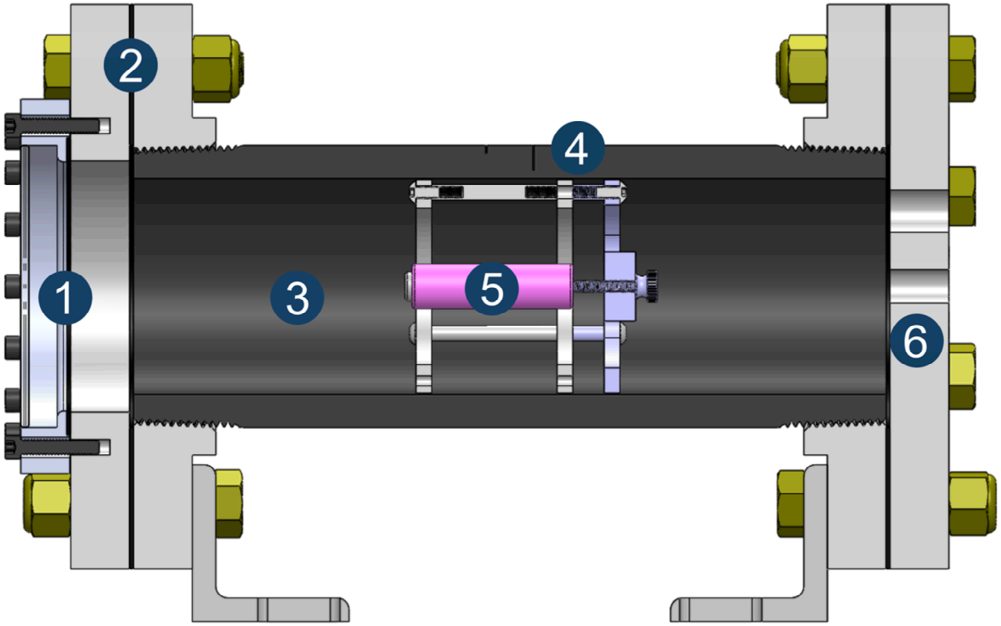
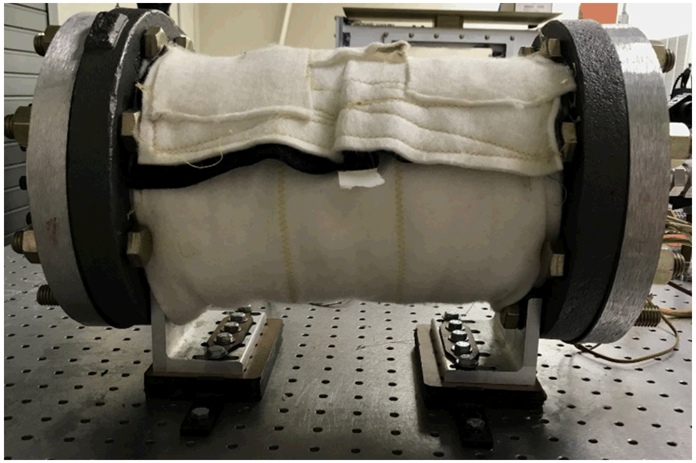
1. Lab overview
2. Battery holder
3. Chamber with insulation box
4. Window view

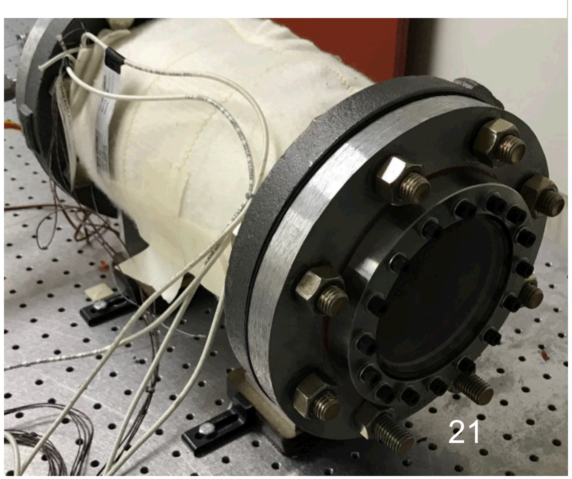
Test chamber for strain measurement experiments



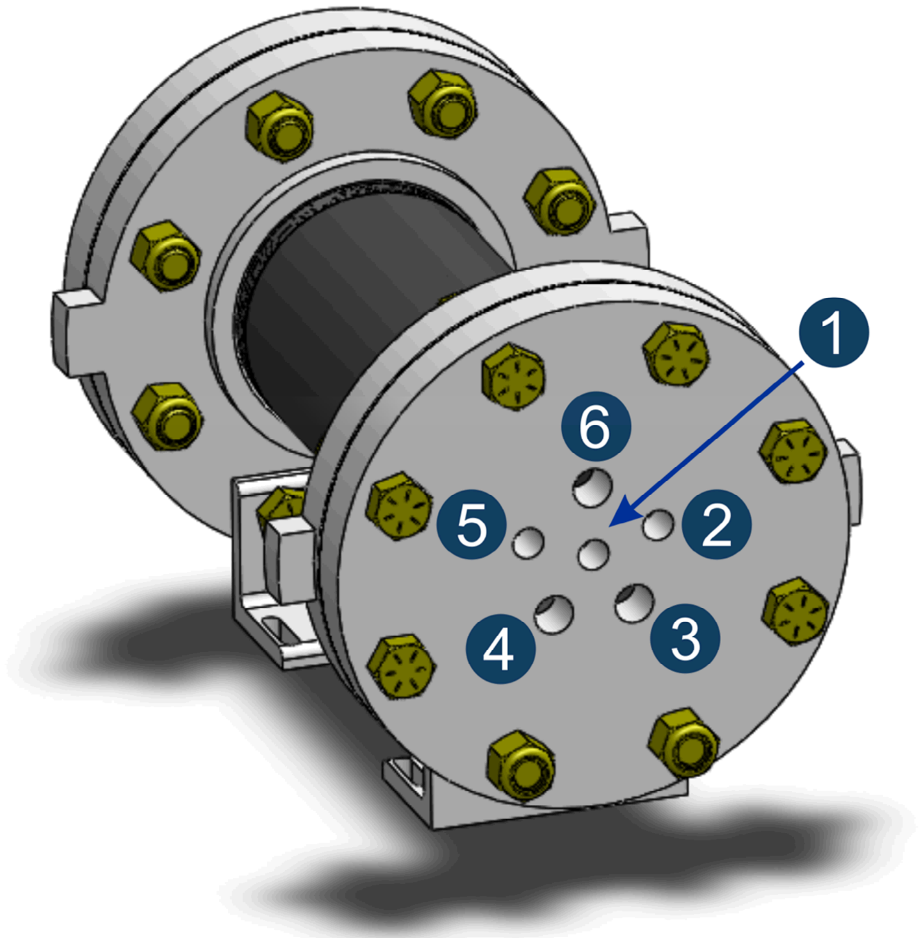
Features:

1. Viewing window
2. Sealed flange ends
3. 4 NPT steep pipe with heater wrap
4. Embedded thermocouples to measure heat flux
5. 18650 format cell with attached strain gauge
6. Ports for instrumentation

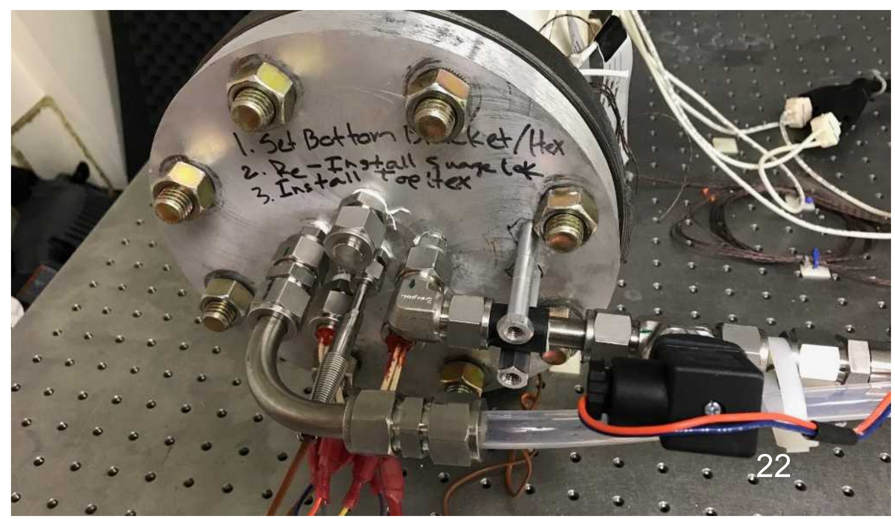




Test chamber end-cap instrumentation ports



Port Number:
1. Gas temperature
2. Purge inlet
3. Strain gauge hoop
4. Strain gauge longitudinal
5. Purge outlet
6. Battery surface thermocouples



Data acquisition system details

Thermocouples:

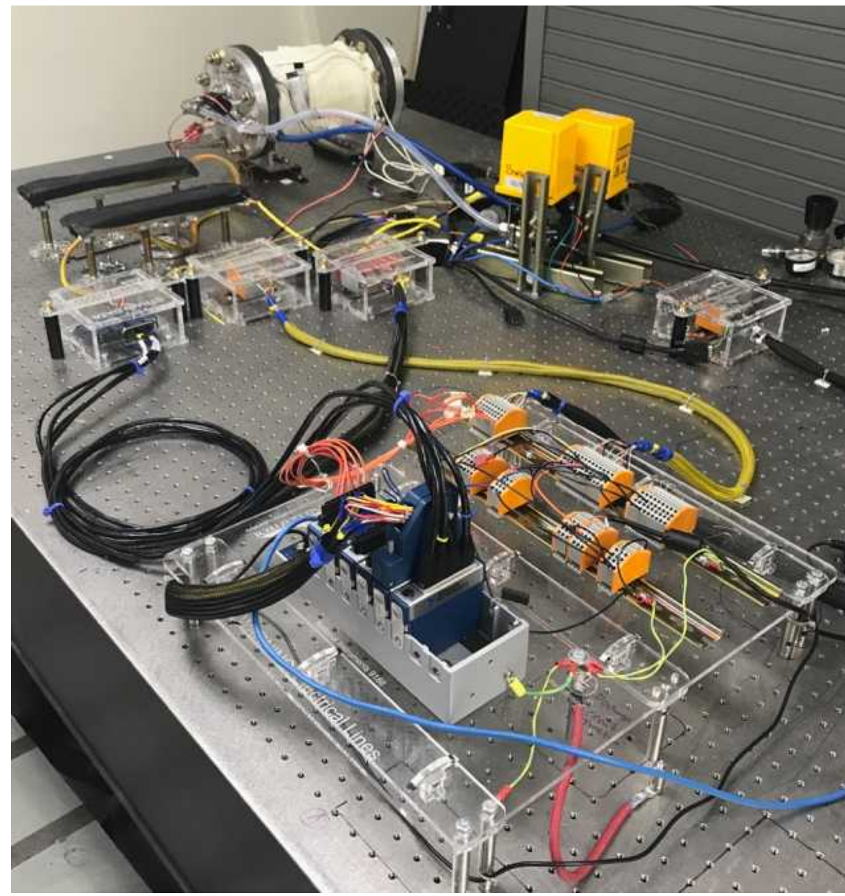
- Heat flux through pipe
- Gas temperature
- Battery terminal
- Battery side

Strain gauges:

- Hoop strain
- Longitudinal strain

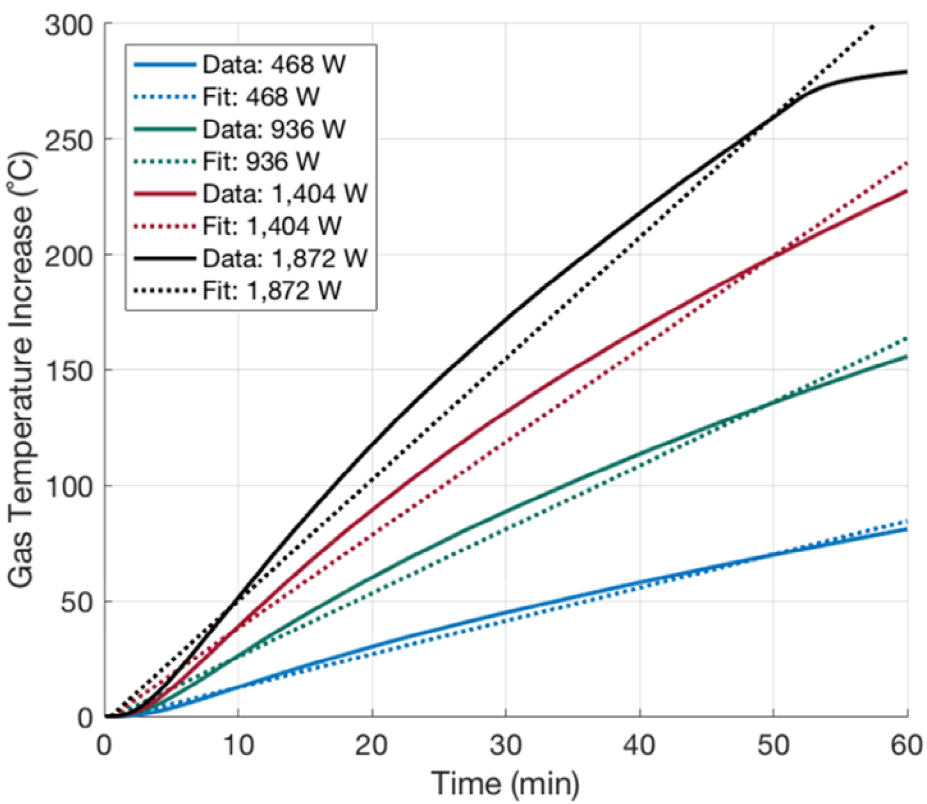
Analog voltage:

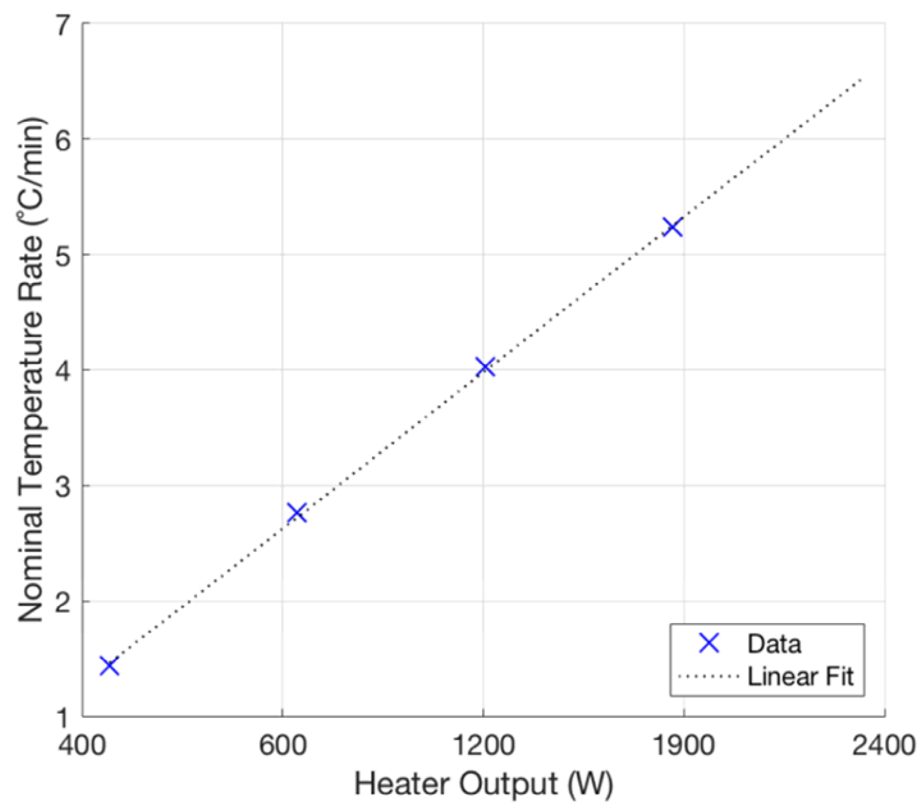
- Chamber static pressure



Calibration tests performed to determine test chamber heating rate

- Tests performed between 20% and 100% of maximum heater power of 2,340 W
- Nominal heating rate determined by linear fit





Planned trials for strain measurement experiment

Validation experiments with simplified geometries:

- 18 mm diameter, thin wall steel tube to confirm identical thermal strain
- Pressurized gas cylinder under increasing temperature as internal pressure response can be predicted accurately

Tests on LG HE2 cells at 100% SOC:

- Trial with two strain gauge pairs placed on opposite sides of battery
- Sets of three trials with single pair of gauges on cell at 2˚C/min and 5˚C/min

Progress and expected outcomes from thermal abuse and direct pressurization testing

- Designed and validated test apparatus to measure the burst pressure and opening area of vent caps from 18650 cells
- Direct pressurization tests describe when vent caps can be expected to open and how subsequent flow of gases and liquids will occur

- Fabrication and heat rate calibration for test chamber to be used for measurement of battery case strain
- Case strain measurements will give quantification of how internal pressure increases leading up to battery venting

Questions?

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