Range Safety Testing of FTS Batteries

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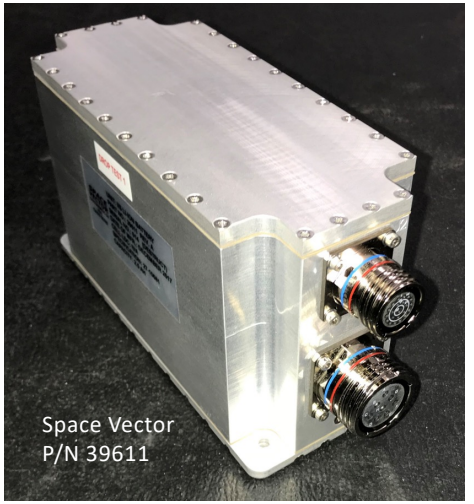
Flight Termination System (FTS) Battery

- In 2021 Space Vector completed Range Safety Testing on our smart Li-Ion Batteries that have an integrated BMS with decoupled flight mode
  - Eight 18650 cells in Series (8S-1P)
    - LG INR 18650HG2 cells were selected for their high pulse discharge capability
  - Battery Capacity 3 Ah max.
  - 28.8 Vdc nominal (33.6 Vdc – 20 Vdc)
  - Battery also previously completed qualification to RCC 319
- Five of these 39611 batteries are used to power the new Integration Instrumentation System (IIS) flown on the Minuteman III test flights out of Vandenberg SFB
  - First flight of the IIS occurred on September 6, 2022
  - IIS replaces the old MOD 7 instrumentation wafer



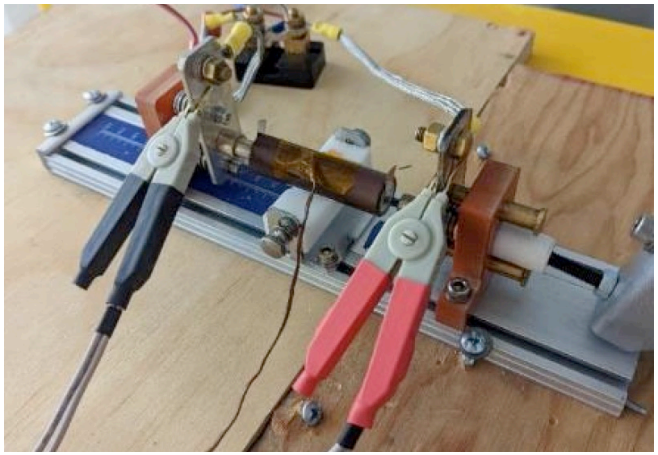
(Image credit: U.S. Air Force/Airman 1st Class Ryan Quijas)

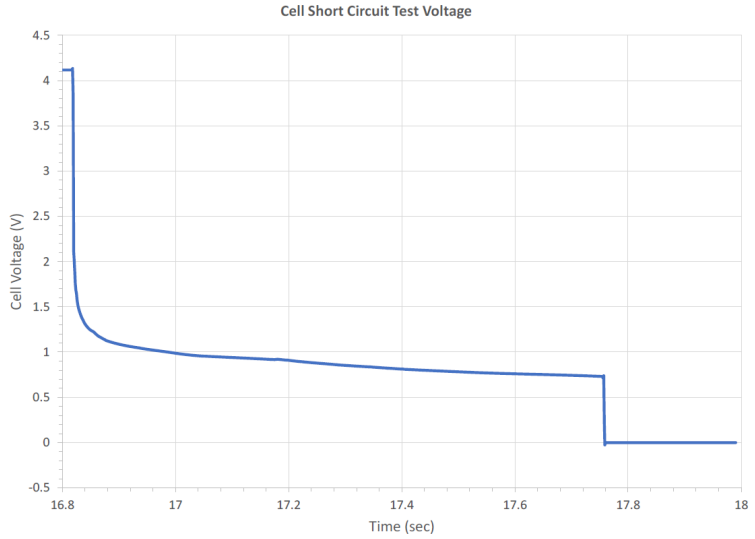
AFSCM 91-710 Safety Testing

- Safety Testing of the batteries was conducted to comply with Air Force Space Command Manual (AFSCM) 91-710, Volume 6
- Some Tests were able to be satisfied by analysis
  - CONSTANT CURRENT DISCHARGE AND REVERSAL
  - BATTERY CASE WITHSTANDING, OVERCHARGE
- BATTERY OVERCHARGE – 3 Units
  - Simply applied 47.5 Vdc and verified the Battery Management System (BMS) regulated and cut off charging at 33.6 Vdc max (non-destructive)

AFSCM 91-710 Safety Testing (Cont.)

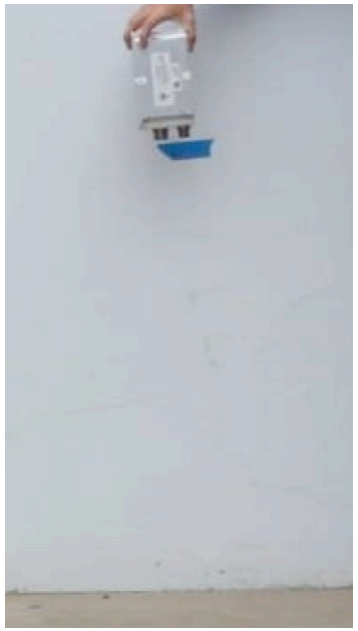
- SHORT CIRCUIT TEST – 3 Cells
  - 3 cells subjected to a short circuit of 10 mΩ (0.010 Ω) for 24 hours
  - The CID Tripped immediately when the battery was shorted
  - A single small clicking noise was heard and the voltage of the battery dropped to zero
  - No venting occurred





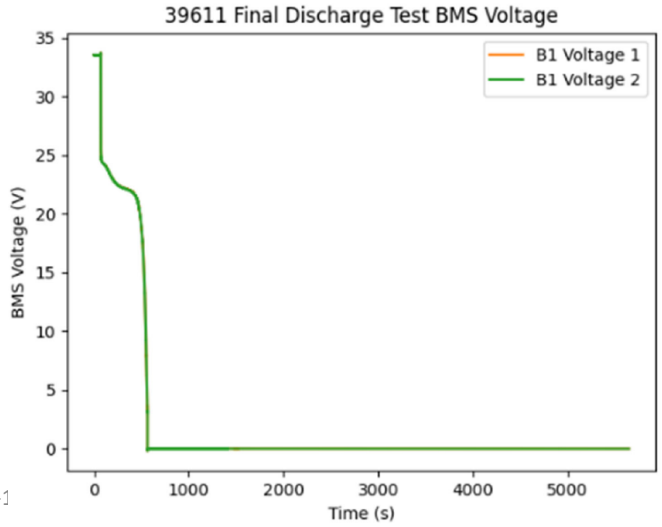
AFSCM 91-710 Safety Testing (Cont.)

- DROP TEST – 1 to 3 Units
  - Dropped the battery from 3 feet onto a concrete surface
  - Left the battery for 15 minutes after each drop and compared the OCV before and after
  - Dropping the battery from a height of 3 feet showed no observable degradation in performance
    - There was minimal material compression when dropped on the housing
    - Deformation of the housing connector was observed when dropped on the connector face
  - None of the drops caused a cell to rupture or go into thermal runaway



AFSCM 91-710 Safety Testing (Cont.)

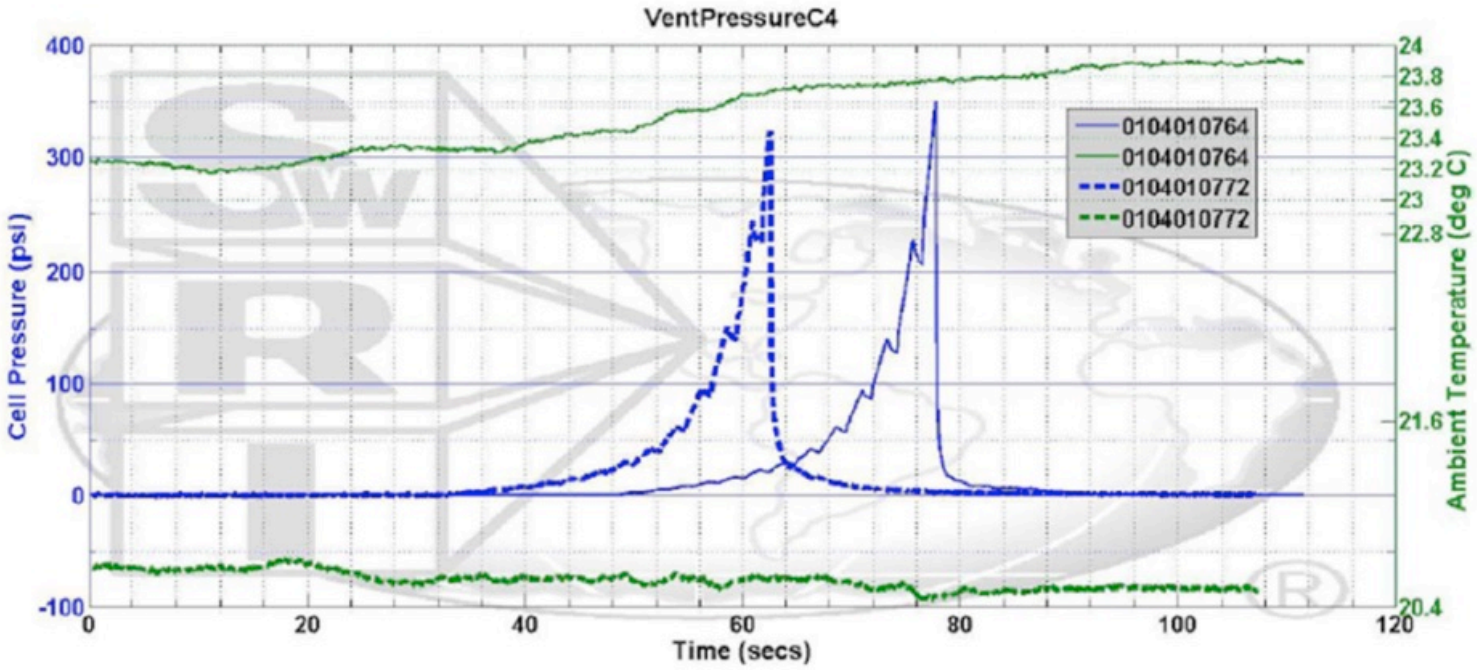
- BATTERY COMPLETE DISCHARGE – 1 Unit
  - Completely discharged the battery at the highest cell discharge rate (20A)
    - 3.0 Ah / 20 A x 3600 sec/hr = ~540 sec
  - No safety circuits were tripped
  - Battery appeared to operate normally through discharge
  - Battery did not vent or start on fire



Battery Design for AFSCM 91-710 Safety

- Driving requirement from Vandenberg Range Safety
  - Design Li battery to withstand all 8 cells venting simultaneously with a 3:1 factor of safety
  - Potential for developing high pressure in the battery with a large safety factor would require significant venting or a prohibitively beefy housing (i.e., pressure vessel)
- Created a detailed Flow Simulation to predict battery housing venting with a cell(s) going into thermal runaway
  - Only cell vent pressure data found was from a presentation made by Dr. Judith Jeevarajan formerly of NASA-JSC around 2014
  - That combined with single cell can produce 1.7 l/Ah x 3 Ah = 5.1 Liters of mostly CO2 Gas at STP per Roth-Ordendorff formed the basis of the vent analysis

Li-Ion 18650 Cell Vent Pressure Test

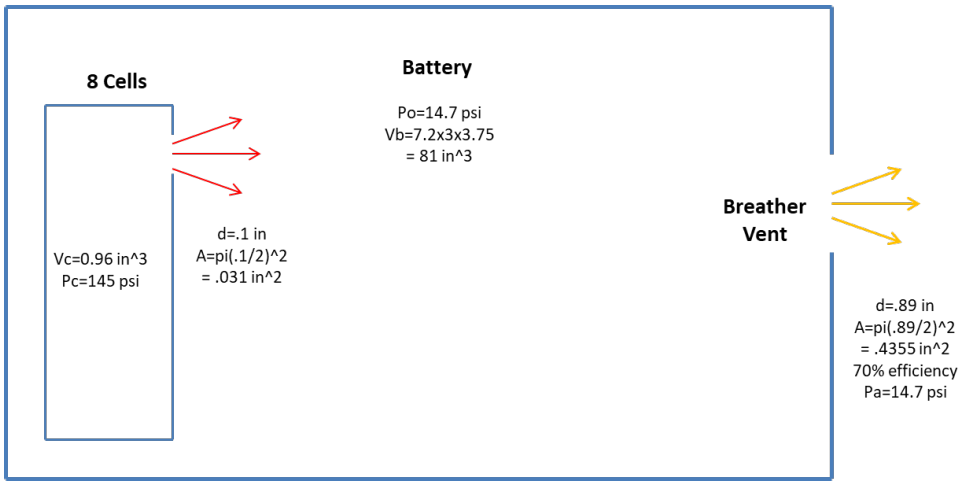


Vent Pressure Test Pressure and Ambient Temperature

Note: No details on how the runaway was inducted or the cells instrumented

Venting Analysis

- Determined a ½” to ¾” Diameter vent would be sufficient
- Procured Gore M12-1.5 (½” Dia.) and Pneuflex Sintered M16-1.5 (5/8” Dia.) breather vent elements
- Tested the flow characteristics with pressurized gaseous Nitrogen and found these vent elements to be overly restrictive
  - 8.4% and 1.4% vent efficiency, respectively wouldn’t relieve pressure build up in the housing very effectively

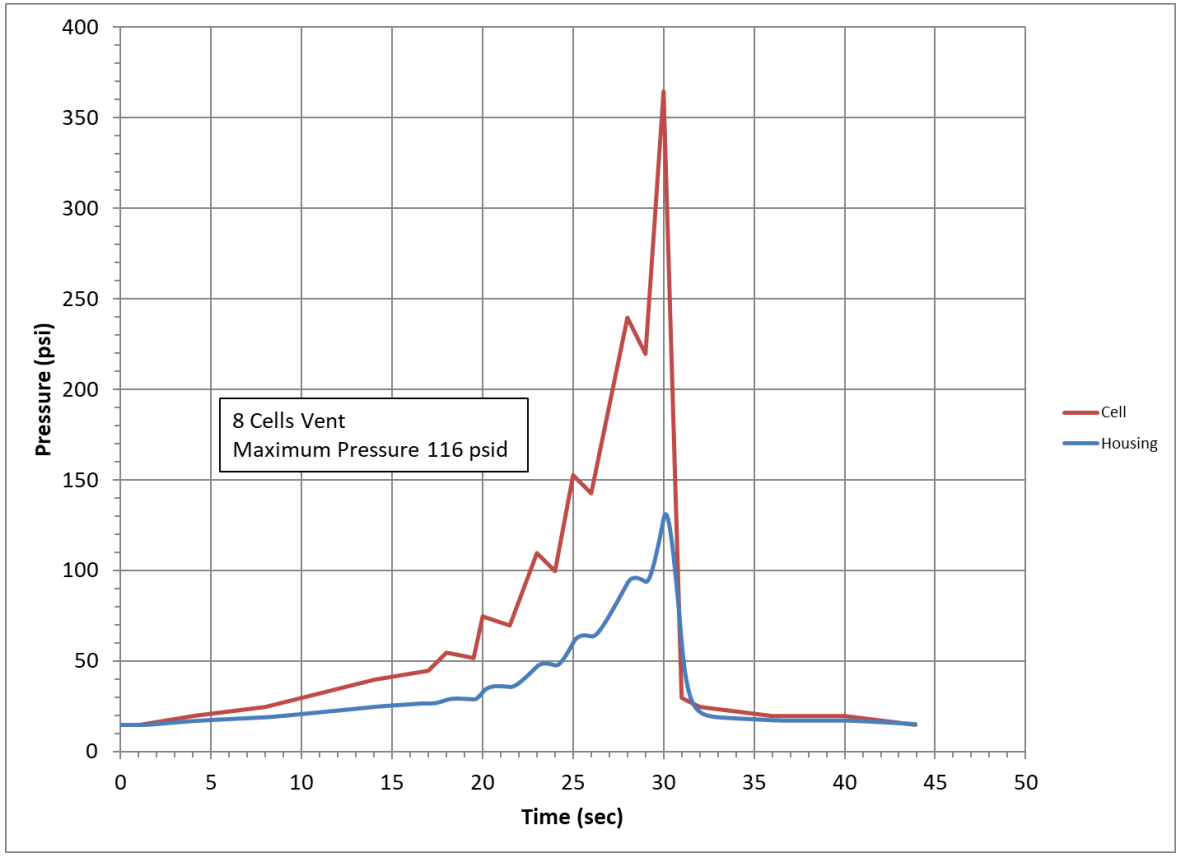


Breather Vent Flow Test Results

Pneuflex Sintered M16-1.5		
Vent ID	0.4	in
Initial Press.	300	psi
Final Press.	145	psi
Time	1.85	sec
Volume	145	in^3
Mass Flowed	0.064	lbm
Mass Flow Rate	0.035	lb/s
Flow Area	0.0106	in^2
Vent Efficiency	8.4%	

Gore M12-1.5		
Vent ID	0.315	in
Initial Press.	202	psi
Final Press.	118	psi
Time	11.66	sec
Volume	145	in^3
Mass Flowed	0.035	lbm
Mass Flow Rate	0.003	lb/s
Flow Area	0.0011	in^2
Vent Efficiency	1.4%	

Prediction of Pressure Rise in Housing

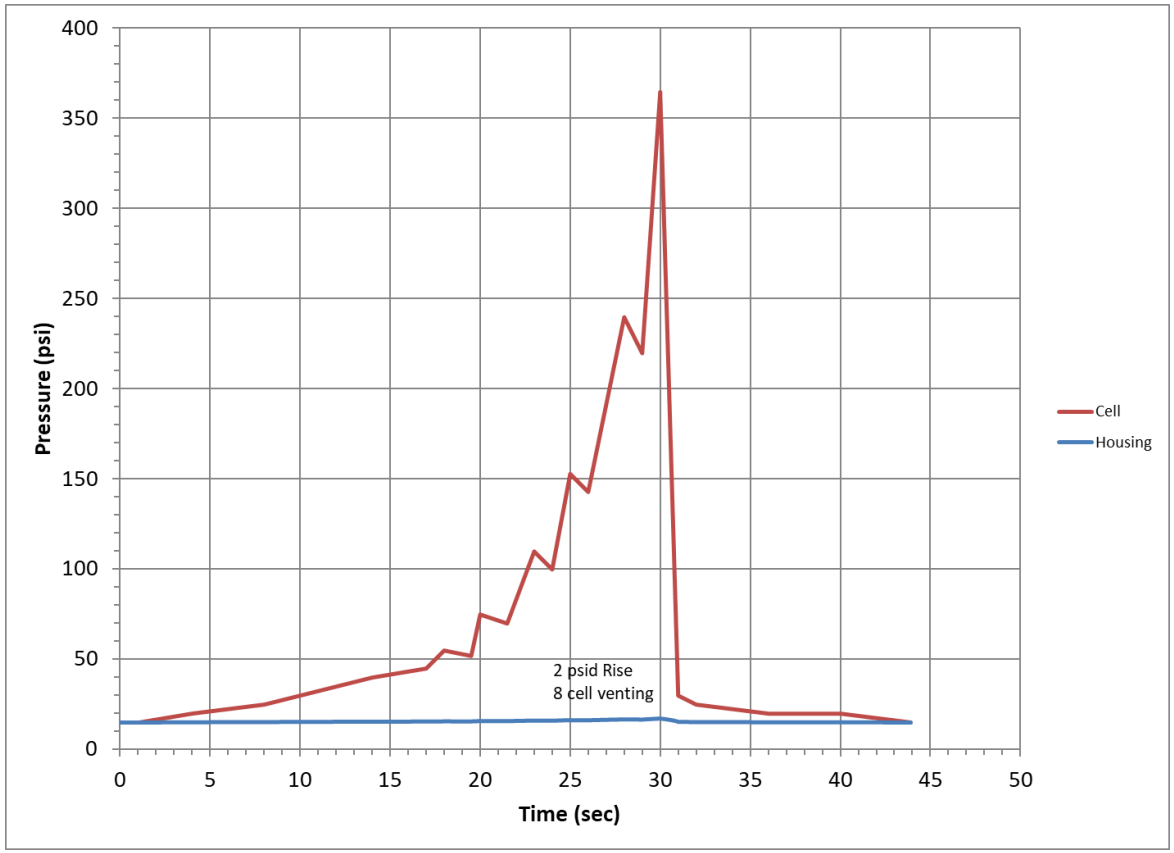


Pneuflex Sintered Stainless Steel breather vent

If 8 cells vent simultaneously, housing would fail with required 3:1 Factor of Safety

Structural Analysis predicted the housing would take about 200 psid pressure buildup

Prediction of Pressure Rise in Housing



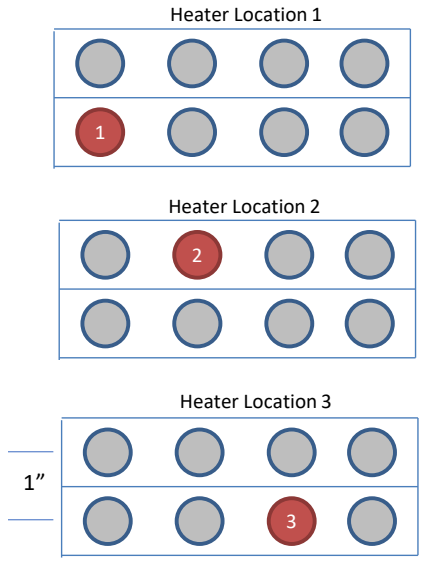
1” Screened Vent

Predicted minimal rise with 8 cells venting simultaneously

Battery also had EMI/EMC requirements to consider

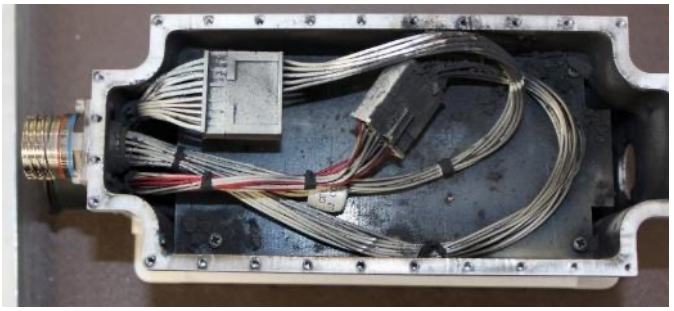
AFSCM 91-710 Cell Propagation Safety Test

- Fabricated 3 batteries with a Kapton resistive cell heater (86Ω) wrapped around a single cell at different locations
- Using a power supply set to ~52 V (31 W) and slowly raised the cell temperature until induced thermal runaway (~1 hour)
  - Increase voltage on subsequent tests to induce runaway in ~15 minutes
- Results
  - Battery housings did not rupture
  - The cell thermal runaway did not propagate to any other cells in the pack or to any other part of the system
    - Used a cell spacing of 1.0” (25 mm) center-to-center or .28” (7mm) between walls
  - The cell wrapped in the heater vented as expected
  - The remaining cells were undamaged and retained their voltage
  - Note that anything placed in front of the housing vent should be protected with flame resistant material



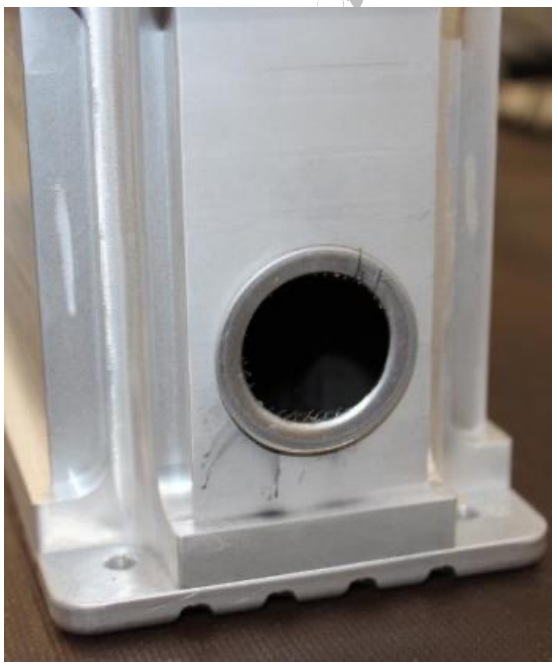
Cell Propagation Test Results

Batteries instrumented with
Pressure Transducer and Thermocouple



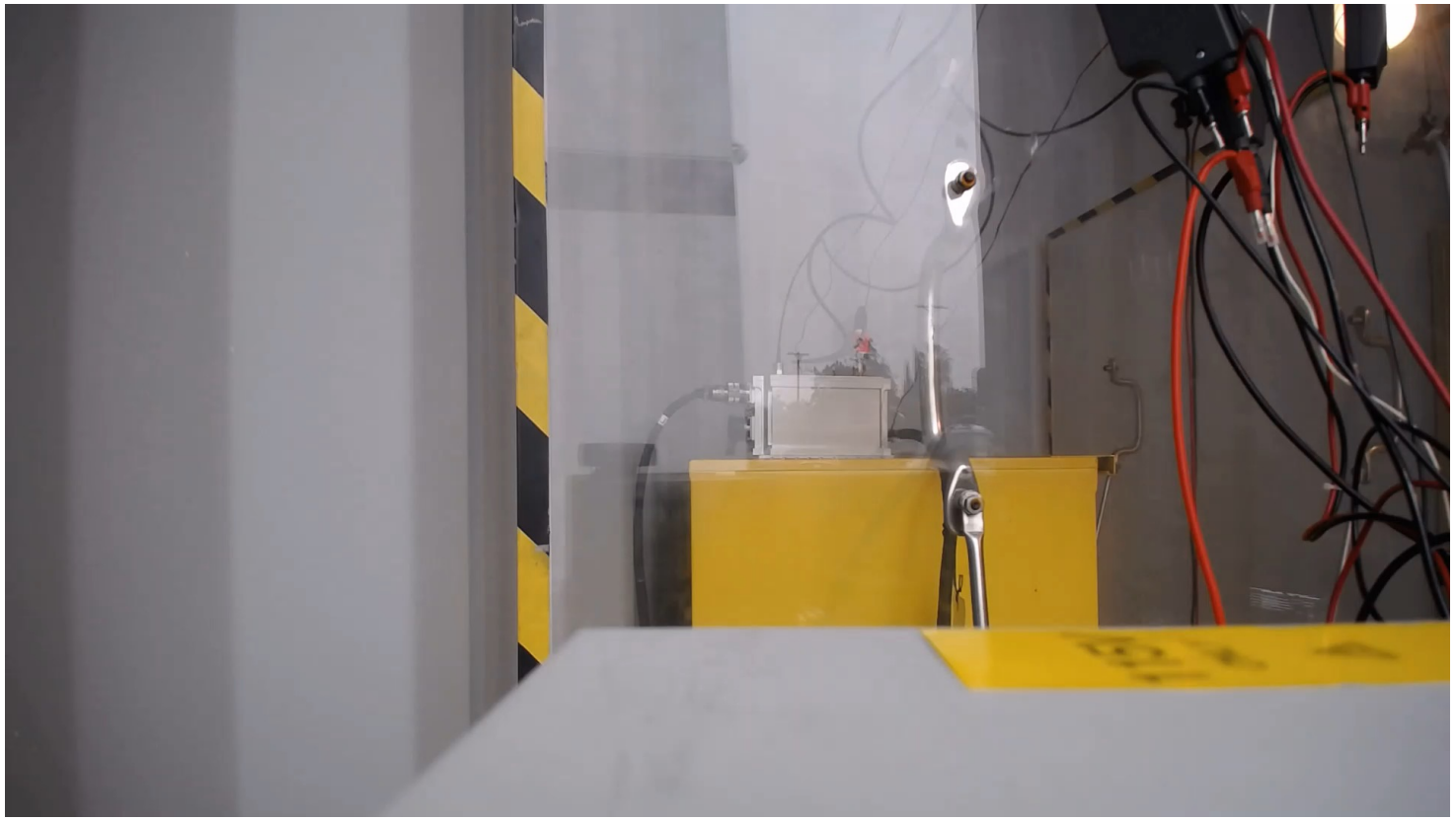
Battery internal wiring and connectors remained intact

Cell tab interconnects remained in contact
for all cells including the vented cell
No propagation was observed

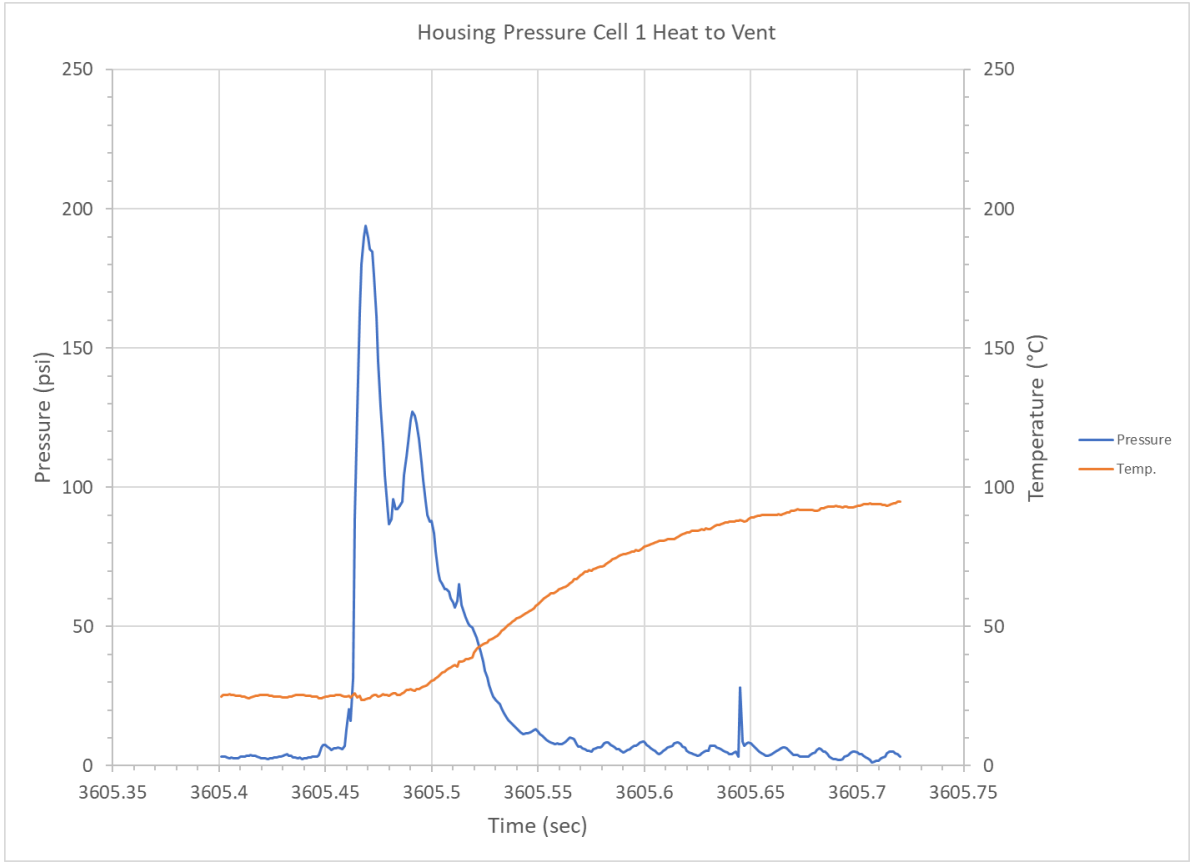


Oxidization of Aluminum screen
after cell vent process

Cell 1 Vent Test Video



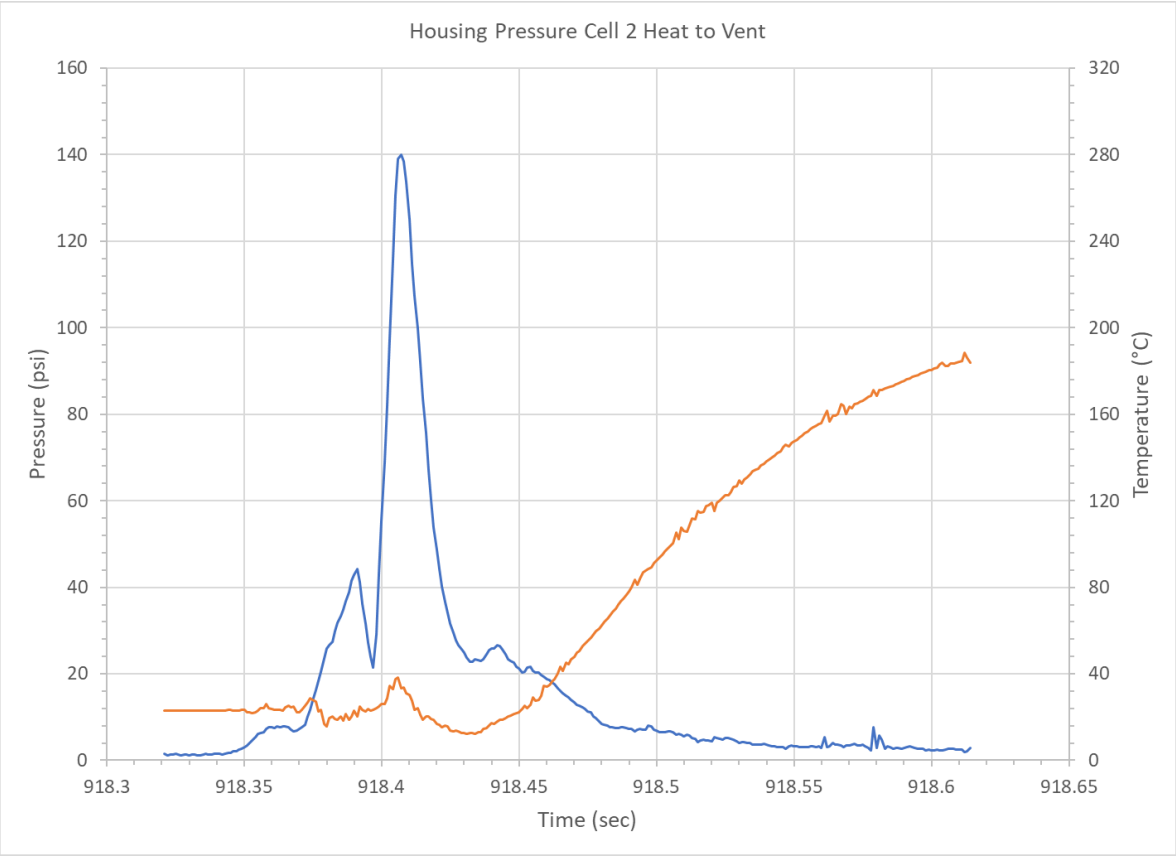
Cell 1 Housing Vent Test Data



Pressure rise in housing was nearly Instantaneous

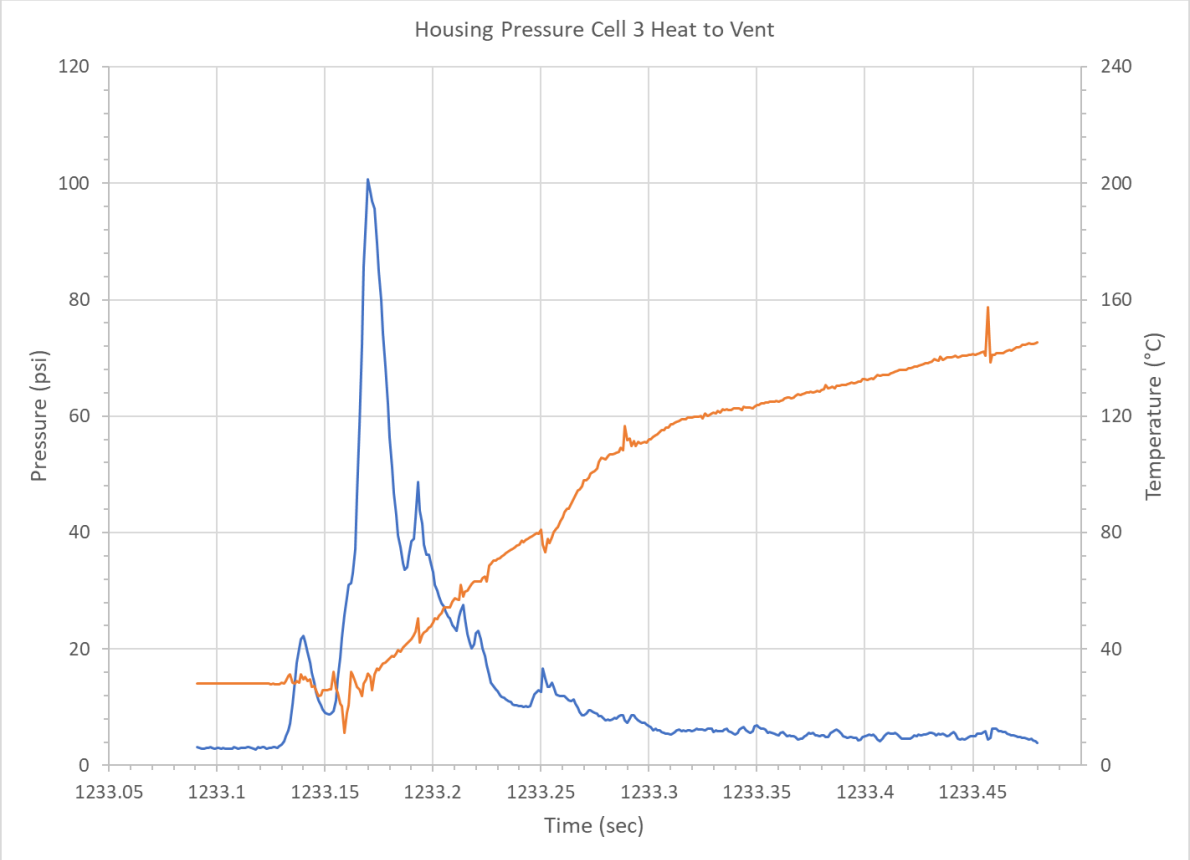
Cell 2 Vent Test Video

Cell 2 Vent Test Data



Cell 3 Vent Test Video

Cell 3 Vent Test Data

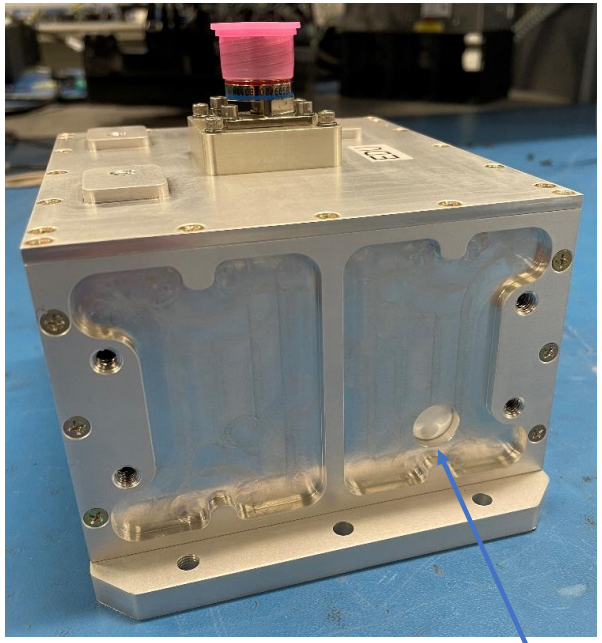


Venting Data Analysis

- Pressure developed in housing much more rapidly than assumed in venting analysis
  - Measured pressure developed nearly instantaneously in ~0.075 seconds (75 ms)
  - Analysis used ~20 second pressure build up based on a single set of data circa 2014
- If battery was more sealed or had smaller vent, pressure would have increased dramatically potentially causing catastrophic failure of the housing
- Difference in rate may be explained by how thermal runaway was induced in the cell
  - Cell heating rate or using a different method like shorting may likely provide different results
  - The wrapped cell method caused a near instantaneous release of gas

Conclusions and Recommendations

- Wrapping a cell in a heater element may not be a great way to induce thermal runaway
  - But it is often the only straightforward way to induce venting during battery safety testing
- Try to maintain adequate cell spacing in the battery to avoid propagation into adjacent cells
- Do not assume breather vents will have sufficient flow to adequately vent battery
  - Space Vector also employs a ½” hole covered by a PTFE membrane that can simply blow out if a cell vents



Li Primary Battery P/N 39161
72 cells (12S-6P)