Internal Short Failure Investigation for the Li-ion Battery for the Spacesuit

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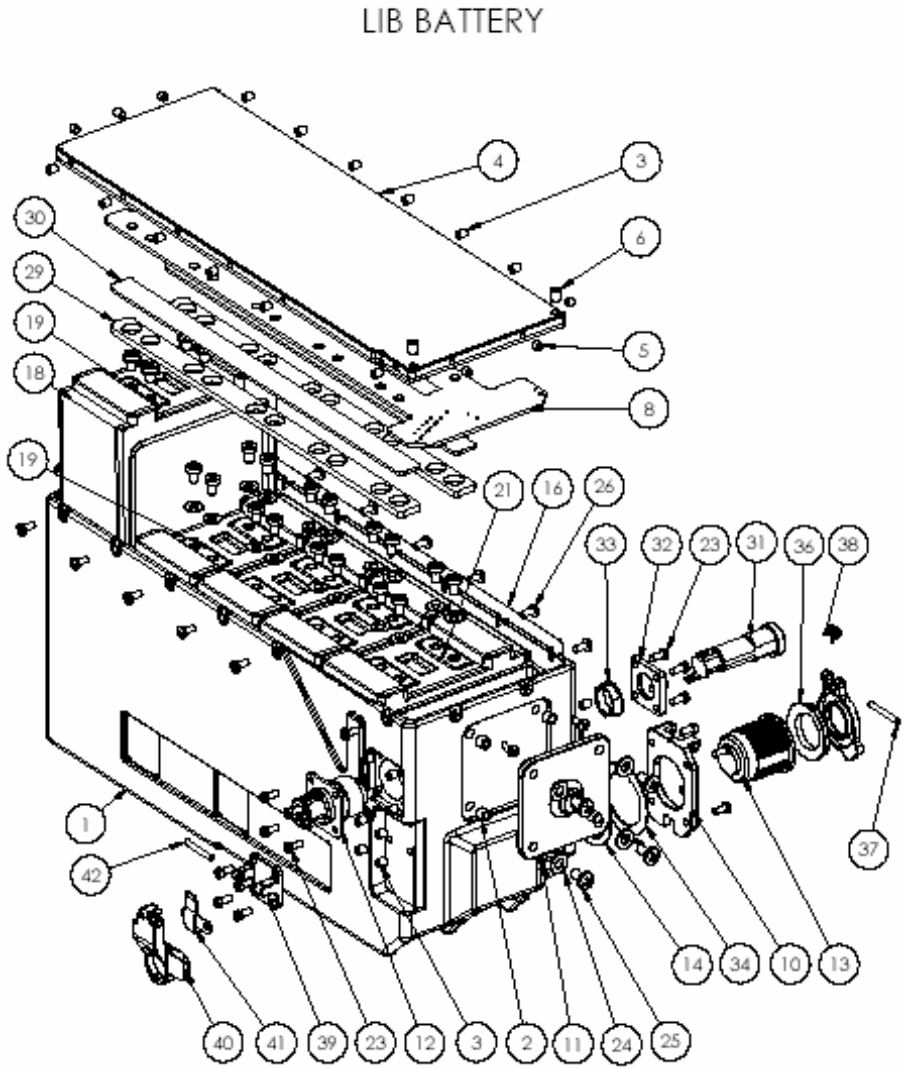
Introduction and Outline

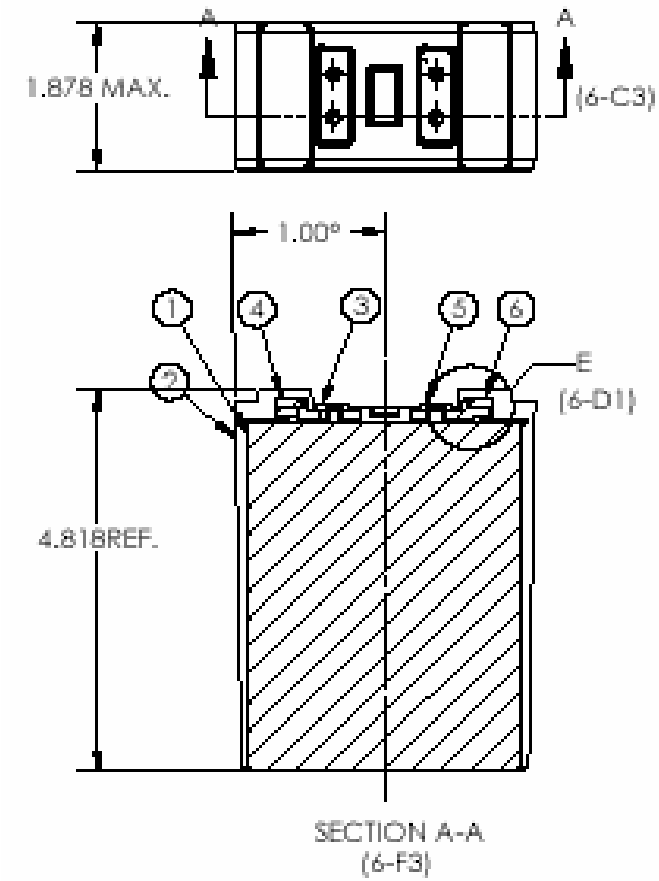
- Objective – To share results of our investigation into an internal short failure of the spacesuit Li-ion battery and lessons learned
- Background
  - LIB S/N 1010 (Flight unit that had passed all acceptance testing in Oct 05) was brought out of storage to support power quality testing of the LIB Charger on 2/2/06 and one of its five cell modules was reading 10 mV instead of 3.78V
  - Investigation quickly determined that root cause were shorts internal to a cell
- Details of the investigation of the most probable root causes
- Proposed corrective actions
- Lessons Learned

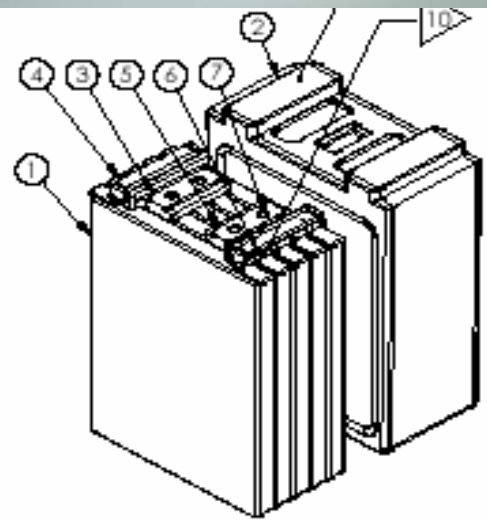
Expanded View of the LIB



- Aluminum housing and lid ass'y
- Discharge and Charge connectors
- 20.5V, 38Ah at BOL, 15.3 lbs
- 5 Cell Modules in series
- 1 Cell Module = 5 cells in parallel
- Achieving at battery level
  - >200 Wh/L
  - >100 Wh/kg

Cell Module





Outer pouch, omitted for clarity, encloses the 5 cells

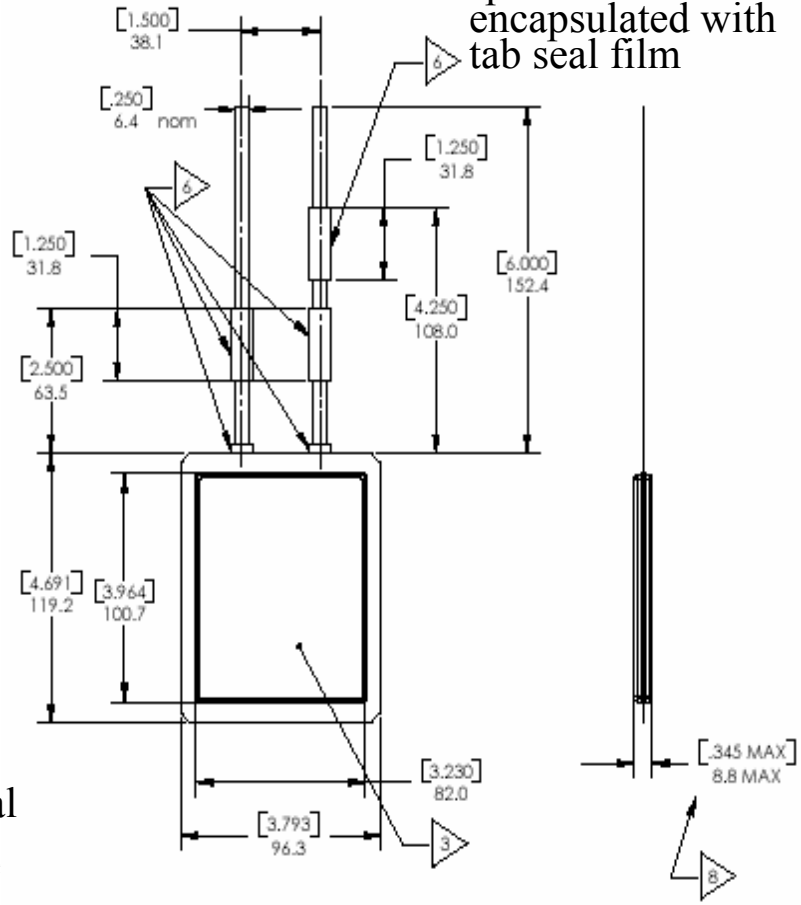
Sacrificial solvent (EC, DMC) stored in plastic bag next to wide face of 5th cell

(EC acts as dessicant while DMC's high vapor pressure lowers the diffusion gradient)

NASA LIB Cell

Mass ~ 160 g

Al-Ni tab RSW splice connection encapsulated with tab seal film



Utilizing pouch cell technology

- Lithiated carbon anode
- Lithium cobalt oxide cathode
- Liquid electrolyte imbedded in polymer in separator and active material
- Plasticized aluminum pouch enclosure

Removal of Cell Modules from LIB 1010 Housing

- Removal was difficult because of pressure build-up in cell module 1
  - Had to fasten a lexan board to terminals of a neighboring cell module to get enough leverage for removal
- Once removed, cell module 1 showed obvious puffing
  - Mass was measured at 964g (lost 2g since assembly at Electrovaya)
  - Thickness measurement was 62 mm (vs 47 mm at assembly)
    - Thickness grew after moving it to the AC Impedance test set up
  - 1 kHz AC impedance = 17 mohms (vs 7-8 mohms for the others, as expected)
  - No odor detected

Cell Module 1

What cause this severe internal gassing?

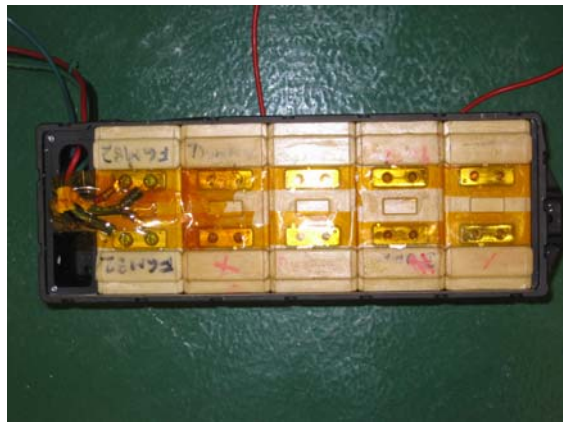
- None of the cell modules behaved this way during the abuse testing of the lot certification effort
  - Short circuit
  - Overcharge
  - Overdischarge
  - Ovenheating
- No evidence exists that cell module 1 experienced severe overheating
  - Short circuit is possible within ~150 mΩ to 1 k Ω
    - ~150 mohms would not produce overheating discoloration
    - 1 kohm requires 100 days to pull down 10Ah from the cell module
  - Overcharge - only experienced ~30 minutes of charge during power quality testing with voltage reaching a maximum of 18V (~2.6V for cell module 1)
  - Overdischarge, very likely, but our 3.8A reversal test did not produce as much swelling
  - Reversal – only 2s worth during a 9A, 2s pulse perform when cell module 1 OCV was 0.1V…it was 0.01V afterwards…and stayed there.

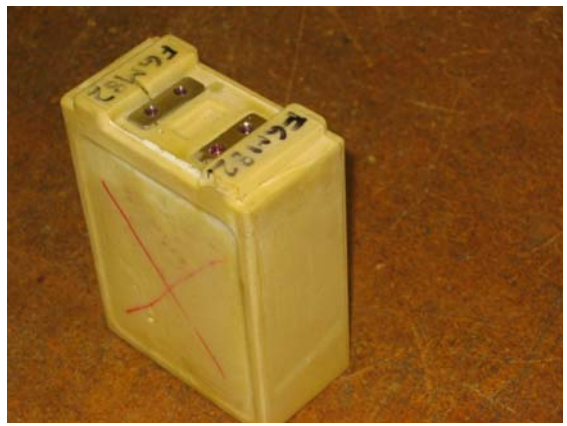
Cell Module External Short Circuit

- Cell module inside LIB housing with neighboring cell modules
- ~18 mohm, >151A peak
- Cell module leaked solvent
  - Experience swelling on the side with the solvent pouch
- Max cell module temp ~ 87C
  - Internal heating cause discoloration of the foam on the side with the solvent pouch
- No fire, no explosion, only solvent pouch leaked

Cell Module Overcharge

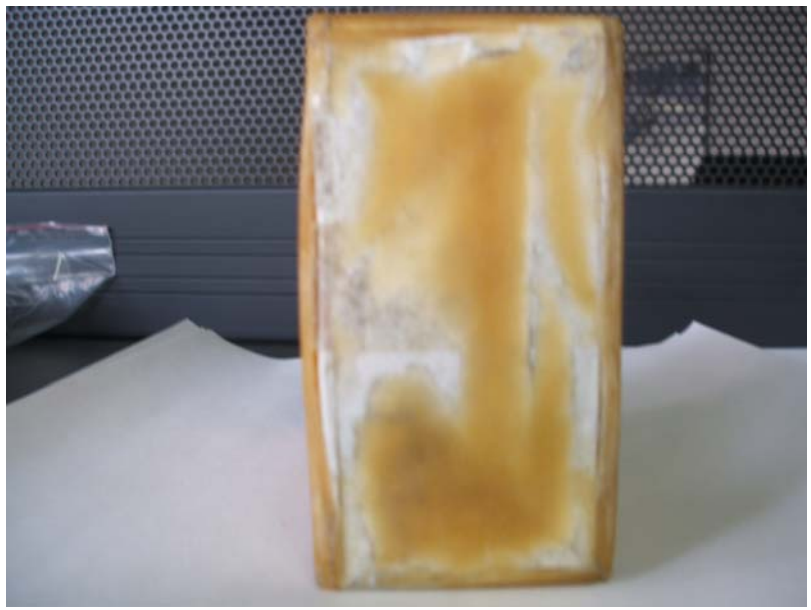
- Cell module inside LIB housing with neighboring cell modules
- Charge at CV to 4.4 with 1.5A current limit (worst case possible scenario with Shuttle airlock charger)
- Allow current to taper long enough to accumulate 13 Ah of charge at 4.4V over 48 hours
- Cell module remained intact without electrolyte leakage
  - Very minor swelling on the wide faces
- No electrolyte leakage, no fire, no explosion





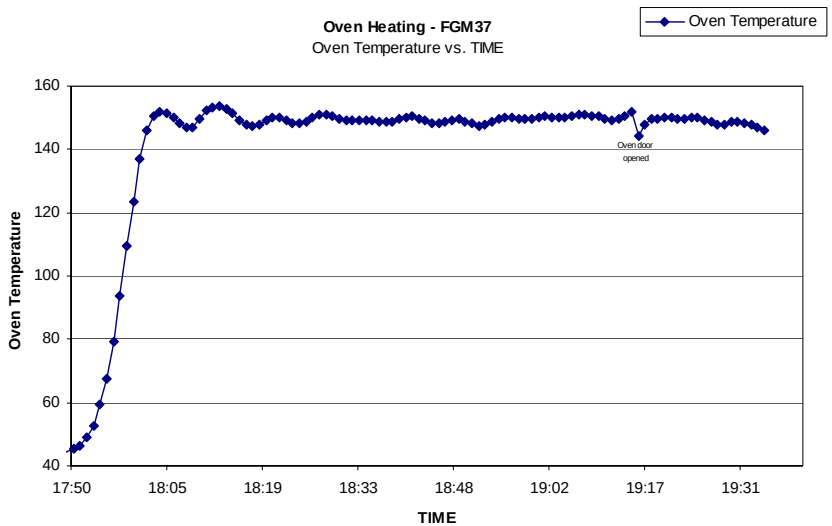
Cell Module Overdischarge

- Cell module inside LIB housing with neighboring cell modules
- Discharge to 3.0V at 3.8A
- Tare capacity, then discharge at 3.8A until 26.6Ah was removed
  - Lowest cell module voltage was -1.0V
  - At end of reversal, -0.3V
- Recharge it at 3.8A for 40Ah
  - Module voltage stayed at +0.2V
- Cell module remained intact without leakage
  - Experience some swelling on its wide faces
- No leakage, no fire, no explosion



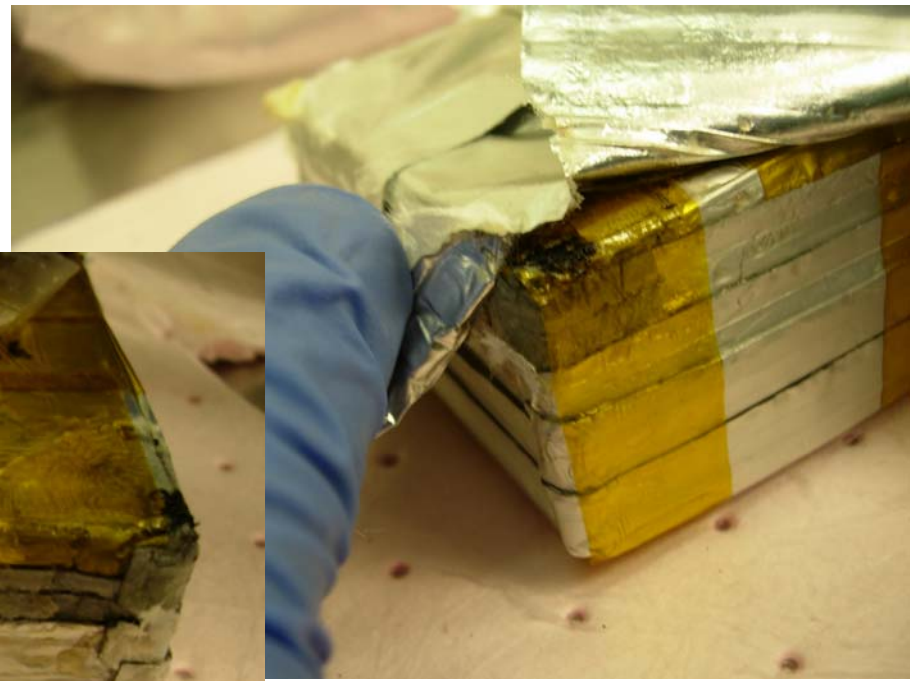
Cell Module 150ºC Exposure

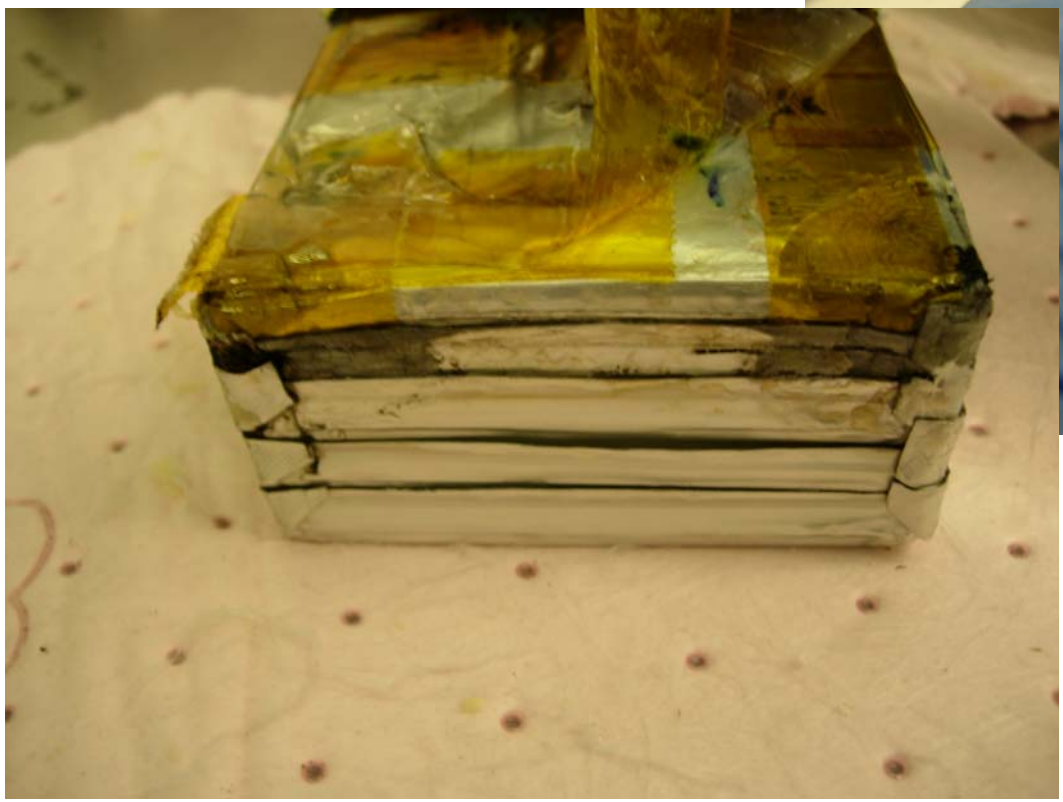
- Cell module fully charged to 4.1V with 1A taper
- Pre heated cell module to 45°C
- Placed it the oven where its skin temperature as raised to 150 °C in ~3 minutes
- Held module at 150 °C for 30 minutes
- Cell module swelled
  - Experienced outer pouch breach and slight odor
- no fire, no explosion



LIB Failure Investigation DPA results

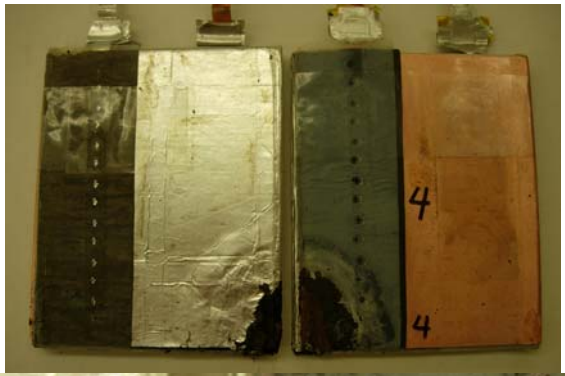
- Cut away the outer pouch to expose the 5-cell stack assembly

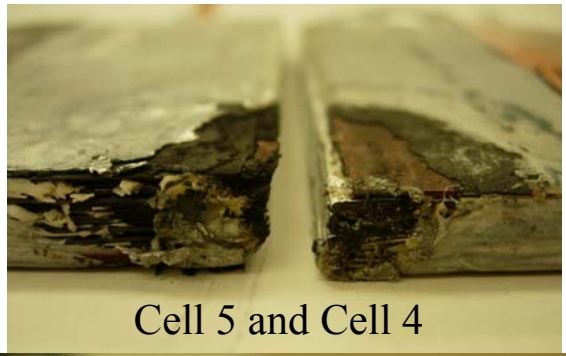




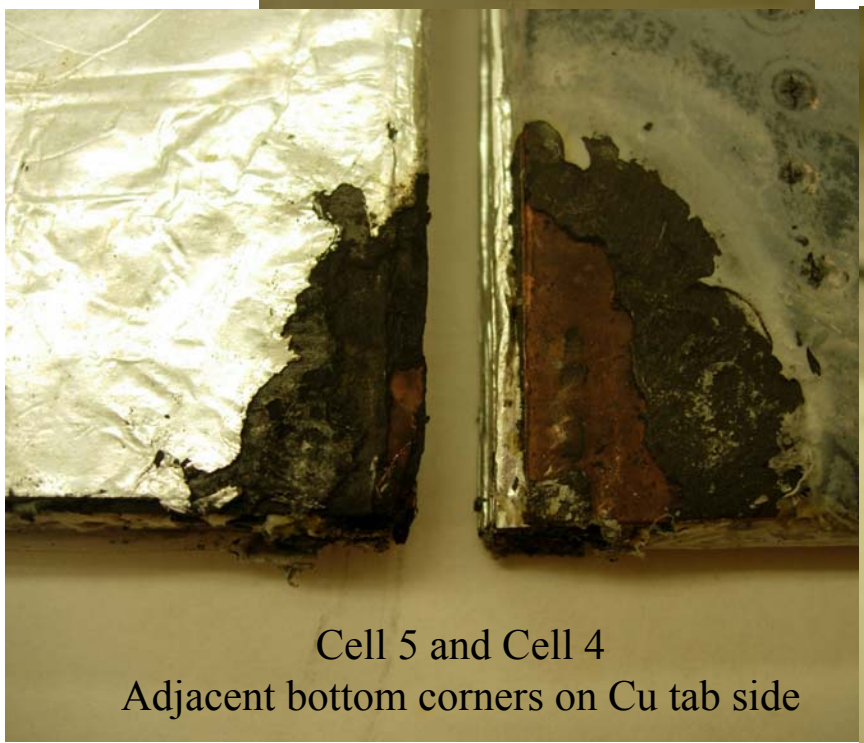
•Cell 5 pouch bottom corners show a large heat affected zone
•Cell 4 pouch bottom corners have been burned away, adhered kapton tape has melted
•Solvent pouch was intact, weighed 4 g

Cell #5 Cu tab side bottom corner appears to be ground zero

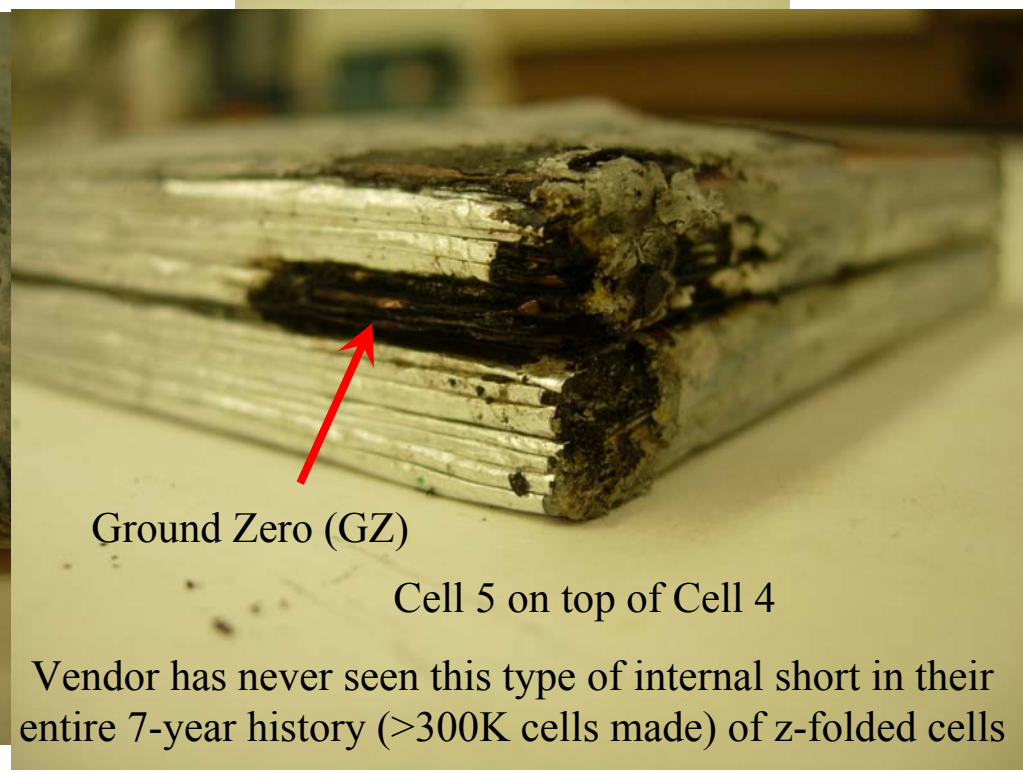




Cell 5 and Cell 4



Cell 5 and Cell 4
Adjacent bottom corners on Cu tab side

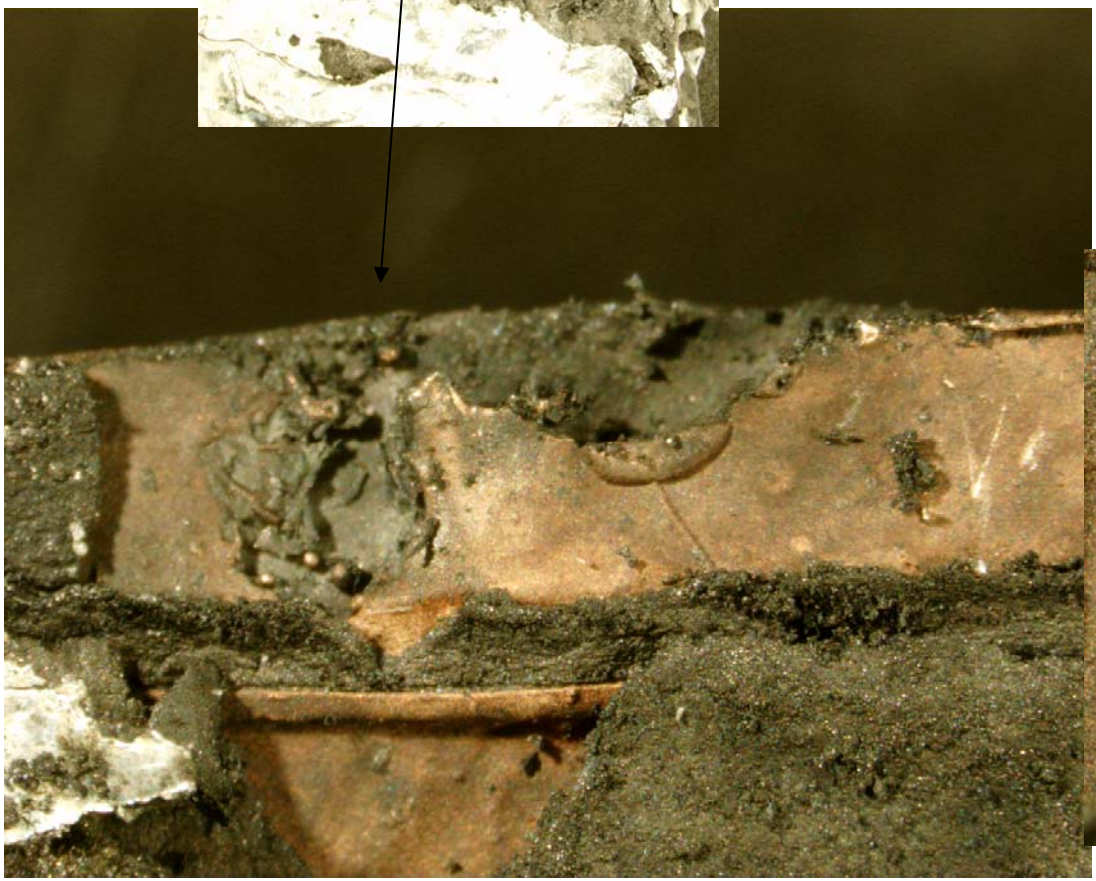


Cell 5 on top of Cell 4

Vendor has never seen this type of internal short in their entire 7-year history (>300K cells made) of z-folded cells

Cell #5 Microphotographs

Torn and molten Cu collector edge damaged by arc from short



E. Darcy/281-483-9055

Cell #5 Microphotographs

Corner opposite the "GZ" corner also experienced an internal short

Bottom with molten separator
On side adjacent to cell #4

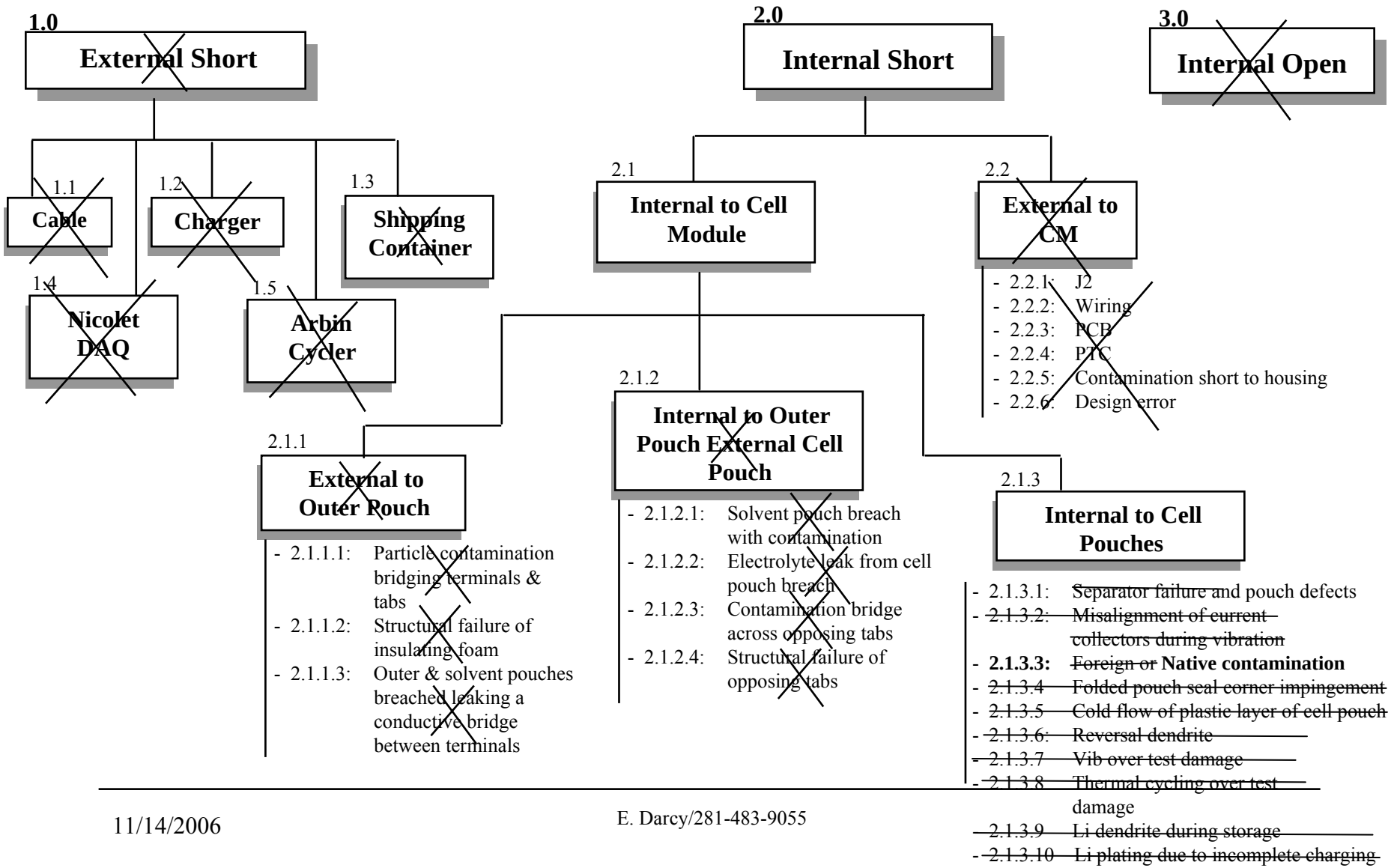
Side with outer Cu folds

E. Darcy/281-483-9055

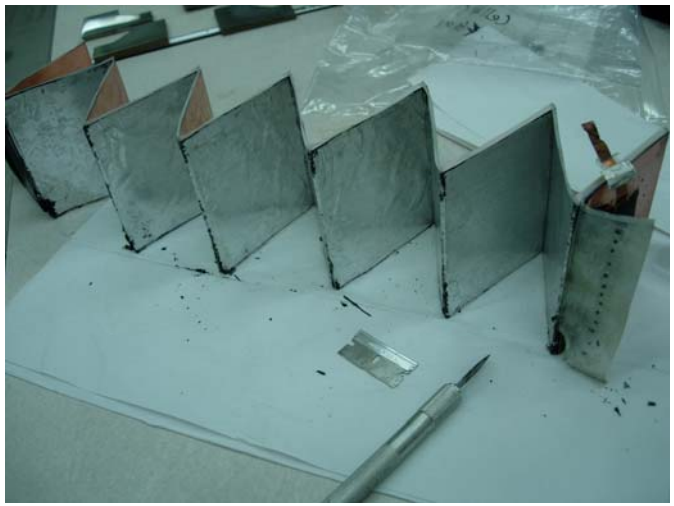
Common Facts that any Root Cause Mechanism must be consistent with

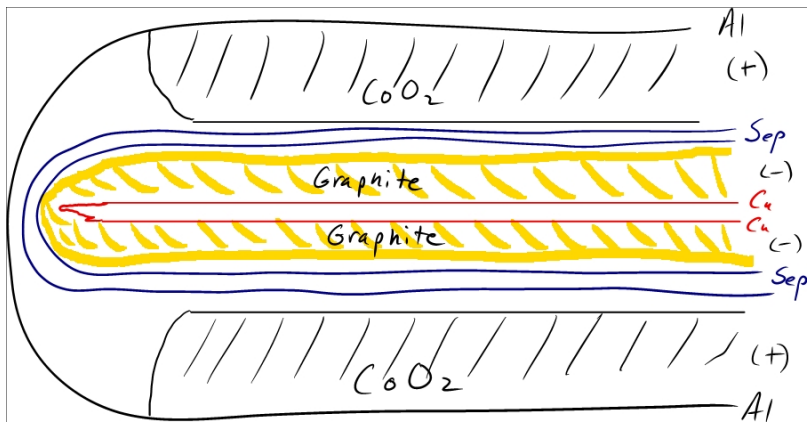
- There are 2 separate internal shorts, both on bottom corners of cell #5 occurred.
- The short at GZ affected several cell fold layers more deeply than the more superficial damage caused by the short at the opposite corner on cell #5
- The damage of cell #4 could have been collateral to what occurred with cell #5.
- 1 minute/axis random vibration acceptance test was performed with the LIBs on open circuit at 30% SoC. OCV tests immediately pre and post each axis of vibration recorded no changes > ± 1 mV.
- Seven days later, the battery was charged, discharged, and recharged to 30% SoC with in family individual cell modules voltages.
- The pre-test capacity cycling test was performed 13 days prior to the vibration testing, and its results were very consistent with the post-test capacity cycling results.
- If 2 internal shorts developed during the vibration, they must have been of high enough impedance to escape detection during the capacity cycling, and then, transitioned to low impedance shorts to cause the thermal damage on the adjacent corners of cells #4 and #5. Or else, the short first manifested itself very shortly after the final post-test capacity cycling, which ends on a 10Ah (30% SoC) charge.

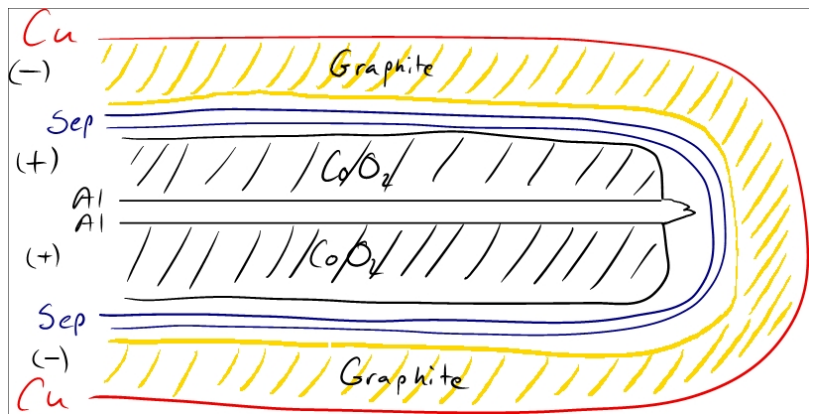
Final LIB S/N 1010 Fault Tree



Electrovaya's Z-fold Cell Design







Most Probable Root Cause Mechanism - Native contamination combined with pouch insulation defect

- Pouch defect in corner opposite ground zero allows Cu folds to contact Al layer of pouch. This polarizes the pouch to the negative potential. This is a no impact defect.
- Active material (i.e., cobalt oxide) particles (clumps) breaks loose from paste bonded to the electrode Al foil current collector and/or Cu current collector creased fold tears, releasing graphite particles, during vibration.
- During vibration or post capacity cycling, particle/Cu tear induces a high impedance short which escapes detection during capacity cycling.
- High impedance short transitions to low impedance at the GZ corner **after** the expansion and contraction of the electrodes during the final charge/discharge/charge cycle.
- Heat from the short melts the pouch inner insulating layer, causing another short in parallel through the cell pouch material, causing the heat affected zones in the pouches of cell #5 and #4.
  - Some 6% of cells fabricated failed soft-short and self-discharge screens due to this phenomena, even with the cleaner, drier, and less violent cell fabrication processes developed for the LIB effort in Electrovaya's Aerospace Dry-Room Facility.
  - Their fall-out rate with commercial cells is higher

Challenges with Replicating Native Contamination

- The progression of damage after a penetration short is dependent on complex mechanisms
  - The resulting internal temperature distribution depends on the power delivered by the short and on the cooling of the heat-affected zone.
    - Power delivered is proportional to the cell voltage multiplied by the cell voltage drop and divided by the internal resistance of the connected cell network.
      - $P = V(\Delta V)/Re$
    - The cooling is mostly internal, by copper and aluminum conduction and by heat-pipe-like cooling (evaporation & condensation of the electrolyte) which is quite variable.
  - Local damage to the separator will result in changes to the resistance of the short, either increasing or decreasing it depending on the extent of damage.
  - The reactions of cell component chemicals depends on temperature and state-of-charge (SoC). The reaction of the positive active material is particularly SoC dependant, with a sharp transition to lower reactivity at about 50% SoC, as demonstrated by ARC tests. Most, but not all, cell chemical reactions are exothermic.
- Nevertheless, Electrovaya was very determined to try

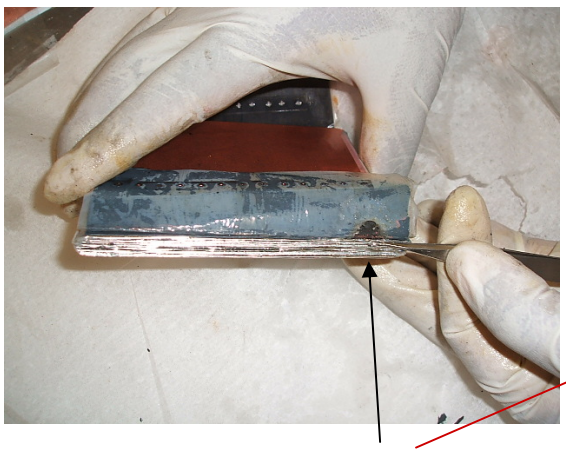
Tests Replicating the Native Contamination Cause

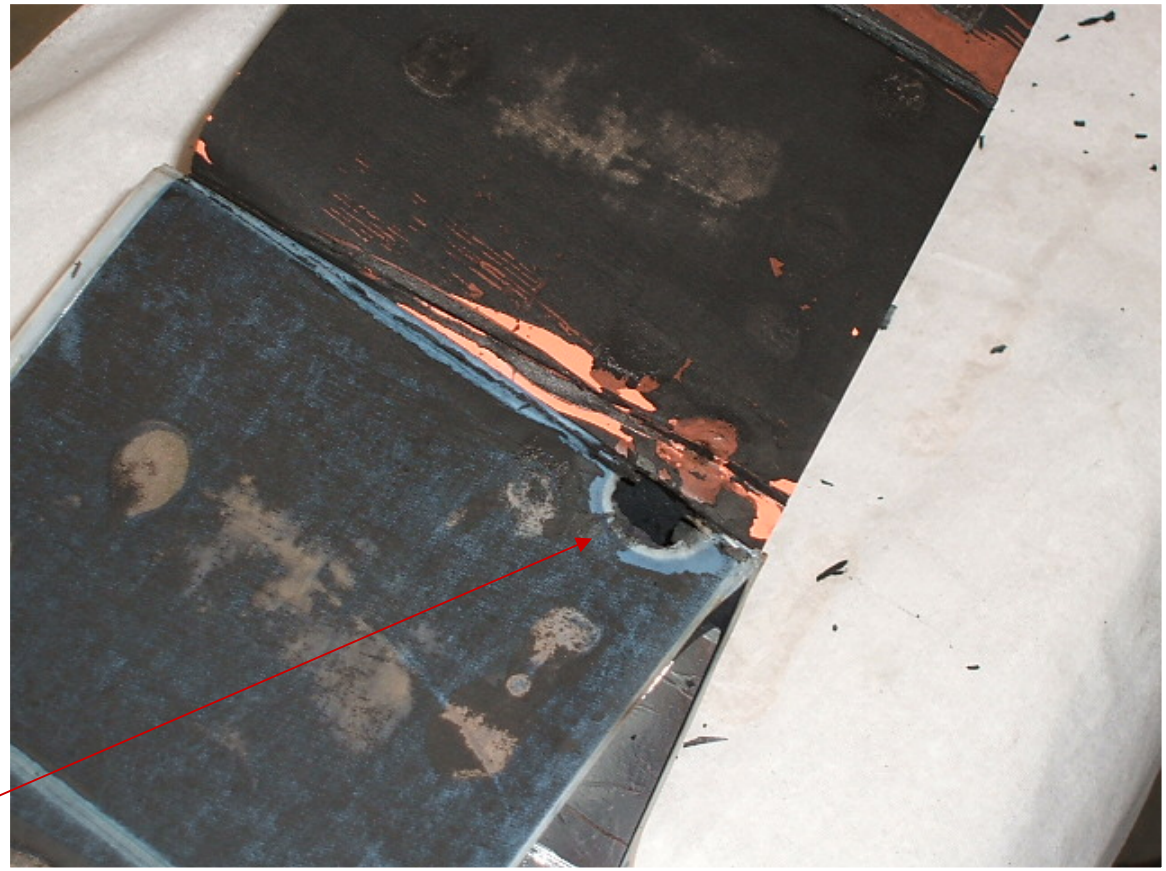
1. 0.16 mm or 0.006" diameter acupuncture needle inserted into Cu tab edge of cell near bottom of 100% SoC cell 5 while sandwiched in urethane foam and compression plates with a fully charged cell 4. Both cells not connected in parallel. Test conducted in an argon flow environment. Result: Small puff of smoke, but contained. OCV only dropped 0.2V in 24 hours. Cell appeared to heal itself of the short.
   - DPA confirmed short occurred at the folded current collectors as intended
2. Same as test #6 except two cells in parallel at 100% SoC. Result: Thermal runaway in cell 5 induced thermal runaway in cell 4.
3. Single cell at 30% SoC under **Ar flow**, 0.006” needle. Result: Small puff of smoke, but contained. OCV dropped to 78 mV in 24 hrs
   - No healing or isolation of the short occurred as in test #1
   - DPA revealed a shark bite signature similar to cell #5 of LIB 1010
4. 5 cells in parallel at 30% SoC under **Ar flow**, 0.006” needle. Result: Small puff of smoke, but contained. OCV dropped to 0.1V in < 15 hrs

Replication of native contamination (cont.)

30% SoC with 0.006” needle over Ar flow

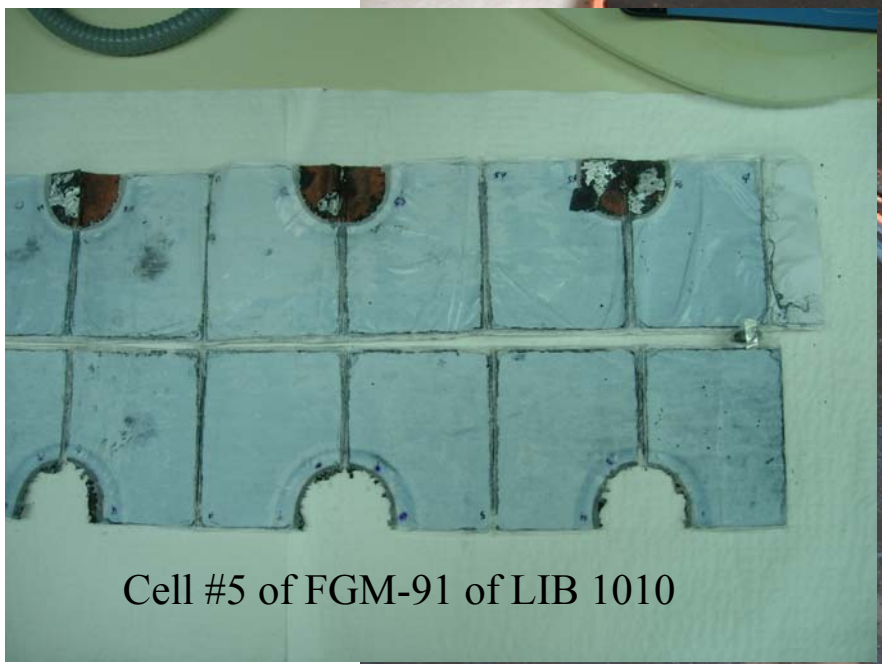
Resulted in a small puff of smoke, followed by drop to 78 mV in < 24 hrs

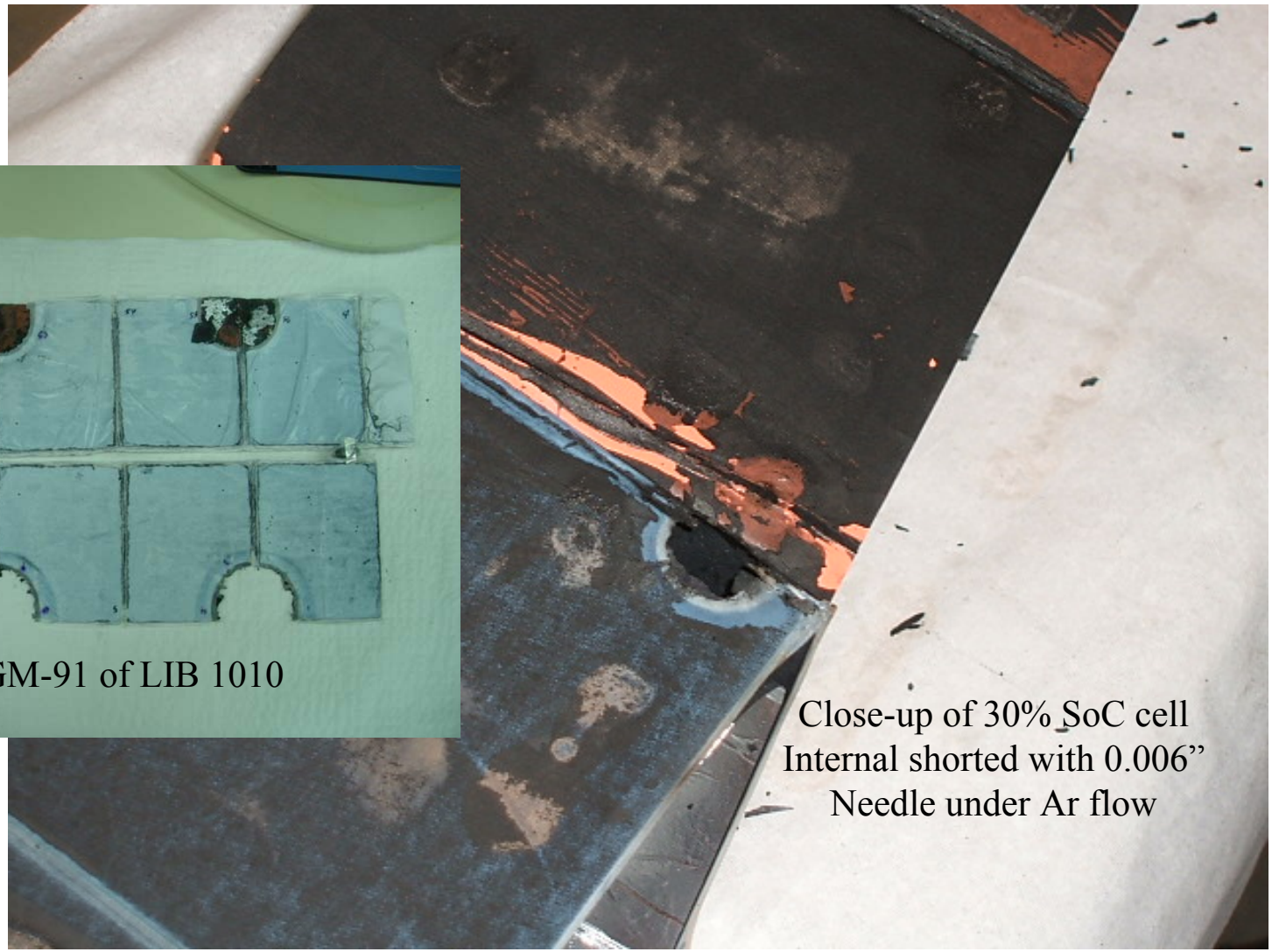




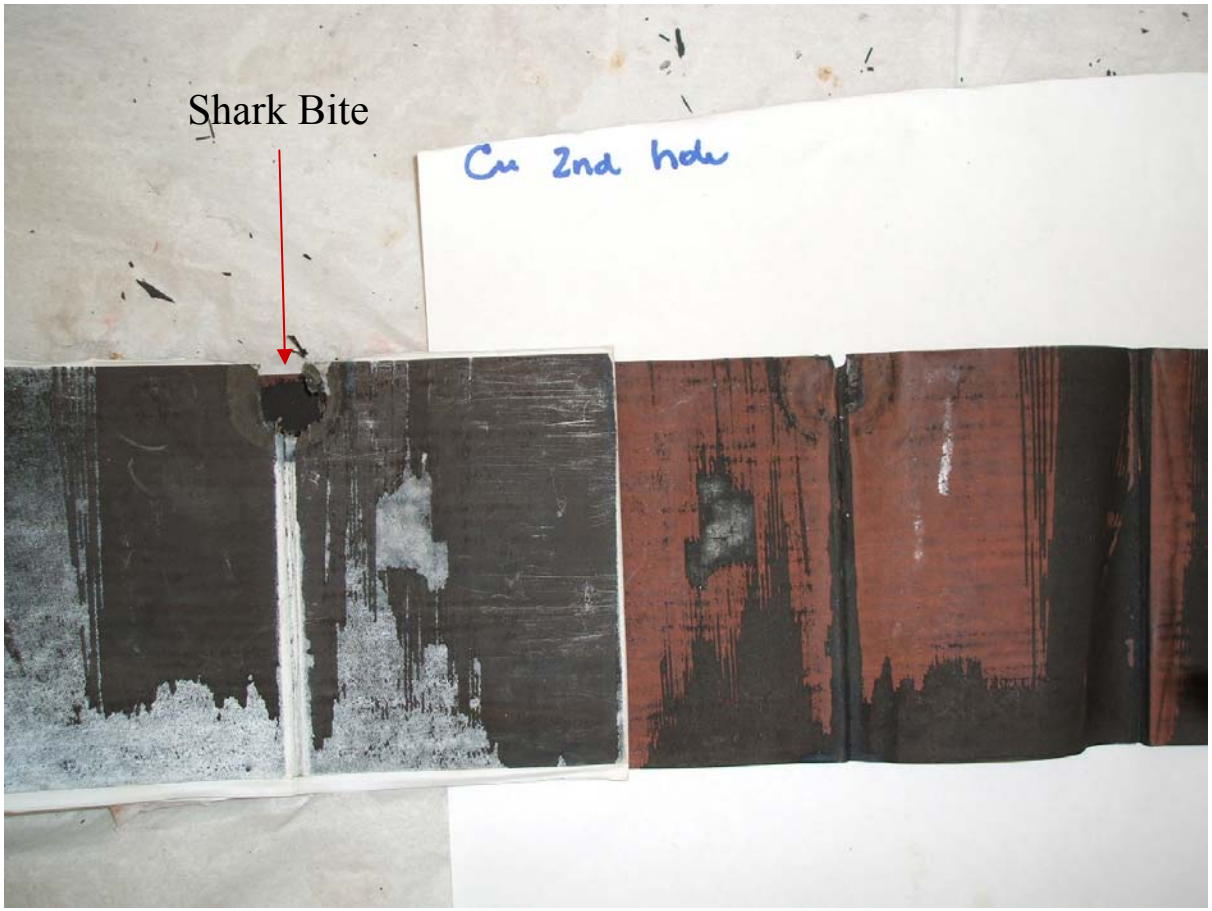
Note the shark bite signature of the heat affected zone with the molten separator shrinking away from the center of the short. This resembles the damage in cell #5 of FGM-91 of LIB 1010.

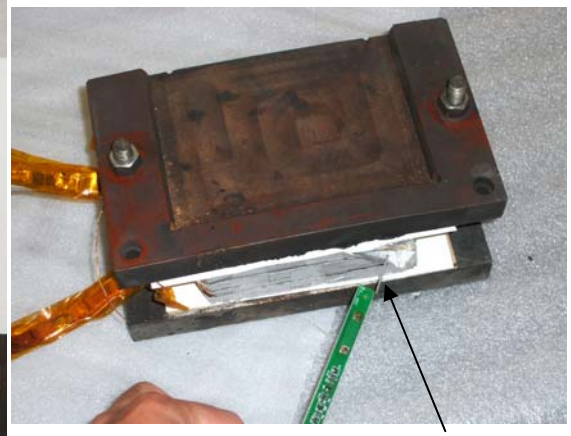
Shark bite comparisons





Small needle on a 5P stack at 30% SoC in Ar flow





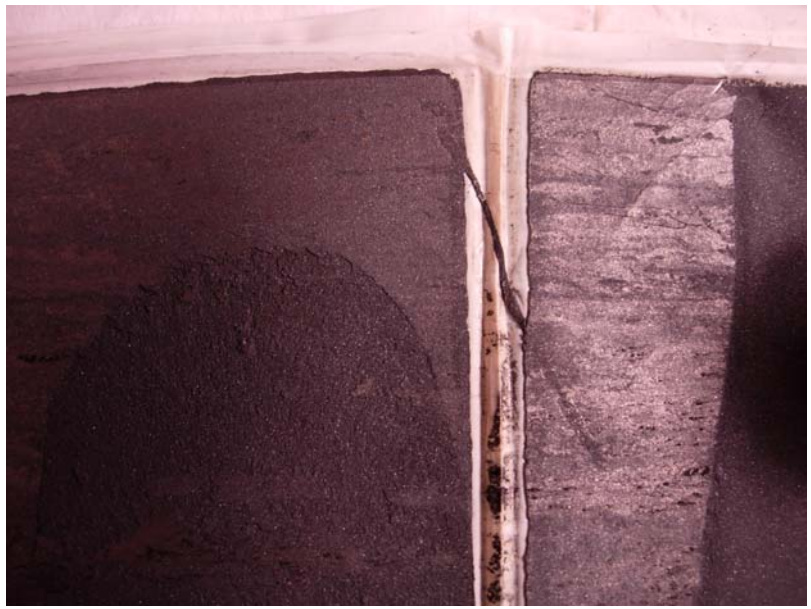
5 P stack with 0.006” needle in 5th cell Cu tab side near bottom

Cell side showing puncture area

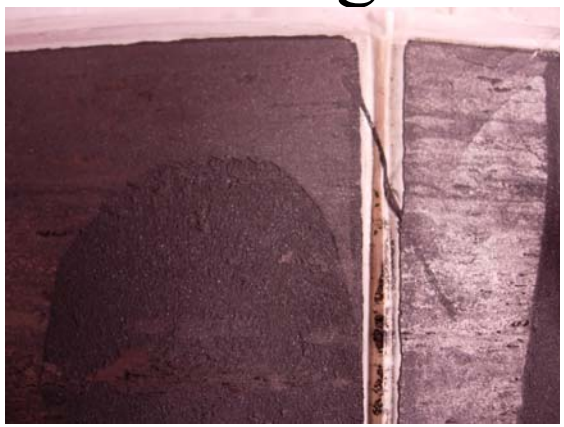
Result: Small puff of smoke initially, OCV dropped to < 0.1V in < 16 hrs. Note the heat affected zones on the cathode folds that radiate in an arc around the center of the puncture.

Examining cells rejected for soft shorts

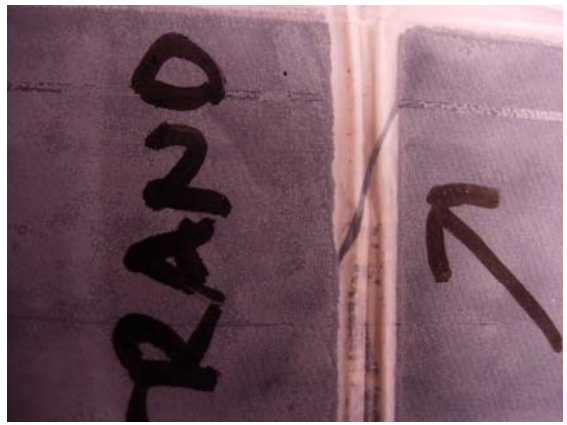
- Definition of cells failing soft short criteria
  - Discharge at CV to 3.0V to a 25 mA taper (very deep discharge)
  - Rest at 25 ± 3 C for 21 days
  - Measure OCV on day 14, 21
  - P/F: $OCV_{21} - OCV_{14} \geq 0$
- 6% of Electrovaya's flight cells failed this acceptance screen
- DPA of 12 of 62 cells has been completed so far
  - Ones with the lowest voltage (strongest soft shorts)
  - Visually found cause in only one



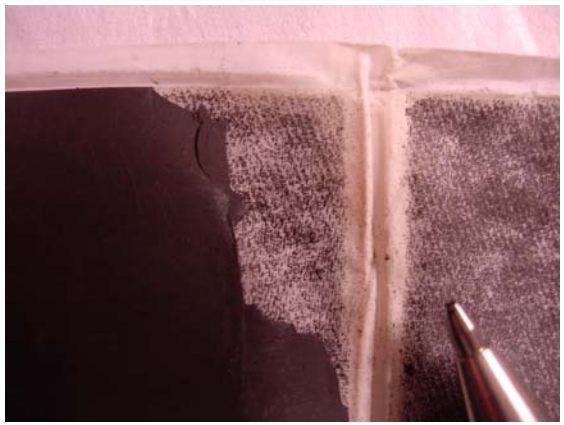
Examining cells rejected for soft shorts



(+) Separator with CoO_2 splinter in fold between CoO_2 plates

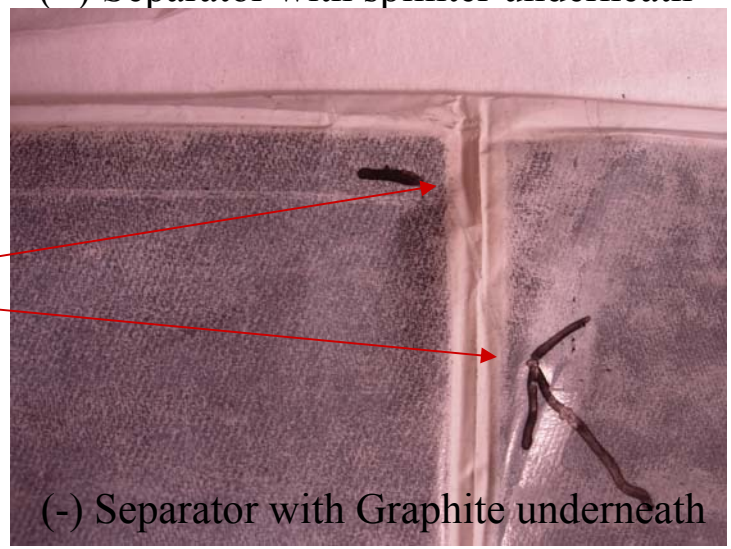


(+) Separator with splinter underneath



(-) Separator with Graphite material

Separator
Tear mark
Due to splinter



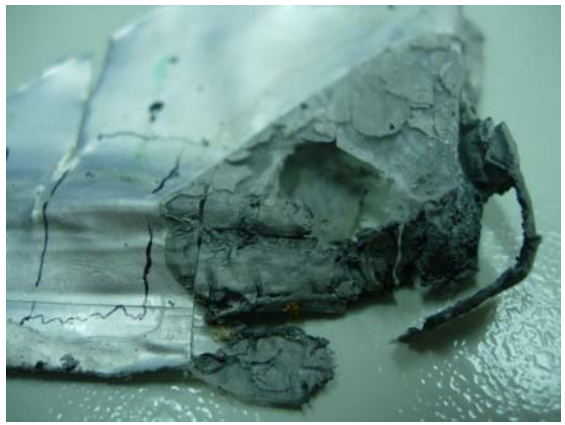
(-) Separator with Graphite underneath

Getting Help from Peer Reviews

- NASA Battery Steering Committee Peer Review (7/27/06 and 8/28/06)
  - Government only meeting attended by
    - NASA:GRC, GSFC, JPL, KSC, HQ, NESC
    - Navy, CIA, NRO, and Aerospace Corp
  - BSC recommends that for the refurbishment of the LIB fleet, we consider the possibility of a new design without the z-fold (i.e., parallel plate design)
  - Decided on a plan for a Delta Acceptance Test to best ensure that the remaining fleet of LIBs is defect free by performing;
    - Additional vacuum cycles
    - Additional thermal cycles
    - Additional mission simulation cycles (thermal/vacuum charge/discharge tests)
    - Repeating the soft short screening test
    - Complete with a capacity verification cycle
  - Offered the opinion that obsolescence risk with Ag/Zn is very significant and advised against going back
- 74th Lithium Battery Technical/Safety Group Meeting in Dayton, OH
  - Also concurred with the Delta Acceptance Plan

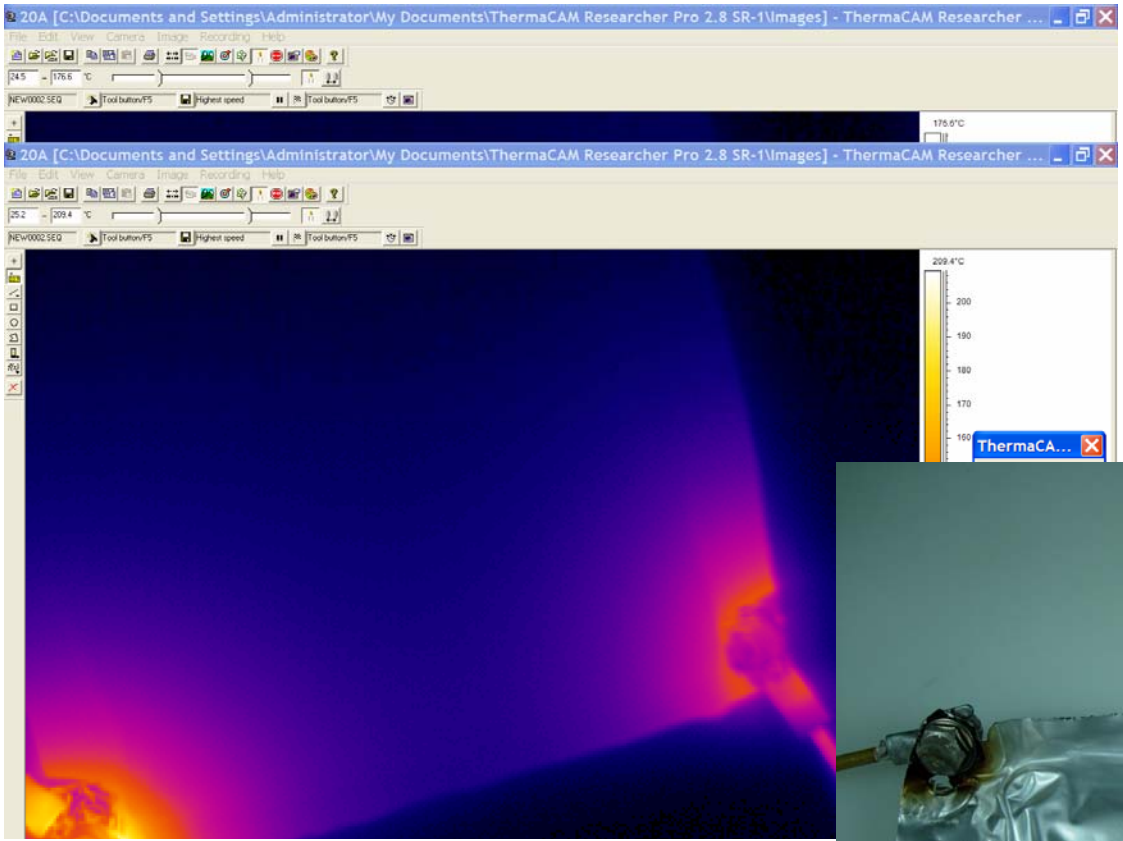
Looking for Pouch Defects

No Li-Al alloy formation found by SEM/EDS in heat-affected corners, but the small Li atom is difficult to detect by EDS, and thus, defect was possible



Examined the cell pouch more conclusively for insulation defects

- X-ray Photoelectron Spectroscopy (XPS) can detect Li present in > 0.1% on the surface of a sample
- Performed the examination with Evans Analytical Group in NJ on 8/18/06
  - 2 samples for the cell #5 corner pouch (GZ and opposite corner)
    - Found evidence of Li concentration in the Al layer **on both corner samples**



Thermal imaging while conducting 50A through the Al layer of the pouch

Note that permanent damage
is only at the contact corners.
The middle area stays cool.
Al layer can carry a lot of current.

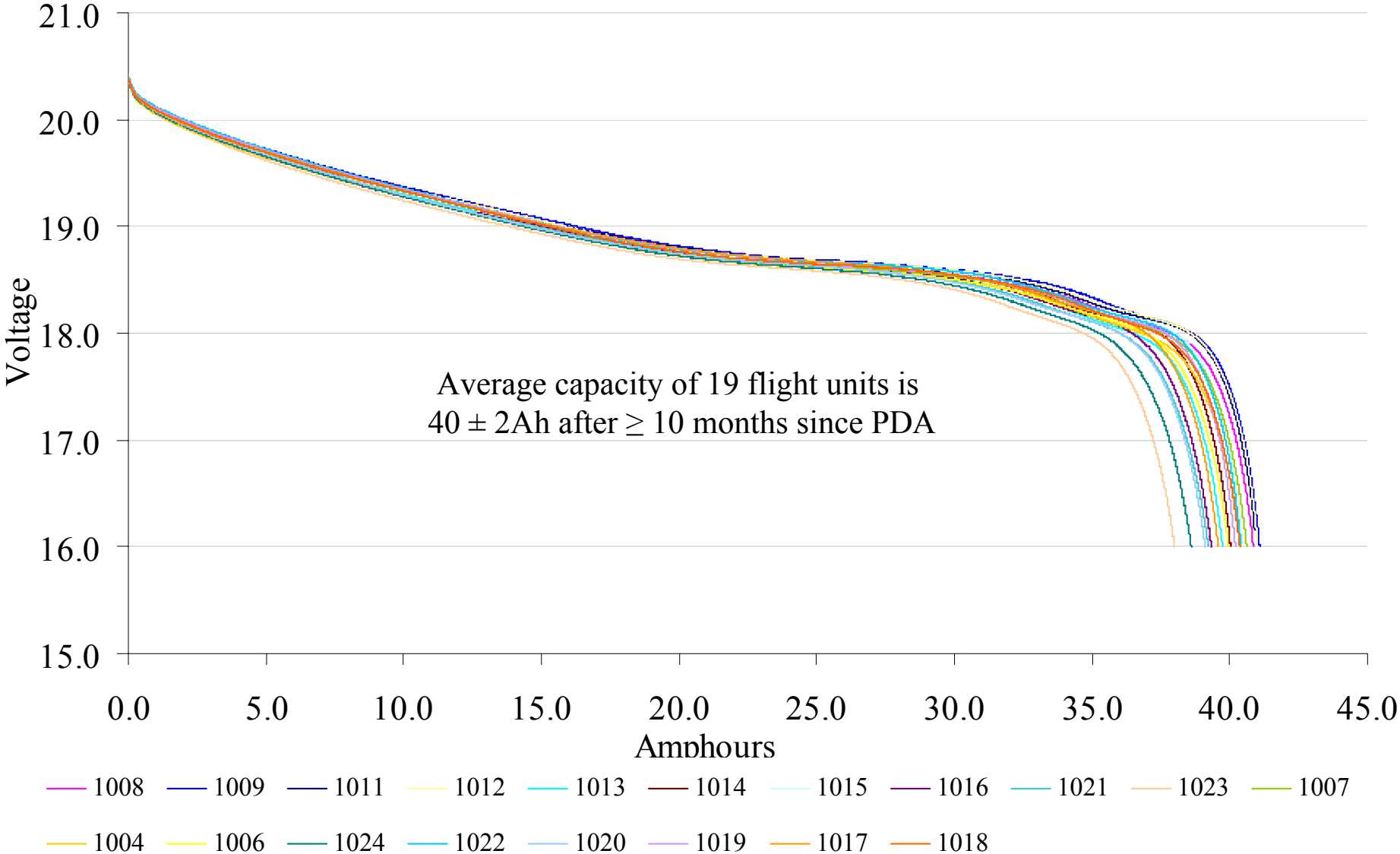
Why didn't our acceptance screens catch this?

- Cell level acceptance is very thorough at screening cells
  - Soft shorts (21 day hold after CV discharge at 3.0V to 25 mA)
    - Only cells with increasing OCV between day 14 and day 21 pass
  - Self-discharge (1 week fully charge stand)
    - Only cells with capacity loss < 250 mAh and capacity gain < 50 mAh
  - Pouch breach (after 21 day hold, cell exposed to < 300 psia)
    - Cells which lose their taunt look are rejected
- Cell module acceptance is too brief
  - Numerous OCV and AC impedance measurement during assembly
  - But only 2 capacity cycles with DC impedance
  - No thermal cycling, no vibration, and no hold time requirements
- Thermal cycling and vibration acceptance is done at the LIB assembly level followed with capacity cycling
  - No hold time requirements

Proposed corrective actions

- For current fleet of LIB (all are ≥ 12 months past completion of Pre-Delivery Accept (PDA))
  - 1000 cells fabricated and acceptance screened in May to July 05 timeframe
  - 175 cell modules assembled and acceptance tested in June to Aug 05 timeframe
  - 24 (20 flight, 4 qual) LIBs assembled and acceptance tested (PDA) by Oct 05
  - The entire fleet has been exercised supporting numerous tests since then
    - EMU tests: 8ft, 11ft, ETA, SSATA, and EMI
    - LIB Charger tests: Acceptance, EMI, Acoustic, ESD, Power Quality
    - None have sat idle (all have at least 10 charge/discharge cycles dating back to cell acceptance cycles)
  - Completed last autocycle (discharge/charge/discharge/top-off) of each flight LIB followed by a volts check (in May 2006 with LIB Charger)
    - **Capacity performance is within 40 ± 2Ah range at ~1.5A to 16V with very low cell module to cell module variations (i.e., excellent performance)**
    - **If another existed internal short had developed, it would have been detected with signature of out-of-balanced module OCVs**
  - **OCVs and CCVs of the entire LIB fleet were remeasured on 8/17-22/06**
    - **No cell module is varying by > 10 mV from others within an LIB and CCVs are all nominal**
  - What can be done to get even more confidence that fleet is defect free?
    - Current fleet experienced 1.5 thermal cycles, 1 vibration run, 1 vacuum check at cell and cell module levels, and at least 7 charge/discharge cycles at cell module and LIB levels (not counting the 3 done at the cell level) and 13 months of storage as LIBs (> 15 months as cells)
    - Combining thermal, vacuum, and charge/discharge at once has not been done and is a better method to wring out any existing latent native contamination defects (Delta Acceptance)

LIB Fleet Discharge Capacities @ ~1.5A (April-May 06)



Remaining Fleet of 19 LIBs is Defect Free

OCVs and CCVs measured during 8/17/06 to 8/22/06

EMU Lithium Ion Battery OCV/CCV Measurements with GSE Charger S/N 5002								
LIB SN	Total OCV (V)	Module 1 OCV (V)	Module 2 OCV (V)	Module 3 OCV (V)	Module 4 OCV (V)	Module 5 OCV (V)	Battery Temp (DegC)	Battery CCV (V)
1003	19.67	3.93	3.94	3.93	3.94	3.94	20.00	18.63
1004	18.84	3.76	3.77	3.76	3.76	3.76	21.00	17.76
1005	19.61	3.92	3.92	3.92	3.92	3.92	21.00	18.62
1006	18.88	3.77	3.78	3.78	3.78	3.78	21.00	17.82
1007	18.85	3.77	3.77	3.77	3.77	3.77	21.00	17.86
1008	18.84	3.76	3.76	3.76	3.76	3.76	22.00	17.78
1009	18.83	3.76	3.76	3.76	3.76	3.76	22.00	17.90
1011	18.84	3.76	3.76	3.76	3.76	3.76	22.00	17.92
1012	18.82	3.76	3.76	3.76	3.76	3.76	21.00	17.94
1013	18.90	3.78	3.78	3.78	3.78	3.78	20.00	17.90
1014	18.90	3.78	3.78	3.78	3.78	3.78	20.00	18.02
1015	18.84	3.76	3.76	3.76	3.76	3.76	22.00	17.90
1016	18.84	3.76	3.76	3.76	3.76	3.76	21.00	17.82
1017	18.82	3.76	3.76	3.76	3.76	3.76	22.00	18.00
1018	18.84	3.76	3.76	3.76	3.76	3.76	22.00	17.84
1019	18.83	3.76	3.76	3.76	3.76	3.76	21.00	17.94
1020	18.86	3.76	3.77	3.77	3.77	3.77	22.00	17.86
1021	18.84	3.76	3.76	3.76	3.76	3.76	22.00	17.82
1022	18.84	3.76	3.76	3.76	3.76	3.76	22.00	17.98
1023	18.84	3.76	3.76	3.76	3.76	3.76	21.00	17.82
1024	18.84	3.76	3.76	3.76	3.76	3.76	22.00	17.84

Max deviation between cell modules within each LIB < 0.01V
Note that 1003 and 1005 not at 30% SoC since they are qualification units supporting charger acceptance tests

What kind of Delta Acceptance for the LIB?

In discussions with BSC and SAIC battery experts, the recommendation was

- 10 Depress/repress cycles while OCV at 30% SoC (done)
  - Qual unit 1001 experienced > 94 such pressure cycles
- 10 thermal cycles while OCV at 30% SoC (done)
  - Qual unit 1003 experienced 24 cycles to greater extremes w/ little impact
- 5 worst case mission simulation cycles (qual unit saw >94 such cycles)
  - Start charge 32°C and at ambient pressure
  - Depress to < 7 torr in < 7.5 minutes
  - Discharge at 3.8A to 16.0V while in vacuum on hot plate raising temp to 41 °C
  - Repress to ambient pressure < 15 minutes
  - Allow LIB to re-equilibrate to 10°C, repeat cycle at this temp w/o hot plate heating
  - Alternate between hot and cold cycles until 5 cycles have been achieved
- Discharge to cell modules in each LIB at 3.0V constant voltage to 125 mA taper, then hold for 21 days to screen for soft shorts
  - Reject any LIB with cell modules with decreasing OCV between day 14 and day 21
- Capacity verification with LIB Charger Autocycle function (6th cycle)

Remaining Fleet of 19 LIBs is still Defect Free

OCVs and CCVs measured on 11/7/06 after Vacuum and Thermal Cycles

LIB SN	Batt OCV (V)	FGM-1 OCV (V)	FGM-2 OCV (V)	FGM-3 OCV (V)	FGM-4 OCV (V)	FGM-5 OCV (V)	Batt Temp (C)	Batt CCV (V)
1004	18.831	3.763	3.768	3.767	3.766	3.766	21.2	17.802
1006	18.844	3.766	3.769	3.768	3.769	3.770	20.9	17.829
1007	18.841	3.765	3.769	3.768	3.768	3.769	22.1	17.919
1008	18.841	3.764	3.768	3.769	3.769	3.770	20.5	17.873
1009	18.822	3.760	3.765	3.764	3.766	3.766	22.2	17.938
1011	18.835	3.763	3.769	3.768	3.767	3.766	21.2	17.918
1012	18.818	3.763	3.767	3.760	3.762	3.764	20.9	17.946
1013	18.877	3.771	3.775	3.776	3.776	3.776	21.8	17.931
1014	18.841	3.766	3.768	3.768	3.769	3.770	20.5	17.804
1015	18.844	3.766	3.769	3.768	3.769	3.770	20.9	17.829
1016	18.842	3.763	3.769	3.769	3.770	3.769	20.7	17.968
1017	18.841	3.764	3.768	3.769	3.769	3.770	20.5	17.873
1018	18.837	3.763	3.768	3.768	3.768	3.768	20.9	17.949
1019	18.837	3.763	3.768	3.768	3.768	3.768	20.9	17.949
1020	18.845	3.764	3.770	3.770	3.770	3.769	20.6	17.930
1021	18.838	3.765	3.768	3.767	3.768	3.769	20.5	17.782
1022	18.845	3.764	3.770	3.770	3.770	3.769	20.6	17.930
1023	18.841	3.766	3.768	3.768	3.769	3.770	20.9	17.804
1024	18.818	3.763	3.767	3.760	3.762	3.764	20.9	17.946

Maximum deviation between cell modules within each LIB < 8 mV, 6 months after last balancing

Conclusions and Recommendations

Conclusions

- LIB 1010 failure mode was smart, subtle, and exceedingly rare (1:300,000)
- Case for native contamination is stronger than any other root cause
  - Successfully replicated twice with acupuncture needle tests

Recommendations for Closure Plan

- Complete the DPA or further tests on the 50 remaining cells rejected for soft shorts to seek more understanding of the nature of failure mechanism
  - Crush cells between parallel plates to convert soft shorts into hard shorts
    - Using a press, plan to go to 1500 psia max while charge/discharge cycling
  - Attempt to zap some of the cells with large currents/low energy pulses
    - Trying to cause a phase change in the separator where the soft short is located
- Complete the Delta Acceptance Tests
  - Mission simulation cycles, deep discharge, and capacity verification remain
  - Completion by Symmetry Resources in Arab, AL, is expected by 3/2/07
  - **Fly the LIBs if they all pass (Earliest potential flight: STS-118)**

Lessons Learned

- Internal shorts hazard can not be entirely designed out of high and moderate rate, large capacity lithium ion battery designs with liquid electrolytes
  - Manufacturing and acceptance testing controls play a very signification mitigation role
- With the benefit of hindsight the LIB project should have
  - Not used a z-fold cell design to reduce native contamination risks
  - Included a cell pouch isolation resistance test during the cell manufacturing and acceptance process
  - More rigorously screened the cell modules prior to assembling them into LIB assemblies
    - Thermal, vacuum, and charge/discharge cycles for acceptance
  - Added the deep discharge soft short detection test at the cell module and LIB levels

Back-up

Proposed corrective actions (cont.)

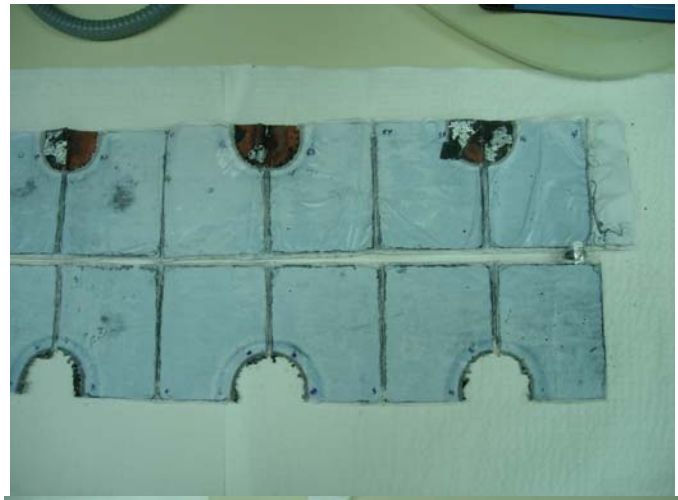
- Strengthening Acceptance for the refurbished fleet of LIB
  - Add cell pouch insulation resistance to cell terminal tests during cell acceptance
    - And closer physical inspection of tab seal plastic alignment pre and post cell manufacture
  - Replace 2 with 10 charge/discharge capacity cycles to stabilize the cell modules
  - Add thermal cycling (10 cycles), vacuum cycling (10 cycles) and vibration while at 30% SoC on cell modules **for internal short screening**
  - Add followed by a capacity cycling with
    - Self-discharge screen involving 1 week stand at 100% SoC
      - P/F: Reject any module with > 455 mAh loss
    - Soft-short screen involving a 3.0V CV discharge to 125 mA followed by a 21 day hold period
      - P/F: Reject any module with a declining OCV between day 14 and day 21
      - P/F: Reject any module with capacity, internal resistance, dimensional, mass, or visual defects
    - Vacuum leak test each module after the 4 week hold period
  - Followed by recharge cell module to 30% SoC to be ready to install into LIB
  - Retain LIB thermal cycling (1.5 cycles) and vibration acceptance plan, but
    - Reduce vibration level to that required for standard workmanship defect detection (0.04 g^2/Hz) rather than the internal short detection level (0.067 g^2/Hz)
    - Add repeat of self-discharge (1 week at 100% SoC) screen and soft short screen (21 days at the equivalent of 15.0V) to ensure health of the flight LIBs

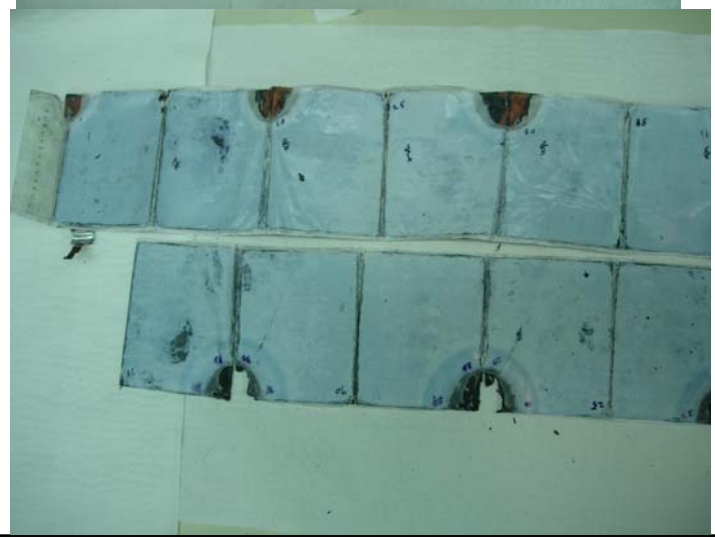
Why are we replacing the current EMU battery?

- Current Ag-Zn Increased Capacity Battery (ICB) limitations:
  - **Wetlife/Capacity**- 300 day wet life with a 12 cycle capability
  - **Cycling** - Requires un-interrupted quarterly cycling on-orbit to maintain performance
  - **Cost** - With activation, cost >$55K each, or ~$6.6 M every 10 years, which is very expensive
  - **Activation** - Delivered dry and requires a 5-week activation process
  - **Relief Valves** - Has low pressure cell relief valves that have a leakage history on-orbit (twice)
  - **Obsolescence** - Ag-Zn electrochemistry has very few vendors and high obsolescence risk
  - **Rest time** - Requires 4 hour rest time between discharge and charge
  - **State of Charge Detection** – accurate coulomb counting is difficult to obtain
- Redesign the current EMU battery to:
  - **Wetlife** - Improved on orbit capacity (5 years, >90 cycles)
  - **Cycling** – 1 per year, reduced crew ops on-orbit
  - **Cost** - Reduced life cycle cost (save ~$4.2M every 10 years)
  - **Activation** – No activation required (additional savings)
  - **Relief Valves** - Non-spillable due to sealed design
  - **Obsolescence** – Dozens of vendors worldwide
  - **Rest time** – None required
  - **Additional Benefits:**
    - Reduce up/down mass requirements
    - State of Charge can be approximated by OCV
    - Reduce # of Critical Items List Hazards from 4 to 2

Current EMU
Increased Capacity Battery (ICB)

Looking for Separator Defects - None found

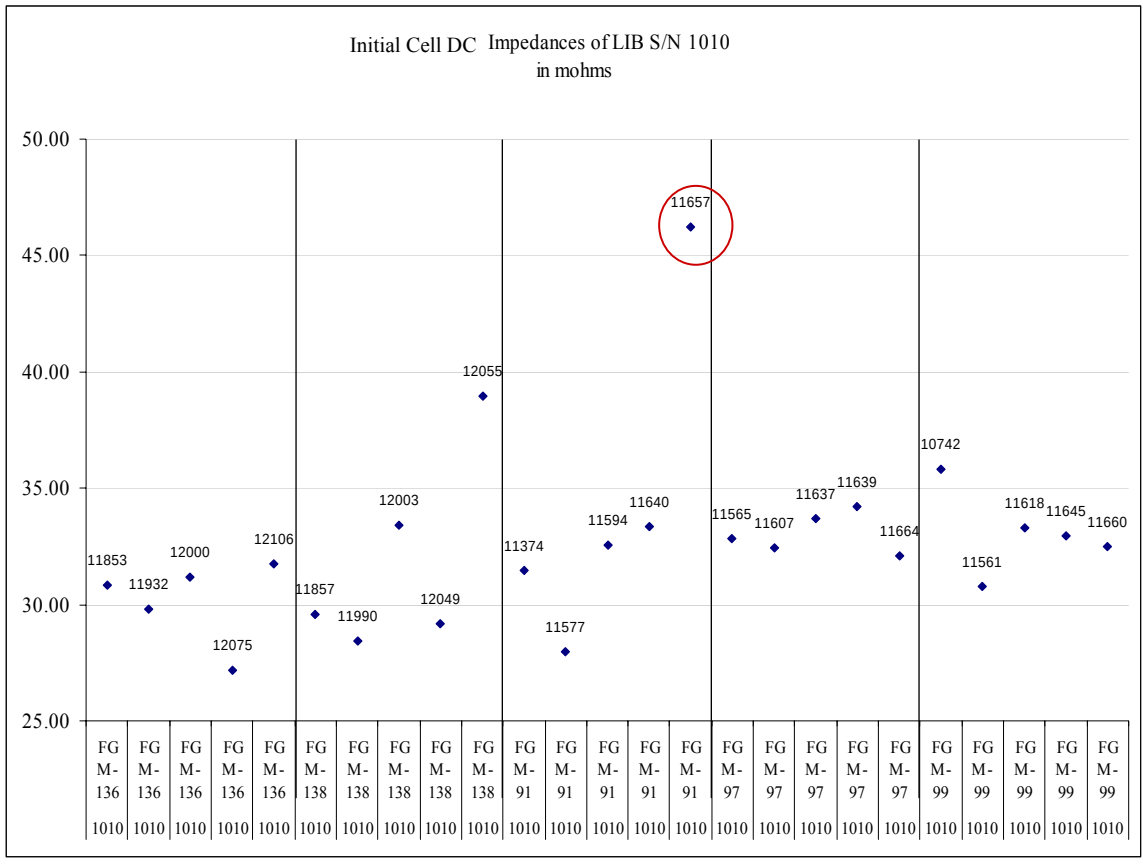




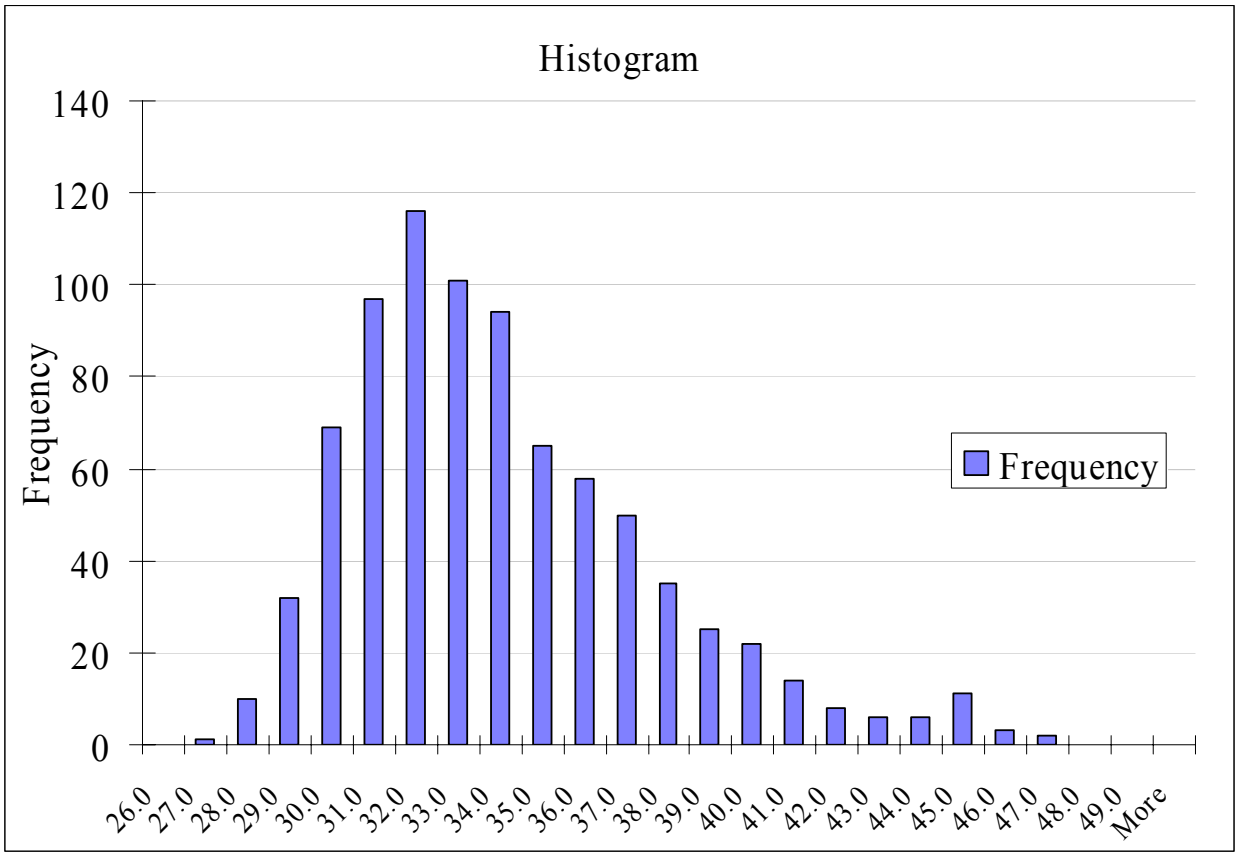
Less Probable Root Cause

- Li plating due to incomplete charge resulting from cell internal resistance imbalances within a cell module (5 cells in parallel)
  - Cell 4 of FGM-91 had ~50% higher internal resistance than the mean of the cells in that module
  - This outlier cell could be more susceptible to lithium plating, leading to a lithium dendrite, leading to an internal short in cell#4 that caused collateral damage to cell#5
  - Not likely because
    - LIB 1010 only received 3 cycles, while LIB 1001 had a similar distribution of cell resistances in its modules and provided 94 cycles before failing to meet capacity due to high resistance and similarly varying end of life internal resistances
    - Lithium plating usually causes loss of capacity and LIB 1010 did not lose capacity abnormally in its 3 cycles
    - Vendor has no experience with cell high resistance condition leading to internal shorts
    - Cell#4 damage is less extensive than that found in cell#5 (no traces of Cu arcing found in cell #4 and two cell pouches separated the two adjacent cells)

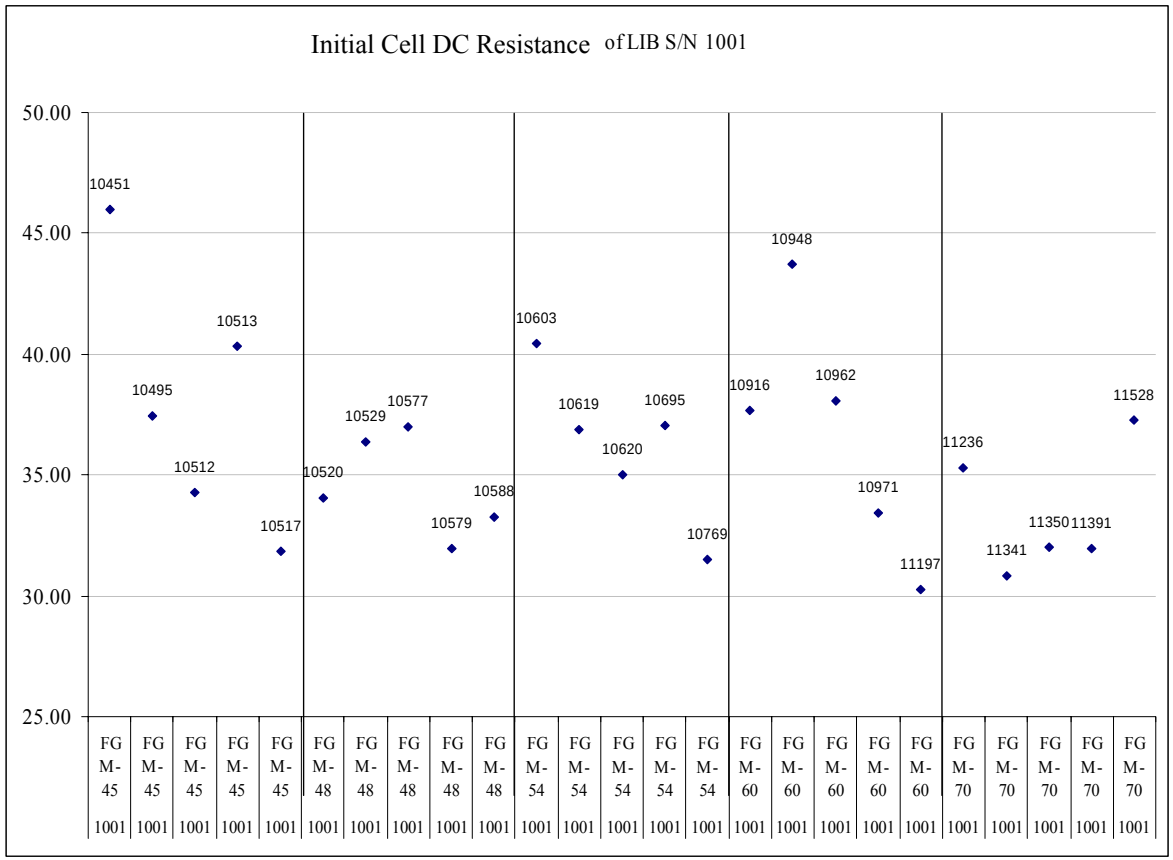
Cell #4 of FGM-91 had the highest DC Re in LIB 1010 and was 48% higher than the mean of the other 4 cells



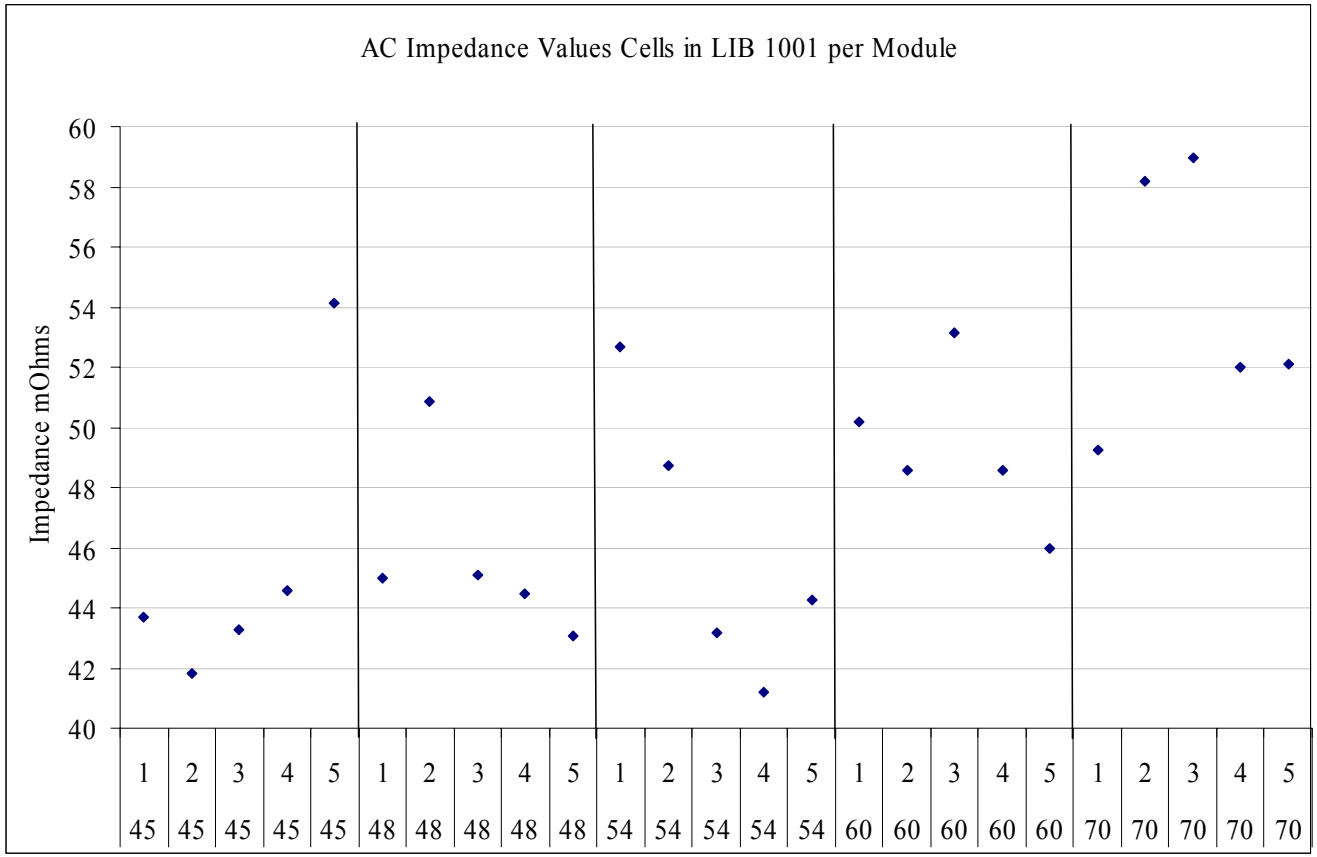
LIB Cell DC Resistance Distribution



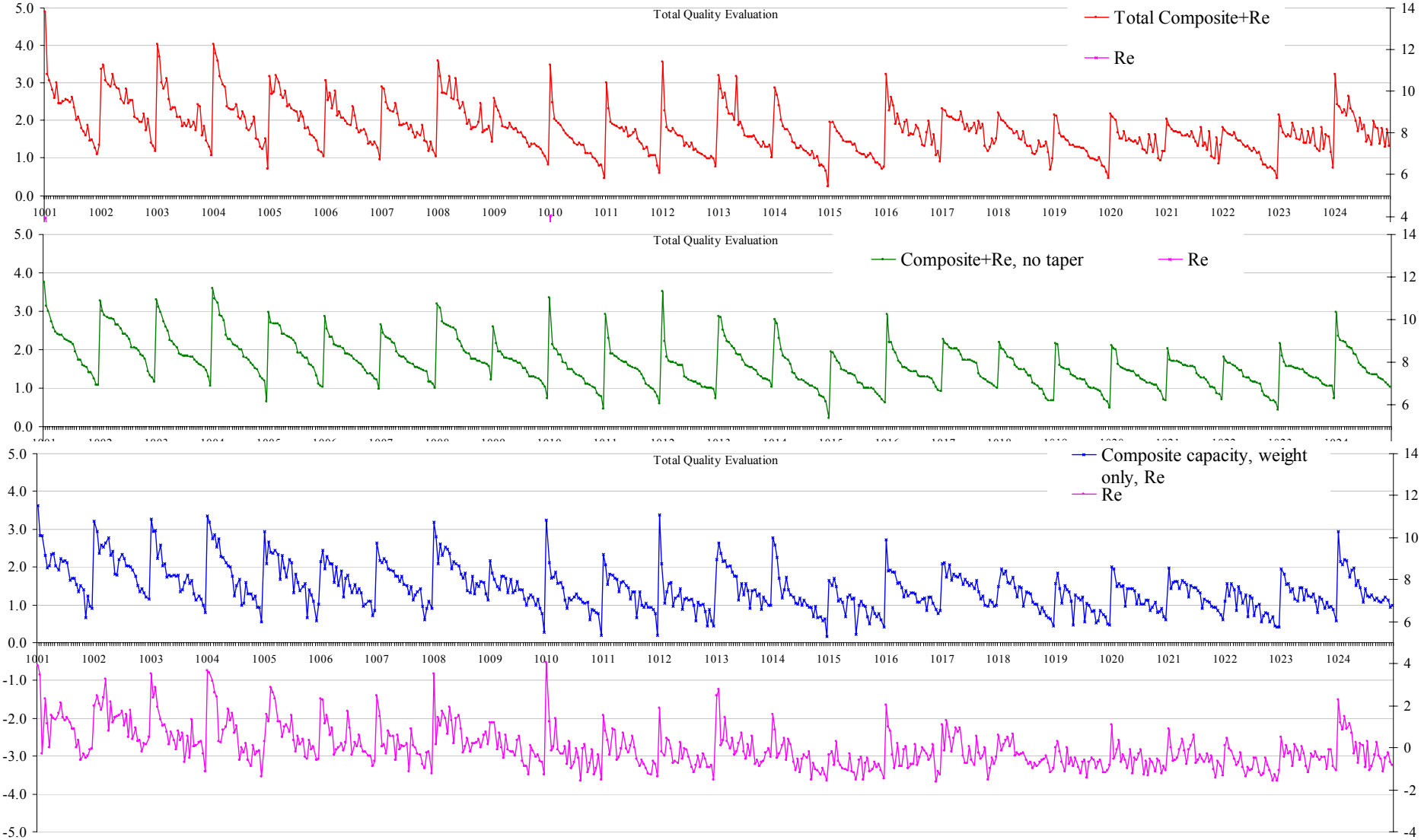
LIB 1001 had a similar condition with FGM-45 & 60 containing a cell with an Re ~ 30% higher than the mean of the other 4 cells at beginning of life. This battery provided 94 cycles before reaching end of life due to cell resistance growth and capacity fade, without any internal shorts



At End of Life, AC resistances of cells within cell modules of LIB 1001 varied significantly



None of these cell modules failed with an internal short, they suffered capacity fade and resistance growth as can be expected with 94 thermal/vacuum cycles under worst case hot conditions



- Total Composite (Re, taper, el, mass, Ah), 3σ removes 12 LIBs: 1001, 1002, 1003, **1004**, 1005, **1008**, 1010, **1011, 1012, 1013, 1016, 1024**
- Total Composite without taper, 3σ removes 7 LIBs :1001, 1002, 1003, **1004, 1008**, 1010, **1012**
- Composite of mass, capacity, and Re, 3σ removes 7 LIBs : 1001, 1002, 1003, **1004, 1008**, 1010, **1012**
- Re alone (42.76mΩ max), 3σ removes 6 LIBs: 1001, 1002, 1003, **1004, 1008**, 1010

Active Flight Units in Bold

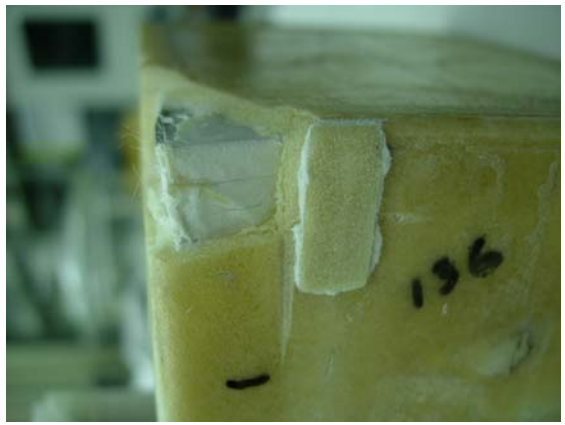
Exonerated Root Causes

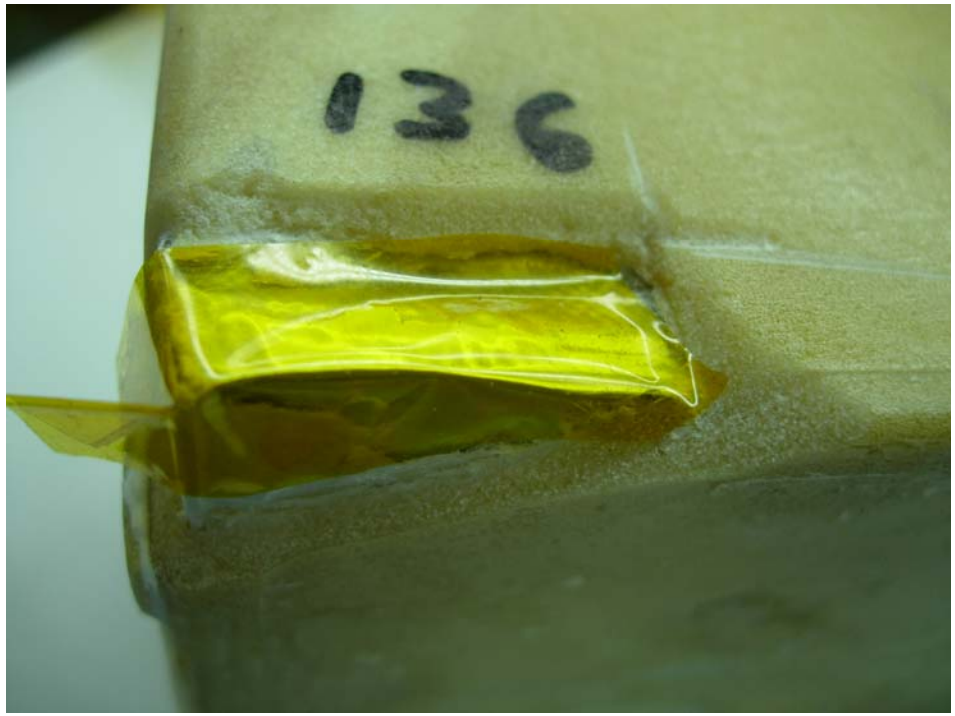
- Replications test results
  - No replication of the foam defect root cause mechanism after 100 days since QAVT (vibration) with expanded frequency range 80-1000Hz at 0.113 g2/Hz (>13 grms)
    - All vibration tests were done on fully charged LIBs
    - Expected fully charged modules to drop ~4 mV over 28 days based on cell module lot cert data
    - 4 intentional modified cell modules, with large foam defects, dropped only 10-12 mV over 100 days
    - **Conclusion so far: LIB design is very tolerant to foam defect failures and vibration**
  - Electrovaya performed cell drop & crush tests to reproduce the folded seal edge impingement failure
    - Only 60” drop of a fully charged cell 4&5 pair stack induced a corner breach of a cell pouch
    - Possible high impedance internal short induced in cell #4 (dropped 30 mV in 4 weeks), but no transition to low impedance yet
    - **Conclusion so far: LIB design is very tolerant to drop impact and crush abuse**
  - No cold flow observed in plastic layer of the cell pouch laminate after 90 days
    - RIFT test with 0.177” diameter ball bearings weighted with up to 1 kg at the drawn corners
    - No change in isolation resistance of the plastic layer as measured with Mohmmeter set at 25V
    - Pre-test cross cut examination of the cell pouch control sample revealed a 0.0003” (or 19%) thinning of inside plastic layer (polyethylene) at the drawn corners
    - Current flow test: pouch can carry 50A with only the contact points being heat affected
    - **Conclusion so far: LIB design is very tolerant to cold flow induced failures**

LIB Cell Module Modifications

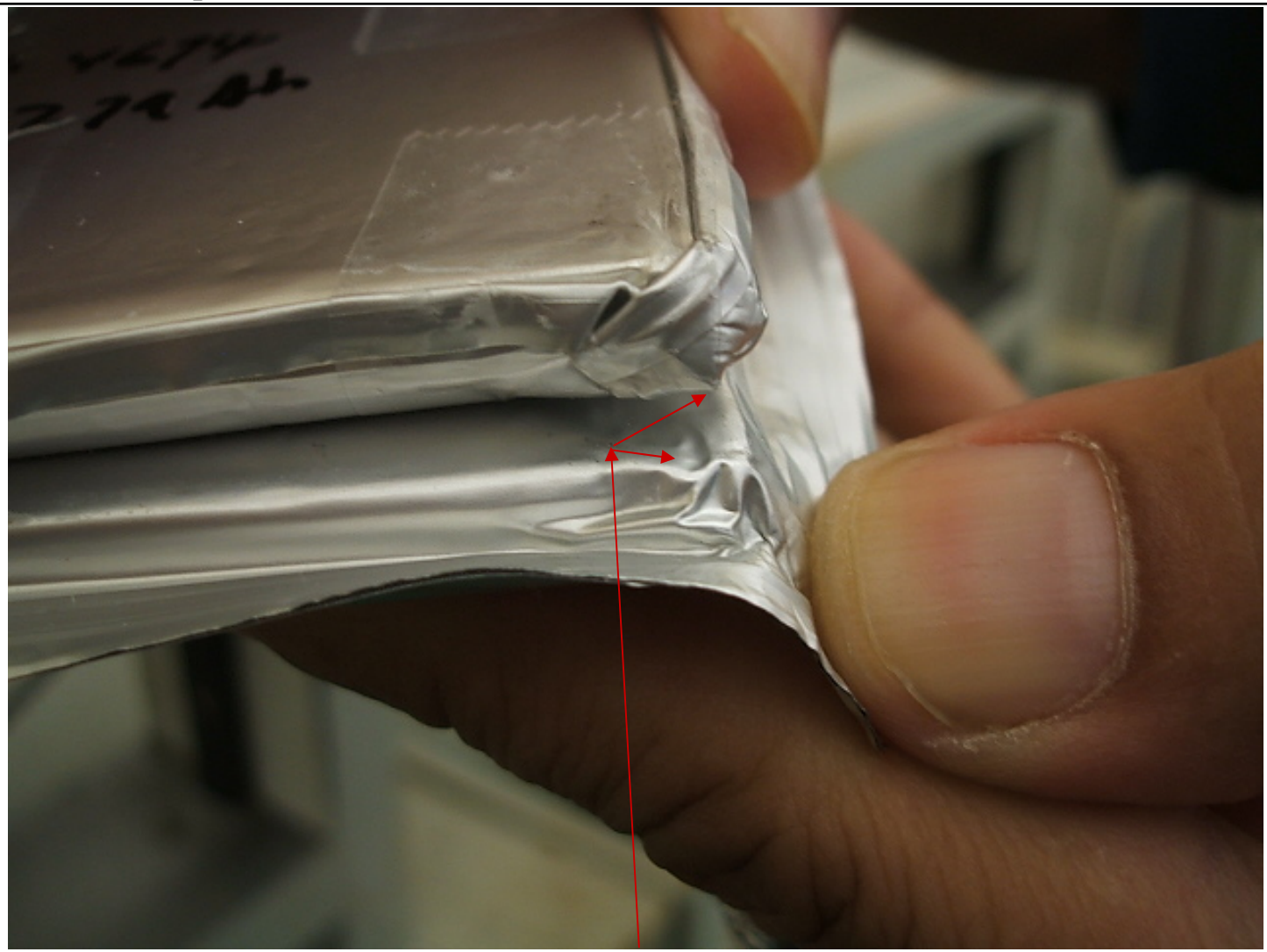
E. Darcy/281-483-9055

Added bump of foam to bottom of FGM-136





Close-up of corner seal folding on cell #5 & #4

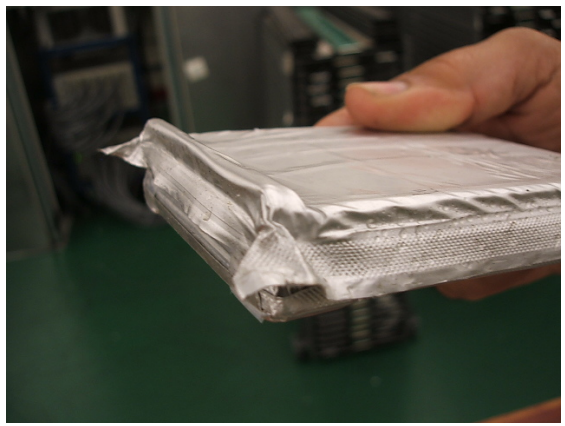


Note the depressions caused by the pouch seal folds of the adjacent cell
However, pouch laminate has proven itself to be very tolerant to mechanical abuse

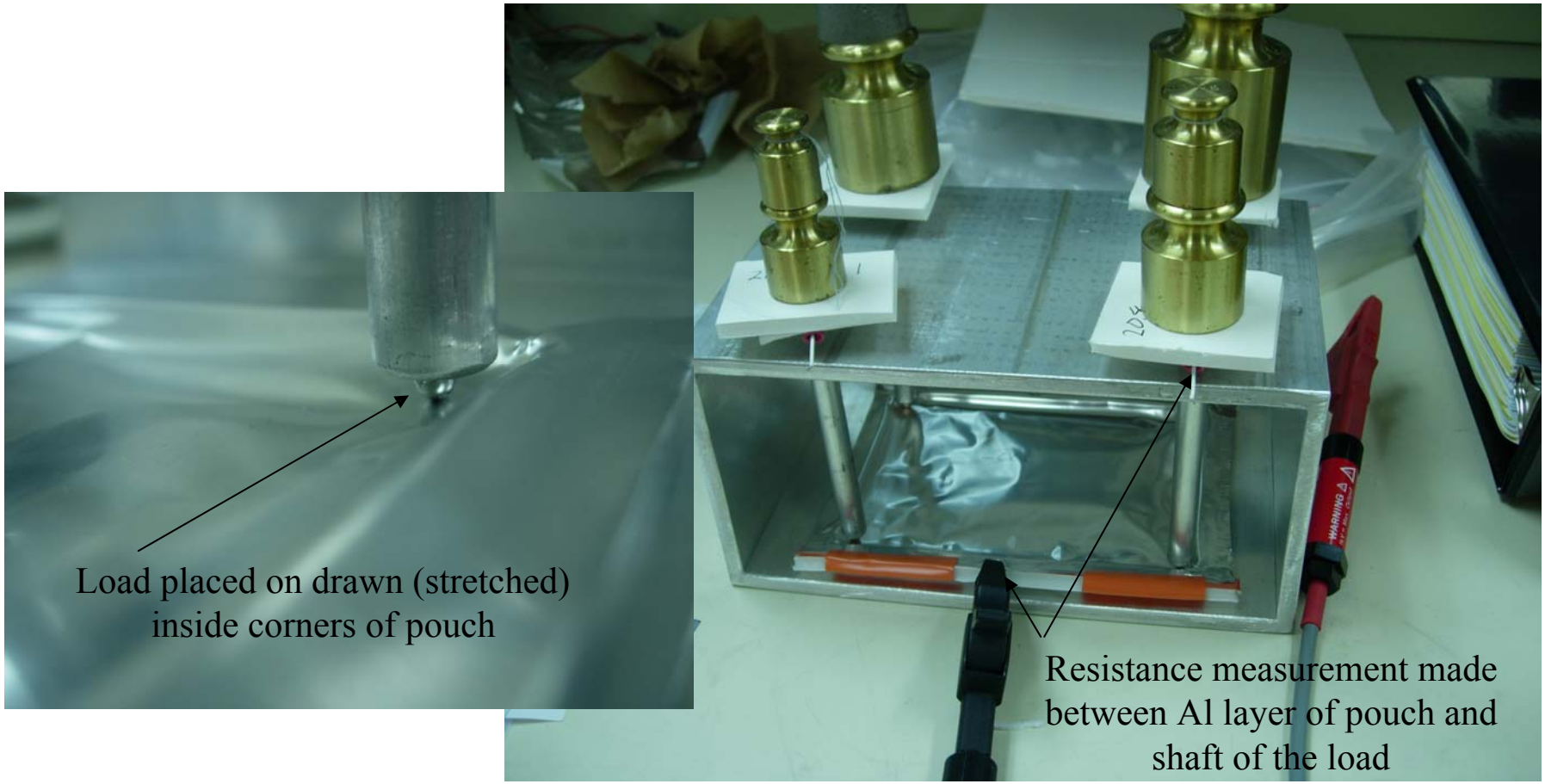
Dropped Cell Pairs (#4 & #5)

Cell pouch tears/breach only occur during drops > 60” and subsequent voltage decay is very minor

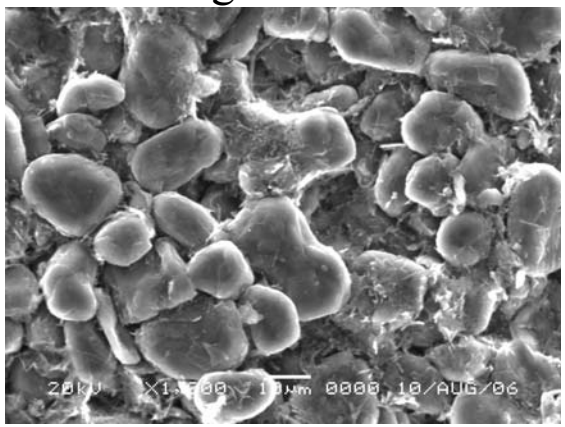
Conclusion so far: LIB design is very tolerant to drop impact and crush abuse



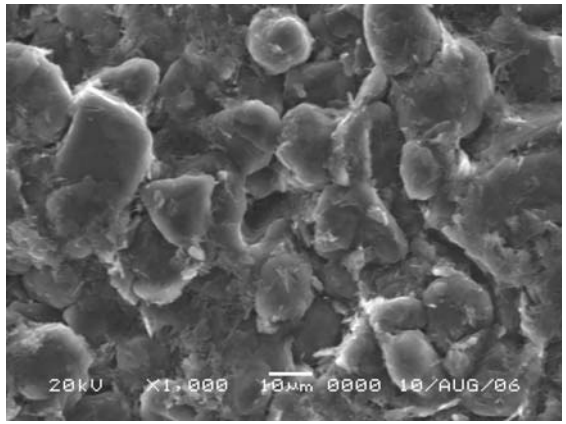
Cold Flow Test of laminate pouch material



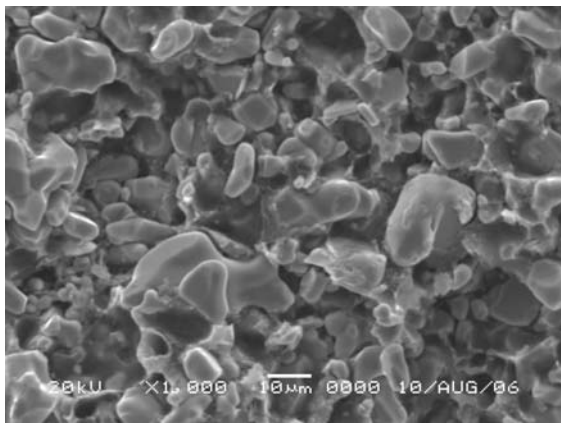
How does the active material of cell#5 compare to that of other cells? SEM photos reveal little difference vs nominal cell (Cell 1) and EDS revealed no evidence of Fe or other foreign contamination



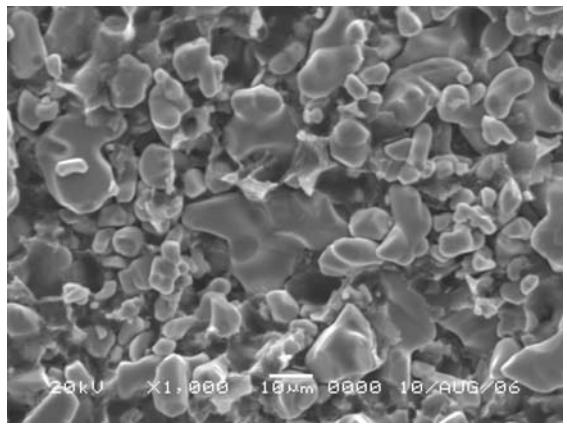
(-) from Cell #5 from FGM-91



(-) from Cell #1 from FGM-91



(+) from Cell #5 from FGM-91



(+) from Cell #1 from FGM-91