Dynamic Drop Testing of eVTOL Energy Storage Systems Part 2: Deformation and Post-Test Forensics Results

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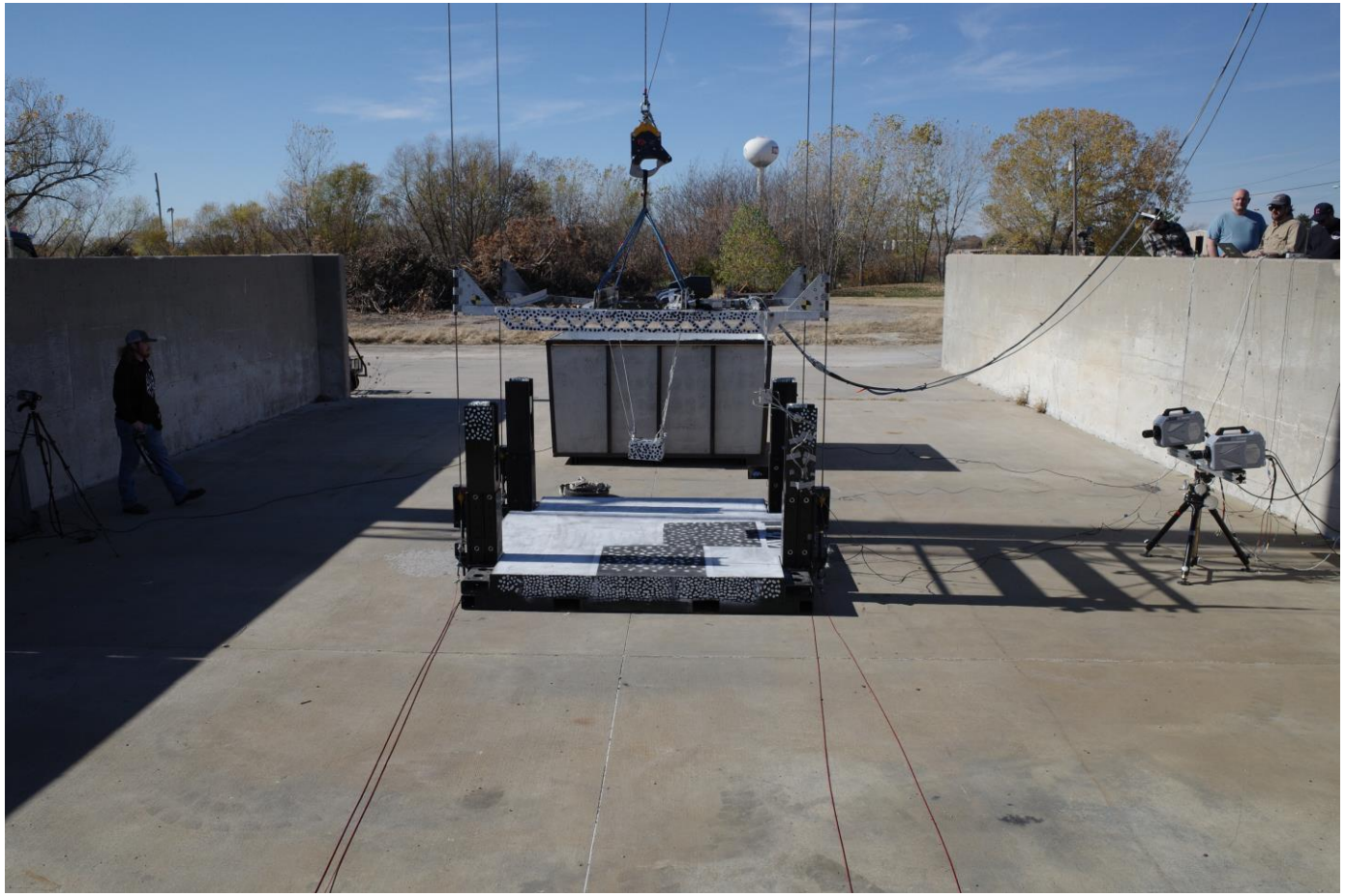


Vertical Flight Society 81st Annual Forum and Technology Display

May 20, 2025

Research background

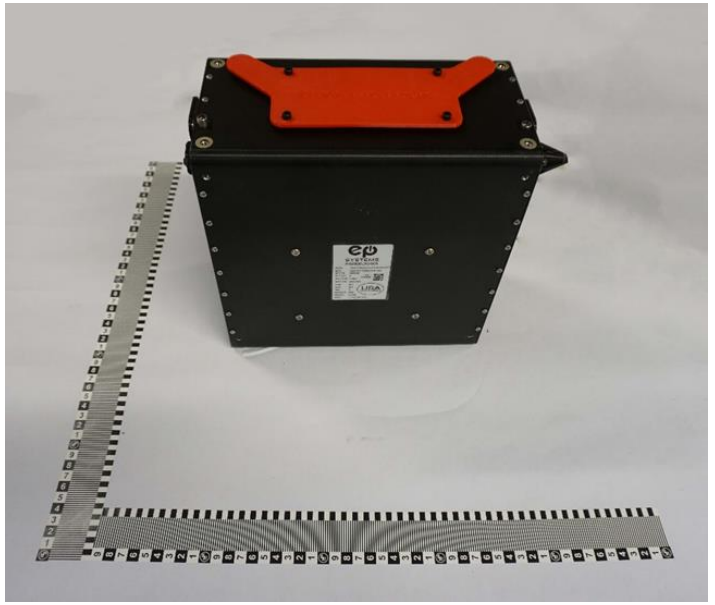
- NASA has decided to include battery crashworthiness as a part of the Revolutionary Vertical Lift Technology Crashworthiness Technical Challenge
  - After talking to stakeholders, and due to lack of data on eVTOL batteries, NASA has decided to undertake a multistep program to provide data to the community
- Some of the questions that we have
  - What does a 50 ft drop test do to Energy Storage System (ESS) modules?
  - What types of failure mechanisms occur if ESS modules are tested under these conditions?
  - Are there ways to mitigate failures through testing and/or configuration changes
    - i.e. mounting “within structure”, mounting a particular orientation
- What we are **NOT** doing
  - Certifying ESS systems for flight
  - Providing commentary on effect of the ESS system result on the aircraft
- Caveat
  - Testing one design from one OEM under one condition to provide data and generate discussion
  - Data is in work

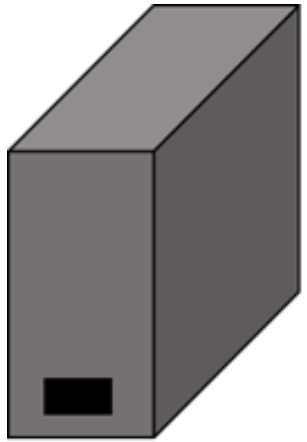
Research Roadmap

- Phase 1 – Module Level - COMPLETE
  - Conduct drop tests of zero state of charge (ZSOC) ESS modules in 4 orientations
    - Right-side Up, Upside Down, Sideways, Flatways
    - No supporting structure present
  - Develop scoring rubric to determine a quantitative way of scoring and comparing the damage sustained by each module
  - Disassemble modules and conduct post-test forensics noting failures, deformations and other mechanisms present post-test
  - Use data to guide Phase 2 efforts
- Phase 2 – Module Level - Conducted 2024
- Phase 3 – Pack Level - Testing preparations in process – scheduled for late 2025

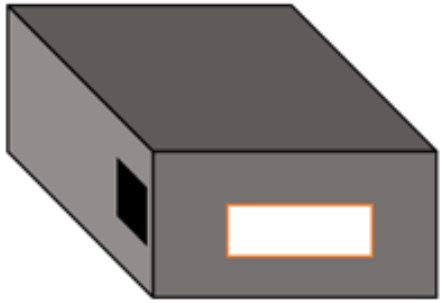
Test Articles

- Electric Power Systems (EPS) EPIC Energy Module AV2300L10-001
- Nominal operation of 39 Volts generating 2.3 kWh of energy
- Per Module
  - 30 pouch cells, busbars, chiller plate, electronics, ventilation, health monitoring
- All modules designed TSO-179b, DO-311a and UN38.3 requirements
- Zero-state of charge
- 4 orientations – noted below by connection block (black) and vent port (white – covered in red in figure)

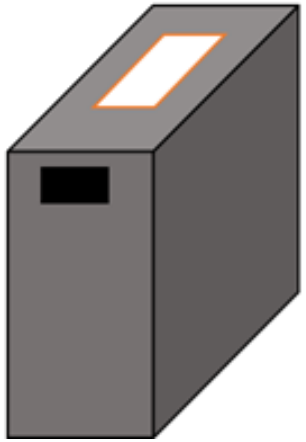




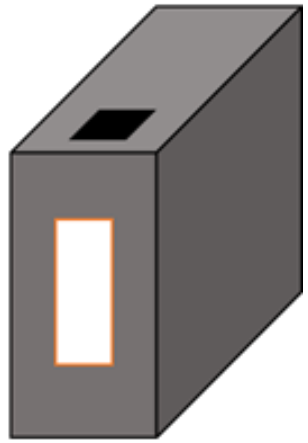
Up-side down



Flatwise



Right-side up



Sideways

Test Rubric – Assembly Level

- Rubric developed at two levels
  - Assembly and Cell
- Assembly examines three systems present to act as containers
  - Enclosure, Containment and Cell
- Comparative way of measuring damage
- Enclosures toward the cells are weighted higher

Assembly	Severity	Multiplier	Score (Severity * multiplier)
Enclosure	Low (1), Medium (2), High (3), Severe (4)	1	
Containment	Low (1), Medium (2), High (3), Severe (4)	2	
Cell	Low (1), Medium (2), High (3), Severe (4)	3	

Test Rubric – Cell Level

- Rubric counts the amount and type of damage observed at the cell level
- Visual - Pouch puncture – external object, Pouch breech – inertial object
- MultiMeter - Electrical shorts
- Smell - Electrolyte

Damage	Number of Cells	Multiplier	Score (Cells * multiplier)
Pouch Puncture		10	
Pouch Breech		10	
Pouch Deformation		4	
Electrical Shorts		3	
Electrolyte Smell (Y/N)		10	

Test Conduct

- Tests conducted at National Institute for Aviation Research (NIAR) outdoor test cell
- Pre-test checks on health of module recorded
  - Voltage
  - Temperature
  - Verify module is at ZSOC, and functional
- Raise 50 ft, drop, collect impact data and video
- Post-test – Monitor/record post-test t+1 hour - thermal runaway (TR)/ delta Temperature
- Move to covered storage and inspect at t+24 hours for long term changes

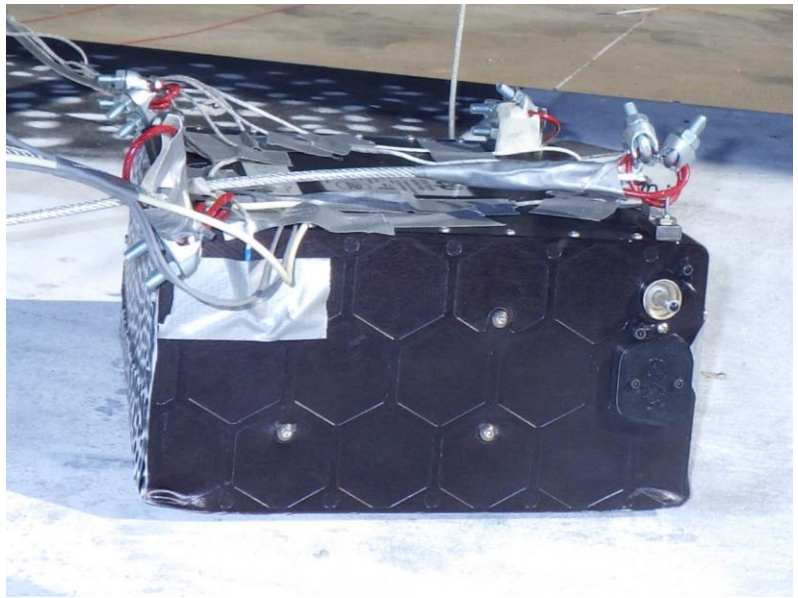
Test Sequence Examples

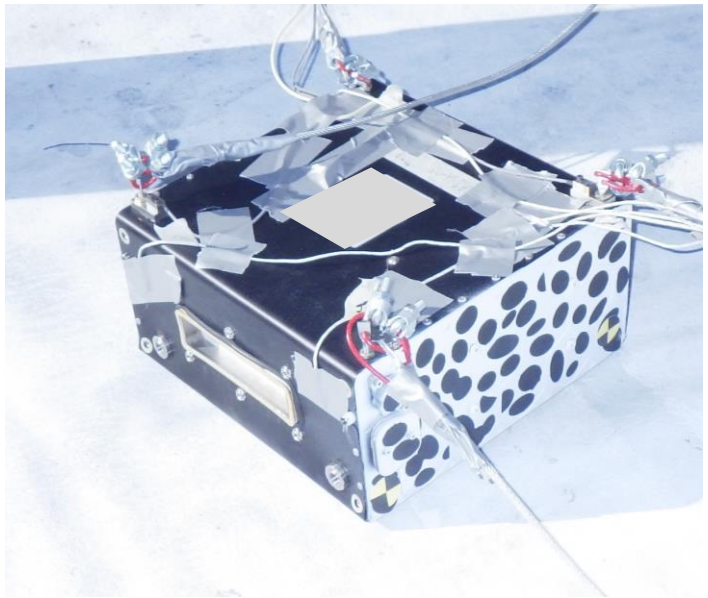
Realtime Camera – Sideways Test

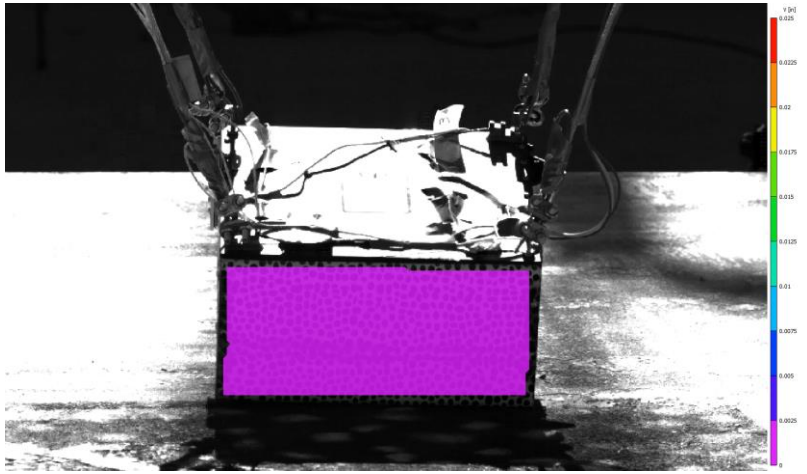
Realtime Camera – Flatwise Test

Flatwise Test

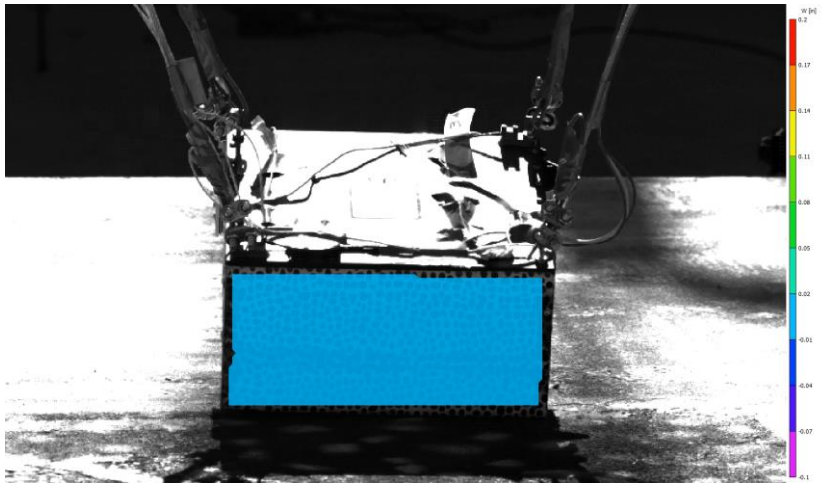
- Deformations on north and south edges due to the rotation during impact
- Fastener orientation changed during impact
- Convex shape of Enclosure Assembly
- Little to now permanent vertical deformation
- Flexing out of plane deformation present





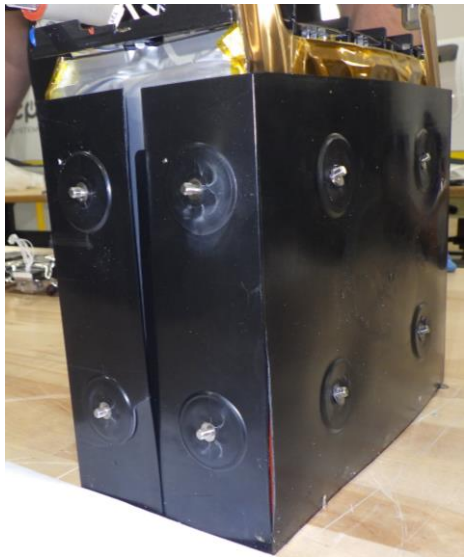


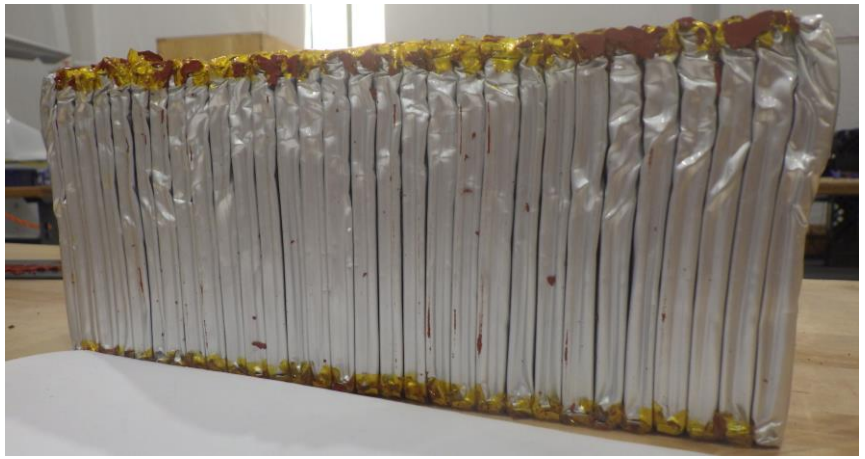
Vertical Deformation



Out of Plane Deformation

Flatwise Test – Post-test inspections

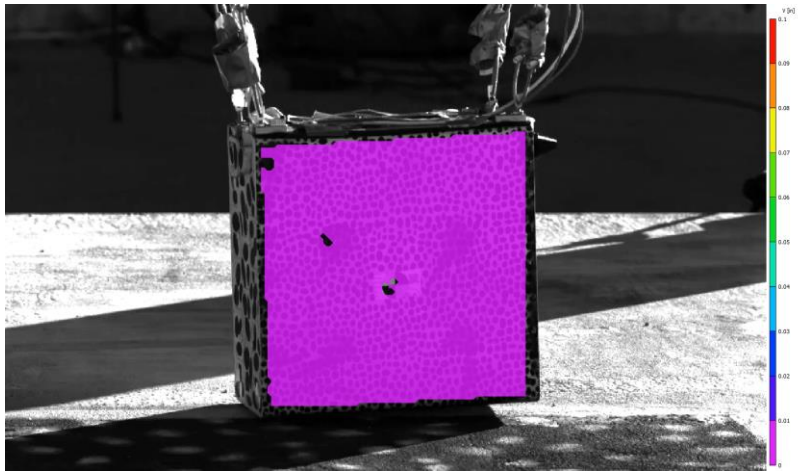




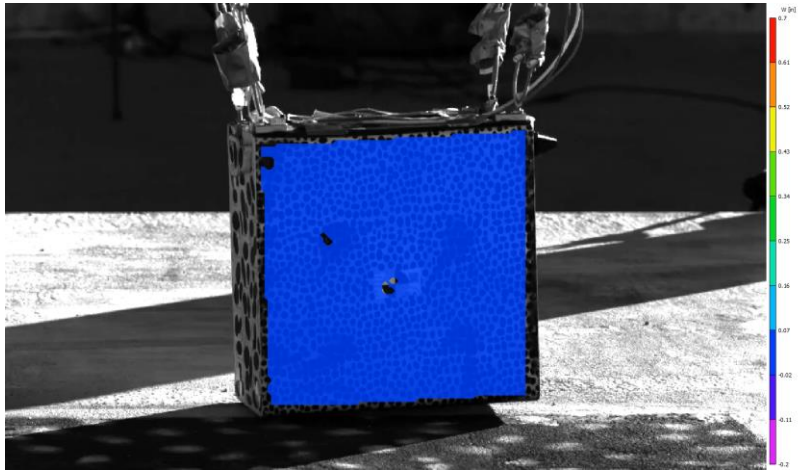
- All cells received damage from the drop test in the form of compression in the lower corner
- Some slight deformation from the case on the impact side of the cells
- Enclosure assembly sustained minimal damage, Containment and Cell assemblies sustained medium amounts of damage

Right-side Up Test

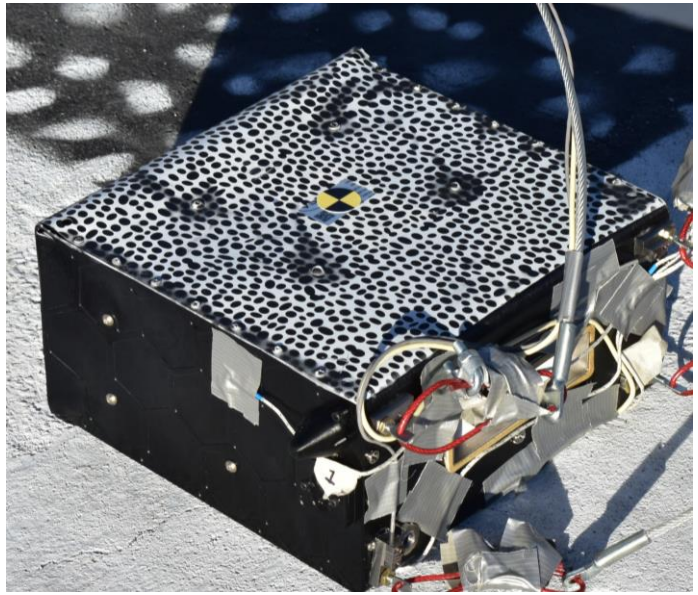
- Bottom, impact surface deformed upward resulting in bulging of the sidewalls
- Fastener orientation changed during impact
- Appeared deformation was localized to the impact location
- Localized vertical and out of plane deformations developed



Vertical Deformation



Out of Plane Deformation

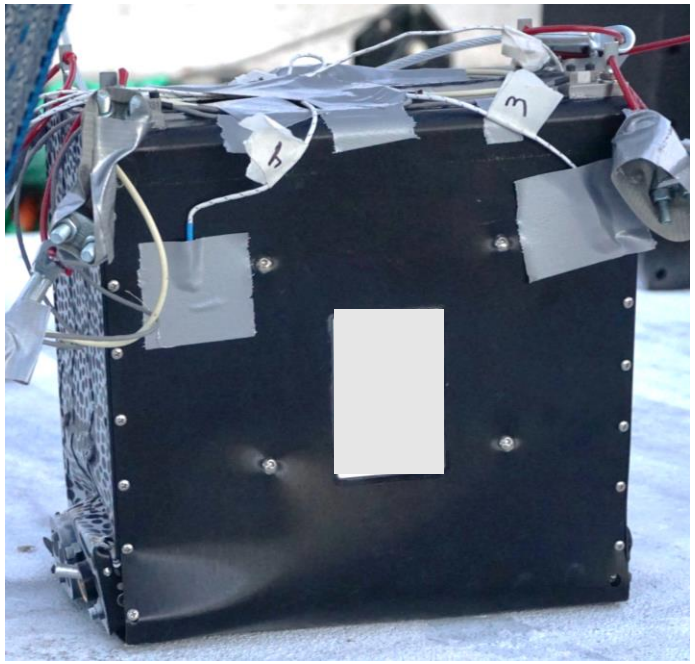


Right-side Up Test – Post-test inspections

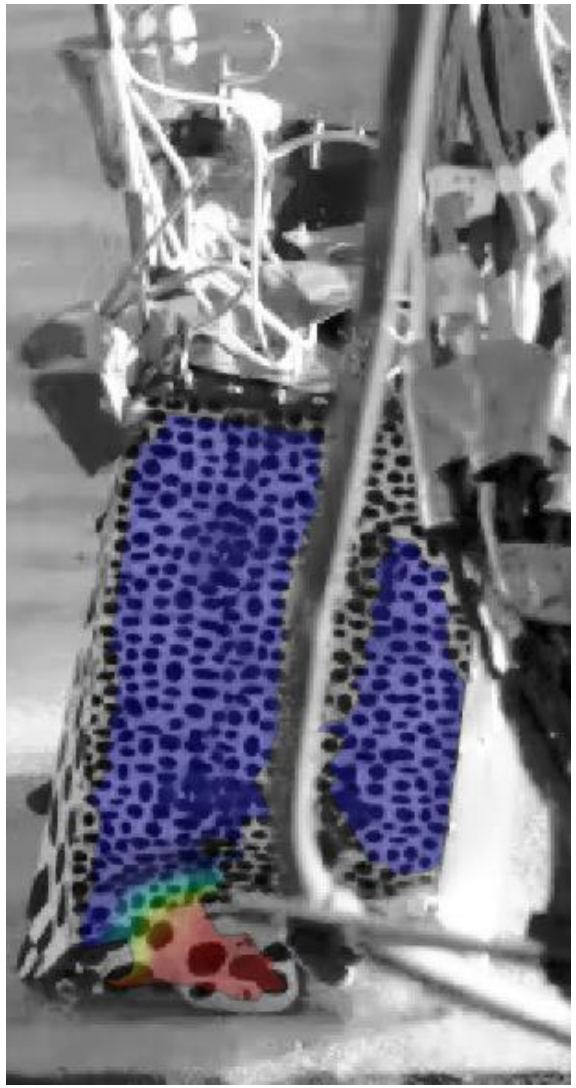
- All cells deformed, electrolyte smell present
- No puncture or breaches visible
- Compressive crushing of pouch cells
- Enclosure assembly sustained medium damage, Containment and Cell assemblies sustained low amounts of damage

Upside Down Test

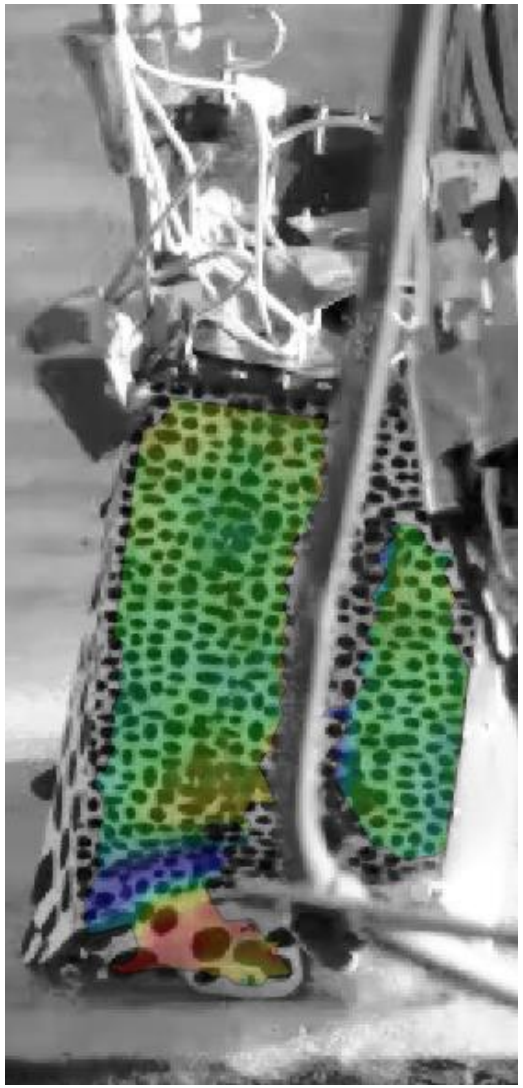
- Non-symmetric impact led to greater deformation on the north side
- Large amounts of crushing on impact side
- Localized vertical and out of plane deformations developed



Vertical Deformation

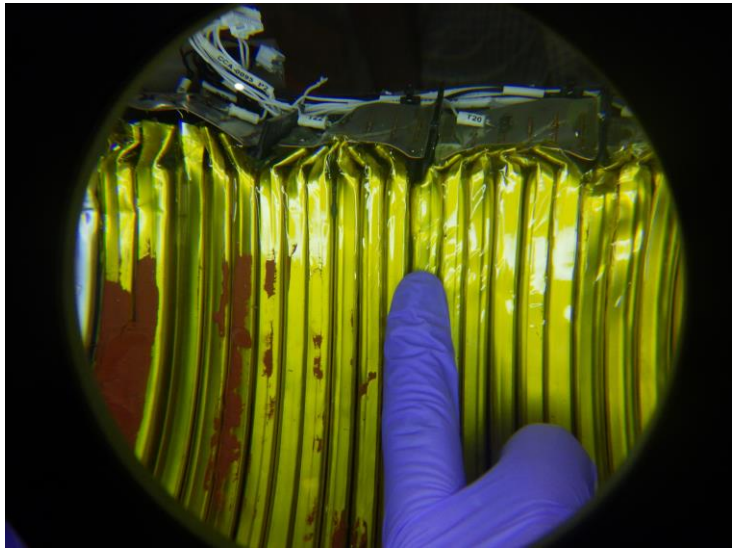


Out of Plane Deformation



Upside Down Test – Post-test inspections

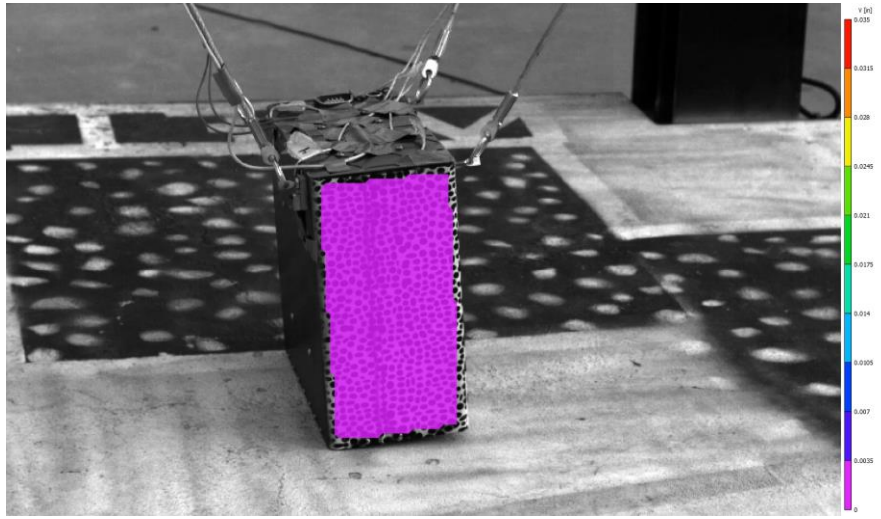


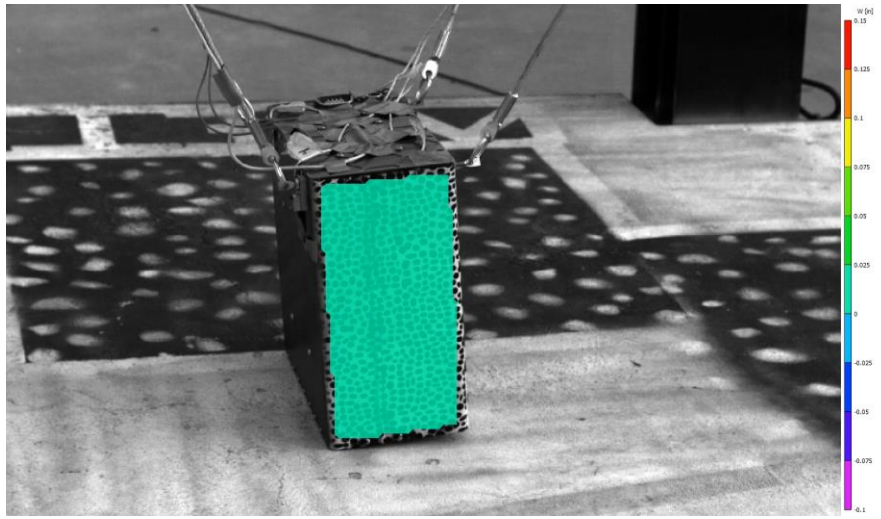
- Internal shorting from cells to enclosure
- Electrolyte smell present
- Cell punctures present
- Significant damage in containment assembly, fastener rotation, punctures in assembly itself
- Generally opposite behavior seen in Right-side up test

Sideways Test

- Sparks observed during testing
- Minimal outer bulging on sidewalls, little deformation on impact face
- Vertical deformations limited to one corner Did not propagate around the edge
- Out of Plane deformation shows flexing



Vertical Deformation



Out of Plane Deformation

Sideways Test – Post-test inspections

- Positive electrode short to containment assembly
- Standoff compression into individual cells
- Strong presences of electrolyte
- Cell punctures present

Rubric Results

- Two highest scores were Sideways and upside down
  - Generally, agrees with visual inspections

Orientation	Assembly Level	Cell Level	Total
Flatwise	11	130	141
Rightside Up	7	130	137
Upside Down	18	147	165
Sideways	20	235	255

- Two highest scores were Sideways and upside down
  - Generally, agrees with visual inspections
- Cell level damage dominated results
  - Different weighing methods for future tests
- Results also paralleled post-test health monitoring checks
- Results do not correlate with acceleration levels presented in Part 1

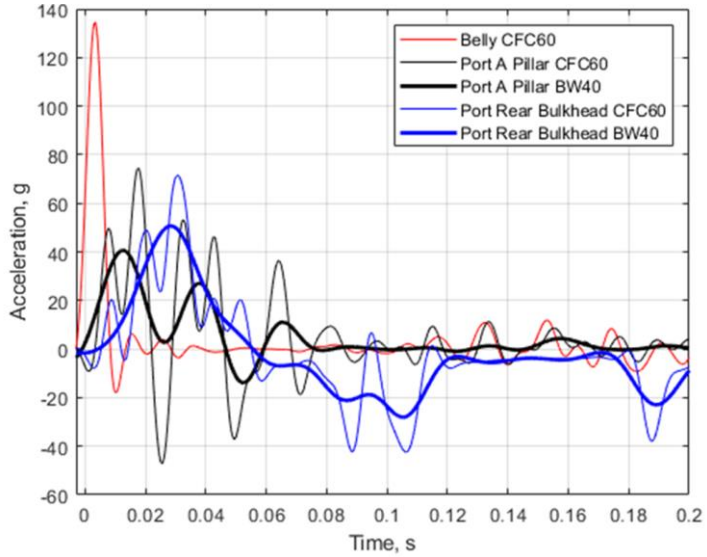
Part 2 Summary

- Post-test deformations observed for all tests
- Digital Image Correlation obtained on outer case, can provide some insight into inner structure
  - Much of the damage is localized to the impact zone
- Module health checks pre- and post-test correlated with qualitative damage determined from visual inspections
- Using rubric, cell level damage dominated the scoring
- Unknown effect on aircraft
  - Other safety improving systems not present such as battery management unit, venting, mid-point disconnect
- Data used to identify cases for Phase 2 research
  - Upside down and Sideways

Going Forward

- Data from one design tested under one type of condition for Phase 1
- Phase 2 – tested two module orientations under two loading magnitudes
  - Attenuation present to bring loading conditions back into crash-type pulses
  - 80 g and 220 g

Phase 2 Test Setup



NASA Lift + Cruise Test, Nov 2022.

Littell, J.D. and Putnam, J.B. “A Summary of Test Results from a NASA Lift + Cruise eVTOL Crash Test.” Proceedings from the Vertical Flight Society’s 70th Annual Forum. West Palm Bean, FL. May 16-18, 2023.

Acknowledgements

- Rob Huculak and NIAR test team

- Joseph James, Spencer Wright, Derek Larsen, Brad Mowery – Electric Power Systems