Dynamic Drop Testing of eVTOL Energy Storage Systems Part 1: Drop Test Data Summary

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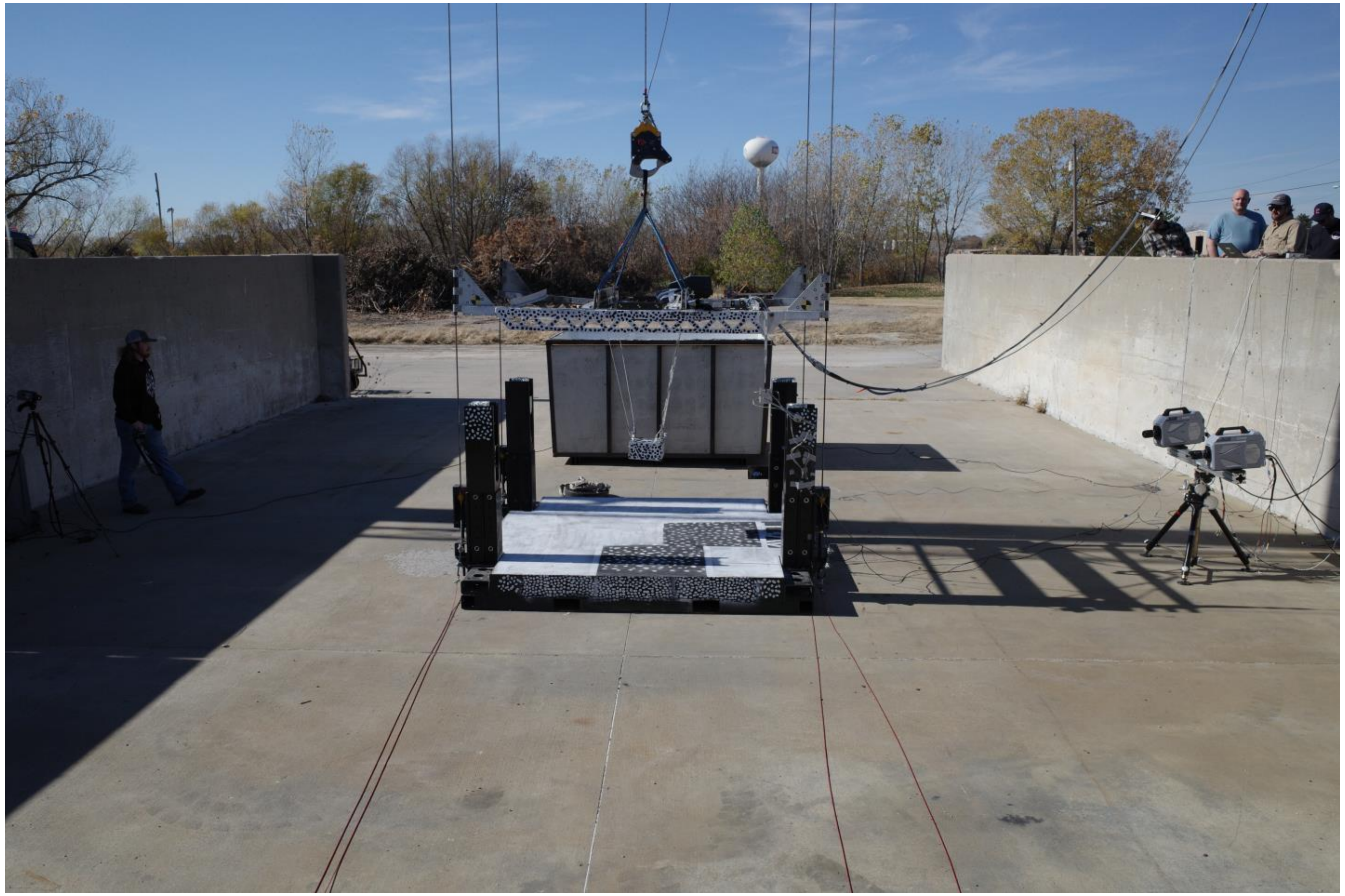


Vertical Flight Society 81st Annual Forum and Technology Display

May 20, 2025

Research background

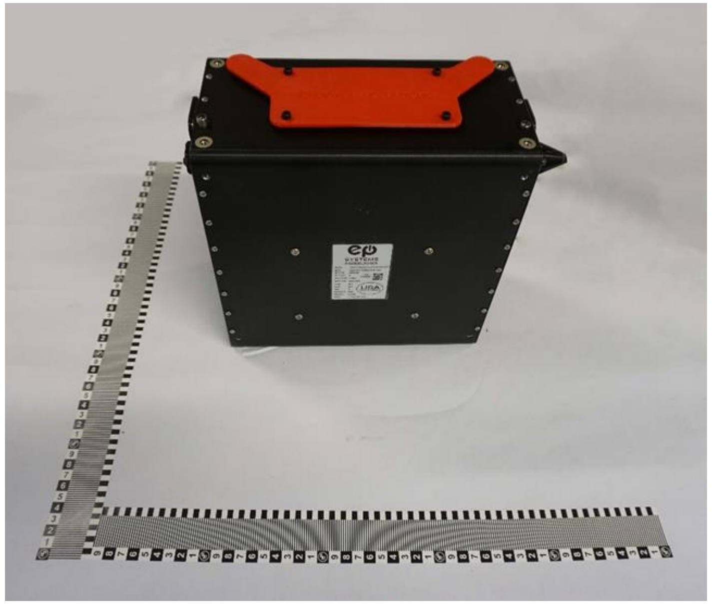
- NASA has decided to include battery crashworthiness as a part of the Revolutionary Vertical Lift Technology Crashworthiness Technical Challenge
  - After talking to stakeholders, and due to lack of data on eVTOL batteries, NASA has decided to undertake a multistep program to provide data to the community
- 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

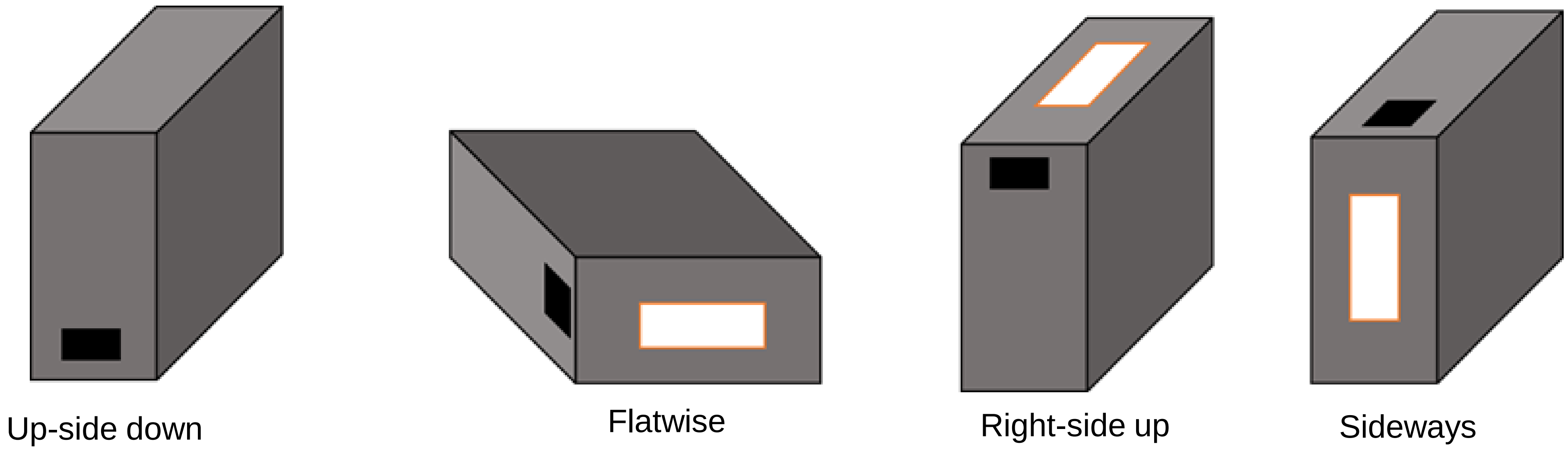
Research Roadmap

- 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

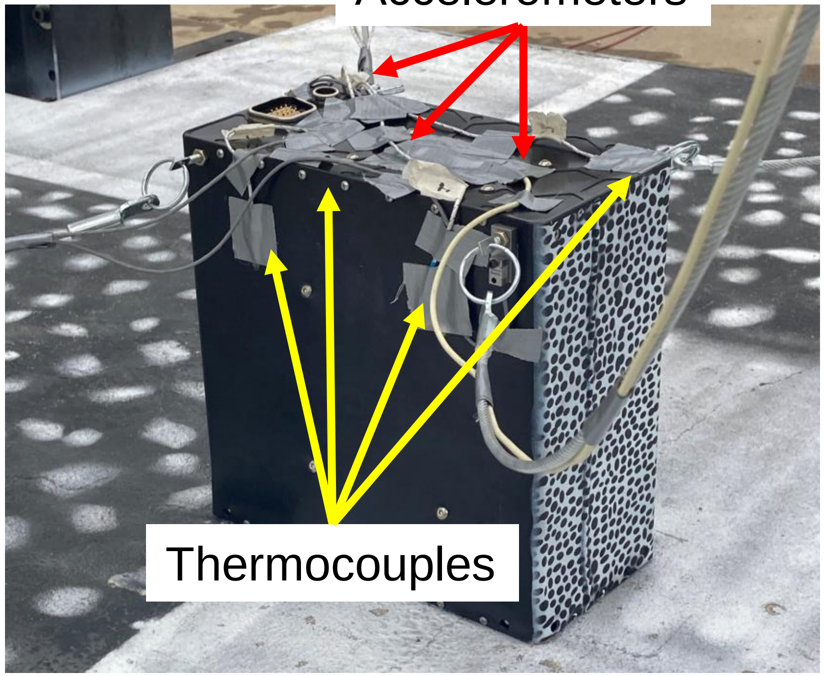
- Electric Power Systems (EPS) EPIC Energy Module AV2300L10-001
- Nominal operation of 39 Volts generating 2.3 kWh of energy
- Per Module
  - 30 pouch cells, busbars, chiller plate, electronics, ventilation, health monitoring
- All modules designed TSO-179b, DO-311a and UN38.3 requirements
- Zero-state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

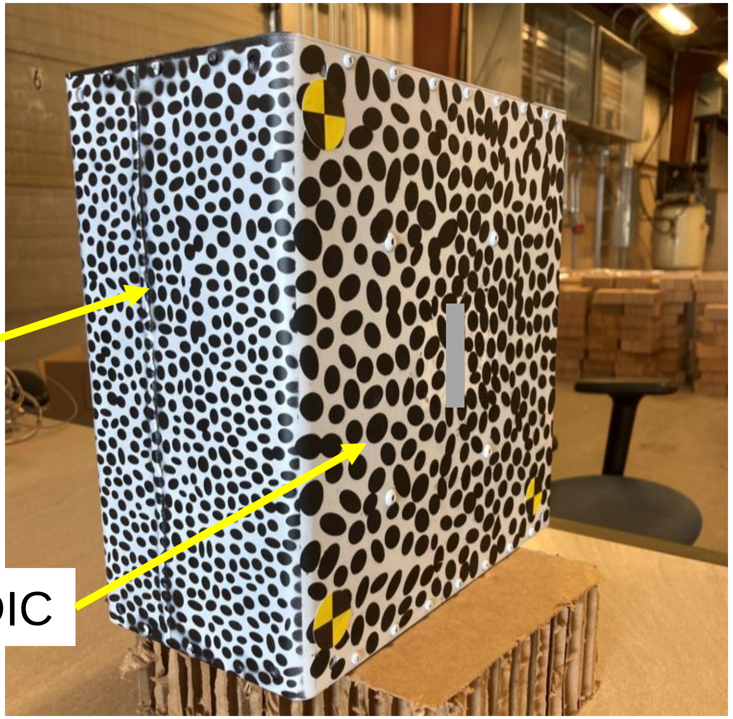




Test Instrumentation

- 2 triaxial accelerometers in upper facing corners – opposite sides if possible
- 1 uniaxial accelerometer in middle or edge of upper face
- 4 thermocouples on non-speckle coated sides
- Two sides speckle coated – 1 local Digital Image Correlation (DIC), 1 global DIC and impact orientation tracking
- Voltage and temperature checks pre- and post-test





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

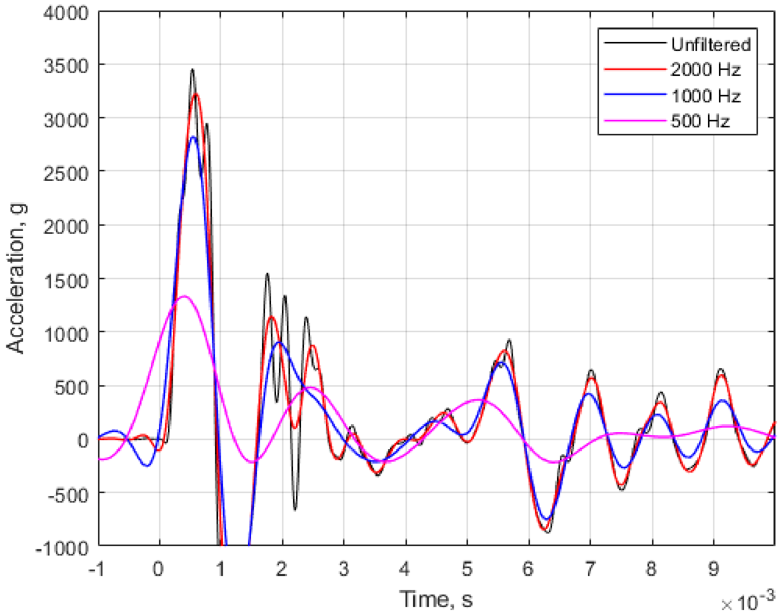
Test Sequence Examples

Realtime Camera – Sideways Test

Realtime Camera – Flatwise Test

Accelerations – Raw to Filtered

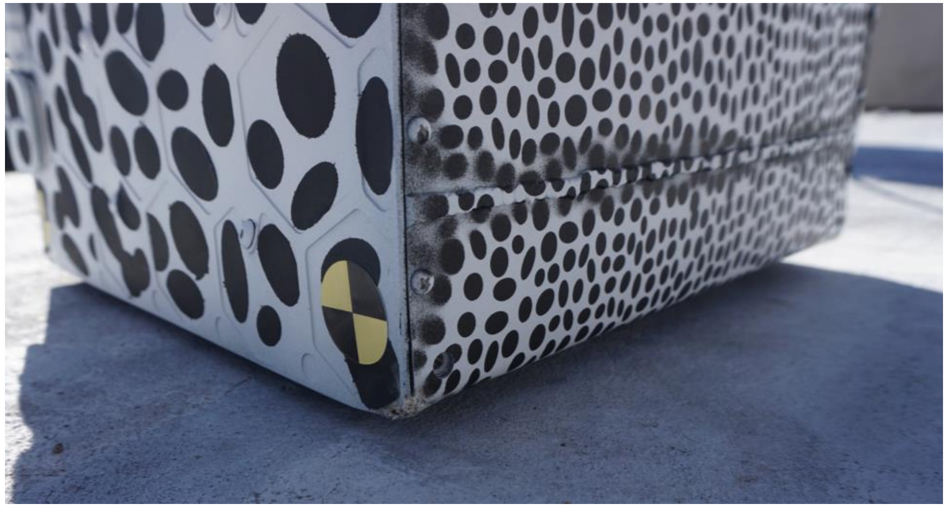
- Loading events on the order of 20 millisecond (ms) or less
- SAE J211 lowpass filter criteria unable to adequately capture pulse
  - 4-pole Butterworth backward and forward low-pass filter used
  - Various cutoff frequencies evaluated to determine viable number
    - Integrate signal and compare unfiltered to filtered
  - 1000 Hz picked due to minimal differences in signal

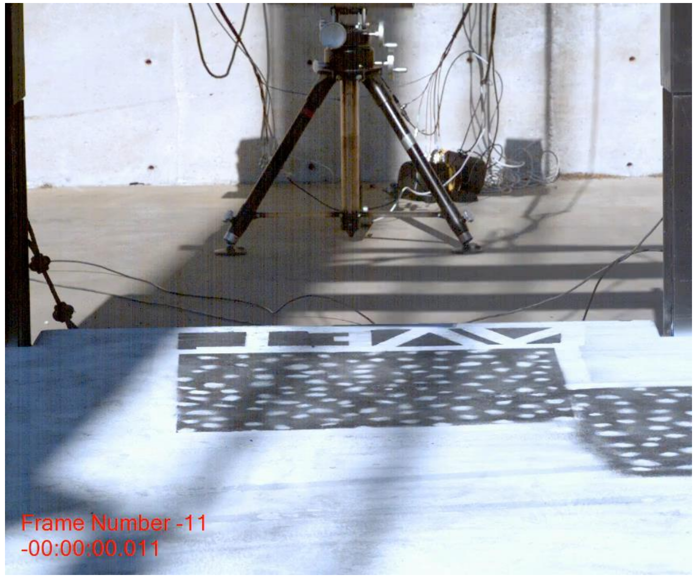


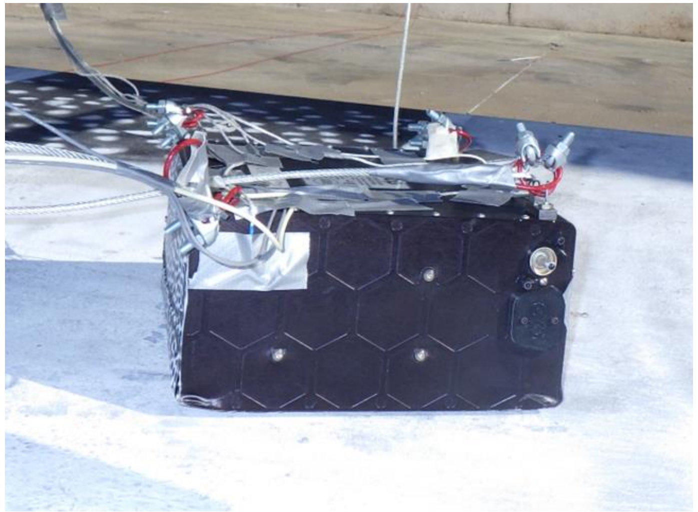
Measurement (integrated signal)	Unfiltered	2000 Hz	1000 Hz	500 Hz	100 Hz
Initial spike (0 < t < 1 ms)	1.00	1.024	1.027	0.677	0.195
Full contact (0 < t < 20 ms)	1.00	1.005	1.014	0.871	0.708

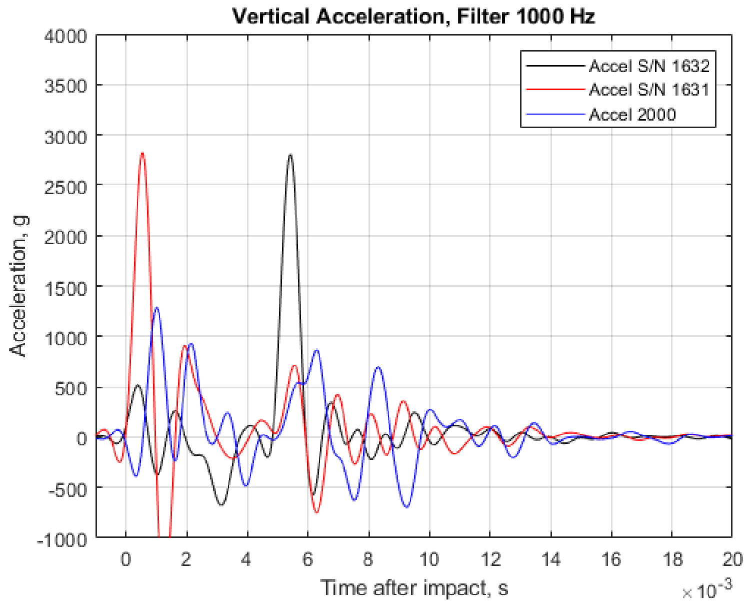
Flatwise Test

- North Side low angle of 17.9 degrees
- West side low angle of 1.4 degrees
- Impact velocity of 46.9 ft/s
- North-to-south rotation through the impact
- South side impact t+4.8 ms
- Some localized deformations but little crushing on impact face
- Post test health monitoring data available



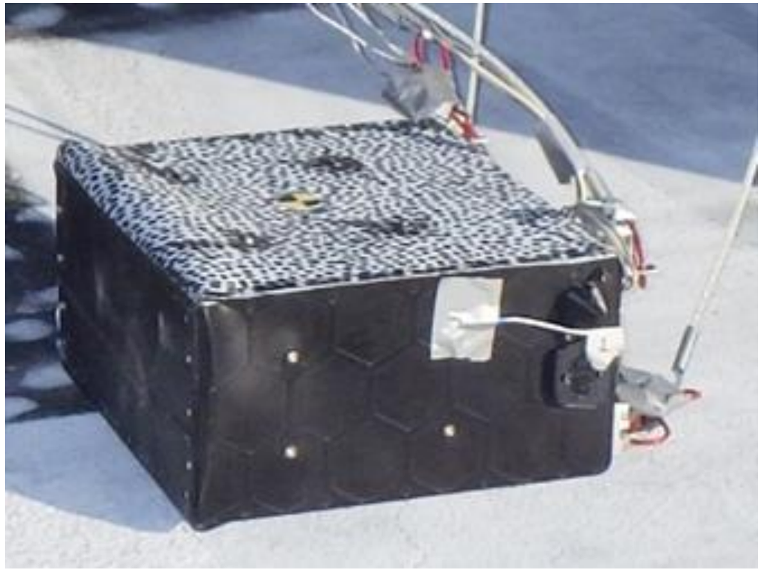


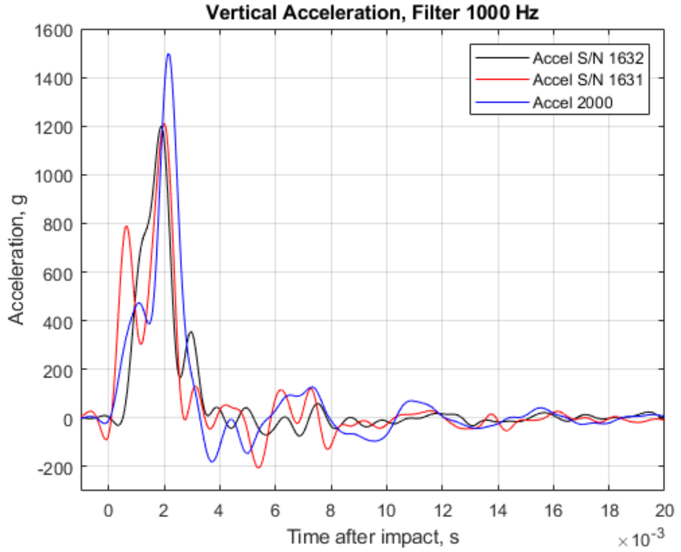




Right-side Up Test

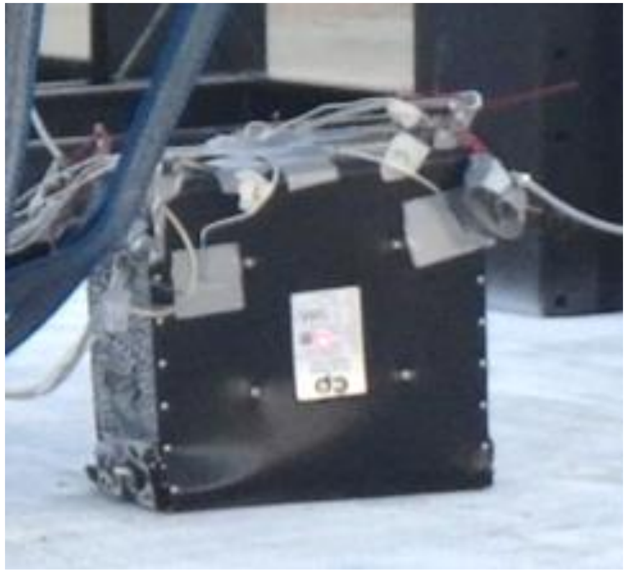
- South side low angle of 2.2 degrees
- East side low angle of 2.6 degrees
- Impact velocity of 52.8 ft/s
- Minor east-to-west rotation
- Side impacts ~1ms difference
- Accel data shows uniform pulse shapes, varying magnitudes
- Post-test configuration on side
- Post test health monitoring data available

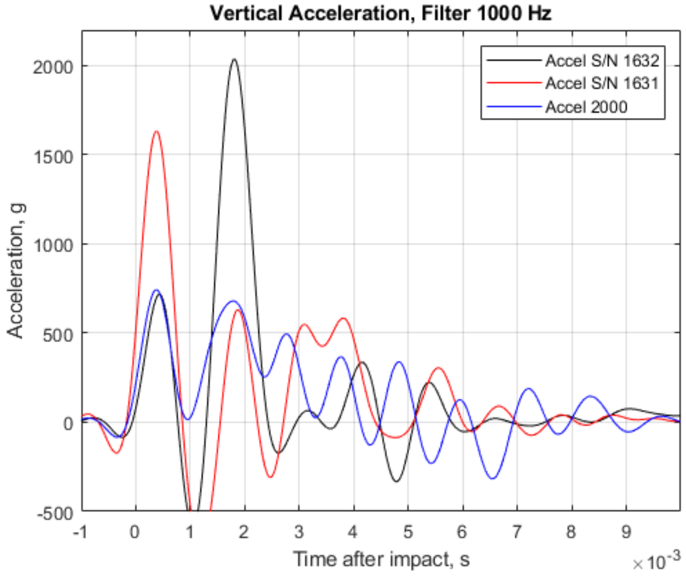




Upside Down Test

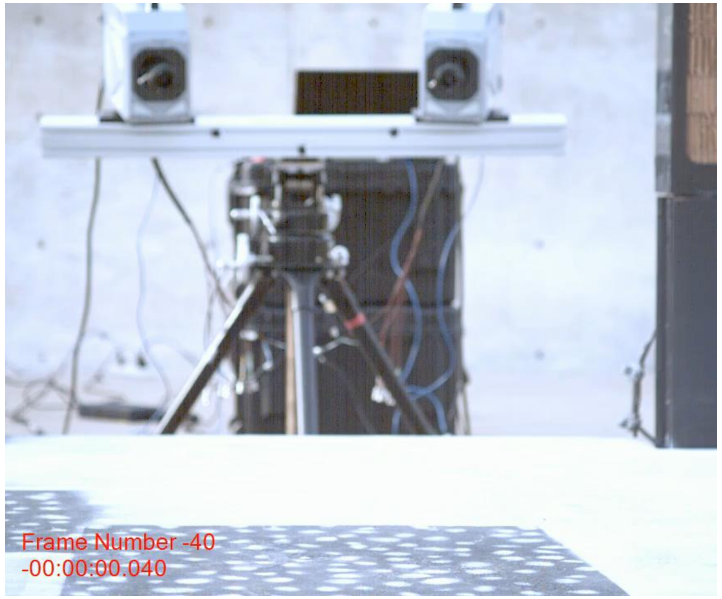
- North side low angle of 6.2 degrees
- West side low angle of 2.3 degrees
- Impact velocity of 48.5 ft/s
- North to South rotation
- Side impacts ~ 1.4 ms difference
- Large amounts of crushing on impact face
- Differences in the middle accelerometer to the accelerometers mounted at the corners
- No post test health monitoring data available

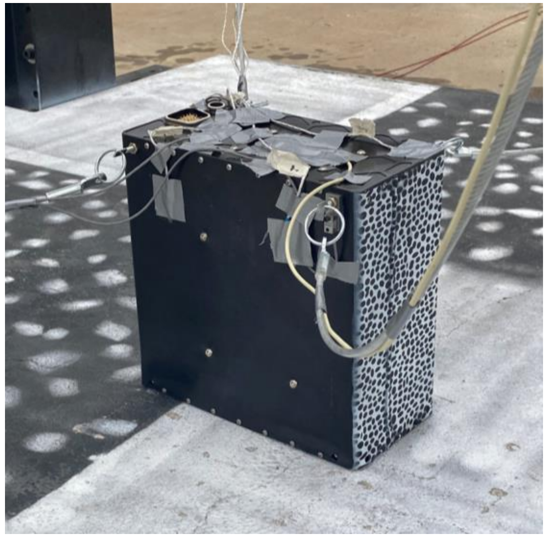


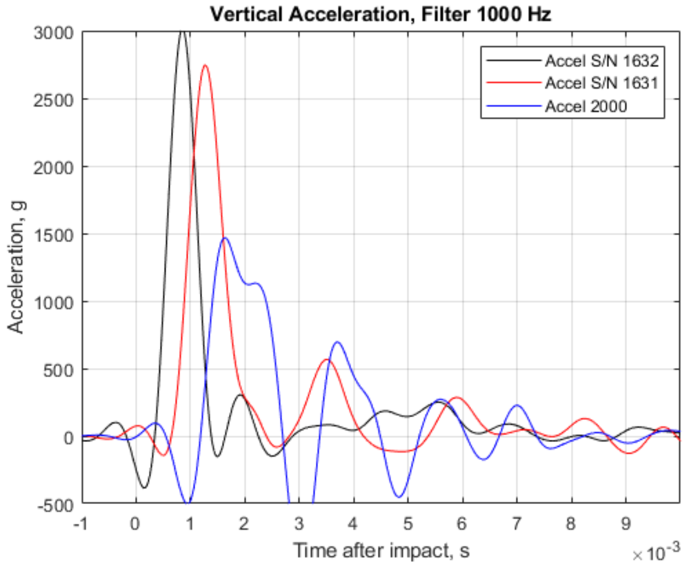


Sideways Test

- Electrode side down – positive protrusion prior to test
- Flat North to South
- West side low angle of 6.5 degrees
- Impact velocity of 50.6 ft/s
- Side impacts approximately same time
- Sparks noted from electrode crushing
- Inward deformation on top surface
- Bulging but little crushing on impact face
- No post test health monitoring data available



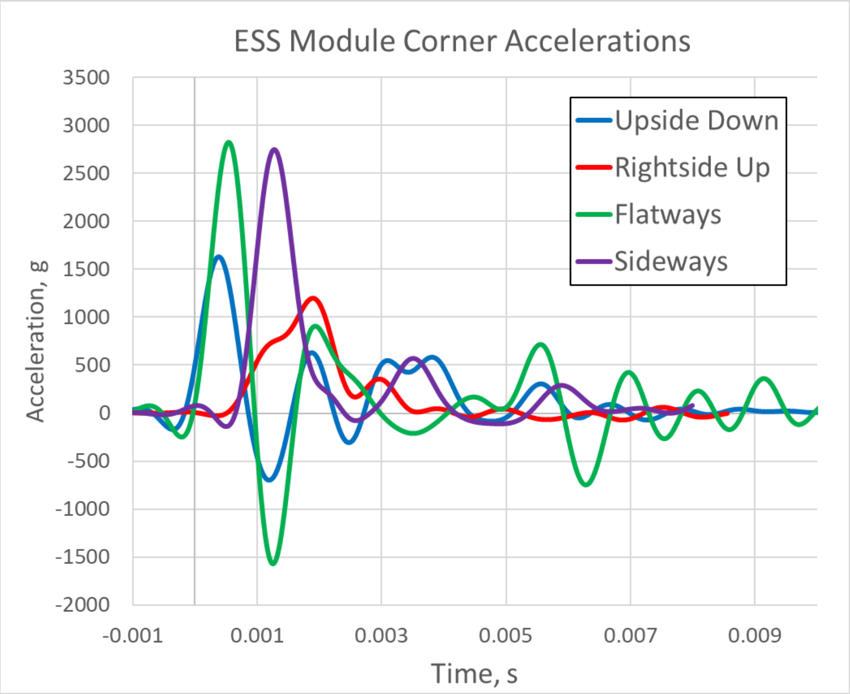




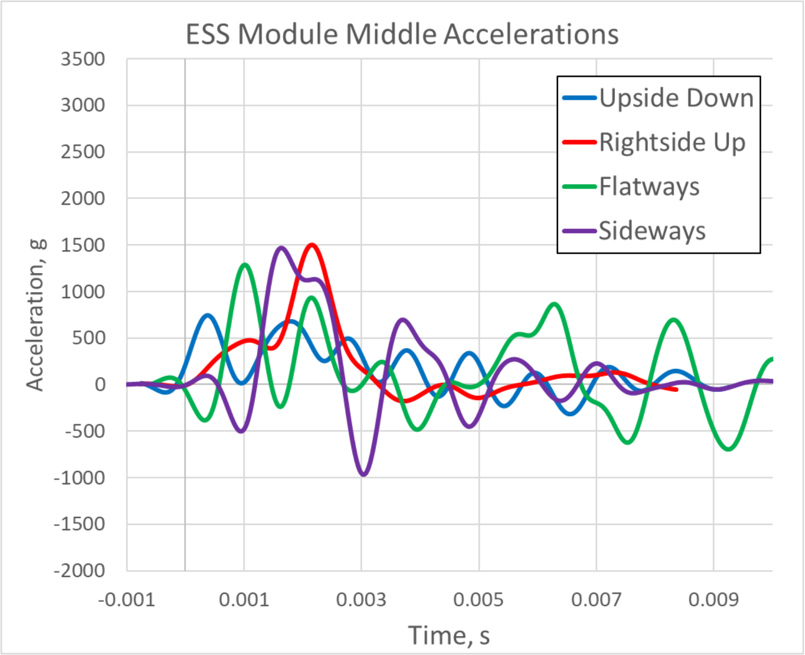
Result Discussion – Impact Conditions

- Impact conditions – angles, speeds - large angles in flatwise
  - Highest impact energy was Rightside Up with no significant angle
  - Flatwise was 78% energy from highest test, and with significant impact angle
  - Sideways was 92% energy from highest test, no significant angle

Corner



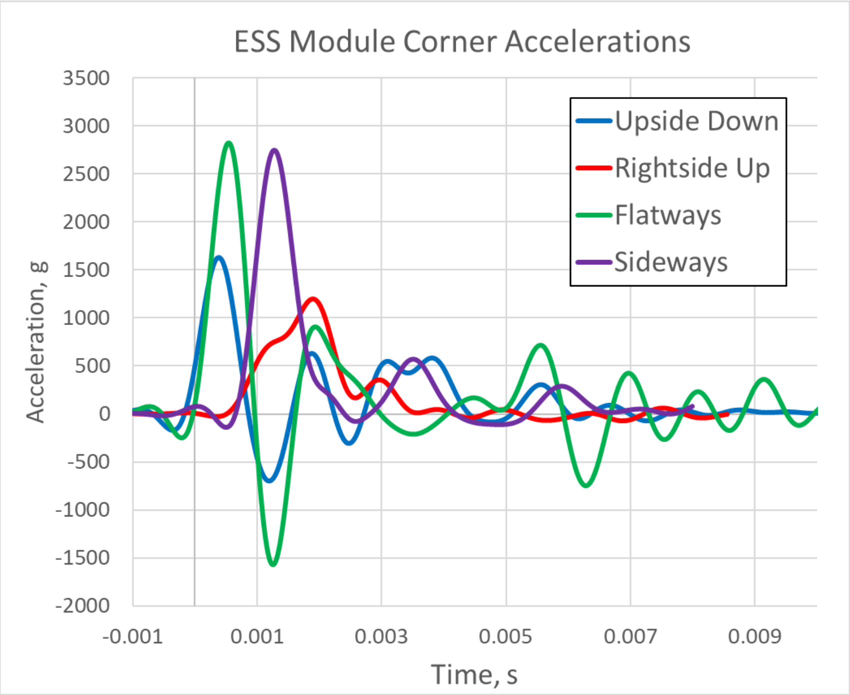
Middle



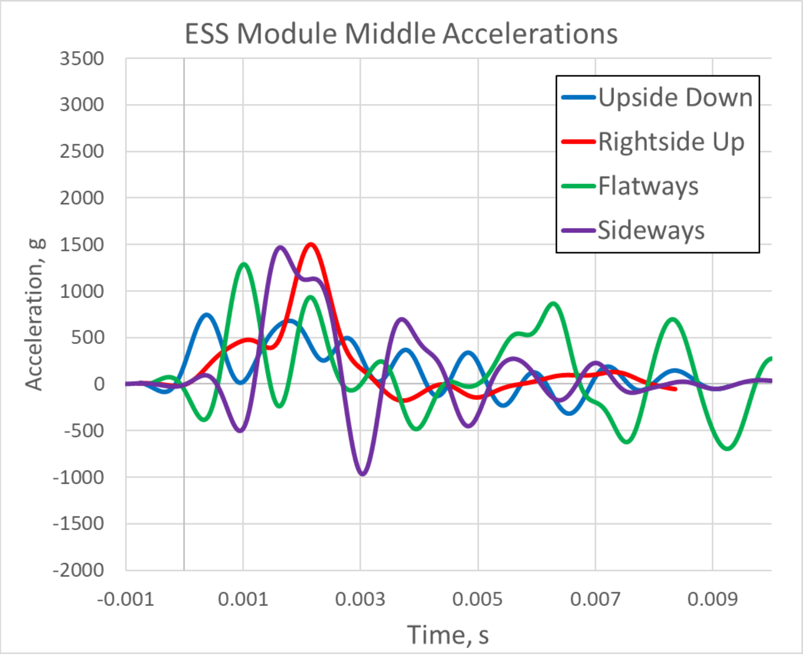
Result Discussion – Accelerometer Location

- Corner accelerometers measured higher results due to their location in the structure where three edges meet
- Right side up approximately the same accelerations
- Accelerometers mounted in the middle of the face experienced differences in response due to other factors

Corner



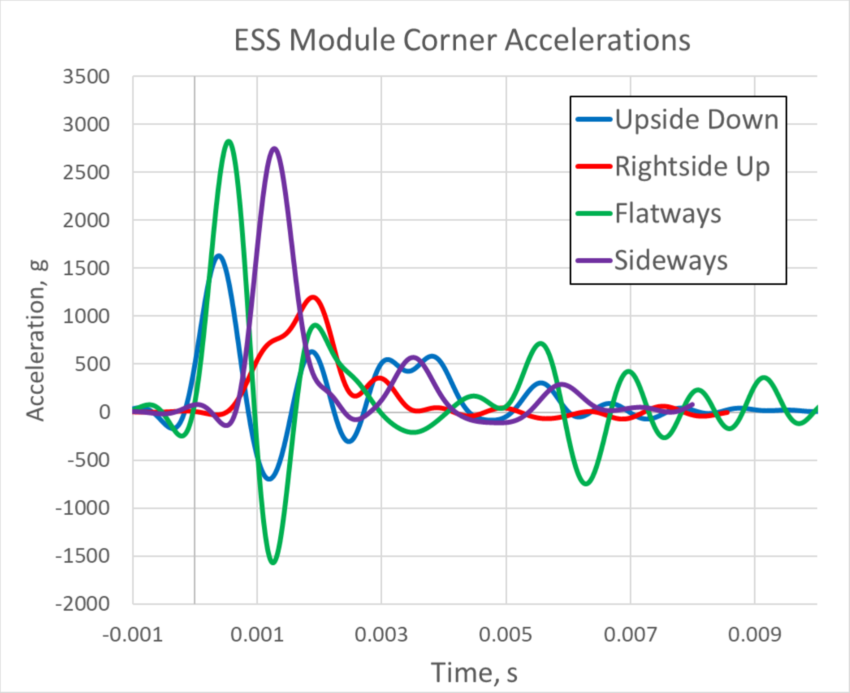
Middle



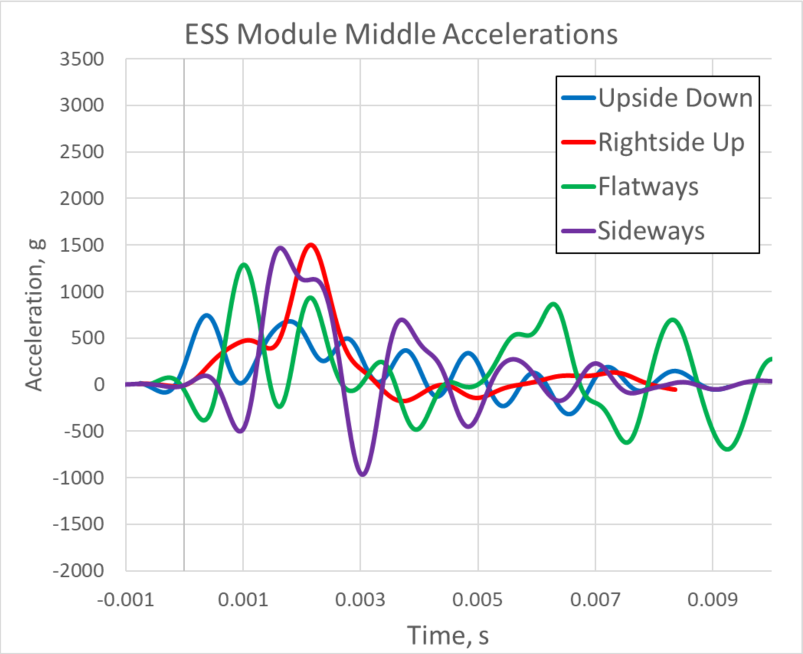
Result Discussion – Module Deformation

- Upside down and Rightside Up tests produced noticeable crushing as determined by visual inspections
  - Generally - 750-1500 g in all locations
- Sideways and Flatwise produces localized deformations
  - Varied results – high in Flatwise and Sideways, but lower in middle

Corner

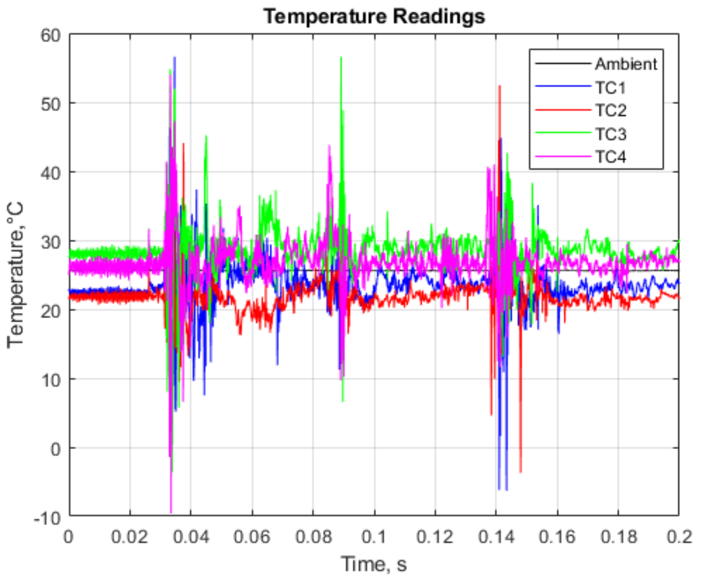


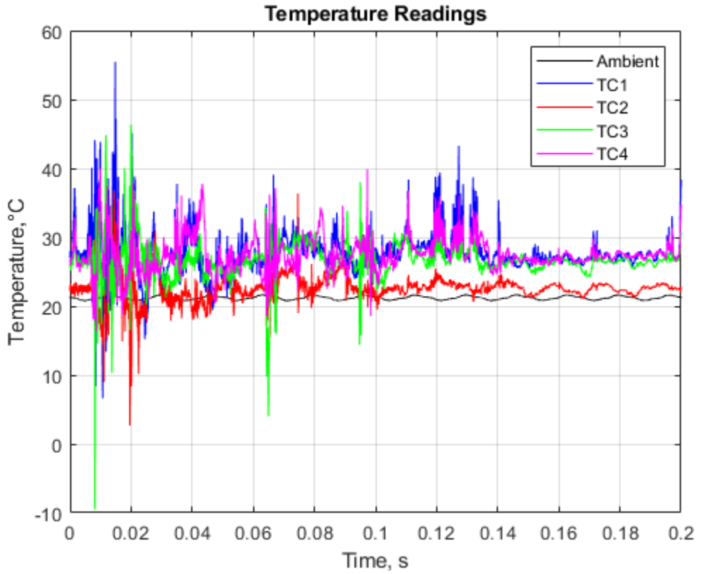
Middle

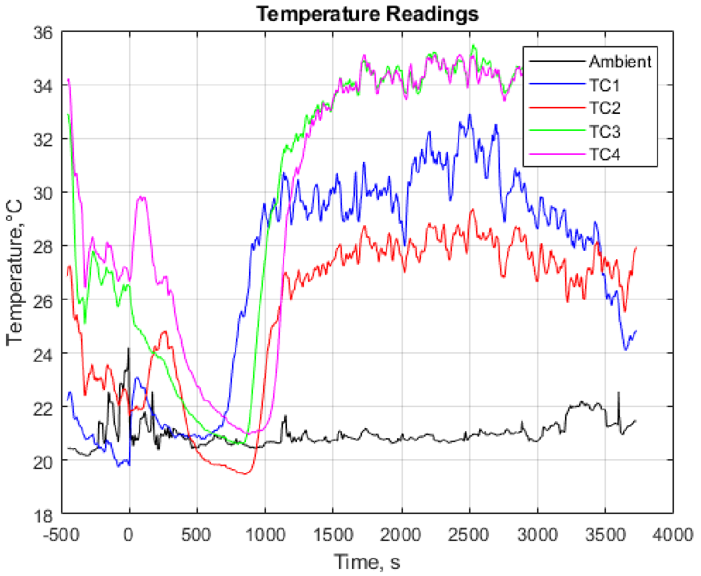


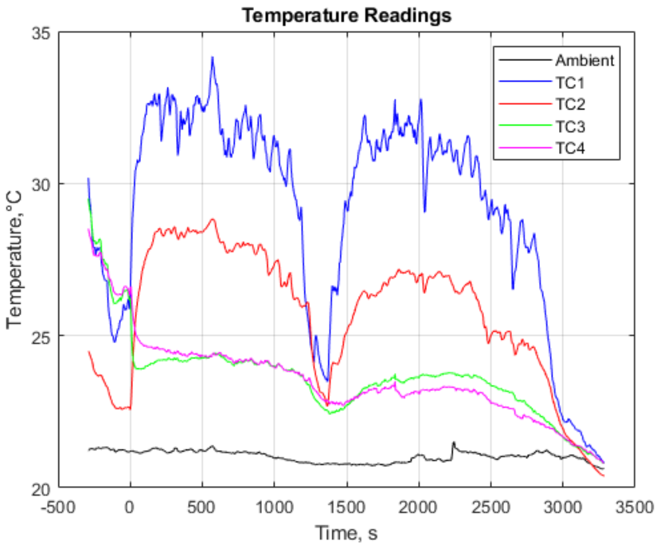
Thermocouple Data

- Temperatures during test do not significantly change
  - Spike but not sustained changes
- Longer duration temperature changes due to changing weather and cloud cover
- No TC data shows steadily increasing temperatures indicating thermal runaway is occurring









Part 1 Summary

- Somewhat inconsistent impact conditions but test method refinement reduced data scatter
- Impacts induced “shock” type (~1,500 g) accelerations into modules even after filtering to higher than typical SAE values
- Highest accelerations measured in modules with little signs of crushing
- Thermocouple data collected showed no signs of TR
- Digital Image Correlation obtained on outer case, working to determine effect on internal structure
- Module health checks pre- and post-test correlated with qualitative damage determined from visual inspections

Acknowledgements

- Rob Huculak and NIAR test team

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