SPACE VECTOR

Development and Qualification of a Compact Rechargeable Li-Ion Range Safety Battery

NASA Battery Workshop 2016

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AS9100C and ISO9001:2008

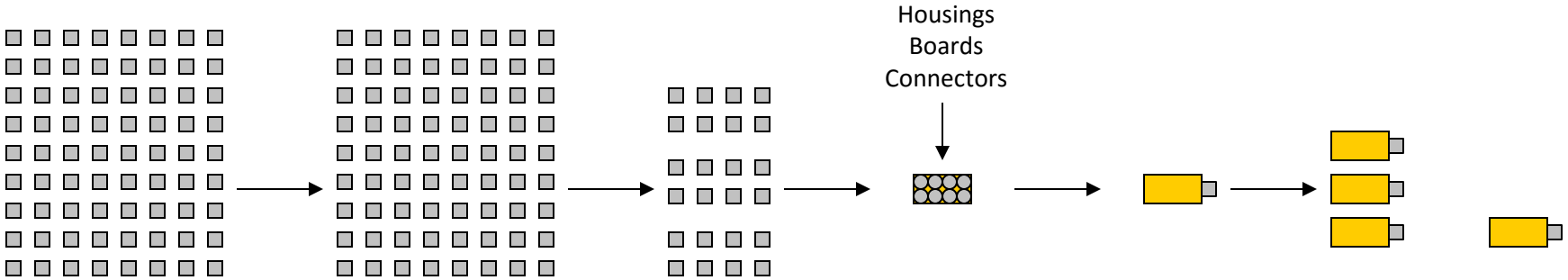
RCC 319 Background and History

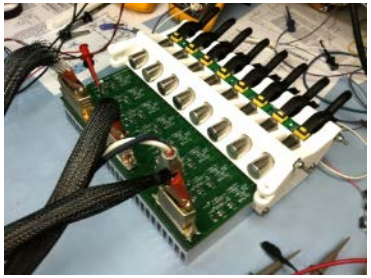
- Range Commanders Council (RCC) covers various Army, Navy, Air Force, and NASA ranges such as VAFB, Cape, WSMR, NAWC, PMRF, RTS, etc.
- RCC 319 Flight Termination Systems Commonality Standard first released in 1992 provides system safety requirements for all FTS components including batteries
- Space Vector qualified its first rechargeable FTS Battery 36441 to the RCC 319-99 back in 2000
  - Successfully qualified 3 different types of batteries (Ni-Cd, NiMH, and Li-Ion) to RCC 319 requirements for use on Army, Navy, and Air Force ranges
  - Also qualified a variety of non-RCC rechargeable system batteries for different applications
- Recent programs testing to the latest RCC 319-14

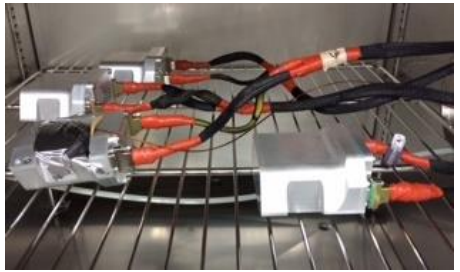
Notable RCC 319 Requirements

- RCC 319 has long list of requirements for FTS batteries
  - Standard covers Ni-Cd (NiMH), Li-Ion, Lead Acid, Silver Zinc, and Thermal batteries
  - Thorough cell screening, acceptance, and qualification test programs required
- Monitor and report Health and Status (H&S) of each cell not just pack voltage
- Range Safety Officer (RSO) typically requires a complete discharge to verify battery capacity prior to a launch
  - Timing can vary but generally as close as possible to launch (within a few days)
  - Requires Ground Support Equipment (GSE) to discharge, record, and display results to the RSO
  - That same equipment used to process in the field is to be used when performing acceptance and qualification testing
  - Affords some flexibility in where you package the Battery Management System (BMS) and how you communicate with the battery depending on the vehicle Concept of Operations (CONOPS)
    - Space Vector has experience with 3 different BMS configurations on the battery (Basic, H&S, Full) depending on the vehicle CONOPS
- RCC 319 also specifies requirements for EEE parts derating and management
  - Specifies EEE parts requirements (Appendix B)
    - Establishes EEE parts baseline for selecting Mil-rated parts or upscreening lower rated parts
    - Screening Test requirements: DPA, PIND, etc.
  - Specifies baseline EEE parts derating and design guidelines (Appendix C)

RCC 319 FTS Battery Test Flow



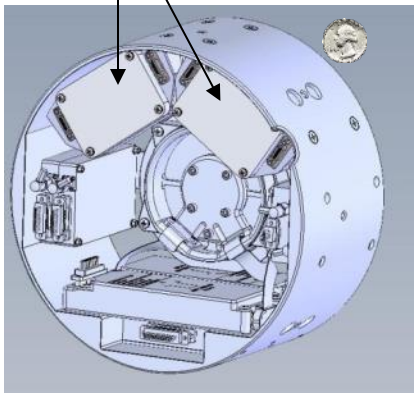




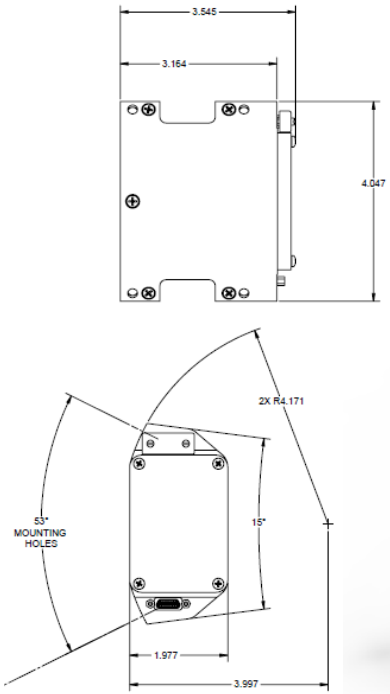
Key Requirements for the Compact Li-Ion FTS Battery

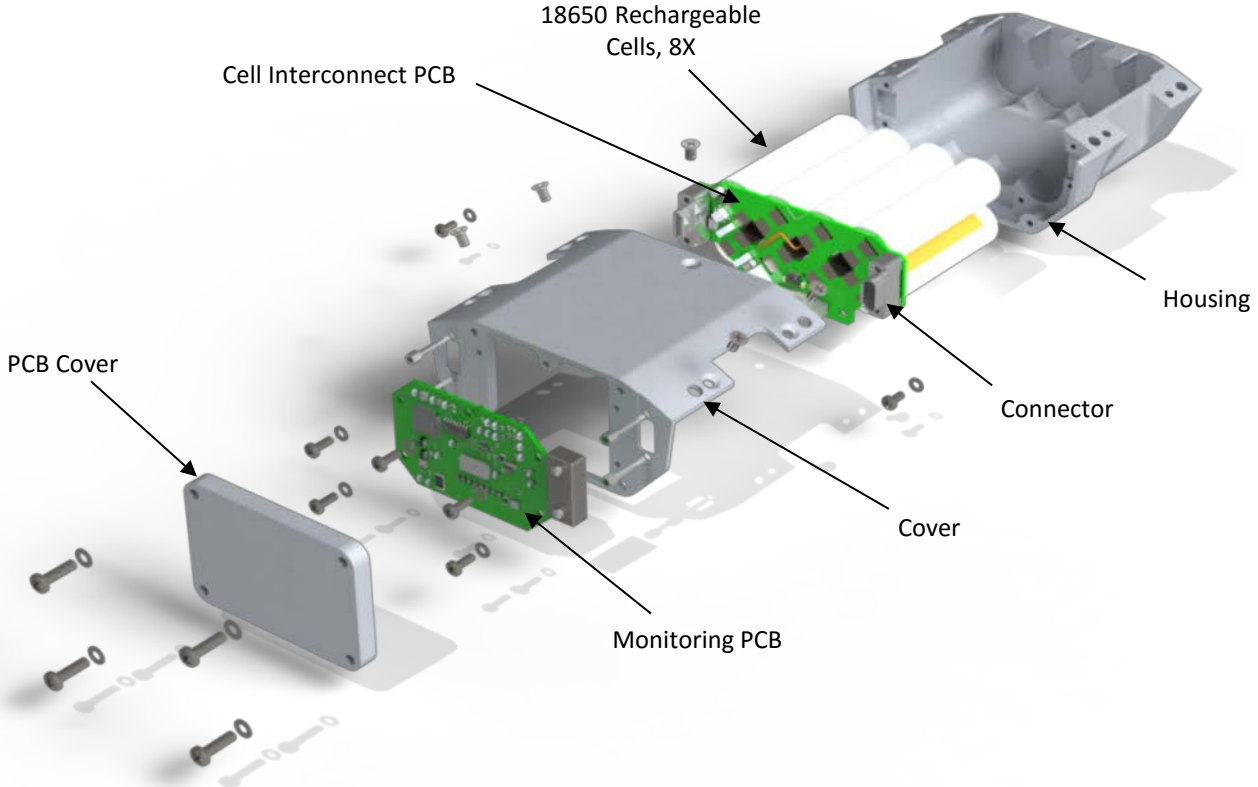
- 28 Vdc nominal pack, 34V – 22.5V
  - 8 cells in series
- 2.0 Ah capacity at 2 A continuous discharge (1C)
- RS-422 Serial Communication
  - Individual cell voltages, current, and temperature
- Lightweight 1.6 lbs (0.73 kg)
- Small Form Factor
  - Battery Envelope 3.5”H (90mm) x 4”W (100mm) x 2”D (50mm)
    - Cell cluster alone is 2.6”x2.8”x1.4”
  - Fit within a 9” (230 mm) diameter x 4” H (100 mm) section
- Severe Environments
  - Conditioned at +70°C operation for 4 days prior to launch
    - Exceeds published cell limits of +60°C for Li-Ion
  - Conditioned at -43°C operation for 4 days prior to launch
    - Requires cell heaters to operate battery
    - Less than the typical -20°C Li-Ion storage recommendations
  - Up to 80 g acceleration
  - Multiple random vibration and shock environments for different missiles
  - High acoustic vibration levels

US Quarter size comparison



Compact Li-Ion FTS Battery Assembly





Cell Selection Trade

- Considered both primary and secondary cell types
  - Primary cells didn't have the capacity or performance and still fit within the design envelope
  - Non-rechargeable cells further complicates the qualification process by having to test and then throw away packs of cells (one shot testing)
- 18650 cells are readily available and come with internal safety devices
  - Integral protection: Current Interrupt Device (CID) and Positive Temperature Coeff. (PTC)
  - Makes Range and System Safety more comfortable with Li-Ion
- Need at least 2.5 Ah rated cells that are capable of handling high pulse loads
  - Advertised cell capacity is usually for a slow discharge at room temperature
  - Found you lose up to 0.5 Ah if used in a pack with high discharge rates and higher cutoff voltages (e.g. 24V, 3V/cell)
- Found the INR (NMC) cells provides the best mix of capacity and high discharge capability
  - Other factors include availability of the cell in single lot date codes and temperature performance both high and low

RCC 319 Cell Screening

- Removed sleeving from cells
- Welded Nickel Tabs onto both cell cathode and anode
- Re-wrapped cell in Shrink Sleeving
  - Positive and Negative tabs sticking straight up and easy to short if knocked over
    - Fabricated wood storage racks
    - Cover positive tab until ready for processing
- Performed RCC 319 Cell Screening

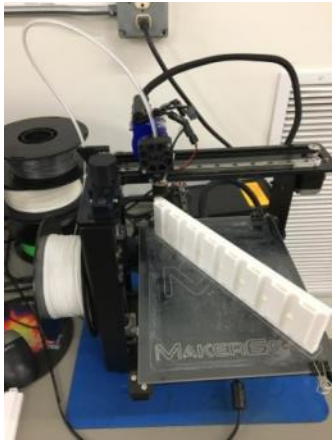
Whoa!
Lesson Learned

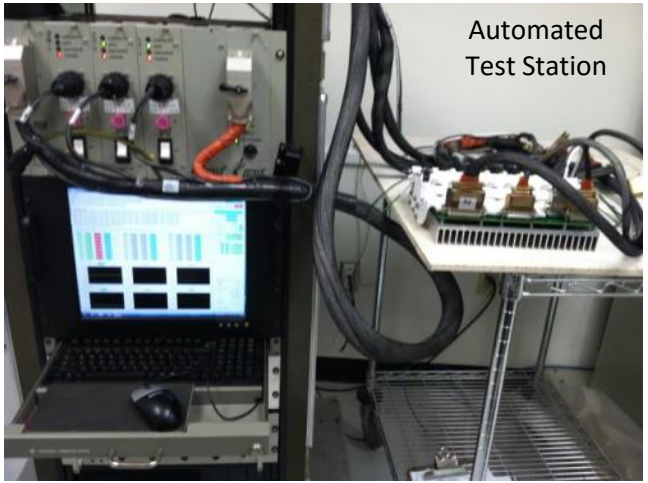
Component Examination ID & Leakage → Cell Characterization → Charge Retention → Low Temp Performance → Final Examination

Space Vector Cell Screening Stations

- Created new Cell Screening Fixture 500461
  - Allows testing of cells after tabs welded on
  - Used 3D printed racks with custom relay board
  - Each rack holds 8 cells
  - 3 racks per Test station x 5 stations or 120 cells at a time
- Adapted to Existing Cell Test Stations 59301 and Cell Test Cable Harness 58741
  - Allows automated and repeatable testing and results.

3D Printed Test Fixtures Work Great!





3D Printed Custom Test Fixture

Cell Screening Sample 91392

Consistent Cell Performance!
Only 8 rejects out of 520 or 98.5%
- 6 during inspection (dents)
- 1 failed charge retention
- 1 out of family

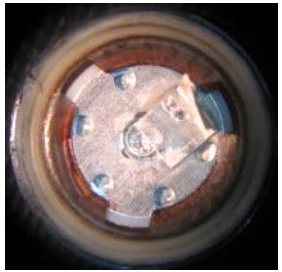
Note:
RCC 319 cell screening is a 6-8 week process

3 weeks for Charge Retention

Slot #	1	2	3	4	5	6	7	8
S/N	0001	0002	0003	0004	0005	0006	0007	0008
3.2.1 Char. Cycle 1 Cap. (Ah)	2.18	2.18	2.19	2.20	2.19	2.19	2.20	2.19
3.2.1 Char. Cycle 2 Cap. (Ah)	2.19	2.19	2.20	2.20	2.20	2.20	2.20	2.19
3.2.1 Char. Cycle 3 Cap. (Ah)	2.19	2.19	2.20	2.20	2.19	2.20	2.20	2.19
3.2.1 Char. Cycle 4 Cap. (Ah)	2.19	2.19	2.20	2.21	2.20	2.20	2.21	2.20
3.2.1 Char. Cycle 5 Cap. (Ah)	2.19	2.19	2.20	2.20	2.19	2.20	2.20	2.19
3.2.1 Char Min 3,4,5	2.19	2.19	2.20	2.20	2.19	2.20	2.20	2.19
3.2.1 Char Max 3,4,5	2.19	2.19	2.20	2.21	2.20	2.20	2.21	2.20
3.2.1 Char. Cycle 3-5 Avg Cap (Ah)	2.19	2.19	2.20	2.20	2.19	2.20	2.20	2.19
3.2.1 Char. Cycle 3-5 Δ Cap (%)	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
3.2.1 Char. ≤1% (P/F)	P	P	P	P	P	P	P	P
3.2.2 Step C Char Retn First OCV	4.13	4.13	4.13	4.13	4.13	4.13	4.12	4.13
3.2.2 Step F Char Retn Second OCV	4.10	4.11	4.10	4.11	4.10	4.11	4.10	4.10
3.2.2 Char Retn Cap.	2.07	2.08	2.09	2.09	2.08	2.09	2.09	2.08
3.2.2 Retn Cap. (%)	94.7%	95.0%	94.9%	95.0%	94.8%	94.8%	94.9%	94.8%
3.2.2 Retn Cap. (P/F)	P	P	P	P	P	P	P	P
Voltage	3.30	3.32	3.32	3.32	3.32	3.32	3.33	3.33
3.2.3 Step G Post Pulse Recovered Voltage under SS load	3.39	3.40	3.40	3.40	3.40	3.40	3.41	3.41
3.2.3 Step H Storage Voltage	3.66	3.65	3.65	3.65	3.65	3.65	3.65	3.65
91392 Pass/Fail	P	P	P	P	P	P	P	P

Cell X-Ray and DPA

- RCC 319 requires X-ray of cells used in the qualification units
- Cell X-ray found not to be of value
  - Can't see internal tab or CID/PTC integrity
  - Discussed with Range Safety and have reached agreements on other programs to just DPA a few cells after qualification is complete



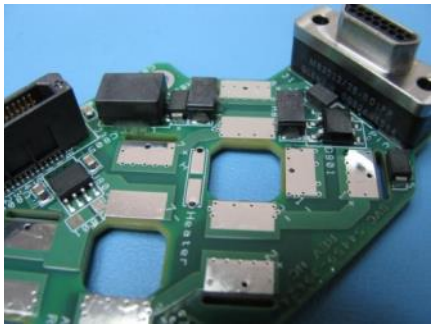
Pack Assembly 39131 Challenges

- Prefer to support cells in non-conductive racks and then tab together and wire to BMS and D38999 connectors
  - Allows spacing of cells and strain relief in tabs
- Developed a custom PCB 39411 to interconnect the cells within the Compact FTS Battery structure
  - No space for wire routing or large connectors

NASA Secondary Payloads Sequencer Battery Pack Assembly

Micro D are not scoop proof
Experienced a few shorts when mating.
Special handling required

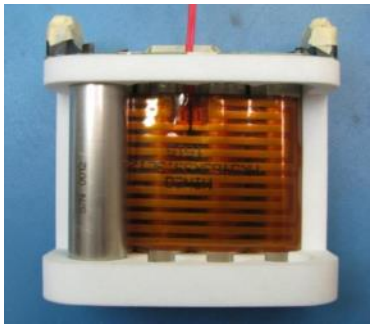
Integrated Micro-D Connectors



Compact Pack Build

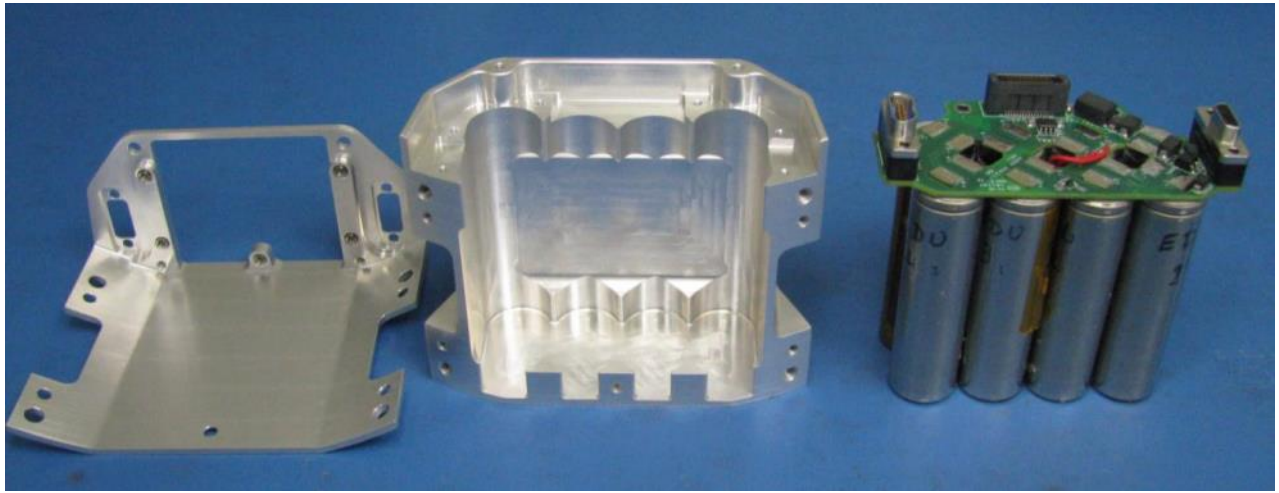
3-D Printed custom tooling to maintain alignment during soldering ops

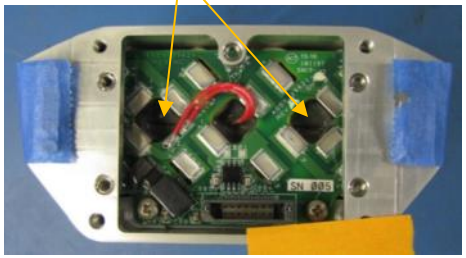
23.5 W Resistance Heater Element

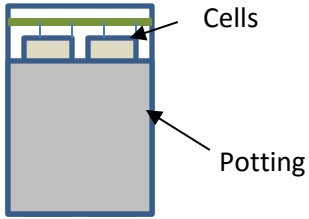


Potting Trade Study

- Evaluated different potting compounds to secure cells in the machined Aluminum housing and cover
  - Selected DC Sylgard 160
  - Best combination of viscosity, work/cure time, temp, thermal conductivity, availability, and cost

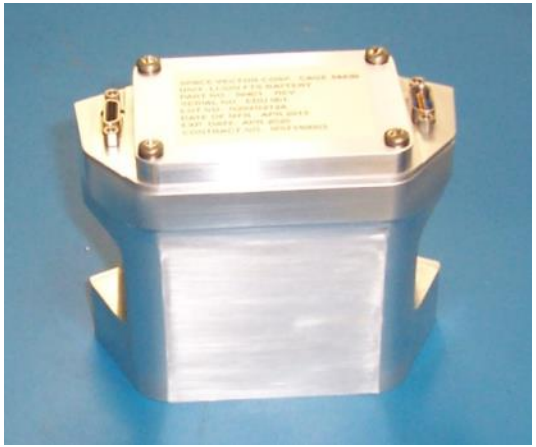






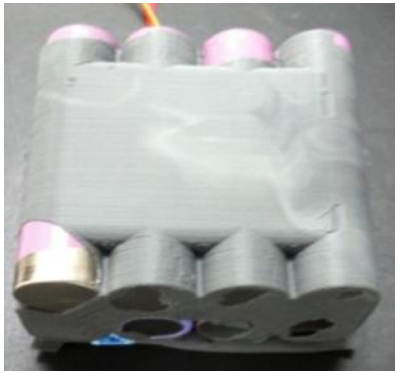
Li-Ion Compact FTS Battery Final Assembly

- Staked critical components prior to conformal coating boards
- Monitor board 39441 mates to cell interconnect board
  - Onboard processor outputs individual cell voltages, current, and temperature via RS-422
  - Battery electronics also provides EMI filtering and isolation
  - Electronic design assures components are not in a battery failure path



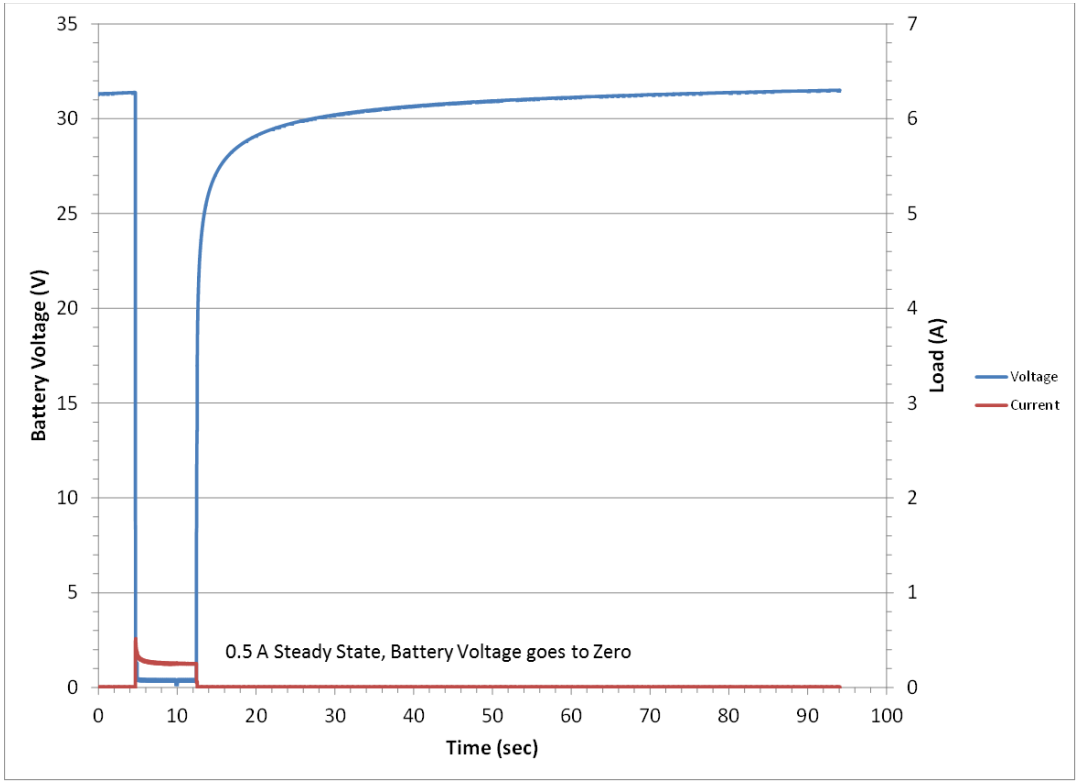
Temperature Testing of Potted Battery

- Condition Battery at -43°C
  - Try loading but prior experience has shown Li-Ion typically won't perform much below -30°C
- Turn On Heater and warm cells from -43°C to 0°C
  - Took 23 minutes or 1.9°C/min in aluminum housing
  - Pulse test near 0°C
- Leave heater on with chamber at -43°C
  - Took 90 minutes to go from 0°C to 17°C and leveled out
- Leave heater on with chamber at -10°C
  - Leveled out at 48°C after 120 minutes (2 hours)
  - No concerns about leaving heater on in cold environment
- Chamber Off (ambient). Turn On heater and warm cells to +70C
  - Took 20 minutes or 2.65°C/min to reach cell maximum temperature
- Evaluate battery at qualification operating extreme temperatures
- Inspection
  - Pulled apart and evaluated potting for adhesion, voids, and coverage
  - No issues



Performance or Lack Thereof at -43°C

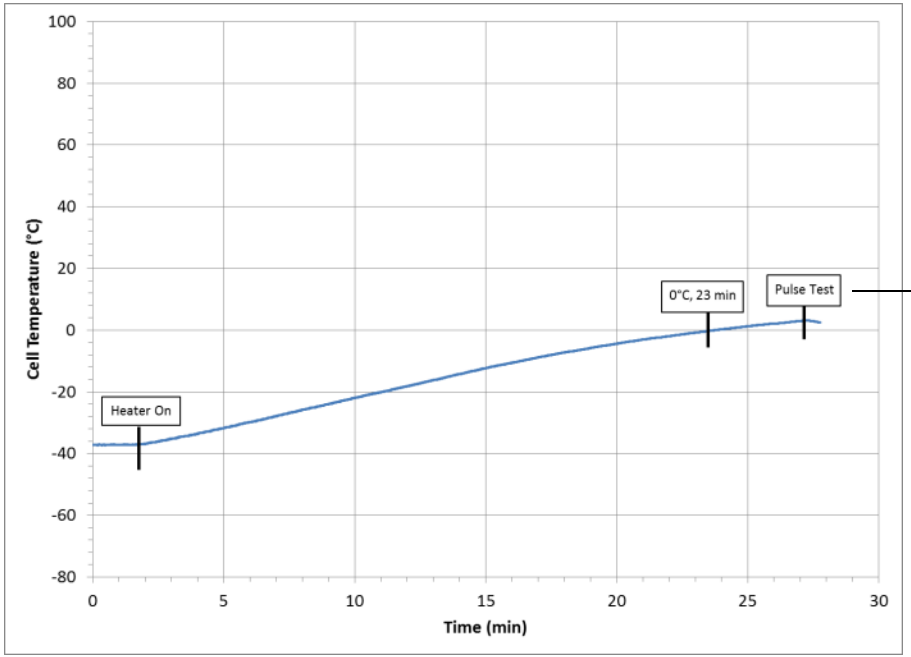
-43°C is too cold for cells to put out 0.5A (C/5)



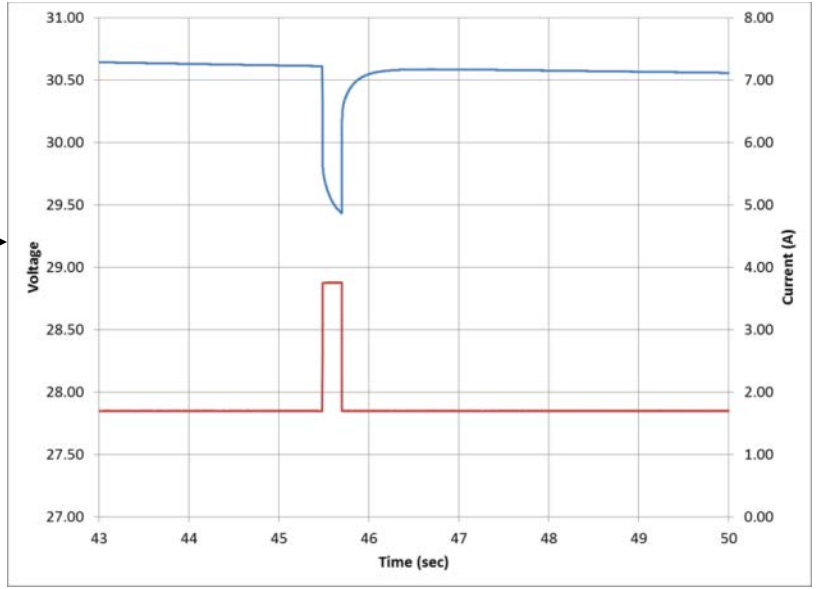
Cell Temperature Rise to 0°C Using Heater

Chamber at -43°C

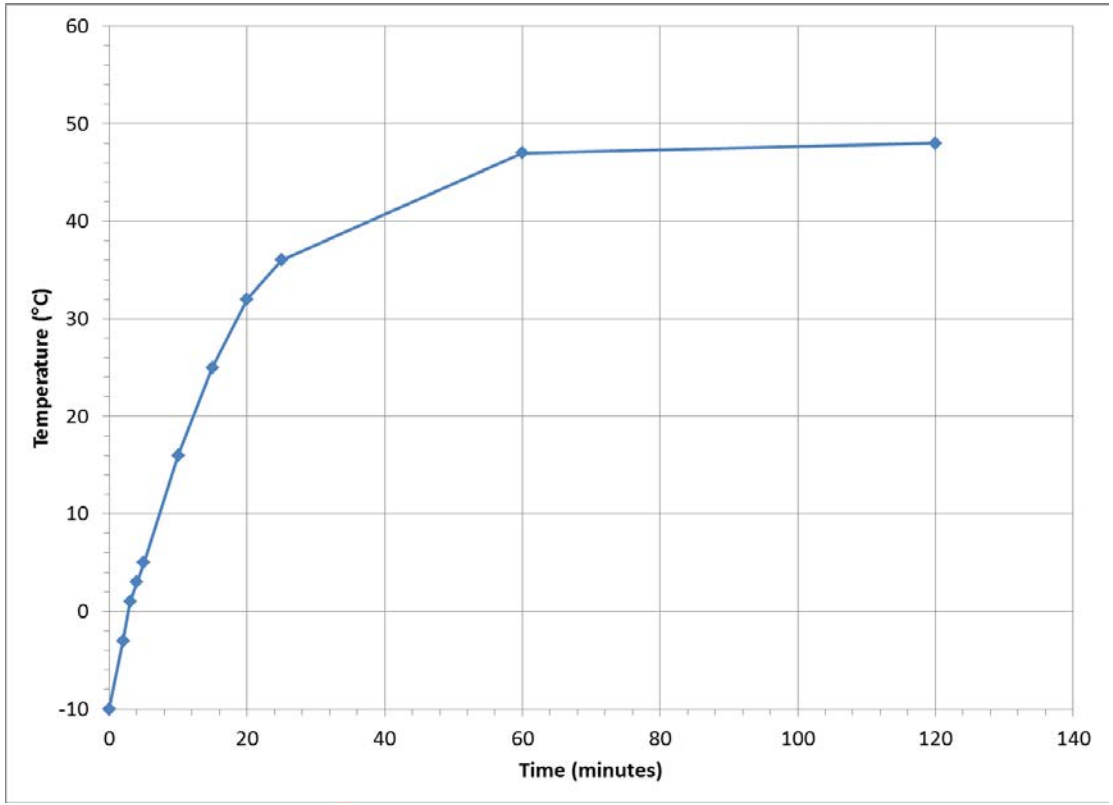
23 minutes sufficient to warm cells prior to launch



2.5°C

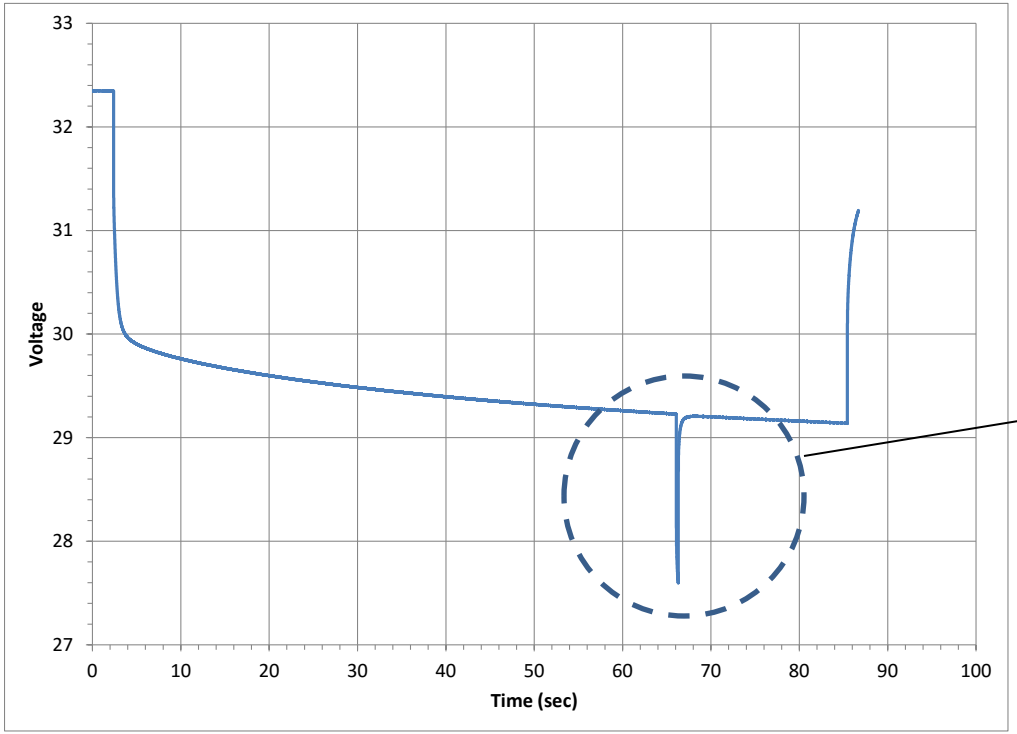


Battery Heater Left On at -10°C

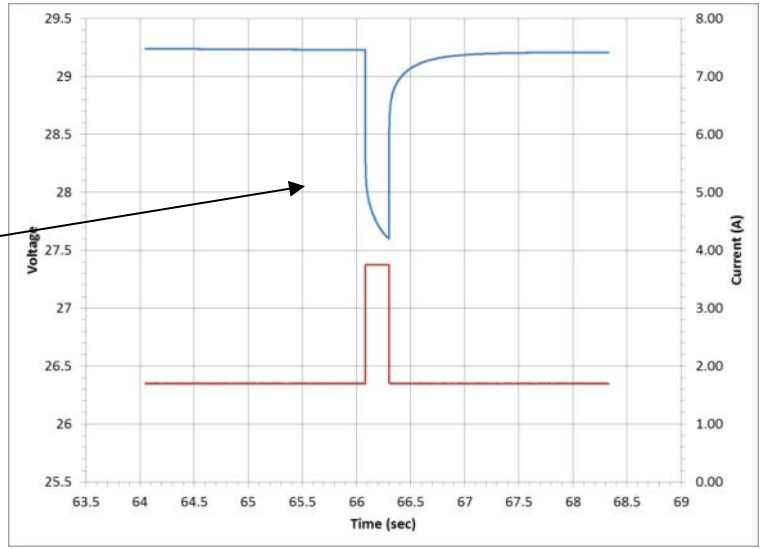


Minimizing concern of overheating cells if heater stuck on in cold env.

Small Pulse at -10°C

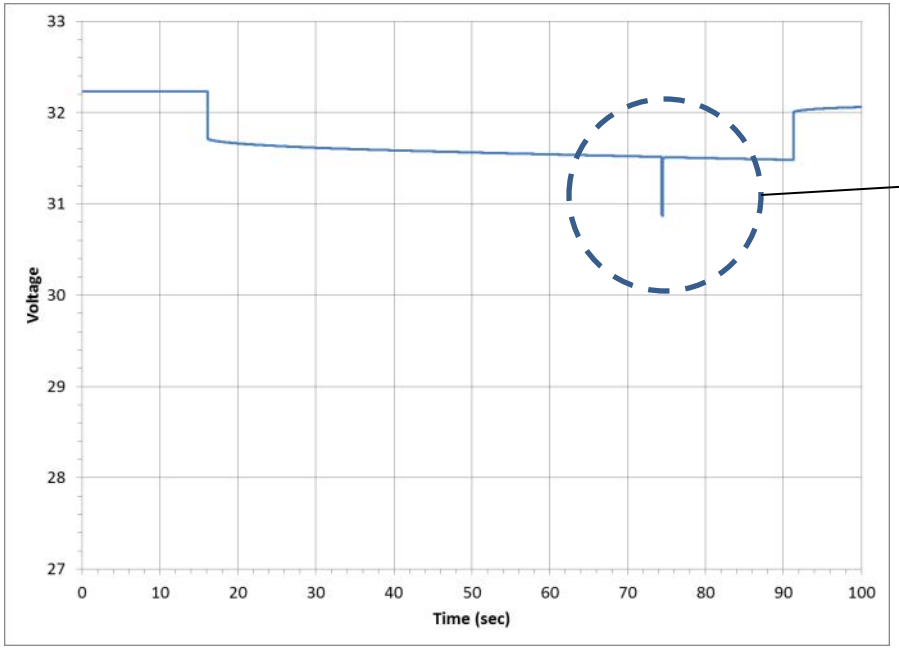


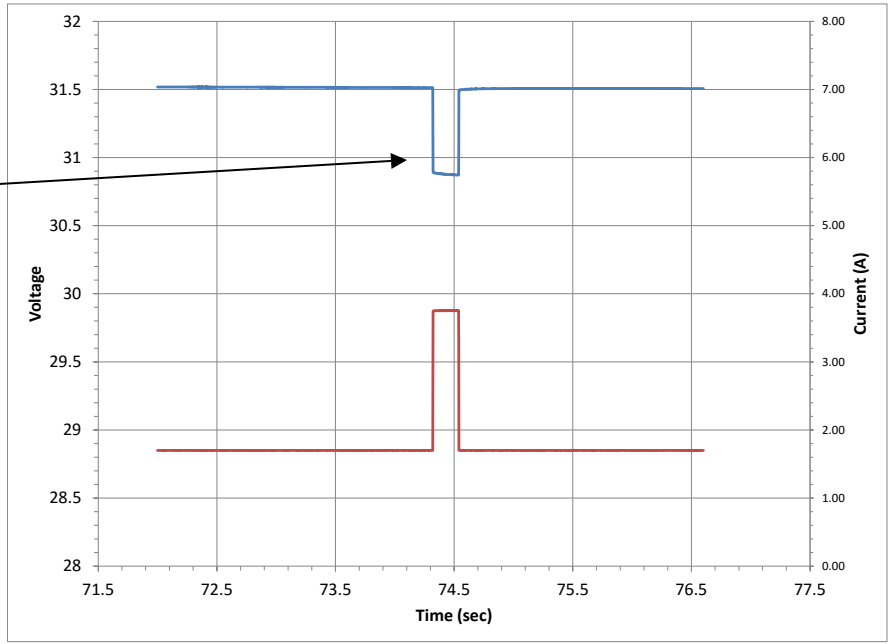
No issue at Qual Op Temp



Small Pulse at 85°C

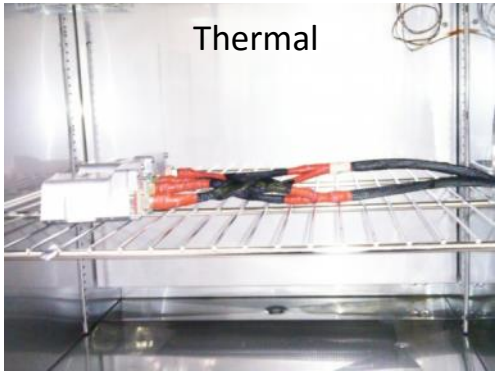
Battery Operates above the
Qual Max Temperature
Push cells beyond their 60°C limit

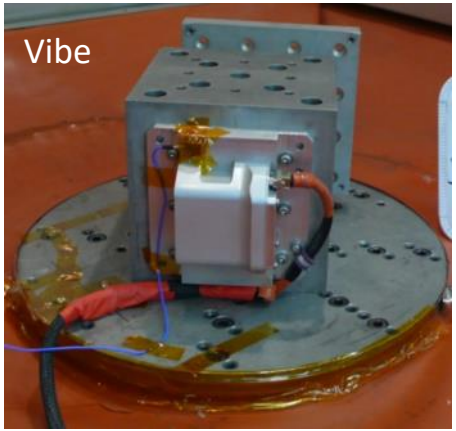




RCC 319 FTS Battery Acceptance Testing 39403

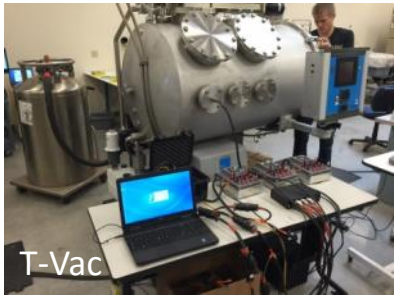
- 3.1 Component Examination
  - Identification Check
  - Visual Examination
  - Dimensional Measurement
  - Weight Measurement
  - Charge State
- 3.2 Initial Performance Verification
  - Continuity and Isolation
  - Heater Circuit Verification
  - Initial Charge Cycling with Analysis
  - Electrical Performance Test
  - Monitoring Capability
- 3.3 Thermal Cycling
- 3.4 Random Vibration
- 3.5 Final Performance Verification
  - Charge Retention Operational Stand Time
  - Electrical Performance Test
  - Continuity and Isolation
- 3.6 Post Acceptance
  - Visual Examination and Case Integrity
  - Final Discharge
  - Storage

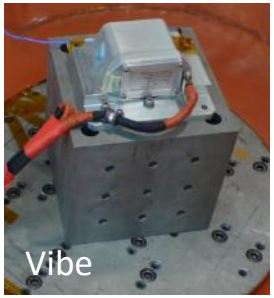


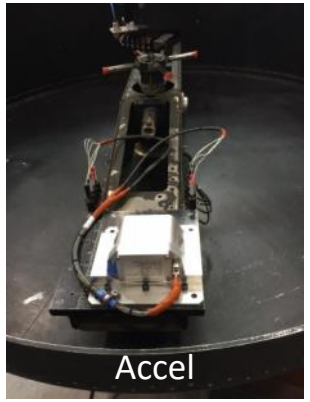


FTS Battery Qualification Testing 91394

3.1 Storage Temperature
3.2 Transportation Vibration
3.3 Transportation Shock
3.4 Bench Handling
3.5 Heater Verification
3.6 Performance Verification
    Continuity, Isolation and Heater Resistance
3.7 Thermal, 24 cycles
3.8 Thermal Vacuum, 3 cycles
3.9 Acceleration
3.10 Shock (multiple,
3.11 Random Vibration (multiple, ~40 grms)
3.12 Acoustic Vibration
3.13 EMI/EMC (CE101, CE102, RE102)
3.14 Final Performance Verification
    Continuity, Isolation and Heater Resistance
3.15 Charge Retention Operational Stand Time, 4 days
3.16 Cycle Life
3.17 Final Examination
    Internal Inspection







Qualification by Similarity/Analysis

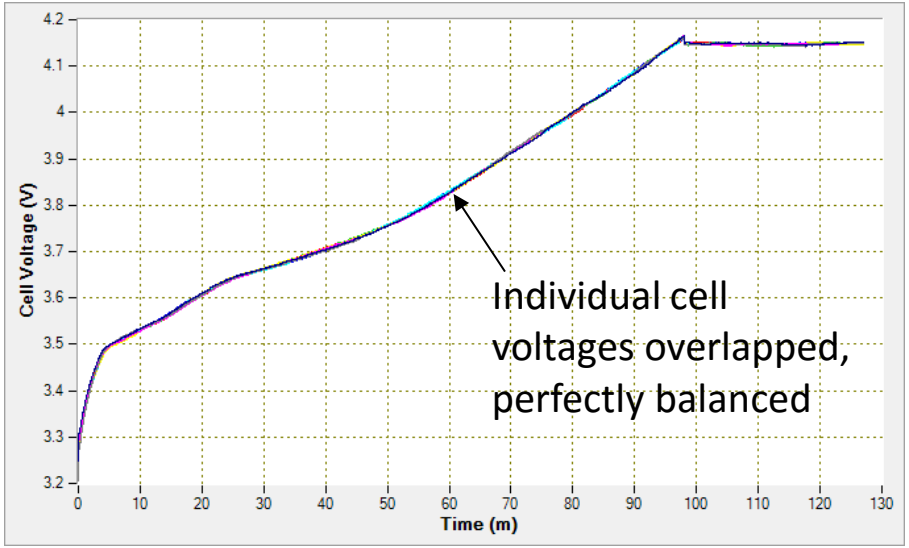
- RCC 319 does allows analysis in lieu of test for certain environments
  - Environments like Fungus Resistance, Fine Sand, Humidity, Salt Fog, and Explosive Atmosphere can often be tailored out if the batteries are shown to be used in a controlled environment and sufficiently protected
  - Operating vibration levels can sometimes be shown to envelope acceleration and/or acoustic levels
  - Thermal vacuum can be accomplished by analysis if structure has sufficient margins at vacuum, device is low voltage and not sensitive to corona discharge, and component temperatures are not effected by vacuum (no convection)

Charger/Analyzer/Tester 500451

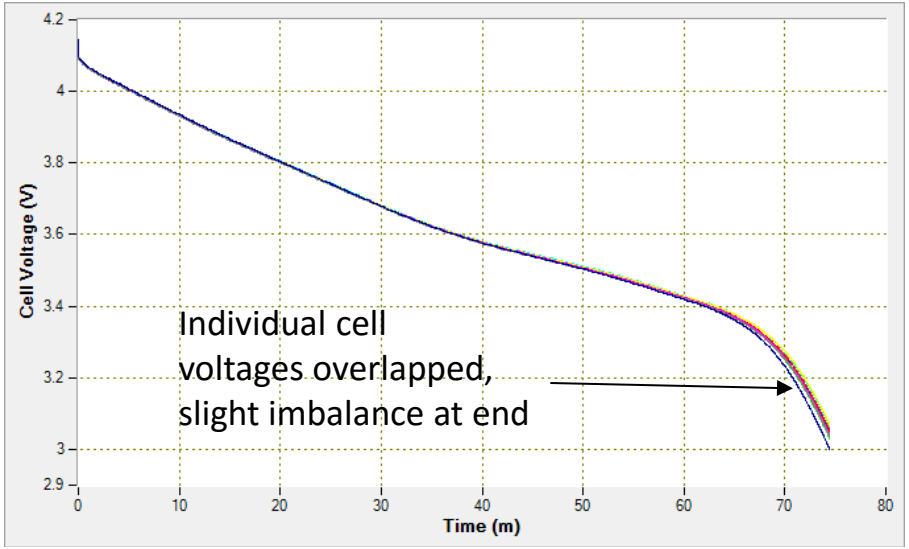
- Checks/reports battery and cell health
- Charges/Discharges battery, measures capacity
- Checks Telemetry TM outputs
- GUI can be installed on any laptop PC with Ethernet connection
- Data files stored on laptop for post processing
- 2U rack mountable
- Discharge on bench (6’) or thru vehicle umbilical (130’)

Cell Voltage Charge/Discharge Curves

C/2 Charge

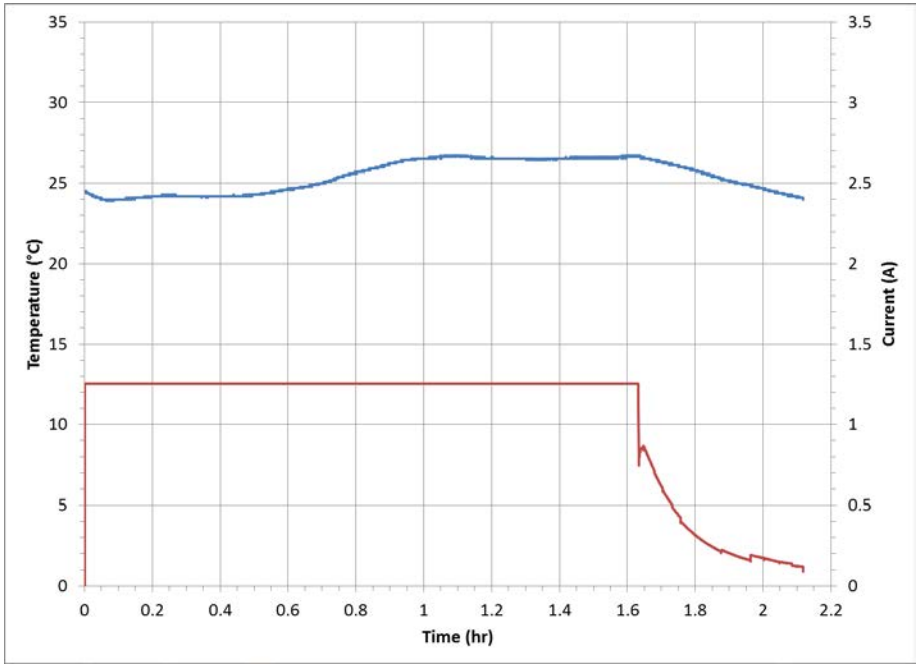


0.7C Discharge

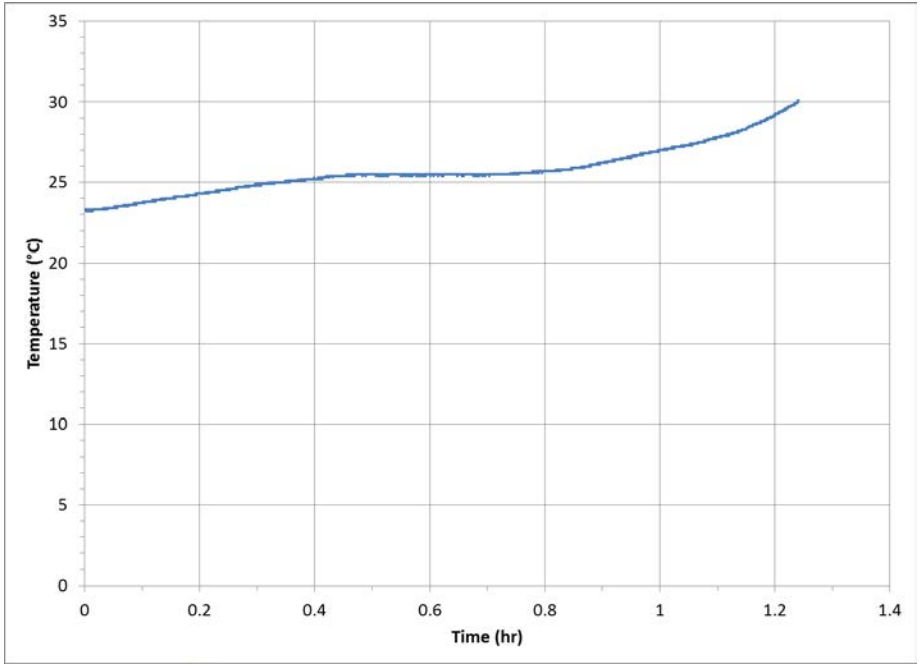


Temperature and Current Charge/Discharge

Charge
24.5°C to 26.6°C
+2.1°C Rise at C/2



Discharge
23.3°C to 30.0°C
+6.7°C Rise at 0.7C



Other Requirements

- Predicated Battery Reliability
  - 0.999899 over 6 minute missile launch (ML) environment
  - Failures per million hours (FPMH) = 1014.816
- Service Life
  - 3 years from date of mfg with extensions per RCC 319
- Storage Temperature
  - -20C to +20C. We recommend 0-5°C for long term storage
- Maintenance
  - Once a year remove from storage and connect to charger/analyzer to perform charge/discharge cycle

Conclusion

- The compact Li-Ion FTS Batteries 39401 currently in production
  - First flight scheduled for Spring 2017
  - Production rate of ~40 batteries per year
  - Delivering 16 more charger/analyzers in 2017
- Space Vector also providing a higher capacity Li-Ion FTS battery 39611 for use at VAFB
  - 2.5 Ah min, 28.8 Vdc nominal
  - Used to power a variety of vehicle systems
  - D38999 Connectors, 3.5 lbs, 4.375” x 7.2” x 3.2”
  - Qualification to RCC 319-14 in 2017
- Just started on a primary battery pack for use on the Orion capsule
  - 18 L91 (Li/FeS2) AA cells, 28-33V, 3 Ah
  - Stay Tuned

39401
Compact
FTS Battery