Li-Ion Polymer *Intelli-Pack*® Battery

For Space Launch Vehicles, Missiles, Hypersonic Vehicles, ISS, Aircraft, Small Satellites, and UAVs

An Intelligent Power System Technology

NASA MSFC Li-Ion Battery Workshop

Edmund Burke, SIL CEO

Nov. 17, 2020

SIL Aerospace Small Business

- Primary business is Space R&D and missile flight unit products for Prime Contractors and Federal Agencies including AFSPC, SMC, MDA, AFRL, NAVAIR, DARPA and NASA
- AS9100D QMS to design, manufacture and environmental test of Avionics, AFTS, GPS Tracking, and Li-Ion Battery Flight Units
- DCAA Approved Accounting System
- DCMA Approved Inventory System
- DCMA Master Inspection Points (MIPS) at SIL for Missile Flight Units delivery
- SIL is located in Santa Maria, CA near Vandenberg AFB

Certified System
SAI GLOBAL
AS9100D
Aerospace

DESIGNED AND MADE IN THE UNITED STATES

SIL Customers

SIL Small Business setup for direct GOVT Contracts

LOCKHEED MARTIN

MIT Lincoln Laboratory

Raytheon Technologies

BOEING

ULA
United Launch Alliance

Nanoracks

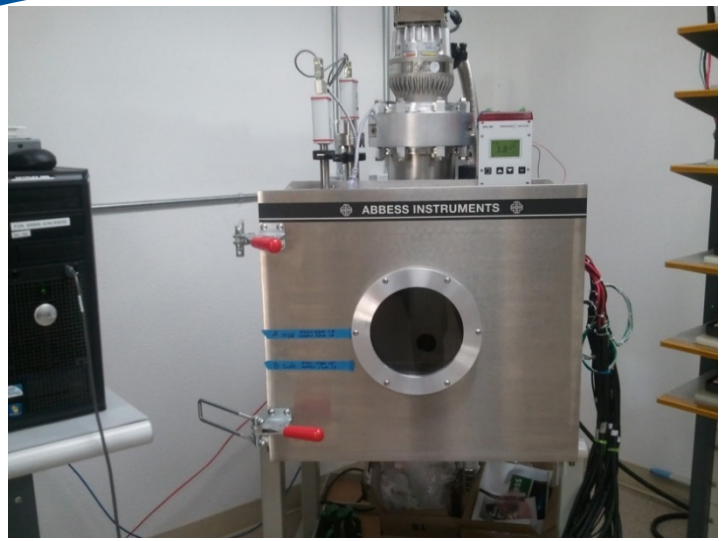
NORTHROP GRUMMAN

FIREFLY AEROSPACE

AEROJET ROCKETDYNE
Coleman Aerospace

Generation Orbit

Space Qual Environmental In-House Test Lab Capability



Thermal Vac Chamber

Vib Machine, 1-25 lbs units up to 40 Grms

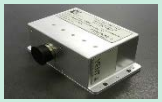
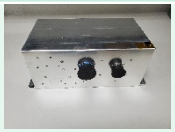
Shock Machine

Thermal Cycle Chambers (three) Thermal Cycle and Humidity Chamber (one)

Li-Ion Polymer Intelli-Pack® FTS, Avionics and Telemetry Battery Technology

USPTO Patent # 9,748,541B2

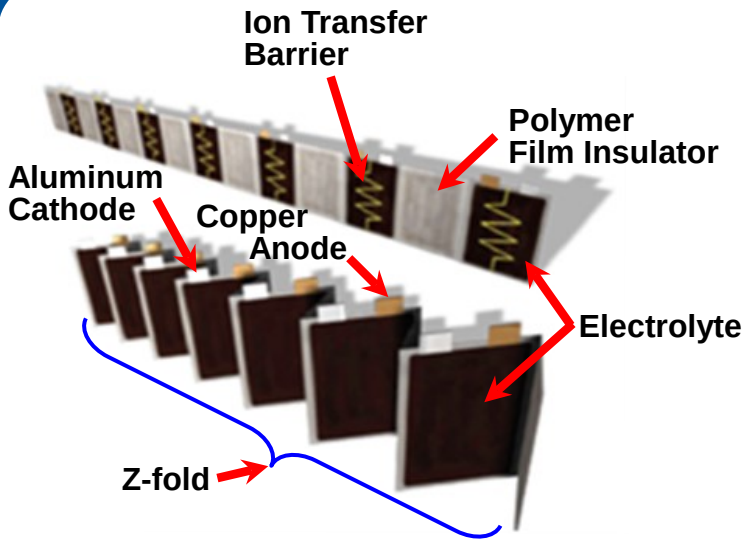
Li-Ion Polymer Intelli-Pack® Battery Product Line 2011-Current

Li-Ion Polymer Intelli-Pack® Battery Products	TRL
8S1P, **2 Ah** FTS 5.7”L x 3.25”W x 3”H, 2.7 lbs 	TRL-8 (2020) TRL-9 (2021)
8S1P, **2.1 Ah** FTS 6.36”L x 3.75”W x 1.5”H, 1.95 lbs 	TRL-7 (2020) TRL-9 (2021)
8S1P, **3.3 Ah** FTS/TM 6.75”L x 4”W x 2.8”H, 3.25 lbs 	TRL-7 (2020)
8S1P, **5 Ah** Avionics/TM 8.7”L x 3.3”W x 4.3”H, 5.75 lbs 	TRL-7 (2020)
8S2P, **20 Ah** Avionics/TM 9”L x 9”W x 3.75”H, 14.5 lbs 	TRL-9 16 Missions (2013-2020), 100% Success
8S2P, **52 Ah** Spacecraft 14”L x 7”W x 5.5”H, 26.2 lbs 	TRL-8 (2020) TRL-9 (2021)
8S2P, **150 Ah** Spacecraft 11.7”L x 11.5”W x 8.5”H, 75 lbs 	TRL-5 (2020)

Li-Ion Polymer Intelli-Pack® Battery Attributes

- Advanced BMS within the battery that automatically protects (overvoltage, undervoltage, short circuit and thermal protection), balances and monitors every cell to ensure safety
- Advanced BMS within the battery with high precision battery and cell voltage, current and temperature measurements with instant viewing with Windows GUI and Data Logger for turn-key battery operations, and real-time battery telemetry data downlink from Space Launch Vehicle, Missile or Satellite
- Turn-Key Battery Operations by technician to reduce life cycle cost
- Li-Ion Polymer Z-fold pouch NMC cells have high energy density (170-250 Wh/Kg) and very low internal resistance (1/10th resistance of 18650 Jelly Roll Li-Ion Cell) that enables high discharge current capability (2C to 30C), rapid recharge (< 1 hour from battery dead state with 1C charge current) and low cell self heating
- No Liquid Electrolyte Leakage
- SIL Battery Packaging works in extreme thermal cycle/vacuum (-40C to +71C, 1*10-5 Torr), Shock (1000-2000G) & Vibration Environments (60 RMS)

Li-Ion Z-Fold Cell Pouch Technology



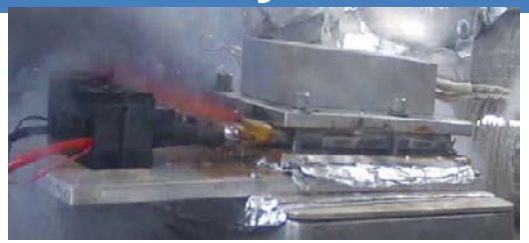
- COTS Li-Ion Polymer Z-Fold cell mass-scale suppliers
- 170 to 250 Wh/Kg Energy Density (LCO & NMC Li-Ion Cells)
- Capacities in .5 to 200 Amp-Hours and 10 Year Life
- Used in Chevy Bolt, Electric Vehicles, UAS, Launch Vehicles, Missiles, SmallSats, etc.
- Very low cell internal resistance (10Amp-Hr Cell, < 3 mΩ) allowing high current discharge (5-30C) and rapid recharge (< 1 hour, 1C Charge) and minimal heat rise

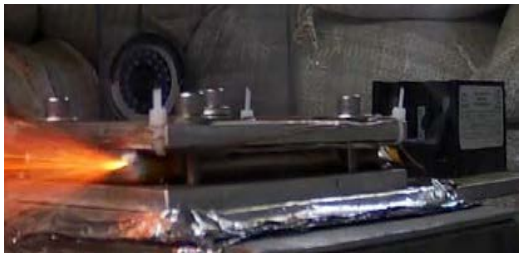
Cell components:

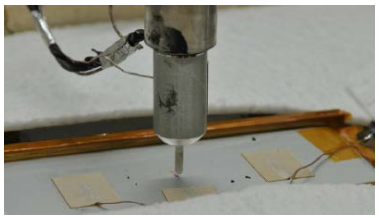
- Cathode (-):
  - Lithium-Cobalt-Oxide (LCO)
  - Li-Nickel-Manganese-Cobalt Oxide (NMC) on aluminum; 2-3x Cycle Life of LiCoO2 cathodes
- Anode (+): Carbon (Graphite) on copper
- Electrolyte (gel):
  - $LiPF_6$ in ethyl carbonate (EC) + dimethyl-carbonate (DMC) + small amount ethyl-methyl-carbonate (EMC)

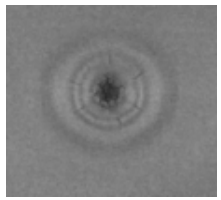
Li-Ion Polymer Z-Fold Cell
S9310 Destructive Test Summary

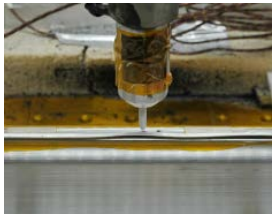
- **Hot Plate with cell between constrained plates**
  - Thermal Runaway occurred at 170C
- **Overcharge with cell between constrained plates**
  - 5.3Vdc at 1C charge rate venting occurred
    - Added 30 AH additional capacity to 10 AH cell
  - 5.3Vdc at 2C charge rate cell went into thermal runaway (added 30AH additional capacity to 10AH Cell)
- **Pinch Test ~1500lbs of force on broad face of cell**
  - No change in open circuit V and/or temperature
  - Slight difference in capacity after 107 charge and discharge cycles
- **Broad Face Indent (Metal and Ceramic Tips)**
  - Internal short circuit induced at 57.6 lbf
  - Induced a thermal runaway condition
- **Narrow Face Indent (Ceramic Tip)**
  - Internal short circuit induced at 37 lbf
  - Induced a thermal runaway condition











Cell Destructive Testing by Aerospace Corp.

Battery Design PPE Overview

Protect, Prevent and Enclose (PPE) Technologies are employed to stop cell failure propagation, limit cell-to-cell thermal transport, and safely contain flames and debris.

- Protect with SIL's advanced BMS housed within each Li-Ion Intelli-Pack® battery
  - Real-time monitoring of all cells and cell balancing during charge to assure safety
  - Protects cells against Overvoltage, Undervoltage, Over Current, Short Circuit and OOT Thermal
  - Arrayed temperature sensing to detect hot-spots and temperature events on cells
  - Customizable, programmable, and designed to trigger prior to hazardous situations
- Prevent with semi-active Thermal Isolating Phase-change (TIP) material for large format batteries
  - TIP material is assembled between each cell pair and around the cell pack
  - Thermally isolating characteristics isolate cell pairs from each other during normal operation
  - Phase change characteristics absorb heat energy if a cell-pair goes into thermal runaway
  - Prevents cascading cell failures, limits thermal propagation, and stifles thermal runaway reactions
- Enclose with SIL's robust and flight proven battery housing
  - Cell pack is further insulated with UL 94 V-0 fire resistant foam to smother any cell expulsion
  - Housing can withstand a cell failure without flame or debris expulsion
  - Heritage battery housing keeps cells safe in highly demanding aerospace environments
  - Tested in high Shock, Vibe, Thermal, Vacuum, Acceleration, ESD, and EMI/EMC environments

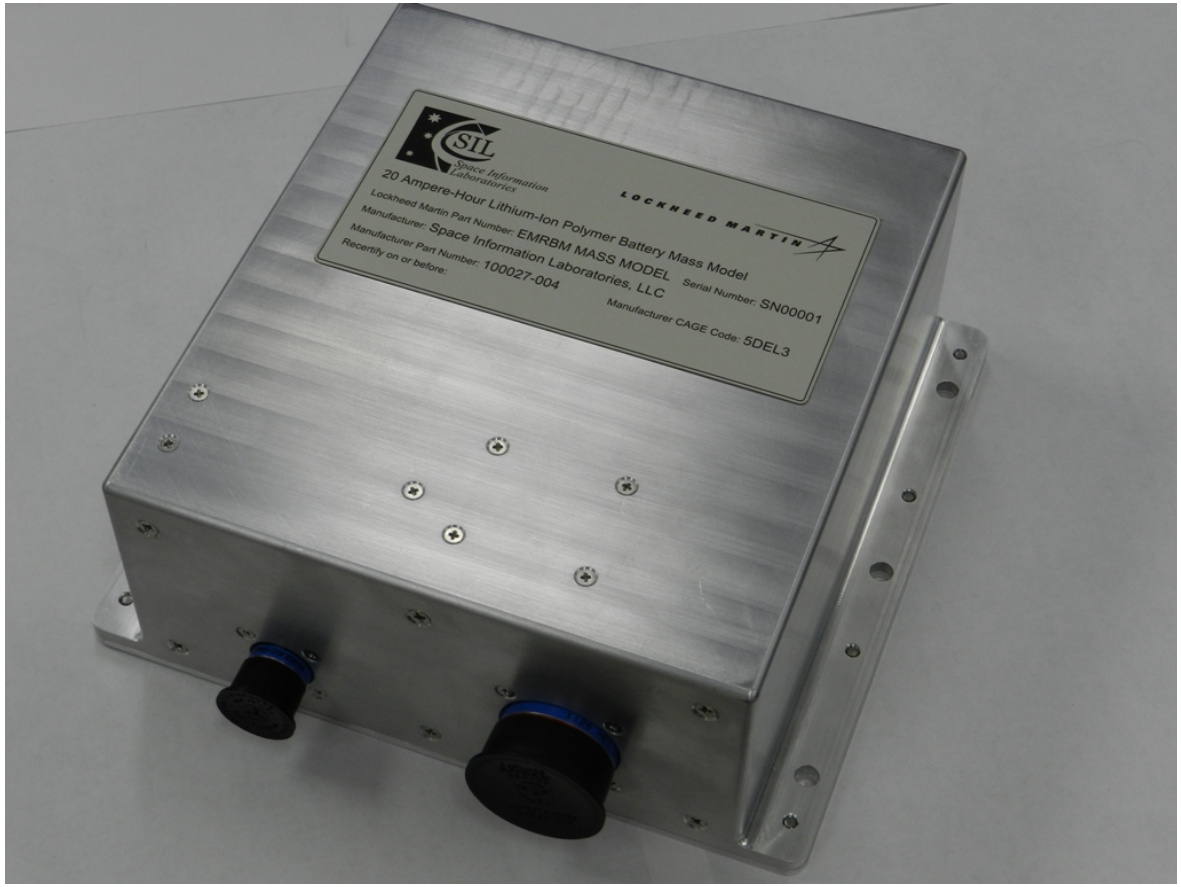
SIL Li-Ion Polymer Intelli-Pack® Battery System (33.6Vdc @ 20 AH)

Weight: 14.5 lbs

Size: 9” L x 9” W x 3.75” H

RS-422 and MIL-STD 1553B Data Outputs

MDA Missile and RV Successful flight history (2013 – 2019): 13 of 13



Shock Video – 20Ah Missile Battery

Range Safety Space Qual (2 batteries) for MDA Missiles and RVs Successfully in 2013, 2015 and 2017

Thermal Cycle: -10C to +55C (24 Cycles), 2 hour dwells

Thermal Vacuum: 1*10-5 Torr, -10C to +55C (4 cycles)

Random Vibration: 16.4 grms, 3 mins per XYZ axis
0 to 2000 Hz

Sine Vibration: 70 and 100Hz, 18G
500 and 700Hz, 7.8G
1100 and 1400Hz, .6G

Shock:

Freq. (Hz)	Shock Level (g)
100	226
1015	400
1800	735
10000	735

Three Hits: +/- XYZ Axis

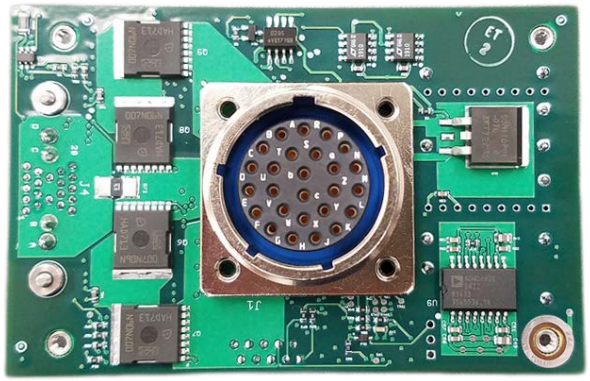
MIL-STD 461 G EMI/EMC: RE102, CE101, CE102, CS-114, CS115, CS116, RS103, CE-07

DoD Guidelines and Standards for Li-Ion Battery Design and Space Qual

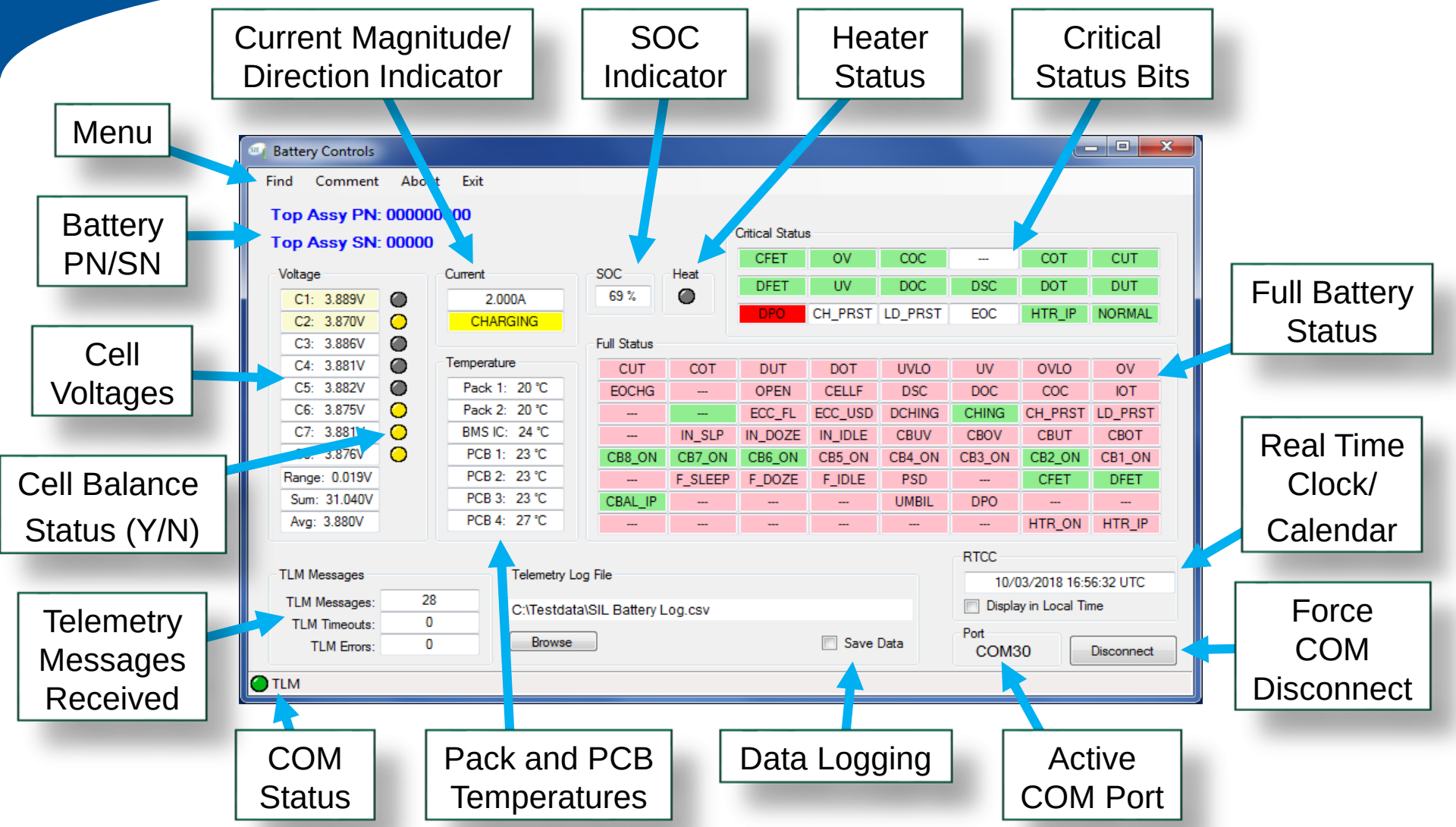
- NAVSEA 9310-AQ-SAF-010
  - Technical Manual for Navy Lithium Battery Safety Program Responsibilities and Procedures
- SMC-S-018, Li-Ion Battery Design Guideline for Launch Vehicle Applications
- SMC-S-016, Test Requirements for Launch, Upper-Stage and Space Vehicles
- RCC 319, Section 4.26 - Li-Ion FTS Batteries
  - Cell Screening requirements and Range Safety Space Qual for launch vehicle applications
- RCC 324-01, Li-Ion Batteries for Avionics and Telemetry Systems
- BMS designed to pass UN38.3 Tests 1 thru 5, and 7

Advanced BMS within Batteries

- Battery telemetry at 1 Hz rate
  - Voltages: 1 mV resolution, pack & cells
  - Current: 1 mA resolution, battery level
  - Temperature: 1°C resolution, arrayed on cells
  - SOC and SOH
  - Diagnostics flags
- Protection Features
  - Charge
    - Over voltage, over current
    - Lockout, cell voltage equalization
  - Discharge
    - Under voltage, over current,
    - Short circuit, lockout, pulse programmable
  - Temperature
    - Over/under protection for all operations
    - Autonomous heaters for cold operations
- Autonomous Built-In-Test
  - Verifies battery is functional
  - Periodically updates SOC, SOH
- Min/Max Data Recorder (Black Box)
  - Saves battery data in event of fault or failure
- Standby Mode
  - Maximizes charge retention when exposed to parasitic (90mA) loads
  - < 300 Ohm (programmable) load required to enter operational mode
- Programmable BMS Agnostic to Cell Chemistry
- Automatic Cell Balancing
- Automatic Heater Control with programmable control from 0 to -55 Celsius



Battery Management Systems
Intelligent Graphical User Interfaces

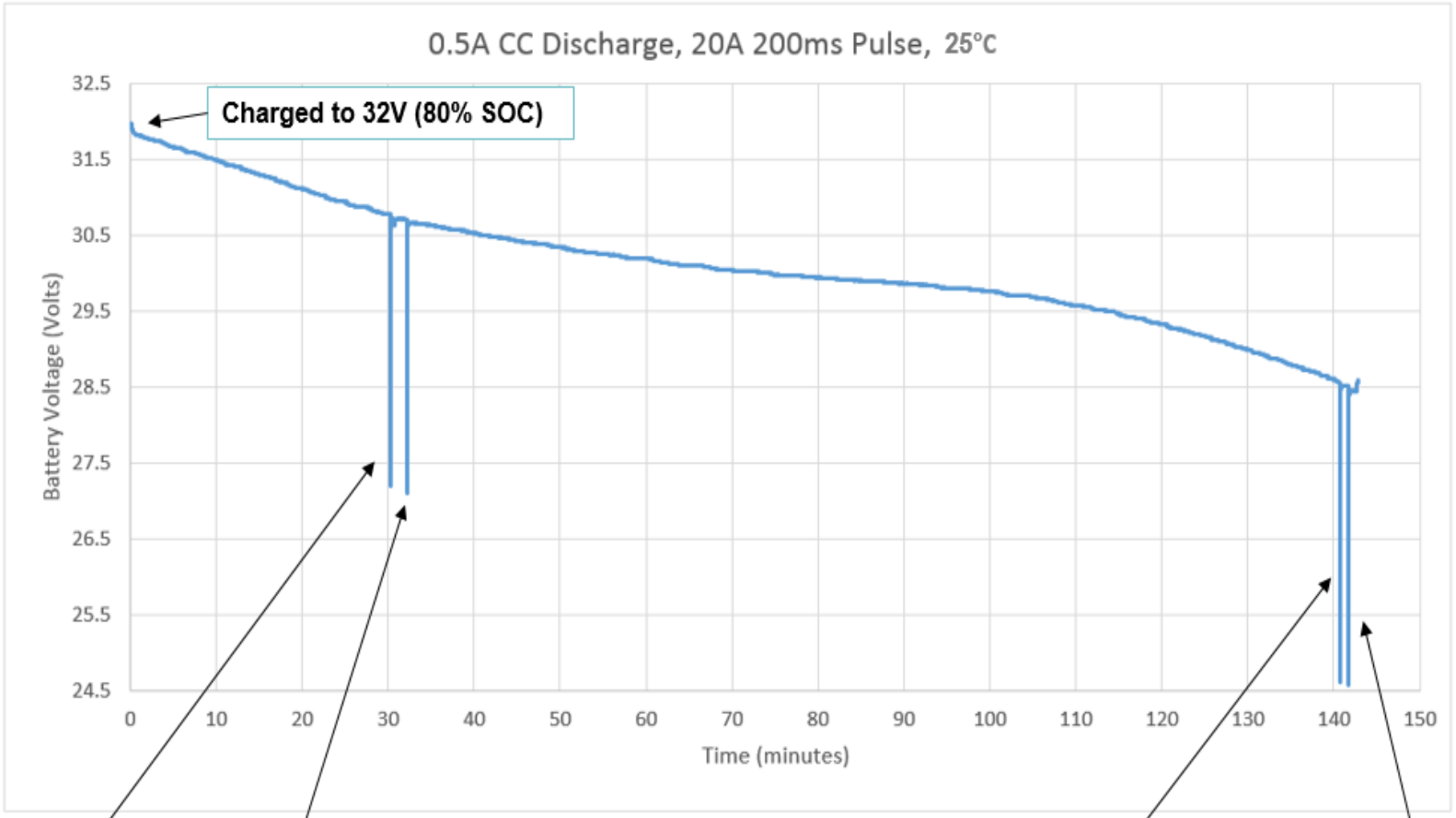


2AH LiPo FTS Battery with internal BMS

Li-Ion Polymer Intelli-Pack®
2Ah FTS Battery Specification

Battery Specification	SIL Li-Ion Intelli-Pack® 2Ah 8S1P FTS Battery
Voltage (J1 Out)	33.6Vdc (Fully Charged)
Capacity	2 Ah at 1C Continuous Discharge (33.6Vdc to 22.4 V dc) 1.9 Ah at 5C Continuous Discharge (33.6Vdc to 22.4 Vdc) 1.6 Ah at 15C Continuous Discharge (33.6Vdc to 22.4 Vdc)
Cycle Life	1000 Cycles to 80% Capacity at 1C discharge and charge
Weight Max	2.7 lbs.
Dimensions	4.5" L x 3.25" W x 3" H (1/2 ” mounting flanges)
Pulse Load	60 Amps (30C), < 200 msecs pulse
Steady State Load	30 Amps (15C)
Telemetry and Real-time Cell Monitoring (J1 Out)	RS-422, etc.
Protection	Full Cell Protection (Overvoltage, Undervoltage, Temperature and Short Circuit) - Disabled in Flight Override Mode
Space Qual Temp Range	-10C to +55C (Battery) -40C to + 55C (Battery with DC Kapton heaters) -34C to +71C (Battery BMS PCBA) Operating Range: -40C to +71C

2Ah FTS Li-Ion Battery Continuous and Pulse Current Performance



2 Ah FTS & 5 Ah TLM/FTS Li-Ion Battery Qual Test Levels

PCBA Level Tests	Levels
Workmanship Thermal Cycle: Verifies PCBA has no outstanding issues	1 Cycle: -40°C to +71°C Non-operational
Operational Thermal Cycle: Thermally stresses the PCBA at minimum and maximum predicted operational temperatures	24 Cycles: 1st & 24th Cycle: -40°C to +55°C 2 hour soak times Real time telemetry throughout Interim Cycles: -40°C to +50°C 1 hour soak times Real time telemetry throughout
Burn-In: Test PCBA at maximum predicted operation temperature	48 hour soak: +71°C 5 A discharge current throughout Real time telemetry throughout

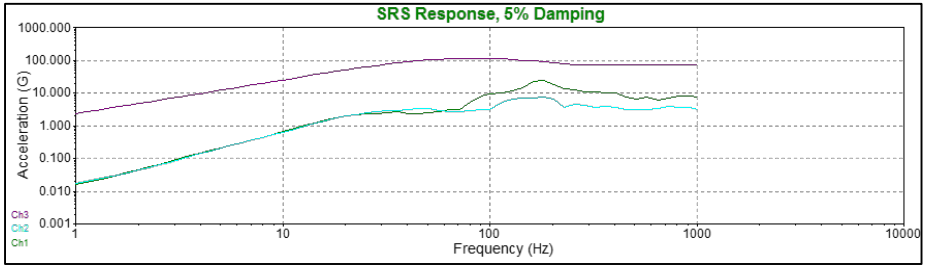
Battery Level Tests	Levels
Thermal Cycle: Thermally stresses the Battery at minimum and maximum predicted operational temperatures	24 Cycles total 1st & 24th Cycle: -40°C to +55°C Real time telemetry throughout Capacity tests at each extreme Interim Cycles: -10°C to +50°C Real time telemetry throughout
Vacuum: Tests battery operation at vacuum conditions	24 hour soak: Pressure below $1x10^{-5}$ Torr Capacity test at vacuum pressure

2 Ah FTS & 5 Ah TLM/FTS Li-Ion Battery Qual Test Levels (Cont)

Operational Shock:
Subjects battery to maximum predicted shock levels in XYZ Axis

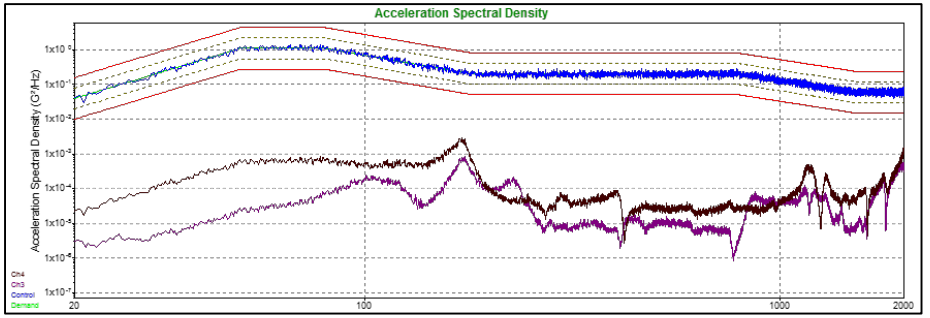
Combined FTS Shock Profile	
Freq (Hz)	SRS (g) (Q=10)
20	10
100	100
100	106

*Upper shock levels were limited by SIL test equipment



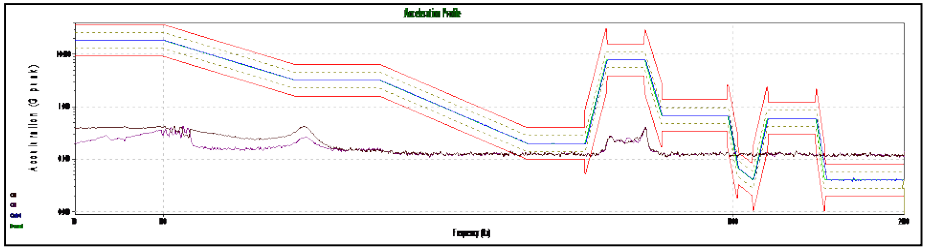
Operational Random Vibration (16.4 GRMS):
Subjects battery to maximum predicted random vibration levels in XYZ Axis, 3 minutes per axis

Combined FTS Op-Vibe Profile	
Freq (Hz)	Level (g)
20	0.04
50	1.1
80	1.1
182.4	0.2
800	0.2
1525.5	0.06
2000	0.06



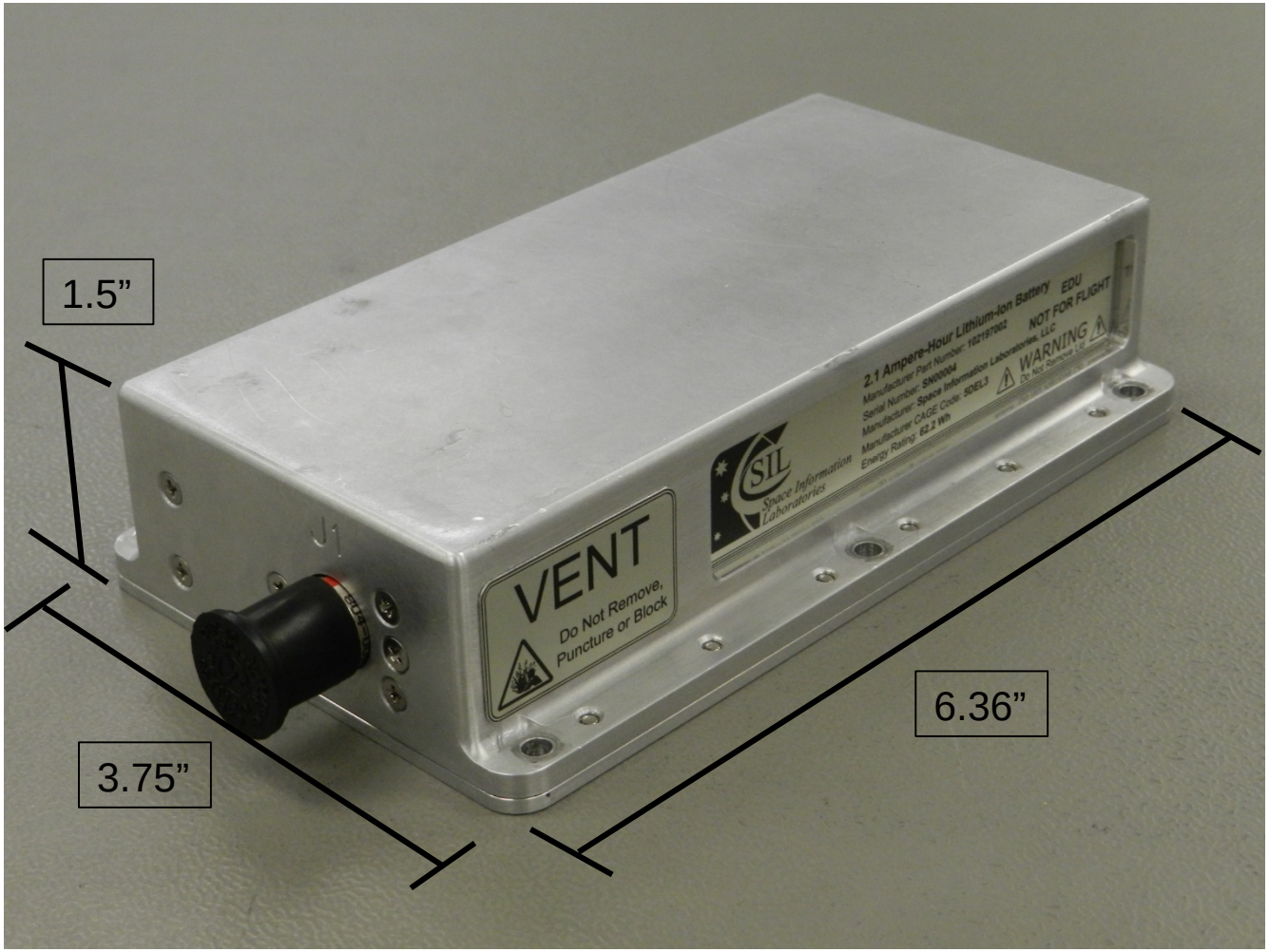
Operational Sine Vibration:
Subjects battery to maximum predicted sine vibration levels in XYZ axis, 3 minutes per axis

Combined FTS Op-Sine Vibe Profile	
Freq (Hz)	Amplitude (g)
70	18.4
100	18.4
170	3.2
240	3.2
435	0.2
550	0.2
600	7.8
700	7.8
750	0.68
980	0.68
1020	0.068
1085	0.04
1150	0.6
1400	0.6
1450	0.04
2000	0.04



2.1 Ah LiPo FTS Battery SWAP

Volume: 35.8 in^3	Max Weight : 1.95 lbs	Power: 62.2 Watt-hrs

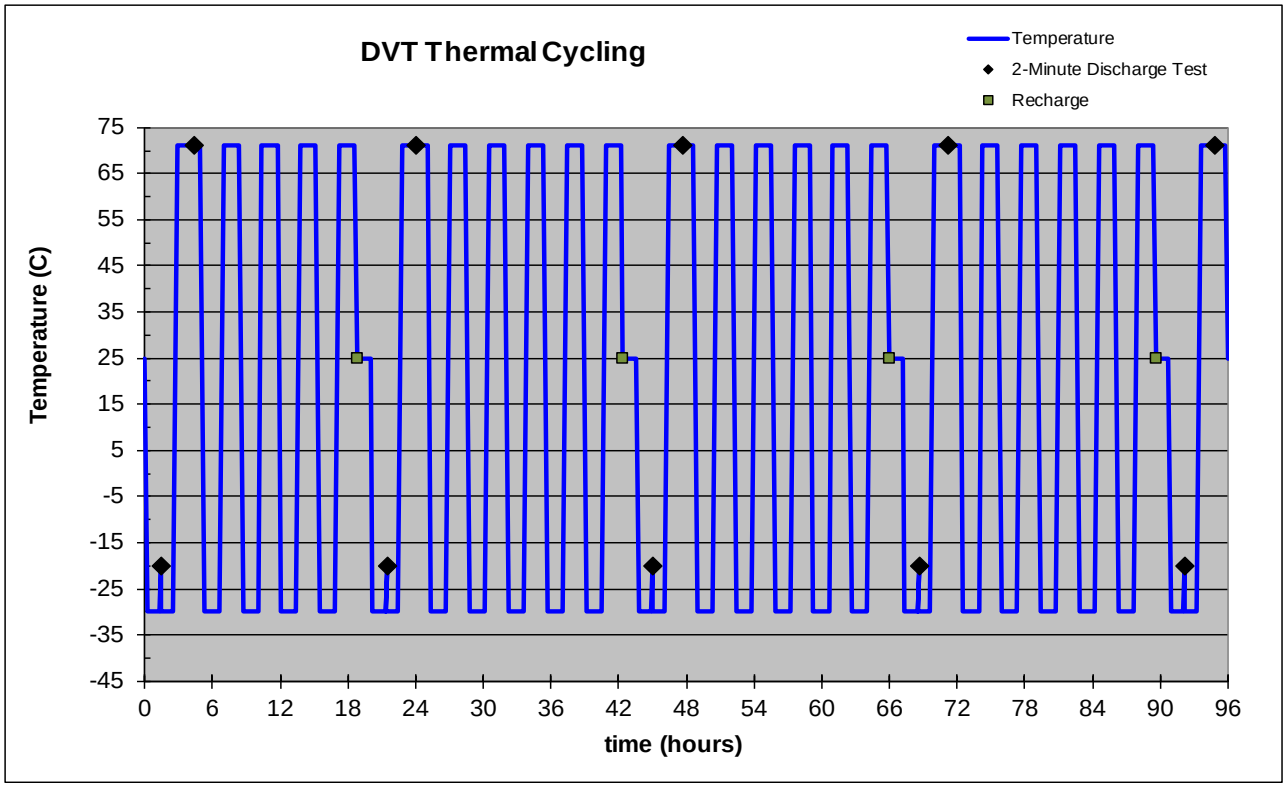


2.1 Ah LiPo FTS Battery Spec Sheet

Battery Specification	SIL 2.1 Ah 8S1P FTS LiPo Battery
Cell Chemistry	173 Wh/Kg, NMC
Voltage Range (J1 and J2 Out)	33.6 – 22.4 Vdc
Capacity (BOL)	2.1 Ah at C/2 continuous discharge 1.8 Ah at 2C continuous discharge
Cycle Life	1,000 Cycles to 80% capacity at 1C discharge and discharge, 100% DOD
Maximum Weight	1.95 lbs
Dimensions	6.36 inch (L) by 3.75 inch (W) by 1.5 inch (H)
Steady State Load	2A (1C)
Pulse Load	6 A (3C), < 10 s pulse
Telemetry and Monitoring	Battery telemetry output at 1 Hz; RS-422
Protection	Cell protection, disabled in Discharge Protection Override
Operational Temp Range	-20 to +71°C (-4 to +160 °F), No Heater
Temp Range with Heaters	-40 to +71°C (-40 to +160°F)

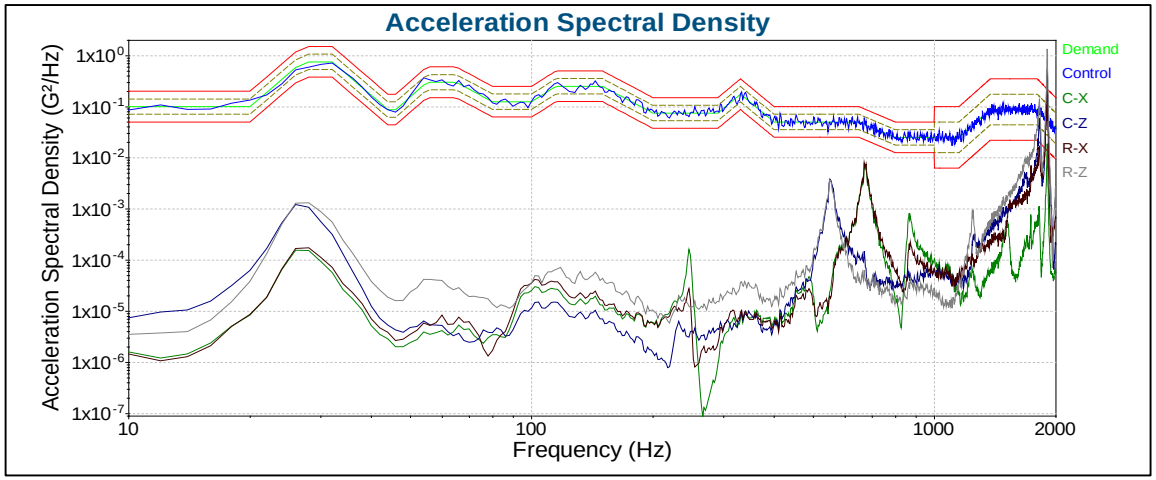
2.1Ah Qual Units DVT Thermal Cycle Test

- Met all RCC 319 requirements during thermal cycle: 24 Cycles, +71°C to -30°C
- 2–minute discharge tests at hot and cold dwells, 10 times throughout test
- Two Qual DVT Units successful post test functional and capacity test show no change it capability



2.1Ah Qual DVT Thermal Random Vibe Test

- Subjected to 60-minute thermal random vibration (RCC 319, 3 mins per Axis only)
- 29.34 G_{rms} in Z-axis, 12.05 G_{rms} in X & Y axis
- Tested at +71°C and -10°C in all axis
- Supplied modified mission load profile throughout
- Two Qual DVT Units successful post test functional and capacity test show no change in capability

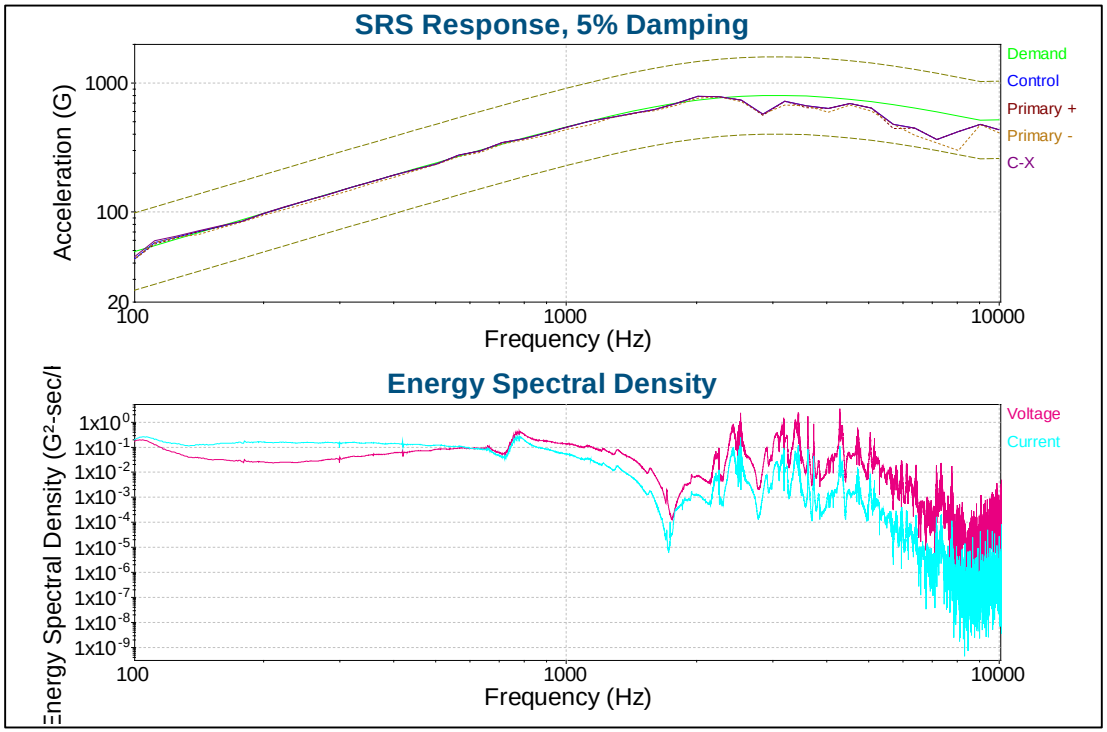


X & Y Axis Qual (MPE + 10dB)	
Frequency (Hz)	ASD/PSD (G2/Hz)
10	0.1004
20	0.1004
27	0.753
32	0.753
45	0.0753
55	0.3012
65	0.3012
80	0.1255
100	0.1255
115	0.251
150	0.251
200	0.0753
290	0.0753
330	0.1757
400	0.0502
650	0.0502
800	0.0251
1150	0.0251
1375	0.08785
1800	0.08785
2000	0.03765
GRMS = 12.05	

Z Axis Qual (MPE + 10dB)	
Frequency (Hz)	ASD/PSD (G2/Hz)
10	0.6275
40	0.6275
55	12.55
65	12.55
80	2.008
88	4.016
100	4.016
150	0.502
170	0.502
200	1.506
250	0.502
285	0.502
320	1.255
400	0.2008
500	0.2008
555	0.1004
1140	0.1004
1290	0.3765
1380	0.3765
1520	0.1255
2000	0.1255
GRMS = 29.34	

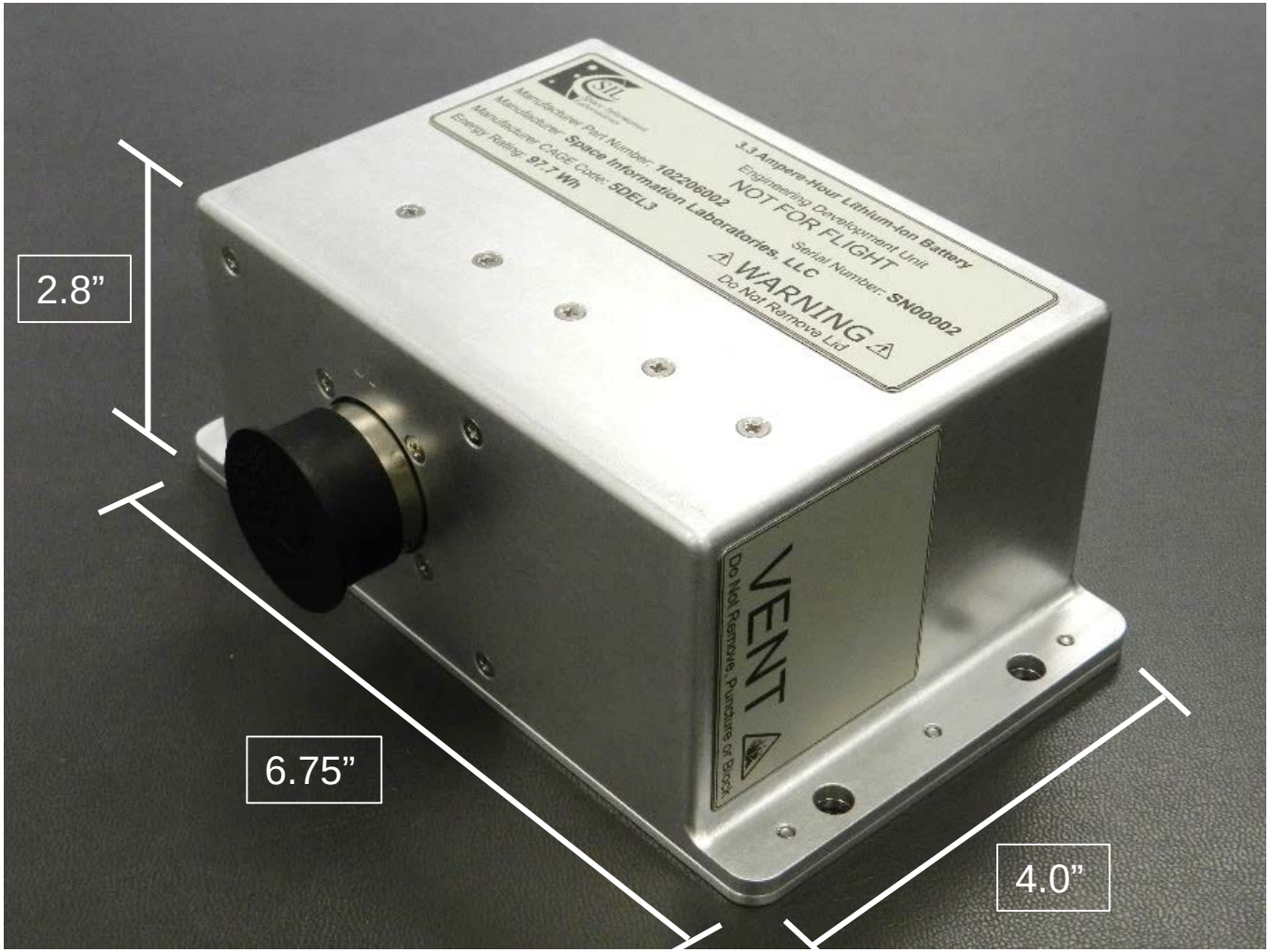
2.1Ah Qual DVT Thermal SRS Shock Test

- Subjected to thermal SRS shock
- Wing deployment shock of >485 g in all axis
- Tested at +71°C and -10°C in all axis
- Voltage monitored throughout: no dropouts
- Two Qual DVT Units successful post test functional and capacity test show no change in capability



3.3AH FTS LiPo Battery with internal BMS

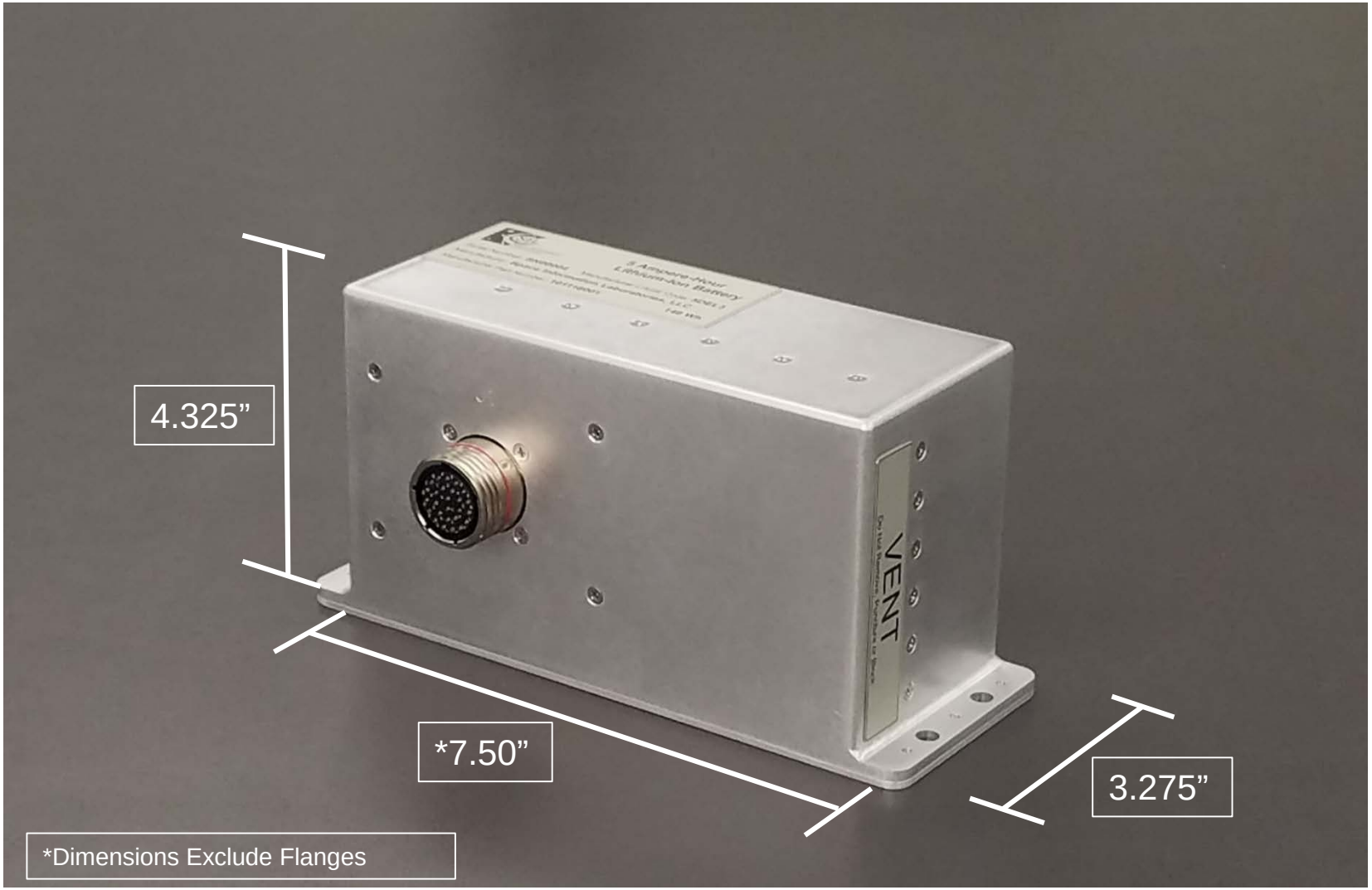
Volume: 75.6 in^3	Max Weight : 3.25 lbs	Power: 97.7 Watt-hrs



3.3 Ah LiPo FTS / TLM Battery Spec Sheet

Battery Specification	SIL 3.3 Ah 8S1P Li-Po Battery
Cell Chemistry	Lithium Nickel Manganese Cobalt Oxide (NMC)
Voltage Range (J1 and J2 Out)	33.6 – 22.4 Vdc
Capacity (BOL)	3.3 Ah at 0.5 C continuous discharge 3.1 Ah at 1.0 C continuous discharge 2.8 Ah at 2.0 C continuous discharge
Cycle Life	1,000 Cycles to 80% capacity at 1C charge & discharge, 100% DOD
Maximum Weight	3.25 lbs
Dimensions	6.75 inch (L) by 4.00 inch (W) by 2.80 inch (H)
Steady State Load	6.6 A (2C)
Pulse Load	16.5 A (5C), <10 s pulse
Telemetry and Monitoring	Battery telemetry output at 1 Hz; RS-422
Protection	Cell protection, disabled in Discharge Protection Override
Operational Temp Range	-10 to +60°C (+14 to + 140°F), No Heater
Temp Range with Heaters	-40 to +71°C (-40 to + 159.8°F)

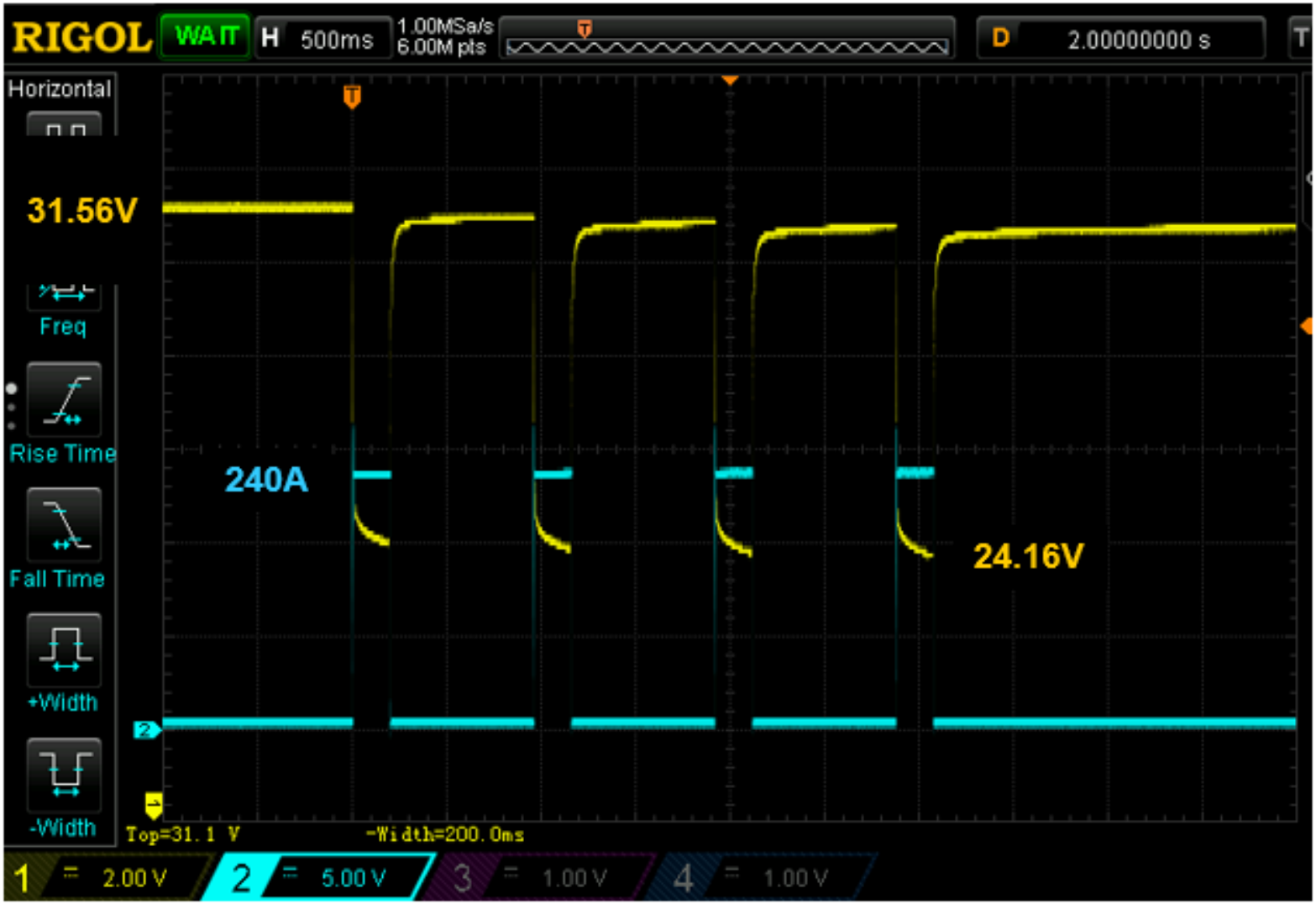
5Ah FTS/TLM Li-Ion Battery with internal BMS



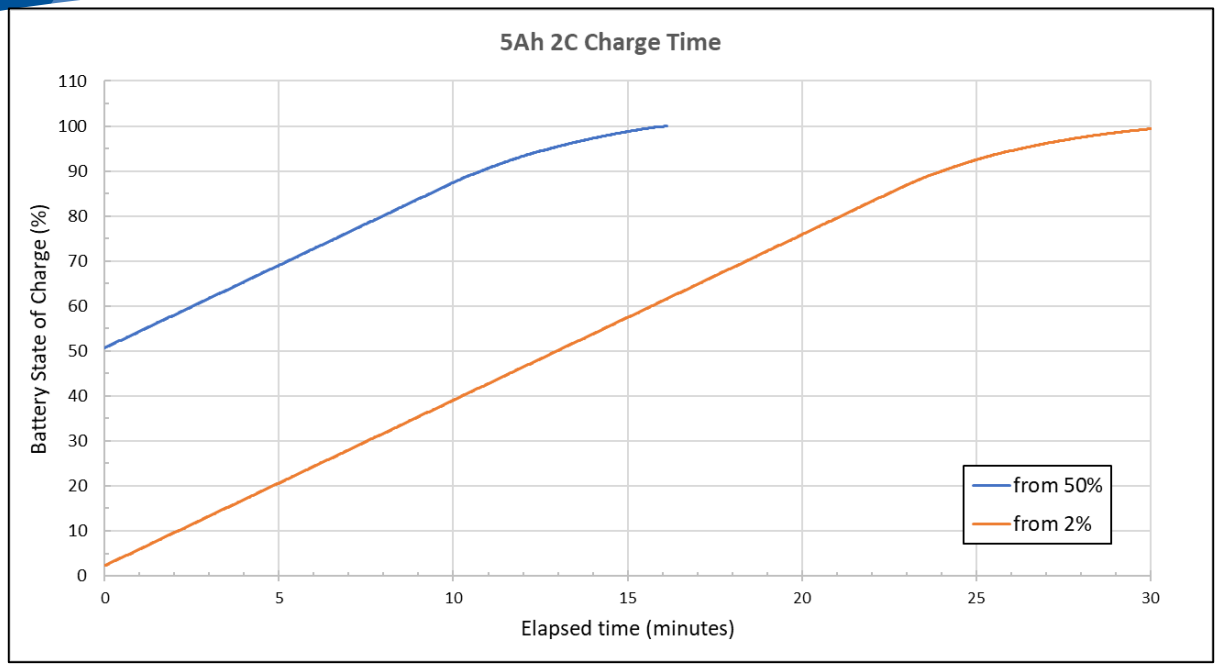
Li-Ion Polymer Intelli-Pack®
5Ah FTS/TLM Battery Specification

Battery Specification	SIL Li-Ion Intelli-Pack® 5Ah 8S1P TM/Avionics/FTS Battery
Voltage (J1 Out)	33.6Vdc (Fully Charged)
Capacity	5 Ah at 1C Continuous Discharge (33.6Vdc to 22.4 V dc) 4.75 Ah at 10C Continuous Discharge (33.6Vdc to 22.4 Vdc) 4 Ah at 30C Continuous Discharge (33.6Vdc to 22.4 Vdc)
Cycle Life	1000 Cycles to 80% Capacity at 1C discharge and charge
Weight Max	5.75 lbs.
Dimensions	7.50" L x 3.275" W x 4.325" H (1/2 ” mounting flanges)
Pulse Load	100 Amps (20C), < 200mecs second pulse
Steady State Load	30 Amps (6C)
Telemetry and Real-time Cell Monitoring (J2 Out)	RS-422, etc.
Protection	Full Cell Protection (Overvoltage, Undervoltage, Temperature and Short Circuit) - Disabled in Flight Override Mode
Space Qual Temp Range	-10°C to +55°C (Battery without heaters) -40°C to + 55°C (Battery with DC Kapton heaters) -40°C to +71°C (Battery BMS PCBA) Operating Range: -50°C to +71°C

5Ah FTS/Pyro Li-Ion Pulse Current Performance



Battery Fast Charge Test

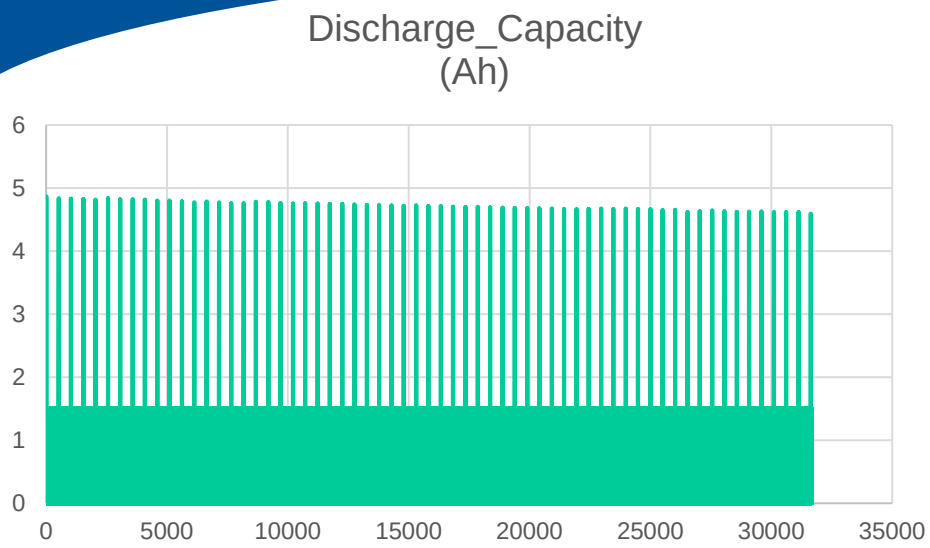


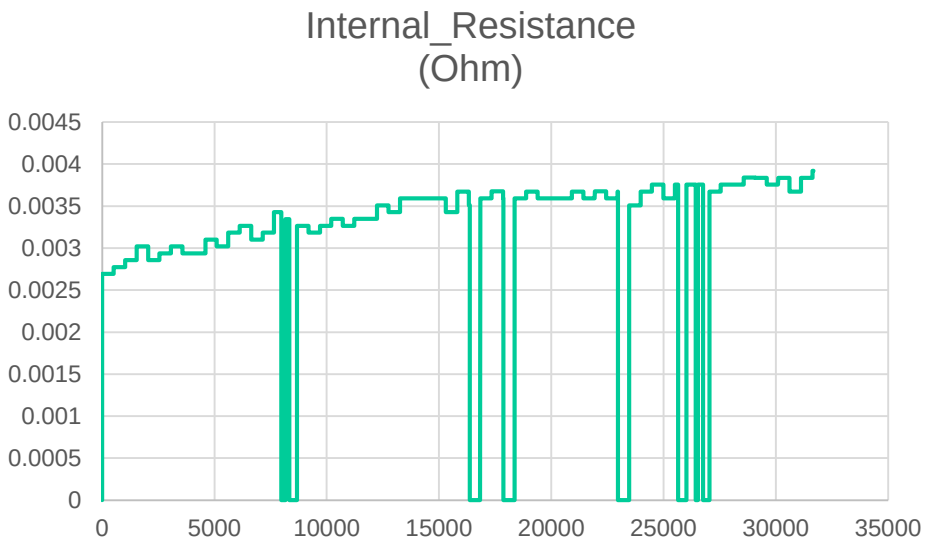
- Battery traditionally charged at C/2 per cell spec sheet and manufacturer recommendation
- Tested 2C “fast” charging with high current capability 5 Ah battery
- BMS includes autonomous charge cut-off functionality so man-in-the-loop is not required

5Ah battery reached 100% SoC from 50% SoC in 16 minutes

5Ah battery reached 100% SoC from 2% SoC in 30 minutes

5Ah LiPo Z Fold cell 1 Year Cycle Life Test in a Vacuum for LEO mission





- 30% Depth of Discharge (DOD)
- Cells charged at .5C (2.5 Amps) until reaching 4.1 Vdc
- Cells discharged at .5C (2.5 Amps) for 38 minutes
- Every 100 cycles, the cells internal Resistance was measured and full Capacity test performed from 4.2Vdc to 2.8Vdc

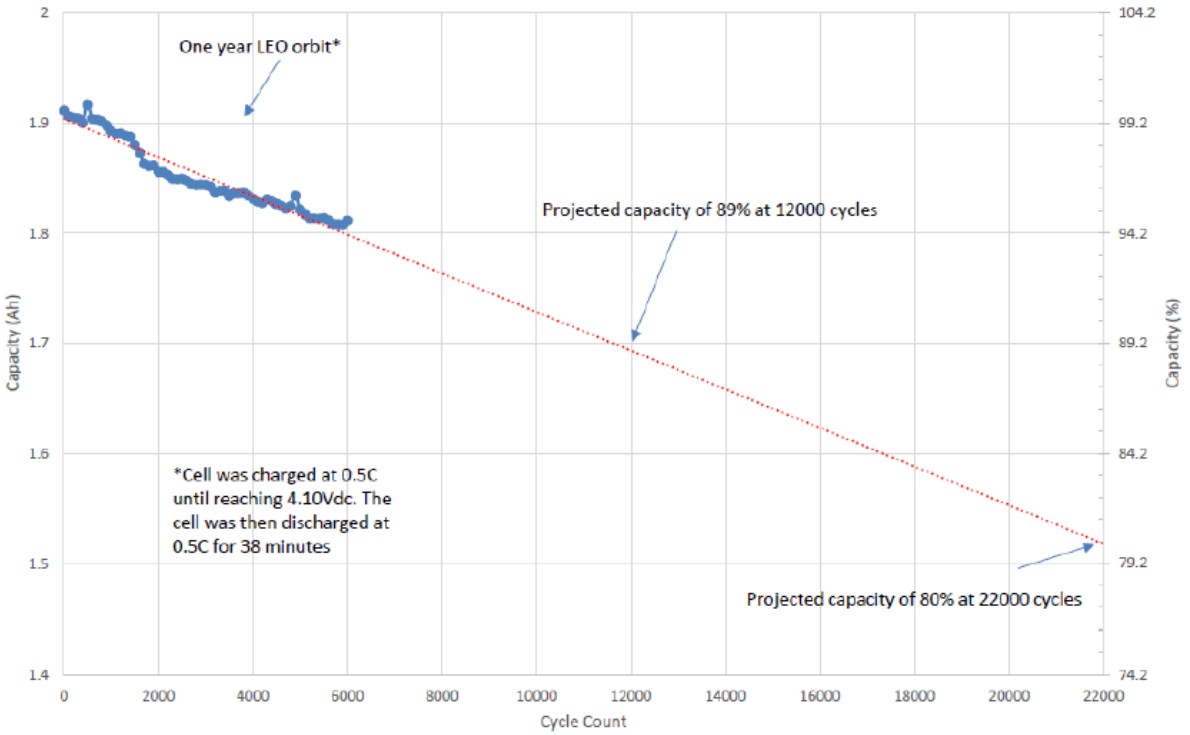
LEO Cycle Life Data Conclusion:

- Li-Ion Polymer NMC Cells have 3X Cycle Life of 18650 and ½ recharge time on-orbit that is a game changer for 6U to 27U CubeSat missions
- Low internal resistance of < 4mohm compared to ~ 60mohm for 18650
- 5Ah Cell is rated for 30C (150 Amps) continuous current and 50C (250 Amps, 1 sec) pulse current that if require high power on-orbit for payloads (SAR, etc.)

LiPo Z Fold NMC Cell 1 Year Cycle Life Test in a Vacuum for LEO mission

- 1-year long cycle test in vacuum (20-30% DOD, C/2 Charge and Discharge rate
- Vacuum pressure of 1 * 10-4 Torr
- Cycle regime imitated a small satellite in LEO (charge to 90%)
- Full capacity test every 100 cycles
- Total loss of 5.7% relative capacity throughout year test
- 6200 charge/discharge cycles
- Control cell in ambient had similar cycle life results

5 Ah Cell Vacuum Cycle Life Test Results



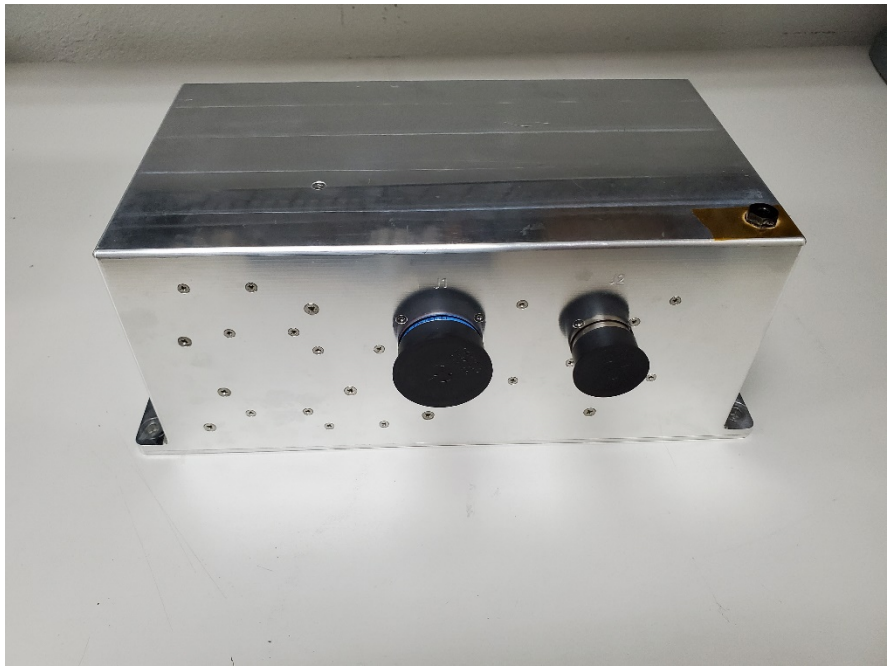
2Ah / 5 Ah Cells performed identically in Vacuum and in ambient conditions

Extrapolation cycle life estimate of 22,000 cycles prior to End of Life (80% Capacity)

52Ah Li-Ion Polymer Intelli-Pack®

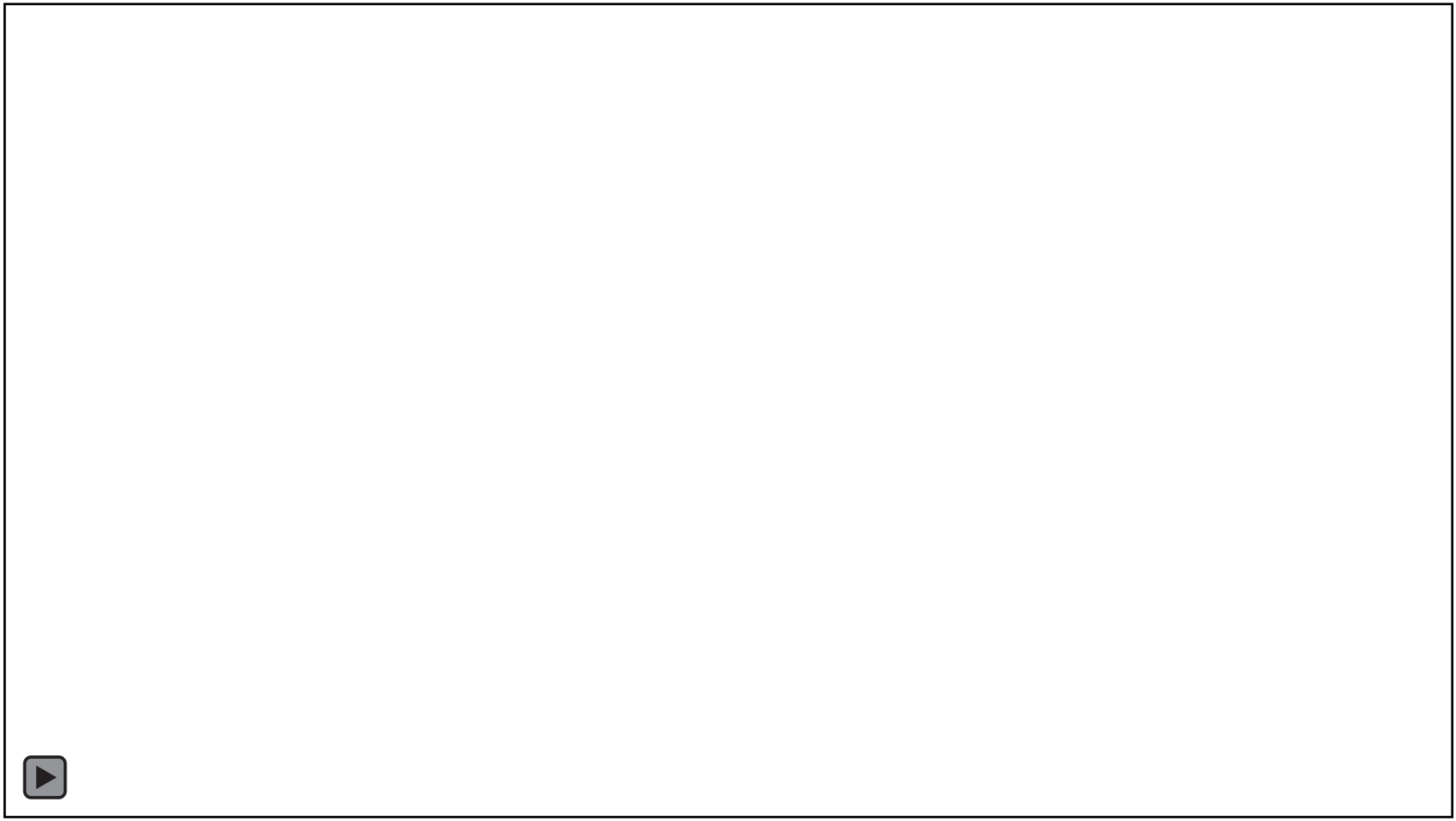
Power: 1539.2 Watt-hrs

Weight Estimate: 26.2 lbs
Mil Alum 6061-T6 Enclosure



Battery Specification	**SIL 52 Ah 8S2P Li-Po Battery**
Cell Chemistry	Ultra High Energy NMC Cell 243Wh/Kg
Voltage Range (J1 and J2 Out)	33.6 – 22.4 Vdc
Capacity (BOL)	52 Ah at C/2 continuous discharge 50 Ah at 1C continuous discharge
Cycle Life	25,000 Cycles to 80% capacity at C/2 discharge and charge, 20-30% DOD
Estimated Weight	26.2 lbs
Dimensions	14.0 inch (L) by 7.0 inch (W) by 5.5 inch (H)
Steady State Load	104A (2C)
Pulse Load	208A (4C), 10 Seconds
Telemetry and Monitoring	RS-422 J1 and J2 Connectors
Protection	Full cell protection, disabled in Discharge Protection Override
Operational Temp Range (no heater)	-10 to +60°C (+14 to +140°F)
Temp Range with Heaters	-40 to +60°C (-40 to +140°F)

52Ah Battery Random Vibration Testing at SIL

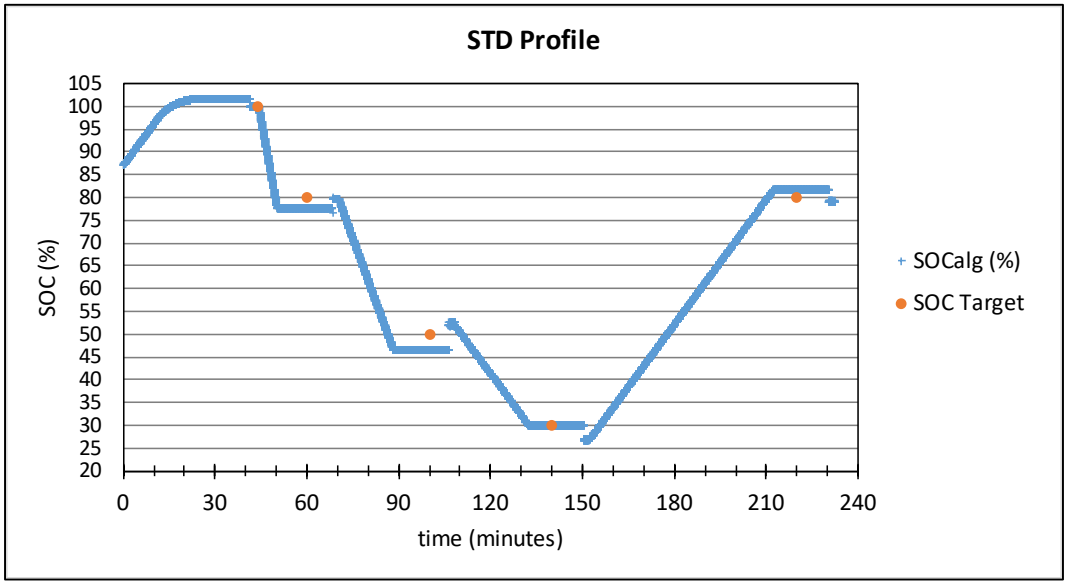


On-Board Intelligent BMS for Li-Ion Intelli-Pack® Battery

- Li-Ion Battery applications requiring mission and safety critical BMS design
- Functions of Intelligent BMS in Li-Ion Intelli-Pack® battery system (in general)
  - Monitor the individual series or parallel cells, and battery performance in real-time
  - Protections for Safety (overvoltage, undervoltage, short circuit, temperature, etc.)
  - On board SOC, SOH (Qc) and RUL Algorithms

State of Charge Algorithm Development

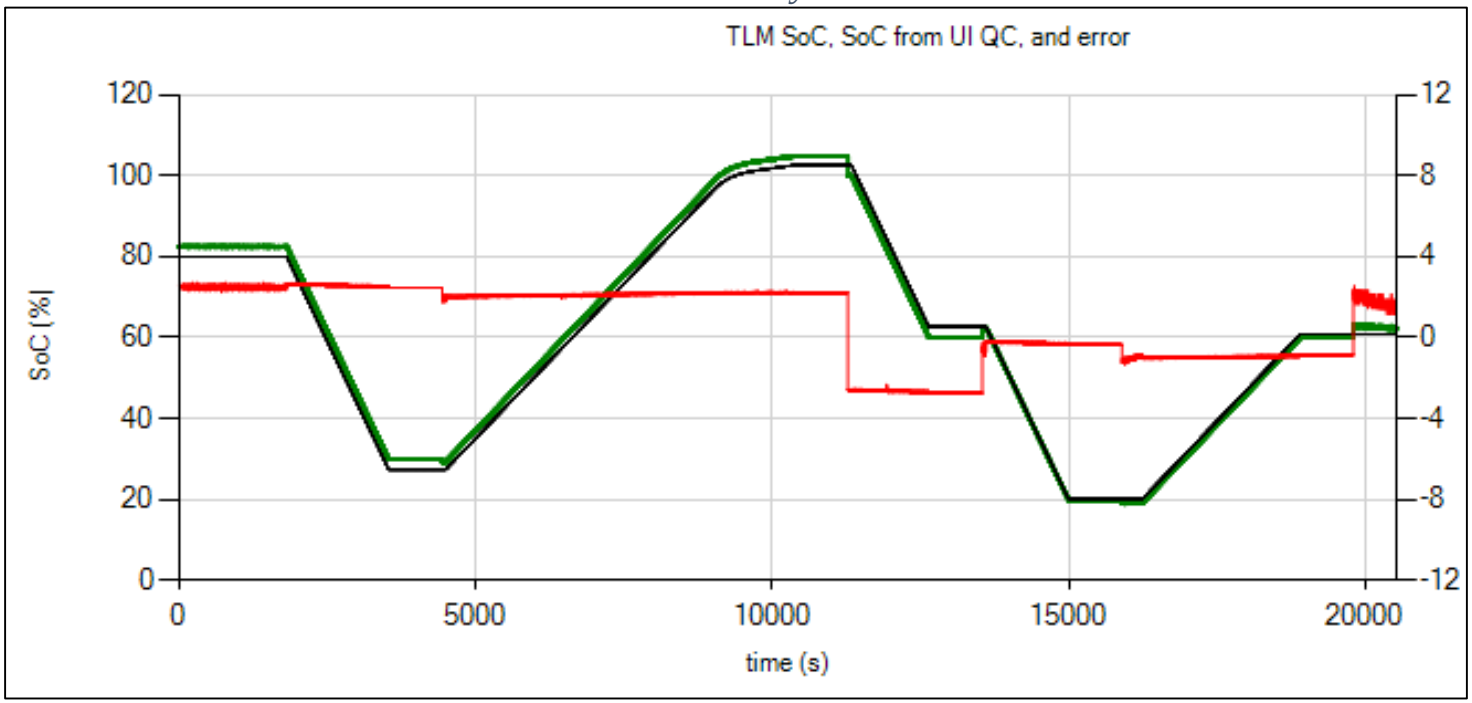
- Each BMS is calibrated during manufacturing
- Pack capacity and SOC as a function of Open Circuit Voltage is measured after the BMS is paired with the pack
- Real-time SOC is based on Coulomb counting
  - Look-up table is used to eliminate integration error
  - Systematic Long-term error is used to compute real-time capacity
- ±3% Accuracy based on testing to date



Battery SOC throughout a test profile

State of Charge Algorithm Test

SoC Accuracy Test

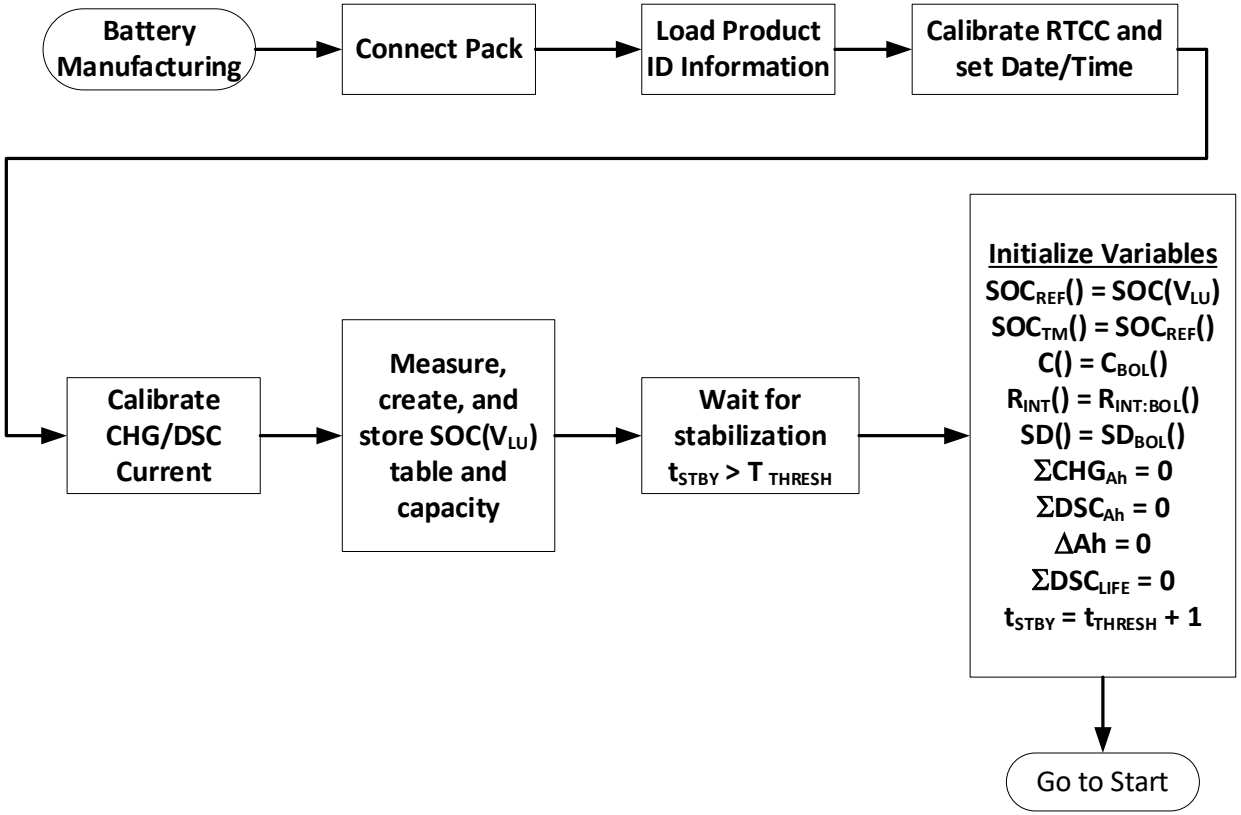


- Microcontroller Based SoC algorithm via Amp-hour summation and calibrated lookup table
- ΔL tracks SoC and is computed as the accumulation of coulomb counting

Difference between SoC and expected never exceeded ±2.7%

SOH Algorithm: Initialization

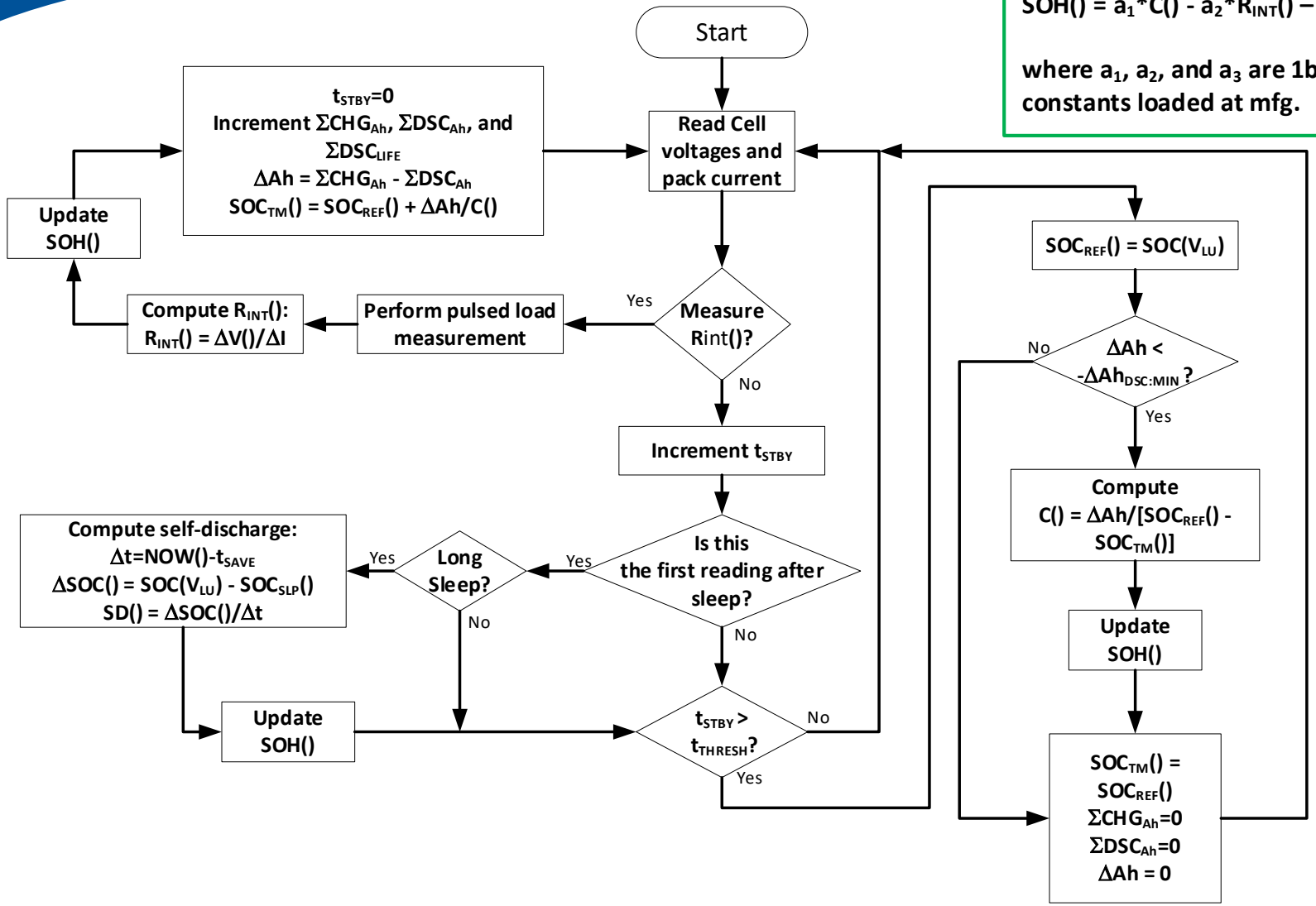
- Implemented in Three Phases: Initialization, Operation, and Sleep
- Governing SOH Equation: $SOH(t) = a_1 * C(t) - a_2 * R_{INT}(t) - a_3 * SD(t)$
  - a_1, a_2, a_3, are 1 byte constants determined for each individual battery and loaded after manufacturing



SOH Algorithm: Operation

$SOH() = a_1*C() - a_2*R_{INT}() - a_3*SD()$

where a_1, a_2, and a_3 are 1byte constants loaded at mfg.



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