DESIGN AND TEST OF THE PAYLOAD ELECTRONICS & IN FLIGHT SEQUENCE DEVELOPMENT FOR THE CSUN CUBESAT1 LOW TEMPERATURE BATERY EXPERIMENT

G.S. Bolotin* K.B. Chin, M.C. Smart, E.J. Brandon, N.K. Palmer

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Grove Drive, Pasadena, CA 91109

*gary.s.bolotin@jpl.nasa.gov

S. Katz, J.A. Flynn

California State University, Northridge

Dept. of Electrical and Computer Engineering

Northridge, CA 91330-8346

29th Annual AIAA/USU Conference on Small Satellites

August 8, 2015

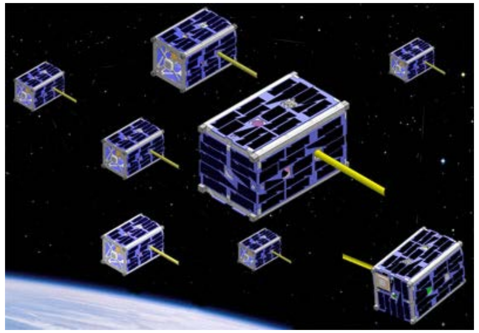
Outline

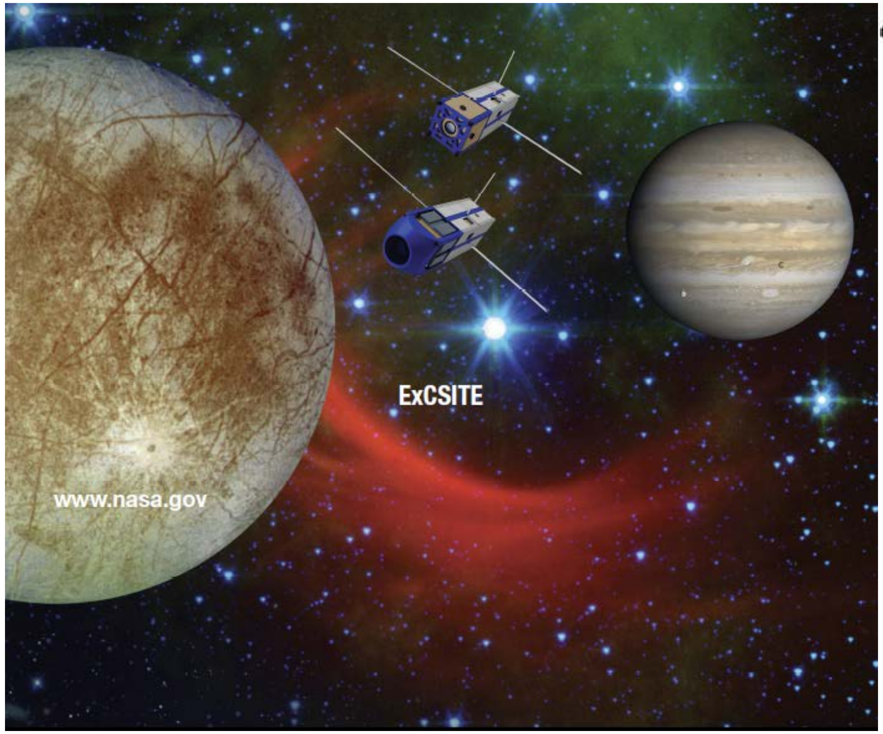
- Motivation
- Technology
- Mission
- Payload
- Testing
- In Flight Sequences
- Conclusion and Future Work.
- Team Acknowledgement

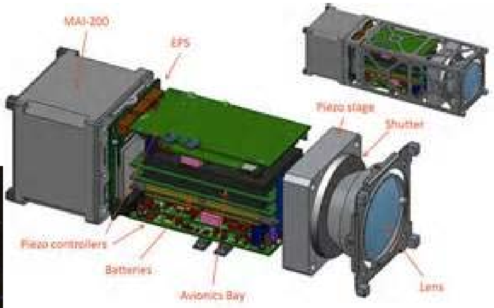
Jet Propulsion Laboratory
California Institute of Technology

NASA’s Future SmallSat Missions

California State University
Northridge







Small satellites beyond LEO orbits will require operation at lower temperatures.
This leads to the need for a cold capable energy storage system.

Low Temperature Li-Ion, Supercapacitor Hybrid Energy Storage System

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Challenge: Small spacecraft and in situ instruments require energy storage technology that can operate at low temperatures and provide power for high power payloads such as communication and propulsion.

Solution: JPL Hybrid Energy Storage System consisting of a new JPL electrolyte Li-ion chemistry coupled with high power super-capacitors to enable high discharge rate at low temperatures.

Capability	Current SOP	Proposed Tech
Operating Temperature	-20C to 20C	-50C to 20C
Discharge Rate	<1C	>10C
Battery Can Seal	Welded (expensive)	Crimped (COTS)

Benefits and Impact

- Benefits
  - Cold temperature operation eliminates energy for battery heating
  - High discharge rate enables high power operations such as communication and instrument operation normally not possible
- Relevance & Impact
  - Enables 3 classes of Missions:
    - Landers & in situ instruments
      - Europa Lander
      - Mars Sample Return
    - Sensor networks
    - Deep Space small spacecraft

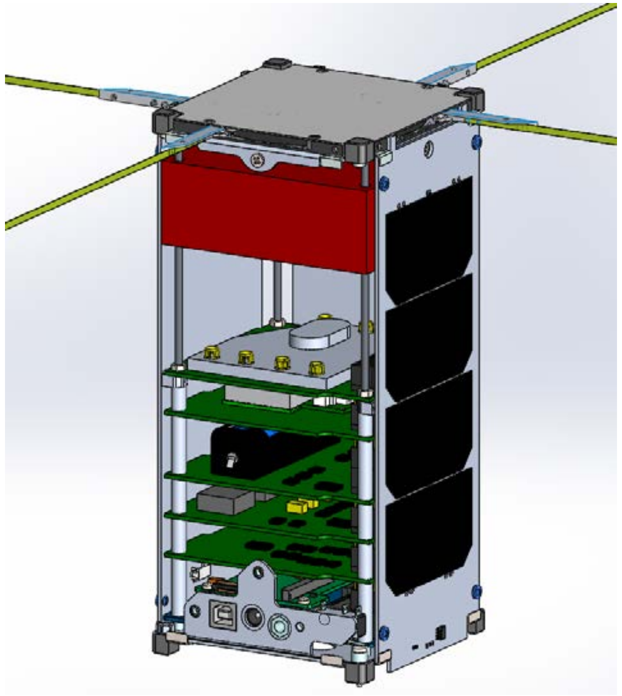
5

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

CSUNSAT1: A CSUN/JPL Collaboration

- Funded by NASA's 2013 Small Spacecraft Technology Program (1 FTE/yr for 2 yrs)
- Time frame: 11/1/2013 – 9/27/2015



JPL Energy Storage Payload

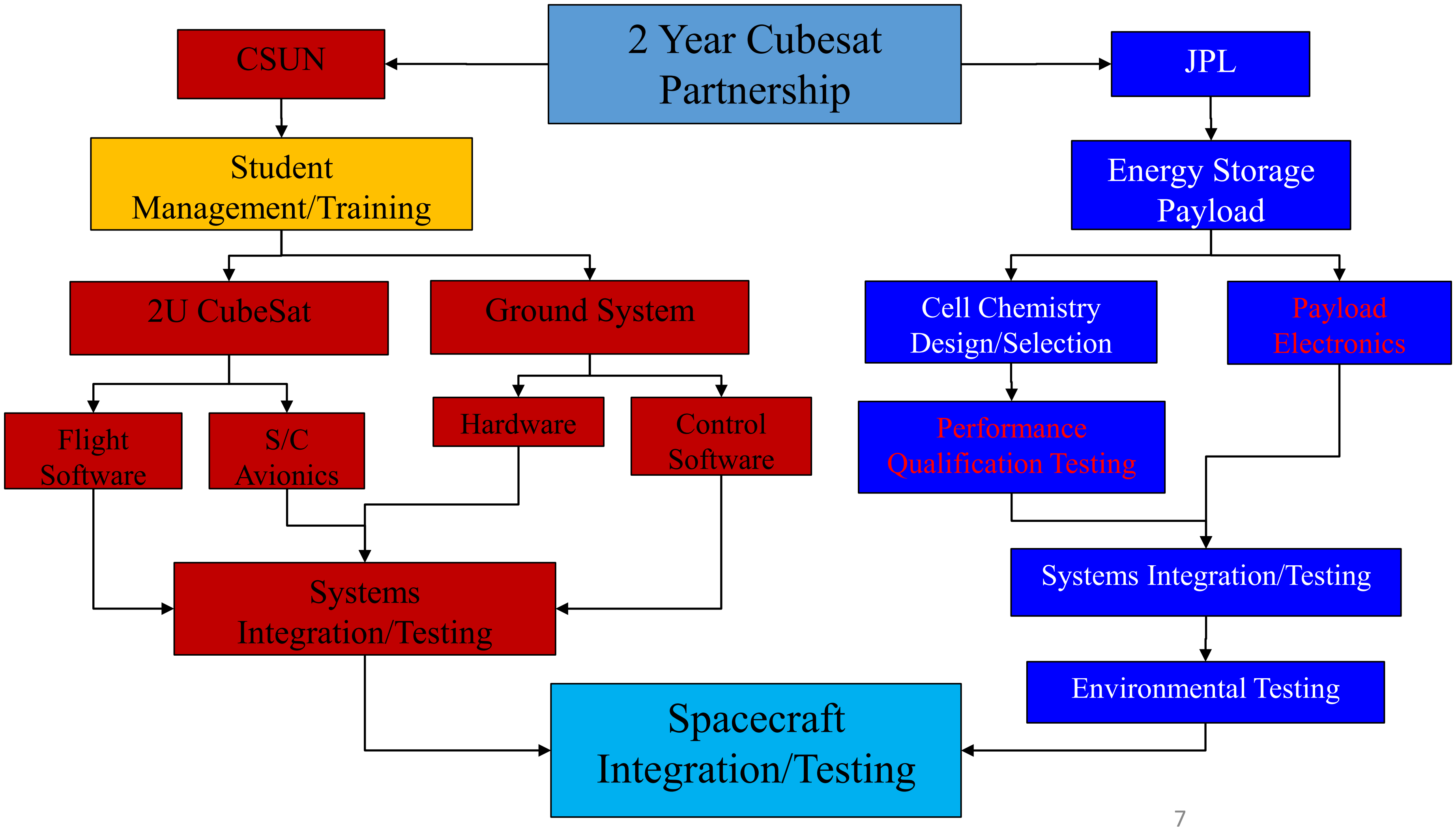
CSUNSat1: 2U CubeSat

- Processor
- Communications
- Power System

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

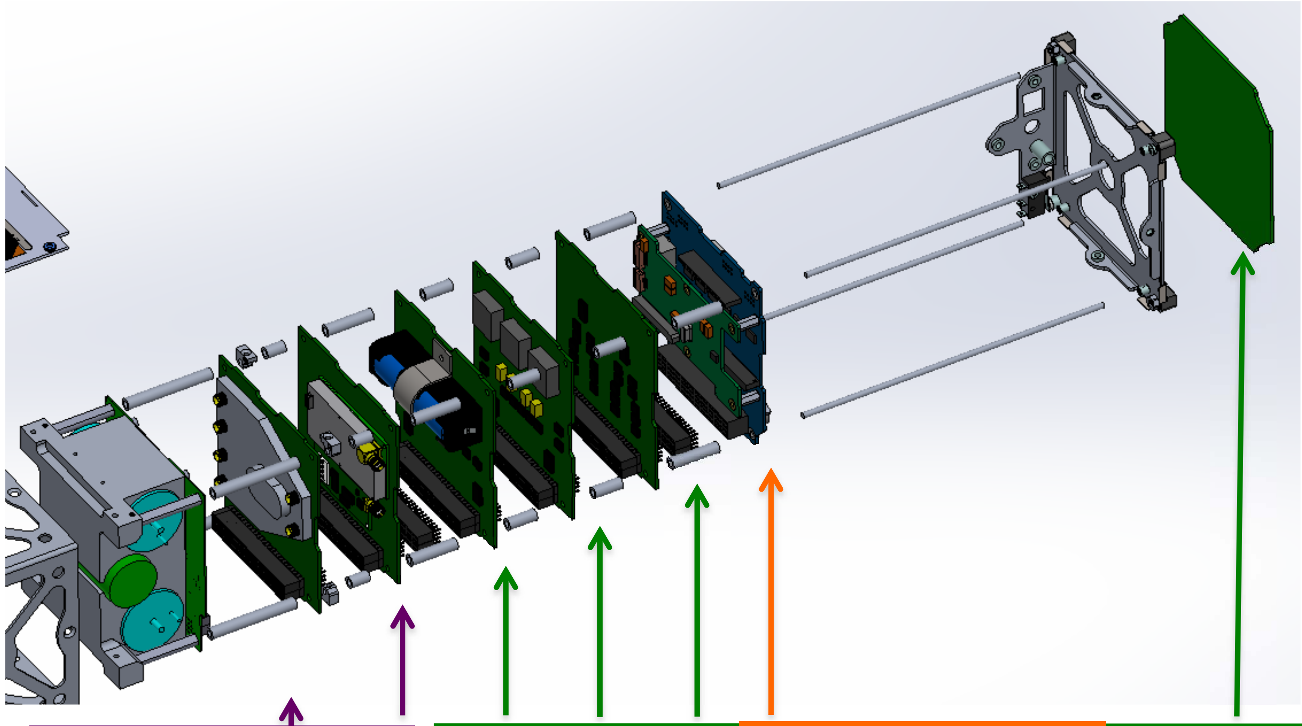
CSUN/JPL Activities



Jet Propulsion Laboratory
California Institute of Technology

CSUNSAT1: Overview

California State University
Northridge



Communications
9.6Kbps transceiver
CW Beacon
Antenna Switch

Power System
Provides 3.3, 5, 12V
Exp. control

Processor
dsPIC33
No RTOS
Command Dict.

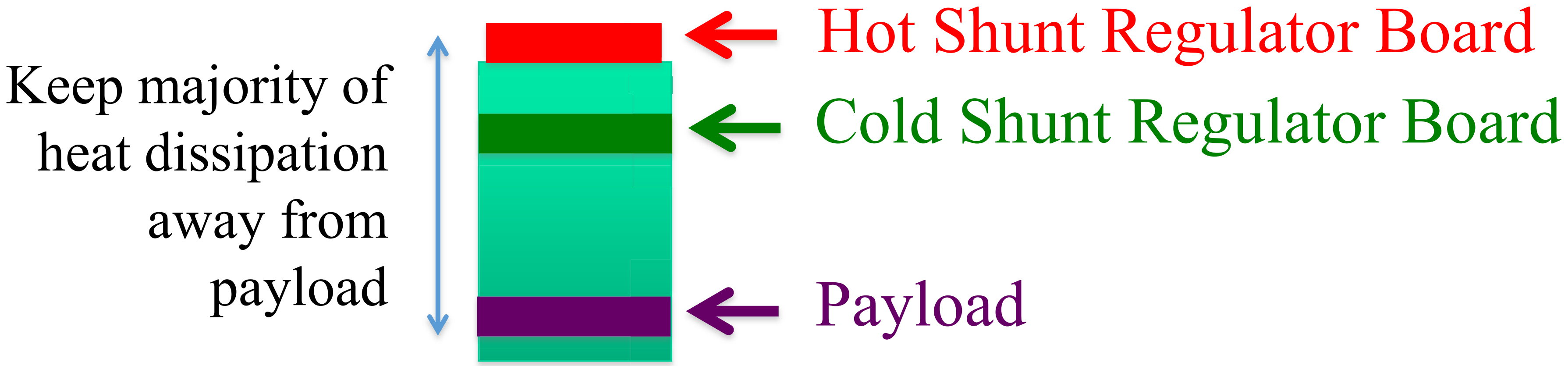
Power System
Hot SRB

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Design Challenges for S/C

- Problem
  - ❖Energy storage payload requires operational temperatures below -10°C.
- Solution
  - ❖Divide shunt regulator into two boards so that heat is dissipated into space.



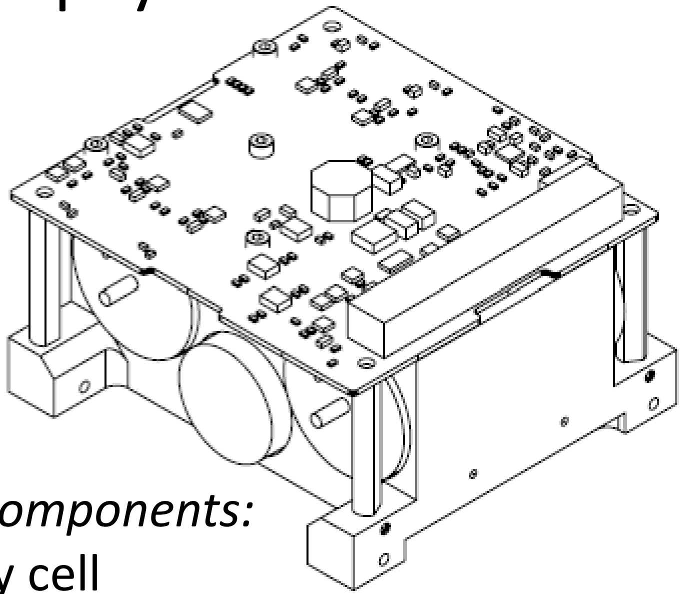
9

Jet Propulsion Laboratory
California Institute of Technology

California State University
Northridge

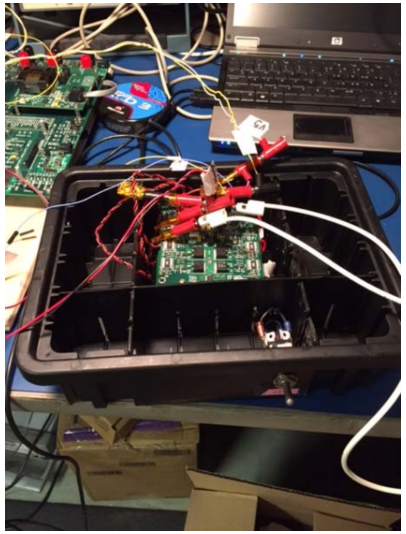
Payload Overview

- The payload consists of an electronics board, 2 supercapacitors and one low temperature Li-Ion Battery
- All interfaces with the CubeSat are through the cubesat connector
- The payload will be tested by JPL prior to delivery to CSUN



Payload Components:

1. Battery cell
2. Super-capacitors
3. Payload electronics



Payload EM2 integrated testing

Payload Physical Parameters	Value
Total Mass (gm)	510.0
Width (cm)	9.0
Length (cm)	9.6
Thickness (cm)	4.7
Total Volume (cm^3)	483.8

10

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Payload Overview: Energy Storage

- **Battery**
  - 2.00V to 3.60V nominal operation.
  - ~ 2.20 Ah
  - [-40C - +20C] operating temperature range

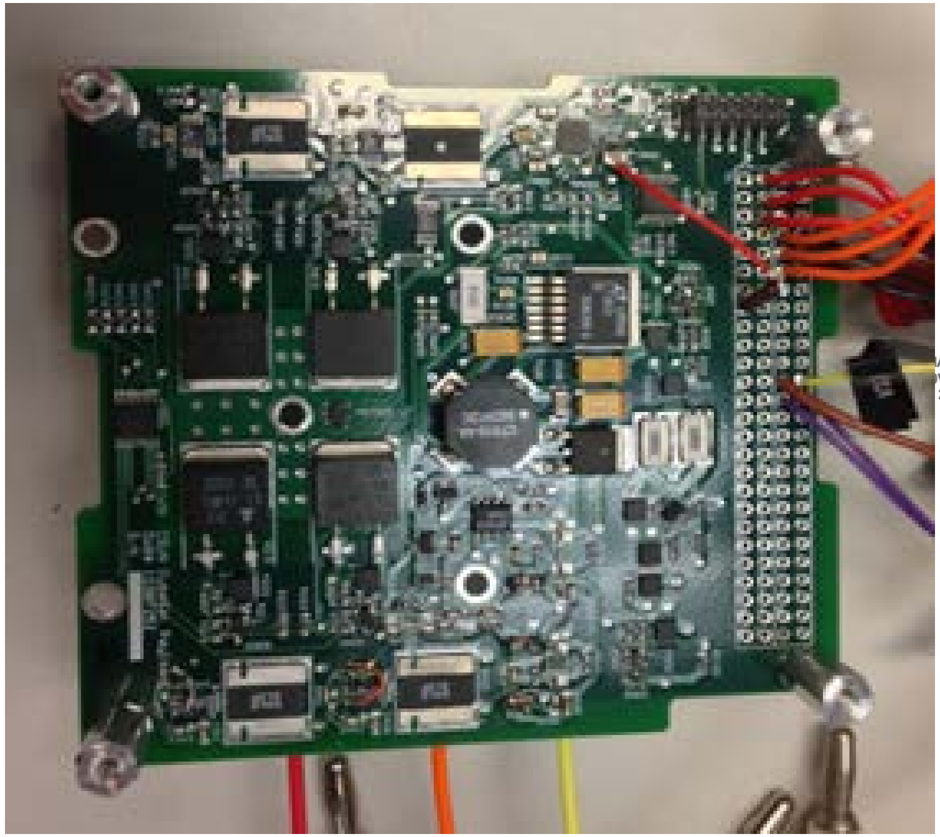
- **Supercapacitor** (2 per payload)
  - 350F each
  - [-40C - +20C] TBR temperature range

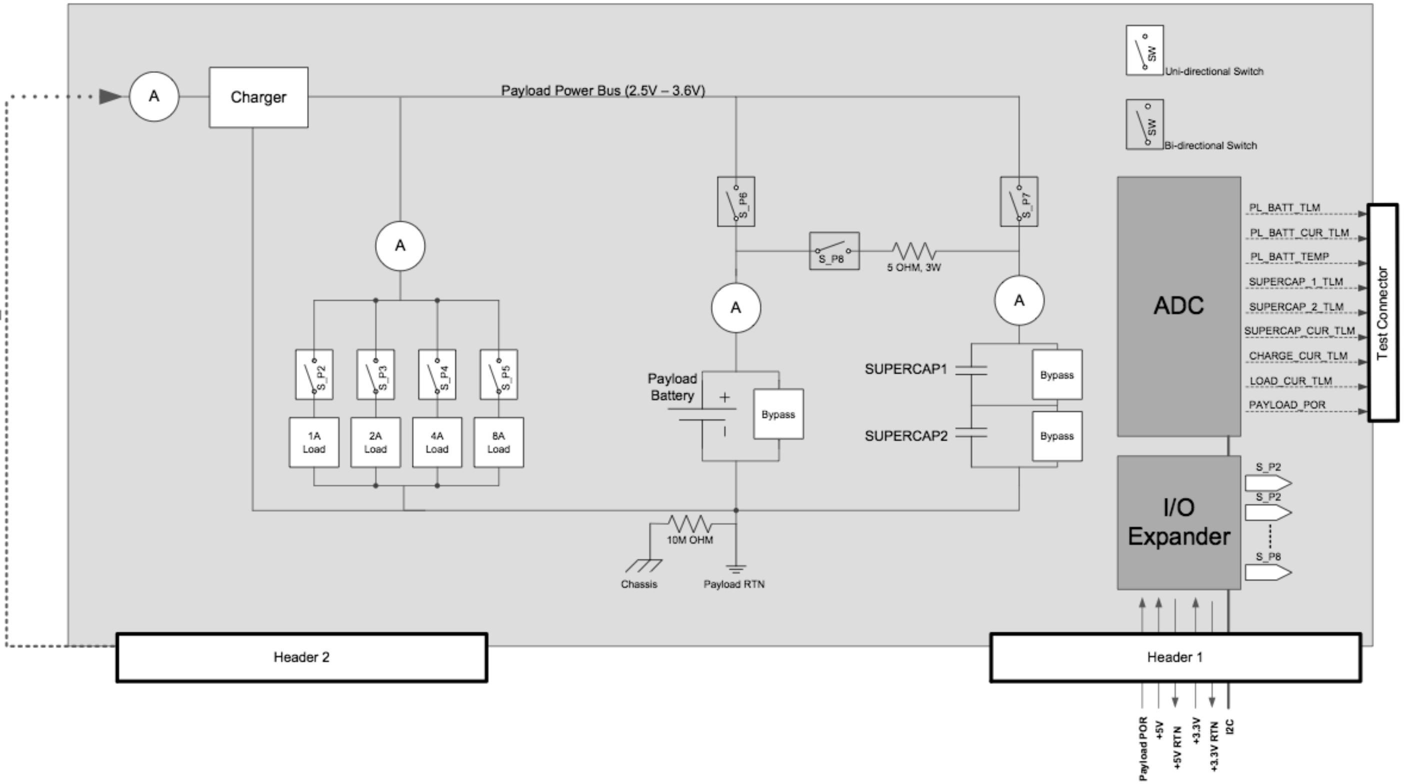
11

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Payload Overview: Electronics





12

Payload Electronics Key Features

- **Simple I2C Interface**
  - **Local ADC and port expander**
- **Telemetry**
  - **Battery and Capacitor Voltages and Currents**
  - **Battery Temperature**
  - **Charger and load currents**
- **Load Circuit**
  - **1-15A in 1A increments**
- **Hardware Fault Protection**

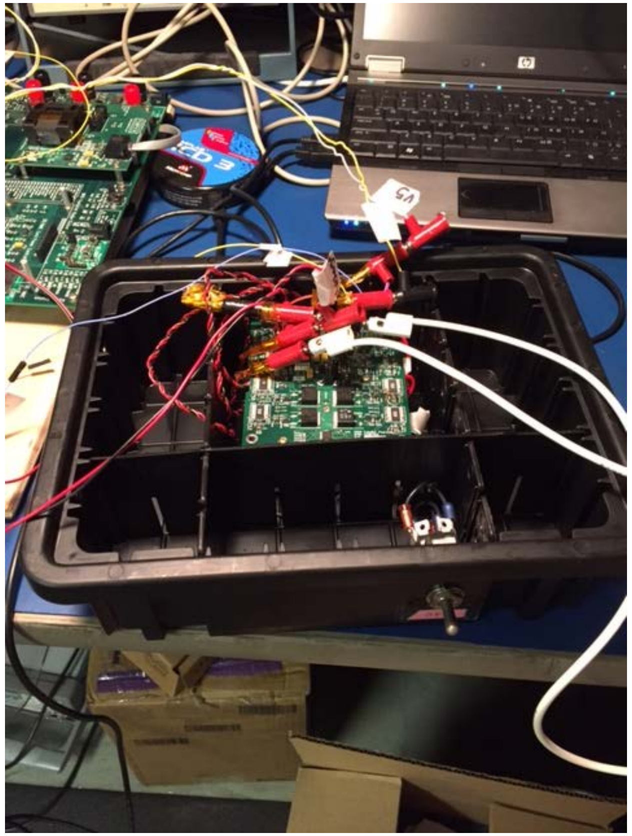
Jet Propulsion Laboratory
California Institute of Technology

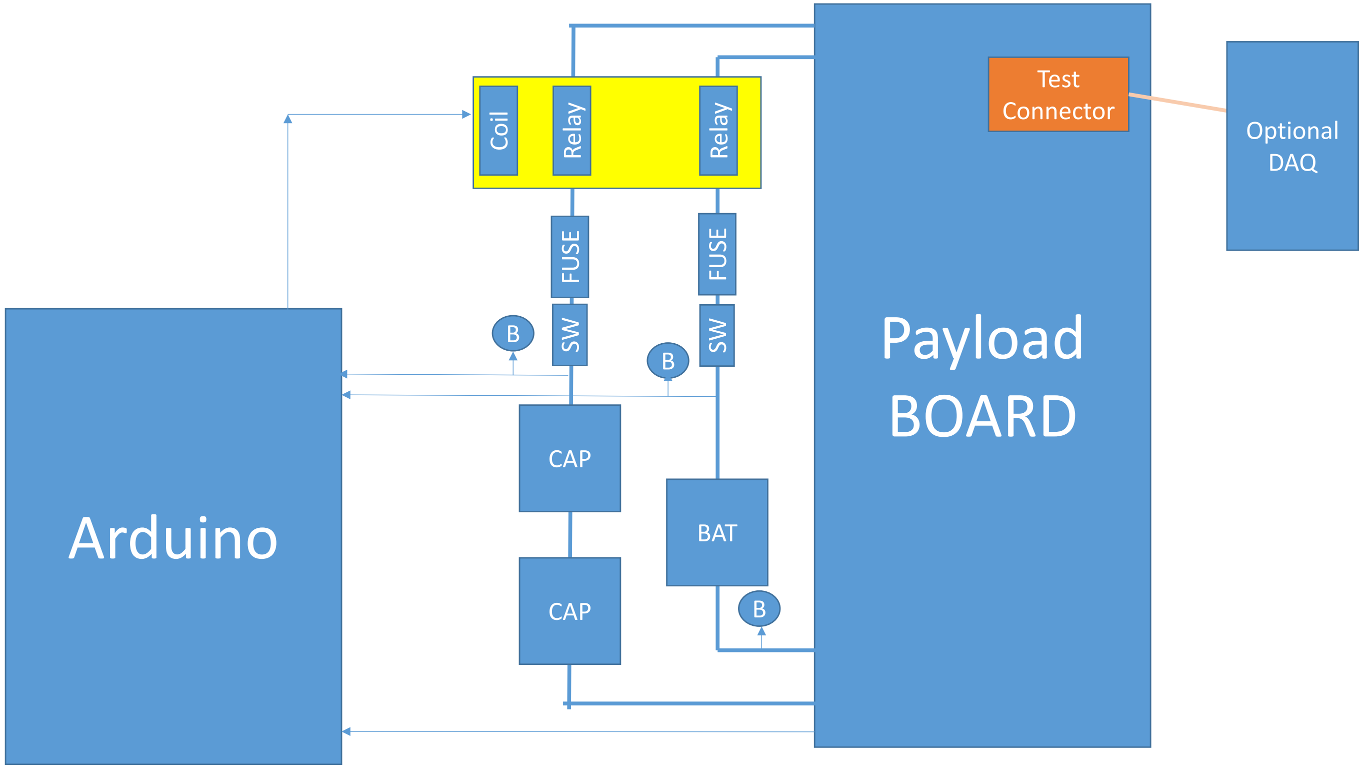
Payload Electronics Fault Protection

California State University Northridge

FP type	Fault Condition	Action	Detection	Cleared	Comments
Battery over voltage	>3.7V	Clamp Battery string	Clamp	Clamp unclamps	Battery is overcharged
Battery voltage	<1.95V	Disconnect discharge FET but not charge FET so battery can charge	Software	Software	Not a safety issue. Battery below min. capacity.
Battery Temperature	>40°C	Switch Off Battery – Switch off both charge and discharge FET	H/W	H/W < 38 °C no longer a safety issue	Potential shorted battery
Supercap cell voltage	>2.85V	Bypass charge current	H/W	H/W	Charge current bypasses the cell
Supercap cell voltage	<0V	Supercap offline	S/W	S/W	Vented?!
Deploy Switch	<0.5V	Ensure that payload battery and Super-capacitor are completely disconnected	H/W	H/W	This signal is to be kept low during launch.

Ground Support Equipment





Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

JPL Ground Testing Overview

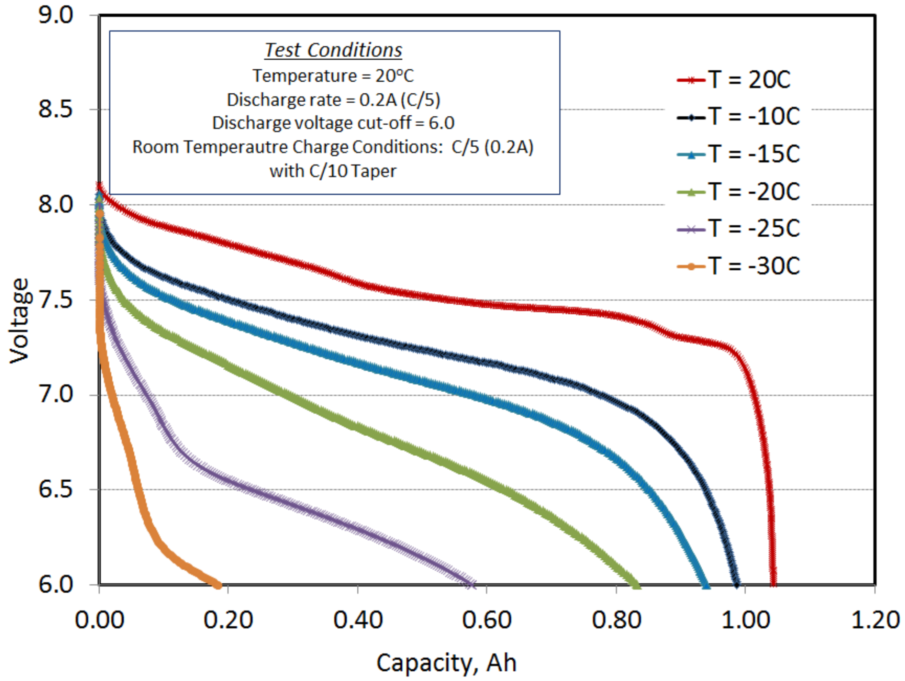
- Performance capabilities down to -40^{o}C.
    1. Baseline Battery Testing.
    2. Low Temperature Battery Cell Testing.
    3. Super-capacitor Cell Testing.
    4. Hybrid Testing.
    5. Environmental Testing.

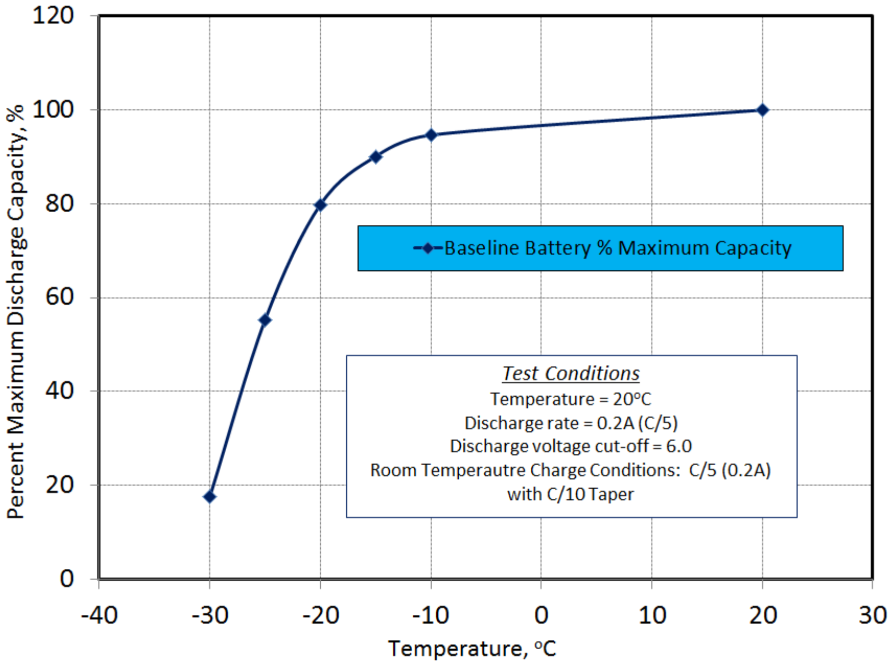
Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Baseline Li-ion Battery Performance

Lithium-ion Polymer Cells





- Sharp decrease in usable capacity below -15°C.
- Less than 20% capacity retention at -30°C.

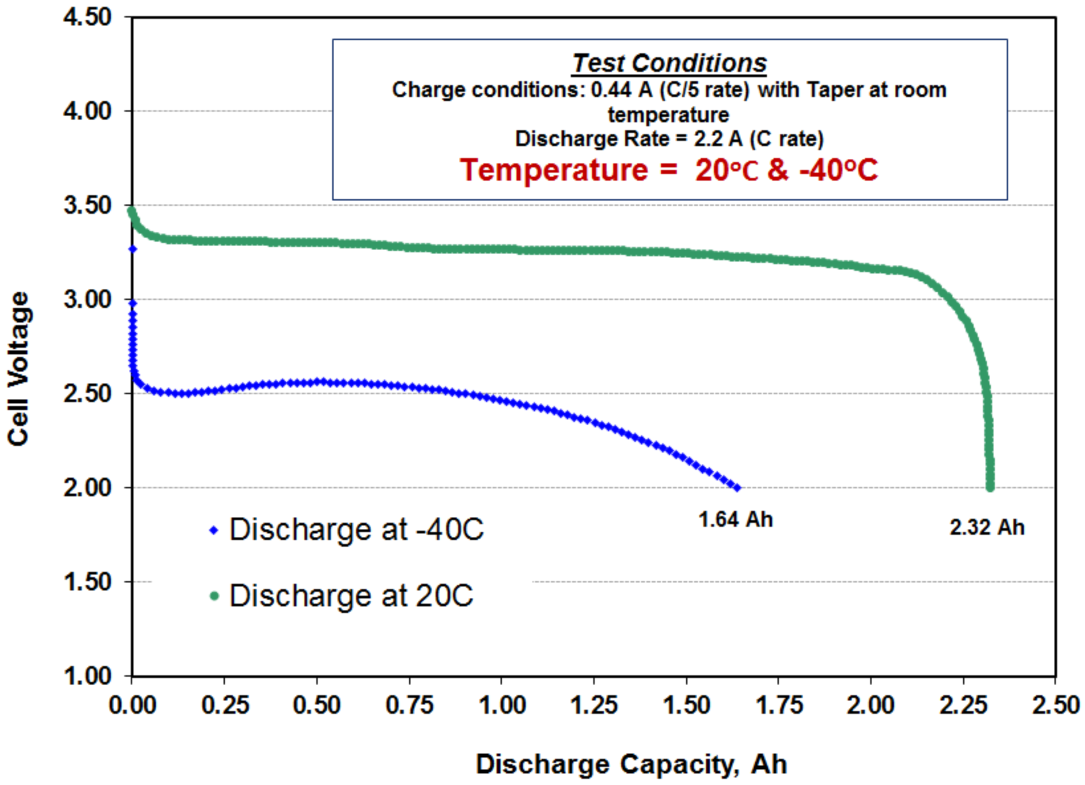
Jet Propulsion Laboratory
California Institute of Technology

Low Temperature Electrolyte Li-ion Cell

Navitas/A123 Li-Ion Cell ($LiFePO_4$)

JPL Electrolyte: 1.20M $LiPF_6$ in EC+EMC+MB (20:20:60 vol %) + 2% VC

California State University Northridge



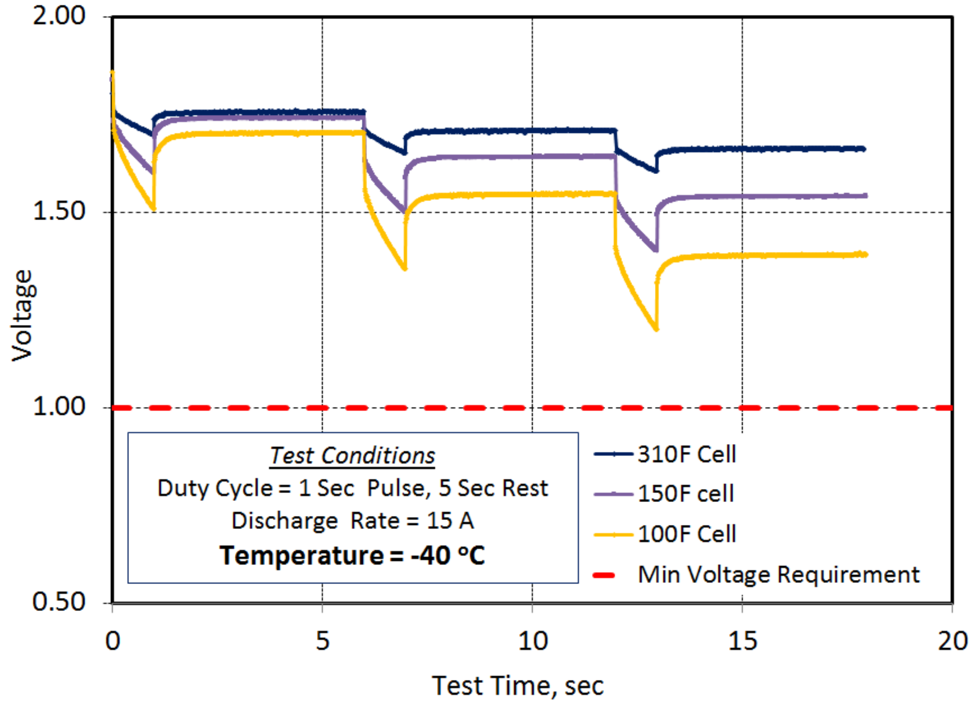
Greater than 2x capacity in 26650-size cell (70 gm).

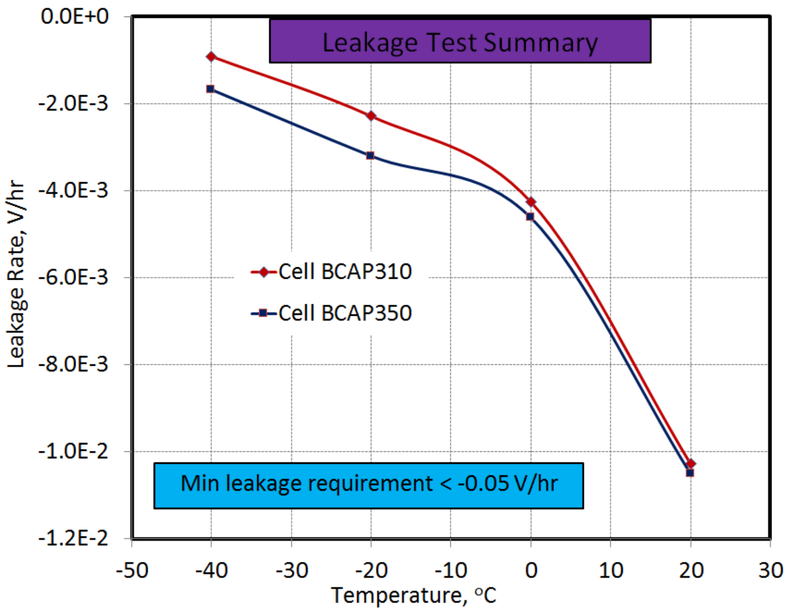
Greater than 70% of maximum capacity retention at -40°C.

Reference: M. C. Smart, B. V. Ratnakumar, K. B. Chin, L. D. Whitcanack, and S. Surampudi, "Performance Characteristics of Lithium-Ion Technology Under Extreme Environmental Conditions," *1st International Energy Conversion Engineering Conference, IECEC*, Portsmouth, VA, Aug. 17–21 2003.

Super-capacitor Cell Test Performance

Maxwell Technologies – 100 to 310F Boostcaps



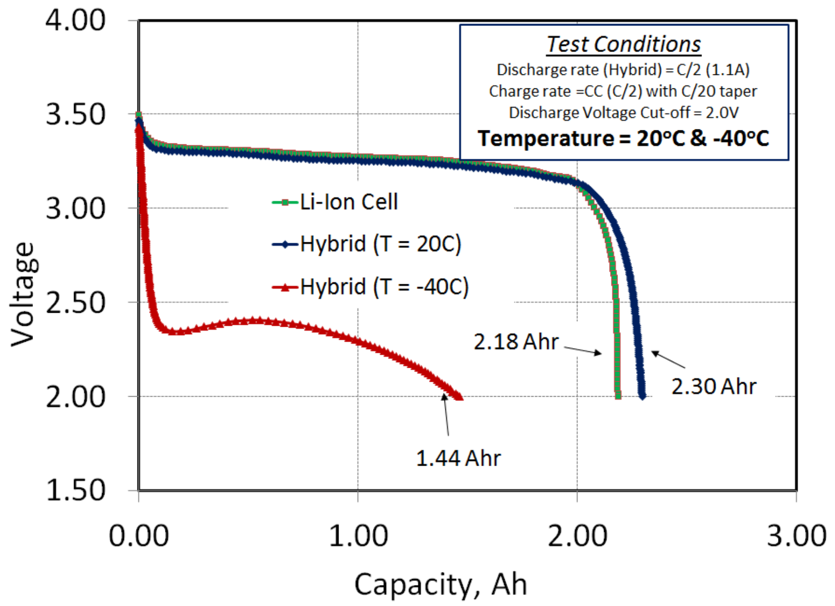


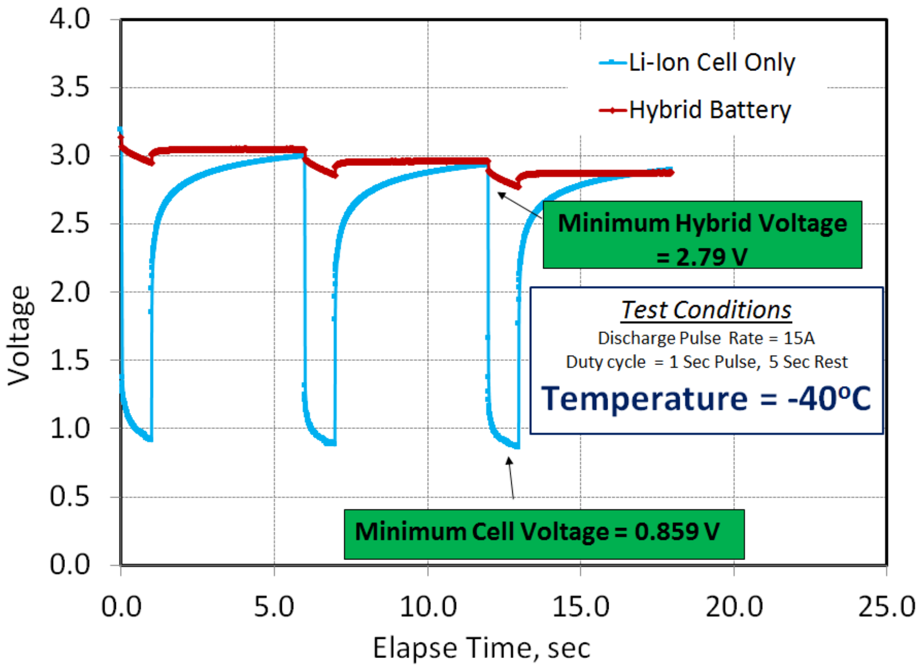
Super-capacitors greater than 100F will support worst-case 15A pulse loads down to -40°C.

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Hybrid Performance





- Excellent capacity retention at -40°C.
- Poor energy enhancement (<10%).

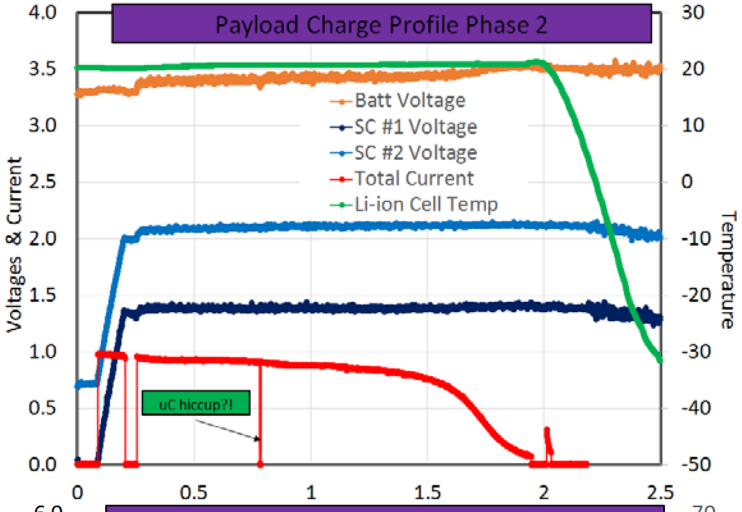
- Substantial power improvements at low temperatures down to -40°C.
- Voltage drop improved by ~2.0V at 15A pulse when compared against low temperature Li-ion cell.

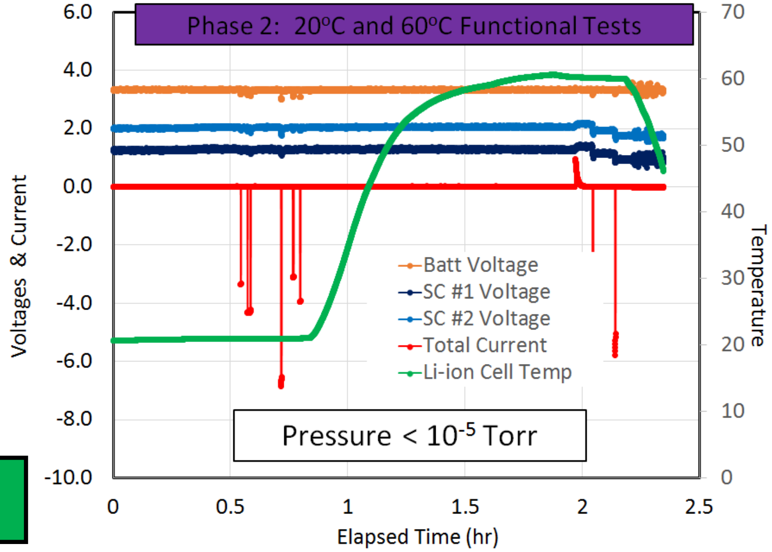
Jet Propulsion Laboratory
California Institute of Technology

JPL Environmental Testing

Pressure < 10^{-5} torr

California State University Northridge





- No mass loss, no cell rupture under vacuum!

In Flight Sequences

22

Concept of Operations: Overview

Storage | Launch

↓

Spacecraft Checkout

↓

Payload Checkout: 1 temperature cycle

↓

Primary Experiment		
Nominal Temp	Intermediate Temp	Cold Temp
Battery, SuperCap and Hybrid Characterization		

↓

Extended Mission

Payload functions as energy storage for CubeSat

23

10.2.4 Phase IV: Payload Checkout (nominal temperature)

- Payload battery capacity check.
  - Conduct at least 1 full charge/discharge cycle on the payload battery using on-board CC/CV charge algorithm followed by C/10 (or similar) discharge down to 2.0V.
- Payload Super-capacitor functional check (if possible).
  - Conduct at least 1 full charge/discharge cycle on the Super-capacitor bank using on-board CC/CV charge algorithm followed discharge (max-rate) down to 2.0V.
- Full payload functional check
  - Ensure Super-capacitor voltage “matches” (+/- 0.2) the payload battery voltage.
  - Connect both battery and Super-capacitor payloads to the power bus
  - Monitor all cell voltages and permit voltages to equilibrate to ~2.0V.
  - Conduct at least 1 full charge/discharge cycle on the hybrid energy system using on-board CC/CV charge algorithm (max-rate) followed discharge (any rate) down to 2.0V.
- Success Criteria:
  - Both battery and Super-capacitor functional.
  - Hybrid system is functional.
  - Capacity loss on the battery is < 10%.

10.2.5 Phase V & VI: Payload Experimentation - Nominal Temp. (T > 0C)

- Test 1: Payload battery characterization at 100% SOC
  - Step 1: CC/CV charge at max-rate up to 3.7V with taper down to C/50.
  - Step 2: At 100% SOC, three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Test 2: Payload battery characterization at 50% SOC
  - Step 1: CC charge up to 100% SOC based on charge duration.
  - Step 1a: Discharge to 50% SOC
  - Step 2: Three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Test 3: Payload hybrid characterization at 100% SOC
  - Step 1: CC/CV charge at max-rate up to 3.7V with taper down to C/50.
  - Step 2: At 100% SOC, three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Test 4: Payload hybrid characterization at 50% SOC
  - Step 1: CC charge up to 50% SOC based on charge duration.
  - Step 2: Three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Success Criteria:
  - All tests completed successfully.
  - Experiments "minimally" substantiates improved performance (e.g., lower polarization and/or impedance) by hybrid system over stand-alone battery.

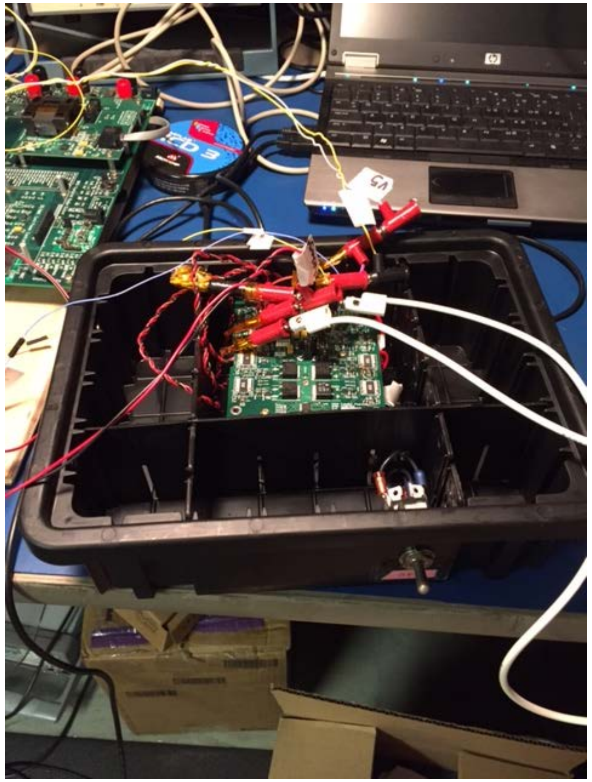
10.2.6 Phase V & VI: Payload Experimentation – As cold as possible – goal ($T = -40^oC$)

- Test 1: Payload battery characterization at 100% SOC
  - Step 1: CC/CV charge at max-rate up to 3.7V with taper down to C/50.
  - Step 2: At 100% SOC, three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Test 2: Payload battery characterization at 50% SOC
  - Step 1: CC charge up to 100% SOC based on charge duration.
  - Step 1a: Discharge to 50% SOC
  - Step 2: Three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Test 3: Payload hybrid characterization at 100% SOC
  - Step 1: CC/CV charge at max-rate up to 3.7V with taper down to C/50.
  - Step 2: At 100% SOC, three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Test 4: Payload hybrid characterization at 50% SOC
  - Step 1: CC charge up to 50% SOC based on charge duration.
  - Step 2: Three 1-sec discharge pulse cycles (1 min rest between each cycle) at 15A.
  - Repeat steps 1 & 2 for 5-sec discharge pulse rates 10A.
  - Repeat steps 1 & 2 for 10-sec discharge pulse rates 5A.
- Success Criteria:
  - All tests completed successfully.
  - Experiments "significantly" substantiates improved performance (e.g., lower polarization and/or impedance) by hybrid system over stand-alone battery.

10.2.8 Phase VII: Extended mission (Optional) – Life testing of battery hybrid

- Test 1 – Life testing of battery hybrid
  - Step 1: Connect hybrid system to main S/C power bus.
  - Step 2: Perform eclipse cycling of the hybrid system (nominal S/C rates).
  - Step 3: Perform intermittent high pulse discharges (three cycles 1-sec 15A) of the hybrid battery over variable temperature range.
  - Step 4: Repeat 2 & 3
- Success Criteria:
  - Demonstrate life and high power capabilities over 200 eclipse cycles.

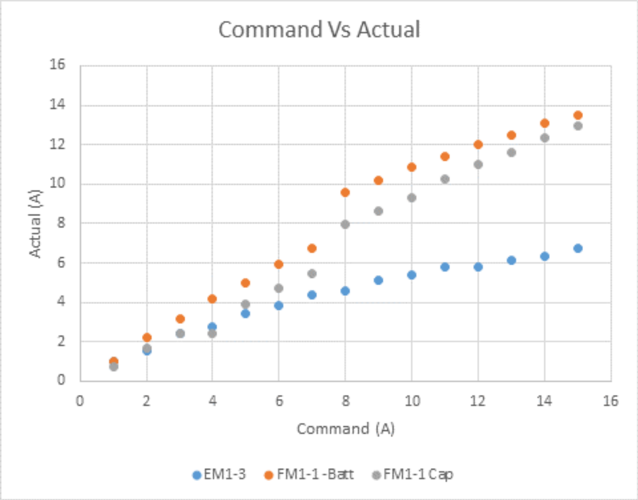
Flight Payload Testing - Successful



Payload FM Integrated Testing

Case E - 14A pulse

CH0 - PL_BATT_TLM is 1.48743 volts - Actual is 2.95958 volts
CH1 - PL_BATT_CURR_TLM is 0.69763 volts - Actual is **-6.96005** amps
CH2 - PL_BATT_TEMP is 0.33875 volts - Actual is 19.60039 C
CH3 - SUPERCAP_1_TLM is 1.50574 volts - Actual is 2.98971 volts
CH4 - SUPERCAP_2_TLM is 0.59265 volts - Actual is 1.10180 volts
CH5 - SUPERCAP_CURR_TLM is 0.62927 volts - Actual is **-7.87281** amps
CH6 - CHARGE_CURR_TLM is 0.00000 volts - Actual is -0.00260 amps
CH7 - LOAD_CURR_TLM is 2.07458 volts - Actual is **14.85834** amps



Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Conclusions

- JPL Hybrid energy storage system exhibited excellent energy storage (>2x) and power (8C-rate) capabilities down to -40oC.
  - Capacity retention >70%.
  - Capacity retention for baseline battery < 20%.
  - Supports >15A pulse current down to -40oC.
  - COTS cell design is functional in space environment.
- Future work
  - Integrate payload to CSUNSat1.
  - Conduct experiments in the space environment.

29

NASA Acknowledgement

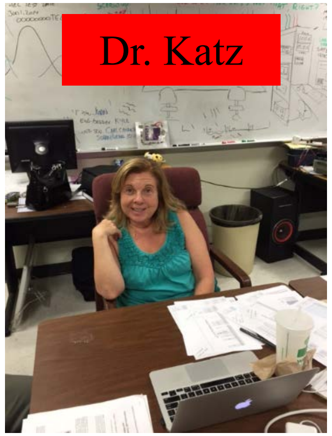
The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA) and supported by the NASA STMD 2013 SmallSat Technology Partnerships Cooperative Agreement Notice.

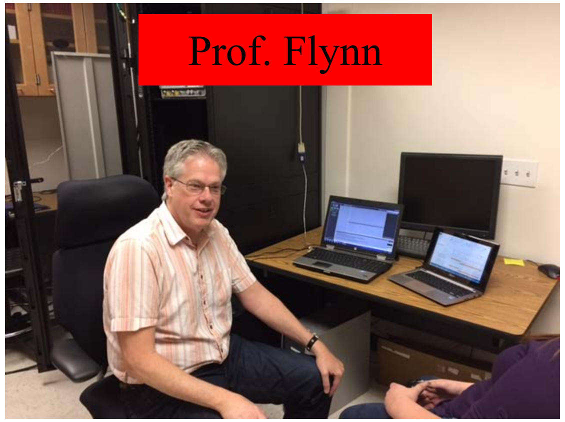
30

Jet Propulsion Laboratory
California Institute of Technology

CSUN Acknowledgement

California State University Northridge





Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

JPL Acknowledgement

- Naomi Palmer - Team Leader/Manager
- Keith Chin – Energy Storage Lead
- JPL Energy Storage Team
  - Marshall Smart
  - Erik Brandon
  - Keith Chin

32

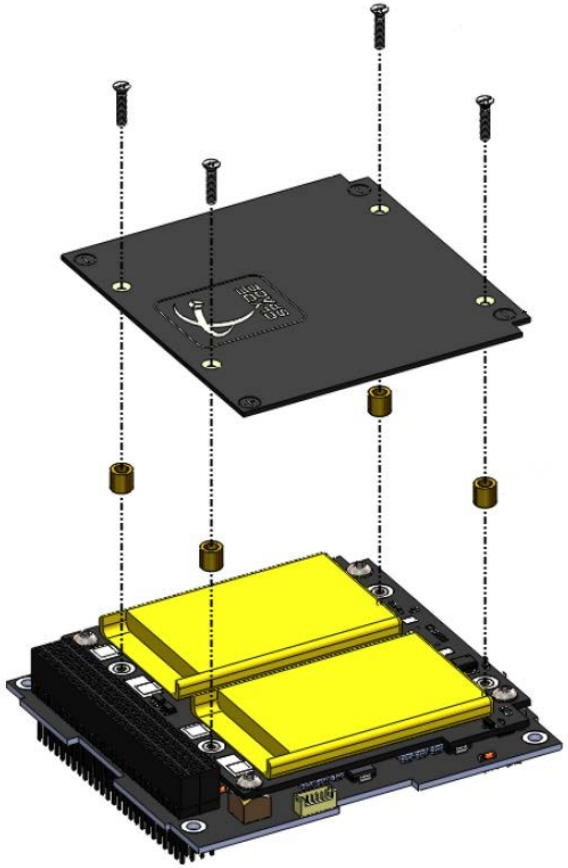
Backup slides

33

Jet Propulsion Laboratory
California Institute of Technology

California State University Northridge

Baseline 10 Ahr CubeSat Battery



Physical Parameters	Value
Total Mass (gm)	125.0
Width (cm)	9.0
Length (cm)	9.5
Thickness (cm)	2.0

34