Lithium-ion Battery Demonstration for the 2007 NASA Desert Research and Technology Studies (Desert RATS) Program

The NASA Glenn Research Center (GRC) Electrochemistry Branch designed and produced five lithium-ion battery packs for demonstration in a portable life support system (PLSS) on spacesuit simulators. The experimental batteries incorporated advanced, NASA-developed electrolytes and included internal protection against over-current, over-discharge and over-temperature. The 500-gram batteries were designed to deliver a constant power of 38 watts over 103 minutes of discharge time (130 Wh/kg). Battery design details are described and field and laboratory test results are summarized.

Li-ion Battery Demonstration for the 2007 NASA Desert Research and Technology Studies Program

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Battery Demonstration Overview

DEMONSTRATION OBJECTIVE:

- **Demonstrate performance of a lithium-ion battery with ETDP-developed NASA electrolyte.**
- **Support field trials with the Desert Research and Technology Studies (D-RATS) EVA cryopac**
- **Complement field test data with laboratory testing under controlled-environment conditions.**

2007 HIGH-LEVEL SCHEDULE:

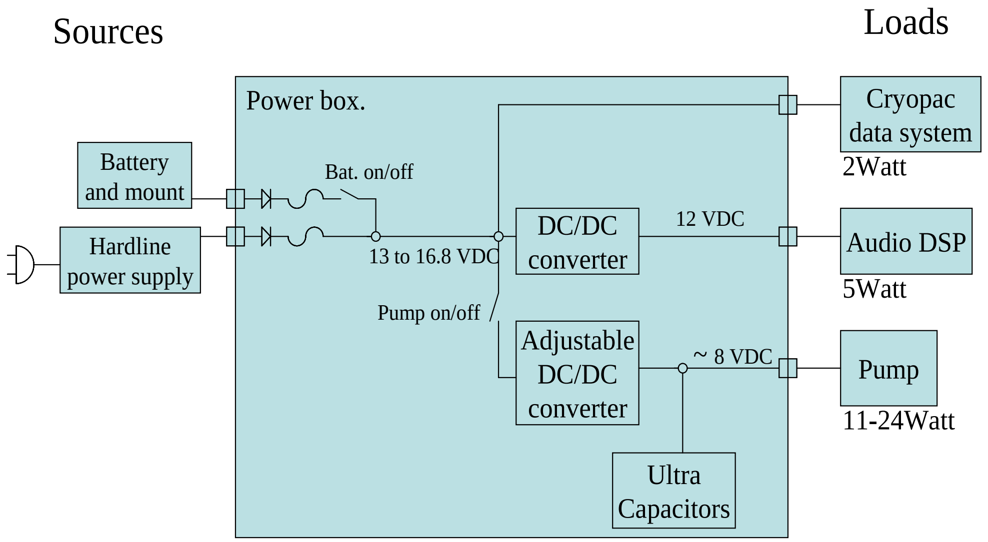
- **Fabrication/qualification testing - May → late-August**
- **Internal GRC Concepts and Safety Review – July 17**
- **JSC Readiness Review – August 8**
- **"Dry Run" at JSC – August 13-17**
- **Final Safety & Readiness Review – August 21**
- **Desert RATS field demonstrations – September 10-14**

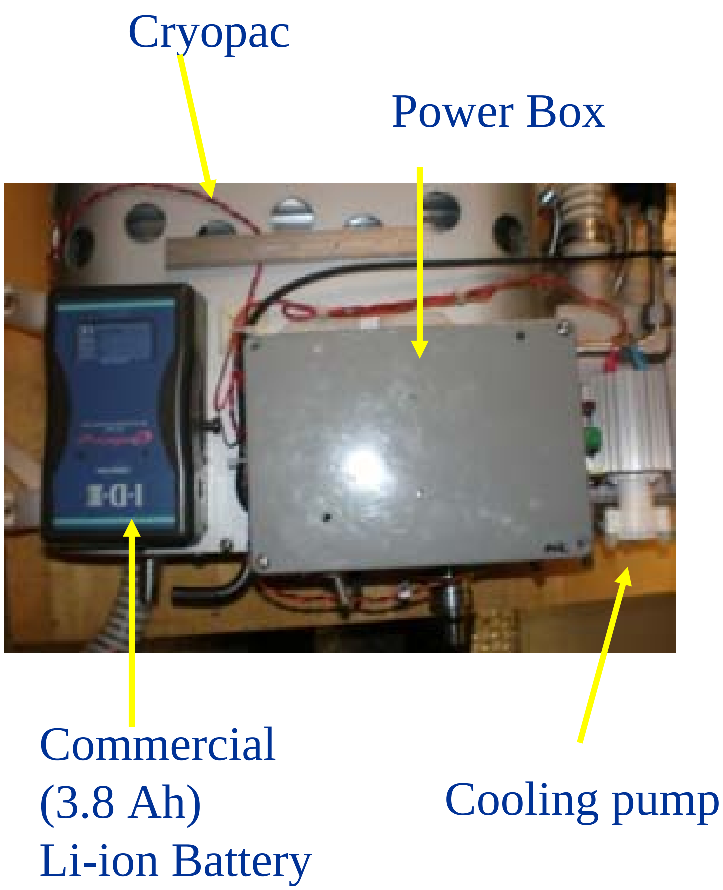
Develop/build 5 working prototypes in 4 months

D-RATS Cryopac Power System

Power System for the MarkIII/I-suit D-RATS Cryopac

- Block Diagram





<u>Required battery output</u>:
22 to 38 W
13 to 16.8 V
2.5 hour run time at 22 W

2006 D-RATS Commercial Battery

Endura "E-50S" Lithium-Ion 14.4V/3.8Ah

- commercial Li-ion video-camera battery
- ~2 hour run time in D-RATS Cryopac
- Quick, easy swap out with commercial V-mount plate
- Dimensions: 86mm (W) x 142mm (L) x 33mm (D).
- Weight: 520g (1.16 lbs.)
- 105 Wh/kg

2007 NASA D-RATS Battery

Experimental NASA-Electrolyte Li-Ion 14.4V/4.5Ah

- four Quallion 4.5 Ah CERDEC pouch cells
- IDX adapter compatible with existing mount
- Dimensions: 76mm (W) x 150mm (L) x 39mm (D).
- Weight: 500g
- 130 Wh/kg

Physically interchangeable with Endura battery

Battery Pouch Cell

VENDOR: Quallion, LLC, Sylmar, CA

The Quallion prismatic pouch cell (part no. QL4500A) was developed for U.S. Army CERDEC under the "Ultra Safe High Energy Density Rechargeable Soldier Battery" Program (Contract No. W15P7T-05-C-P212) to address needs for soldier systems and equipment applications

- **Alternative cathode material with optimized particle size / enhanced safety**
- **Optimized CERDEC cell fabrication processes**
- **200 Wh/kg**

4.5 Ah CELL CHEMISTRY:

Positive Electrode: $LiNiCoMnO_2$

Negative Electrode: Graphite

Electrolytes:

- **Quallion Standard (baseline): $LiPF_6$ in EC/DEC/EMC (all carbonate)**
- **NASA JPL-2: $LiPF_6$ in EC/DEC/DMC/EMC (all carbonate)**
- **NASA JPL-5: $LiPF_6$ in EC/EMC/MP (methyl propionate co-solvent)**

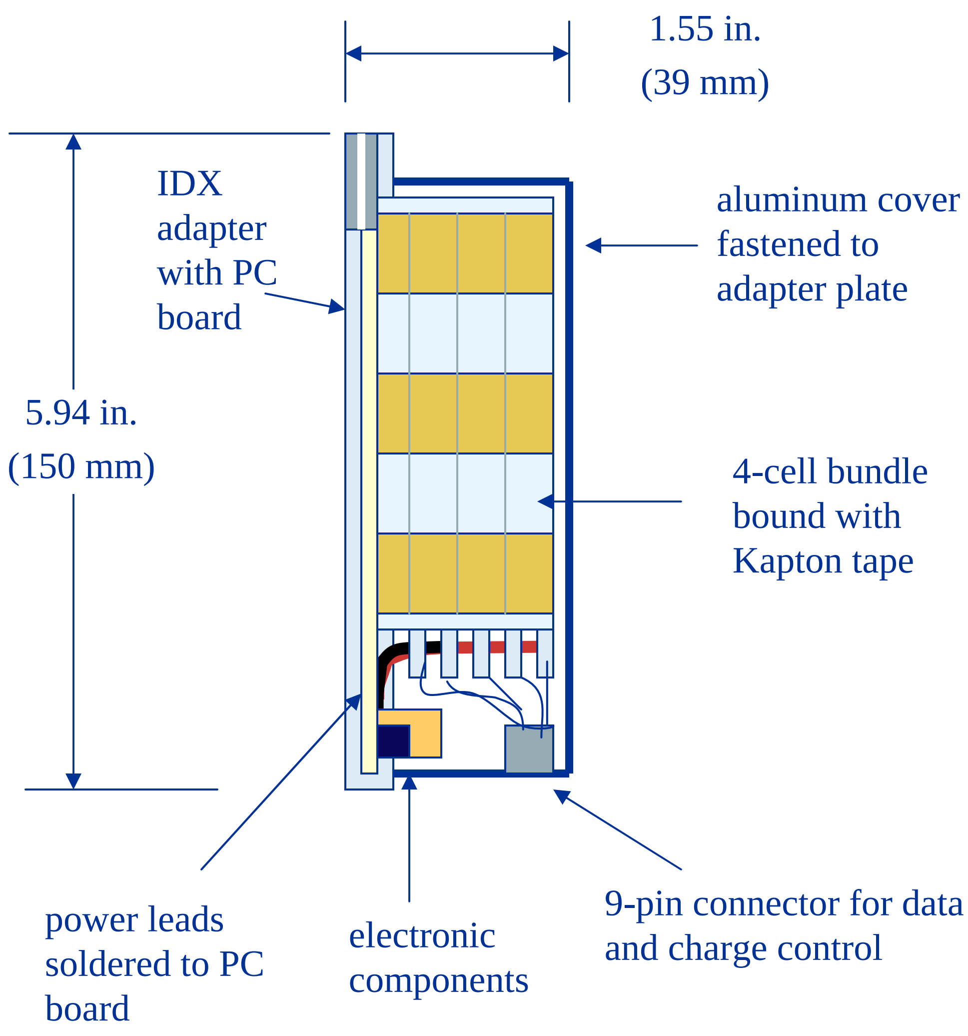
Tight Ah capacity distribution from Quallion acceptance tests on all delivered battery cells

The NASA electrolytes were developed by JPL under the current NASA Exploration Technology Development Program (ETDP) for optimized low-temperature performance

- **Electrolyte blends formulated / purified at JPL**
- **Previously incorporated in other prototype industrial cell designs**

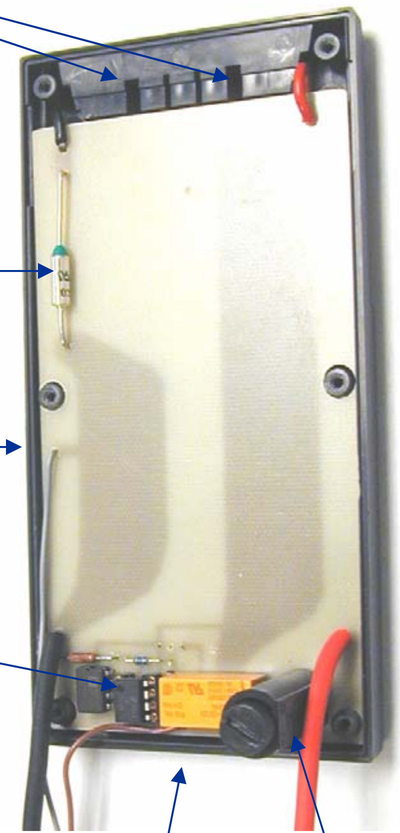
Assembly Concept for Desert RATS Battery

- 4-cell package prepared by Quallion
- modified IDX adapter
- printed circuit board
  - over-discharge control
  - fuse
  - thermal fuse
- aluminum cover
- cells immobilized with heat transfer agents



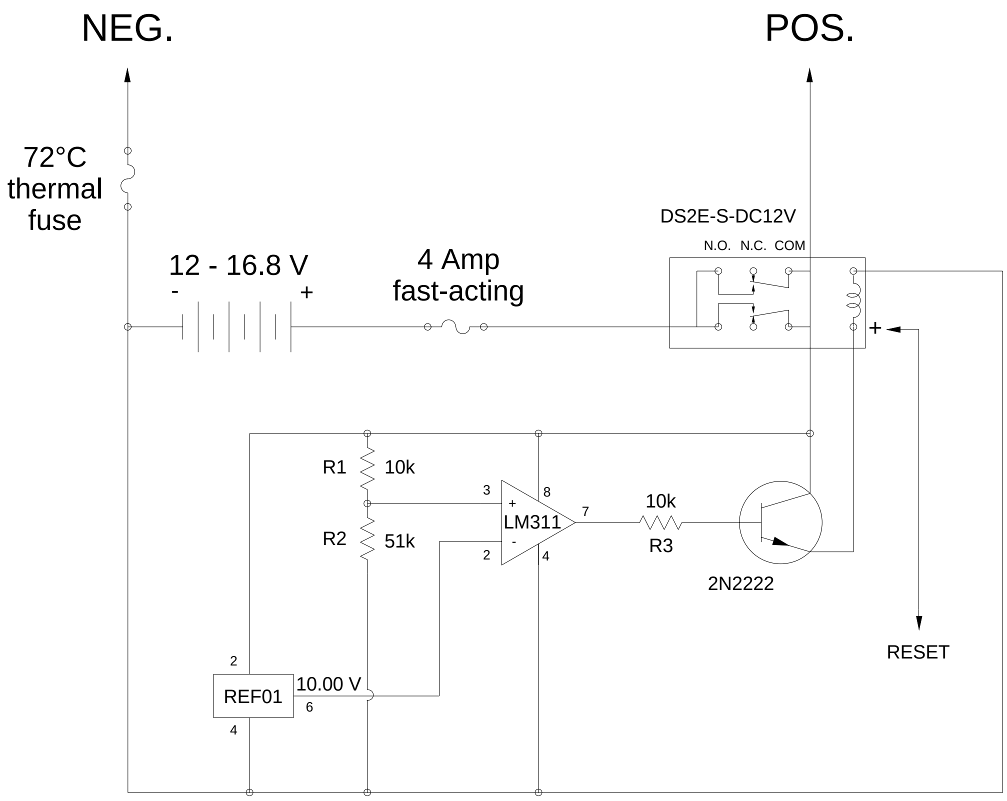
IDX Adapter with PC Board

- Printed circuit includes fuse, thermal fuse and over-discharge protection
- Wide traces carry current from battery terminals to adapter power pins
- Negative current trace serves as current-measuring shunt



Over-Discharge Protection Circuit

- Comparator monitors battery voltage
- Protection circuit turns relay off at <12V
- Requires external reset



Safety Considerations

over charge

- voltage monitor
- temperature monitor
- individual cell voltage control
- manual supervision & procedures

over discharge (cell reversal)

- limited mission time (2 hr.)
- battery shut-down (<12 V)
- monitored cell balance, before and after every use

over-load (short-circuit)

- fuse (4 amp)
- battery shut-down (<12 V)
- shielded connectors

over temperature

- thermal fuse (70°C)
- battery shut-down (<12 V)
- charge temperature monitor

misconnection

- keyed V-mount adapter
- keyed connectors

mechanical abuse

- safety spotters
- encapsulated components

NASA Electrolyte/Quallion Pouch Cell Abuse Testing

	Initial Measurements				Pre-Test Measurements				Post-Test Measurements			
Cell ID	IR (mohm)	OCV (V)	Weight (g)	Capacity (Ah)	IR (mohm)	OCV (V)	Weight (g)	Safety Test	max temp. (°C)	IR (mohm)	OCV (V)	Weight (g)
JPL2-26	6.47	3.40	80.58	4.58	6.35	4.18	80.57	**Nail**	40	6.23	4.12	80.56
JPL2-28	6.66	3.40	80.04	4.57	6.56	4.18	80.04	**Nail**	43	6.35	4.09	80.04
JPL2-29	6.55	3.40	79.86	4.57	6.59	4.18	79.86	**Crush**	190	N/A	0.00	burned
JPL2-30	6.75	3.40	79.35	4.55	6.74	4.18	79.35	**Crush**	62	31.20	0.00	78.42
JPL5-01	6.05	3.39	79.43	4.59	6.00	4.18	79.43	**Nail**	54	5.41	4.01	79.44
JPL5-12	6.07	3.39	79.29	4.60	6.03	4.18	79.29	**Nail**	49	5.59	4.03	79.28
JPL5-18	6.26	3.40	79.46	4.57	5.90	4.18	79.46	**Crush**	88	61.00	0.17	77.76
JPL5-16	6.13	3.40	79.50	4.55	5.99	4.18	79.50	**Crush**	57	15.21	4.03	78.84

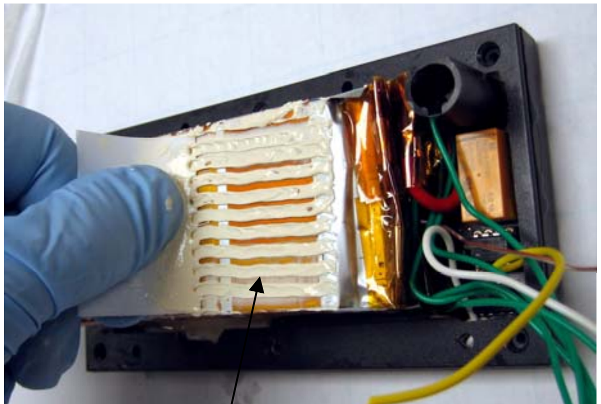
Crush test caused short-circuit and fire in one cell with NASA JPL-2 electrolyte

Significant loss of open-circuit voltage (OCV) in two other crush tests, but no incident

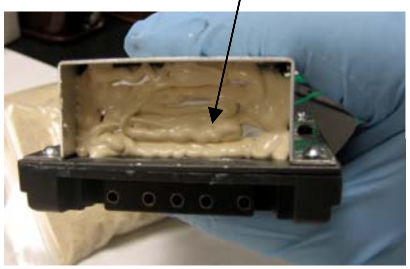
JPL2-29 before

JPL2-29 after crush

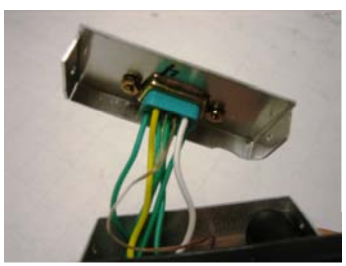
Battery Assembly

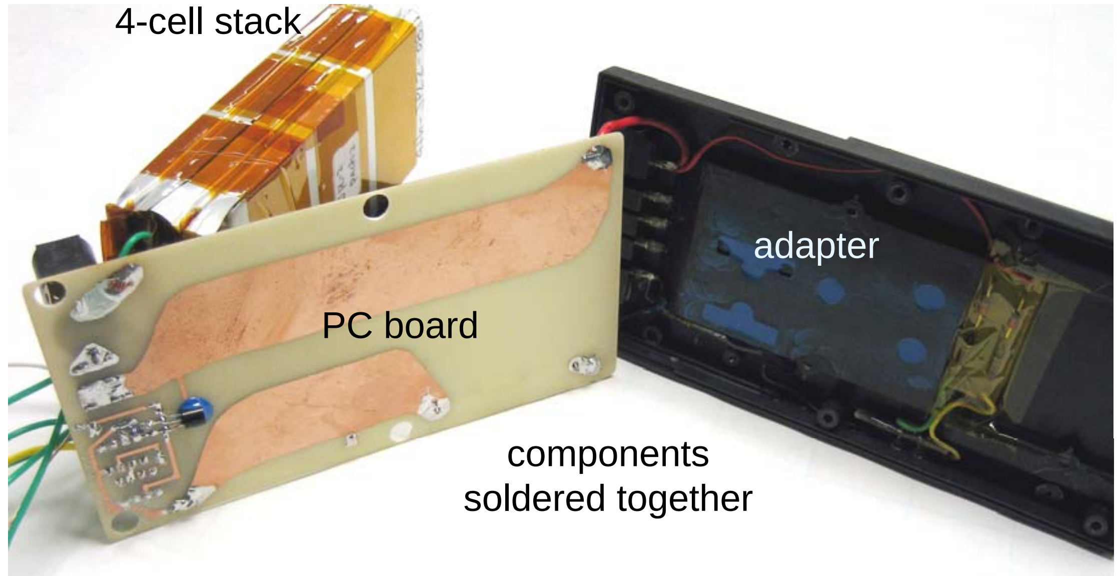


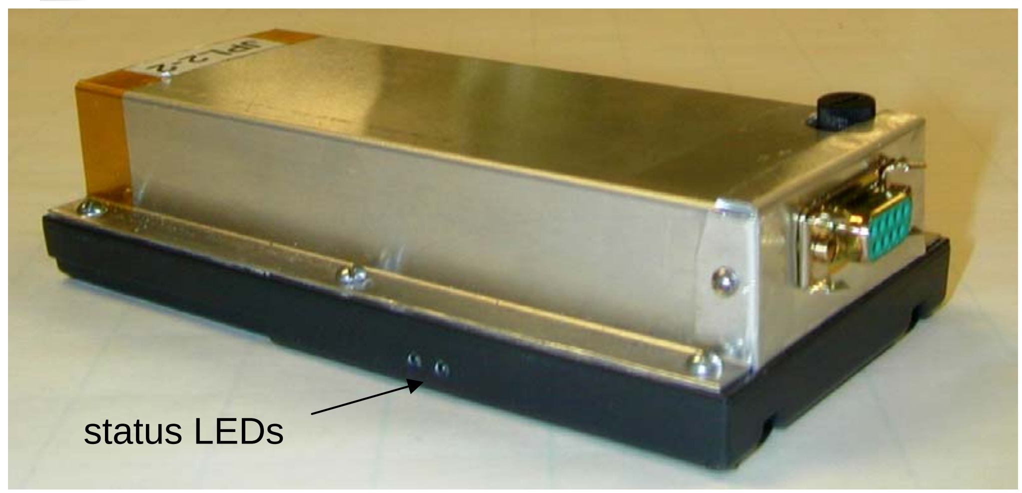
heat transfer agent



data & cell
voltage taps



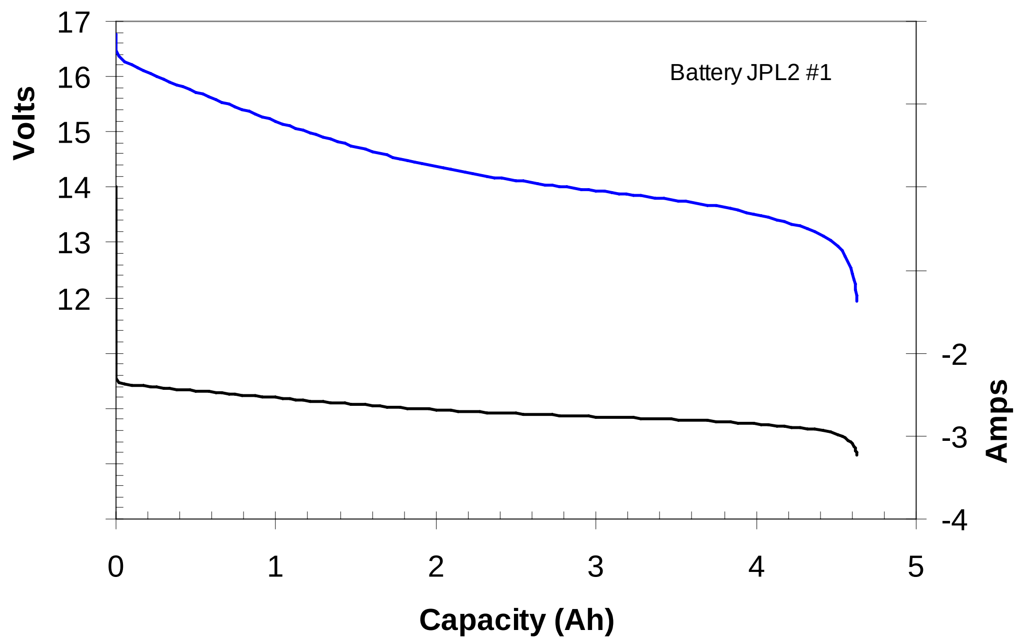


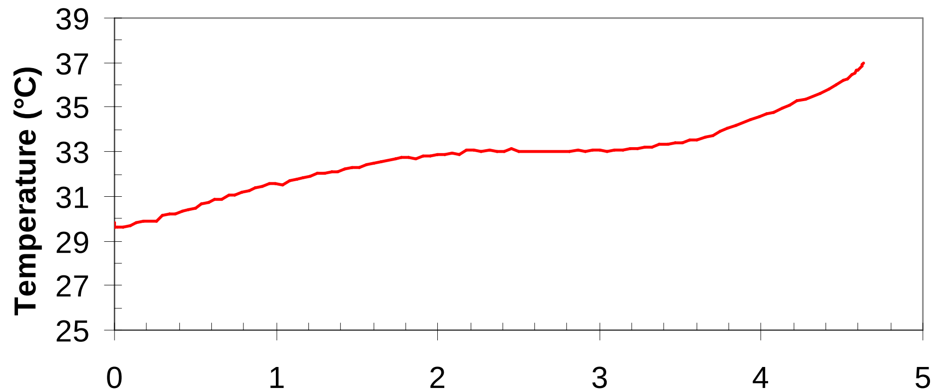


Maximum Power Pre-Ship Test

- 38 W constant power (worst-case test)
- 4.36 Ah / 1.6 hours
- shutdown circuit activates at 12.0 V
- final mid-stack temperature: 37°C

Expected capacity with acceptable temperature increase

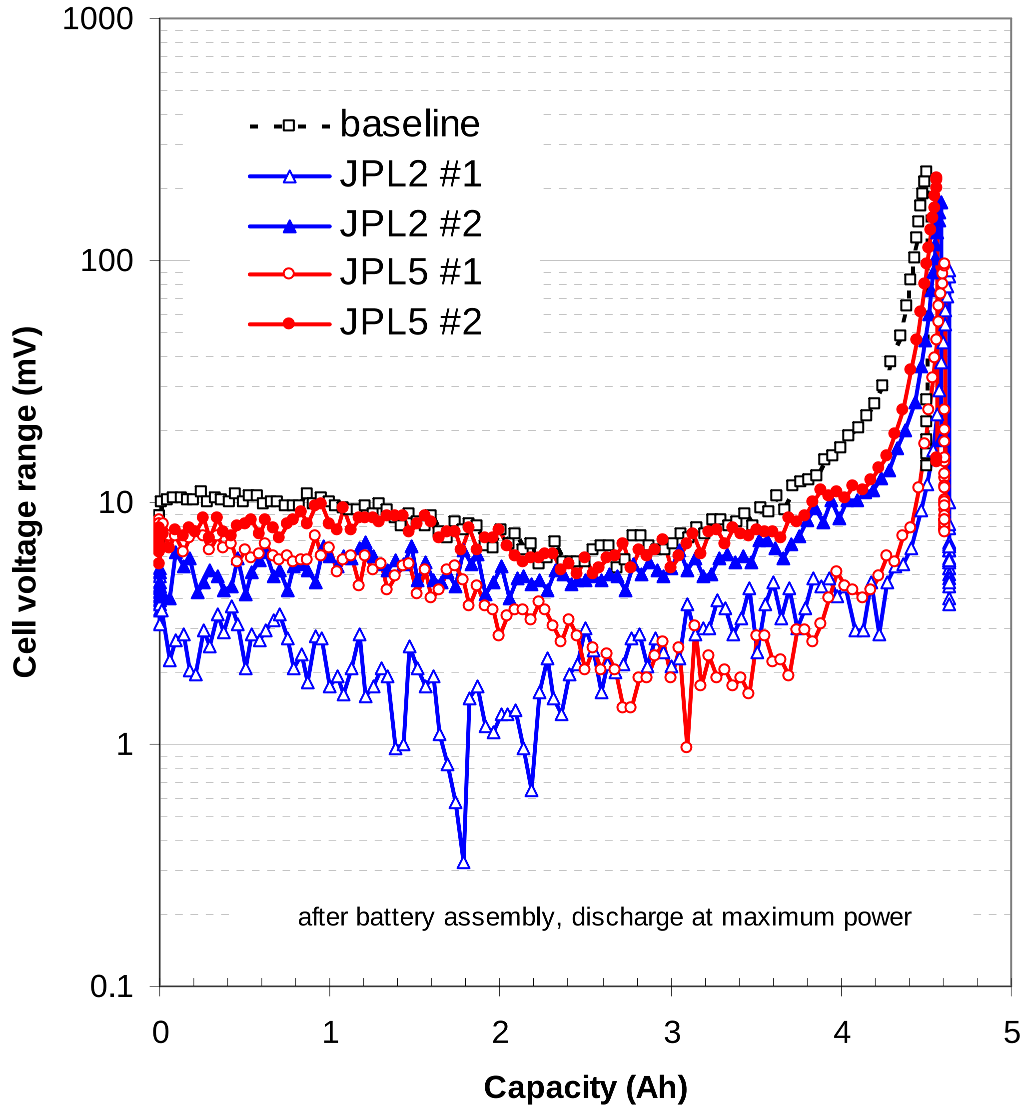




Maximum Power Pre-Ship Test

Battery cell-voltage range under discharge (max – min)

- 10 mV range
- 200 mV at end of discharge



Data Loggers

Pace Scientific XR440

- Battery volts, current & ambient temperature
- 158 grams

Omega OM-CP-TC4000

- cell core temperature & ambient temperature
- 27 grams

Dry Run Trials at JSC - August 2007

Objectives

- confirm fit & function with Cryopac
- test over-discharge circuit
- field trial with data loggers

Results

- three successful suit trials
- expected battery run-time & capacity
- over-discharge circuit activates at <12V
    - false activation at start-up in one trial
- EMI issues with data loggers

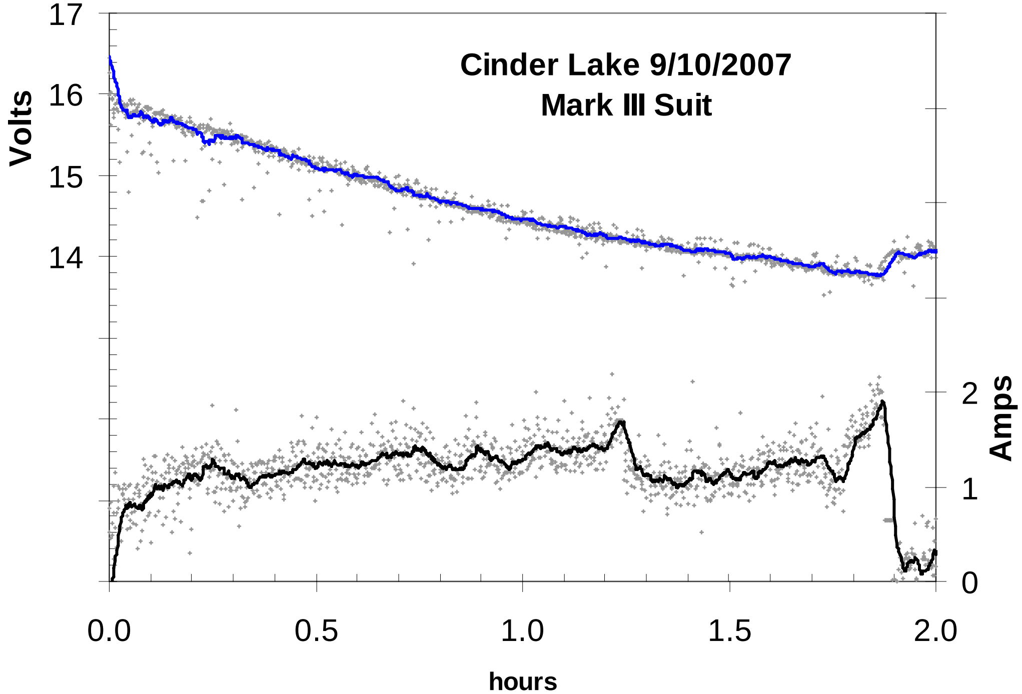
Day-2 trial at JSC “rock-pile”

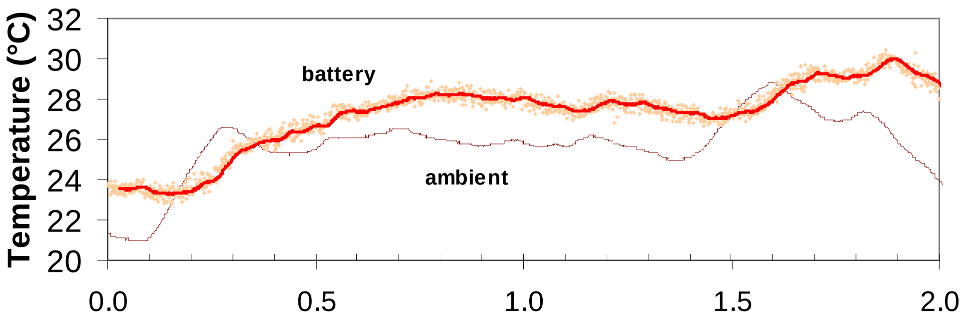
Field Trial at Cinder Lake – September 2007

Day 1 - Mark III Suit Run

- 1.9 hour run time
- 3.7 Ah delivered

logger data





Results:

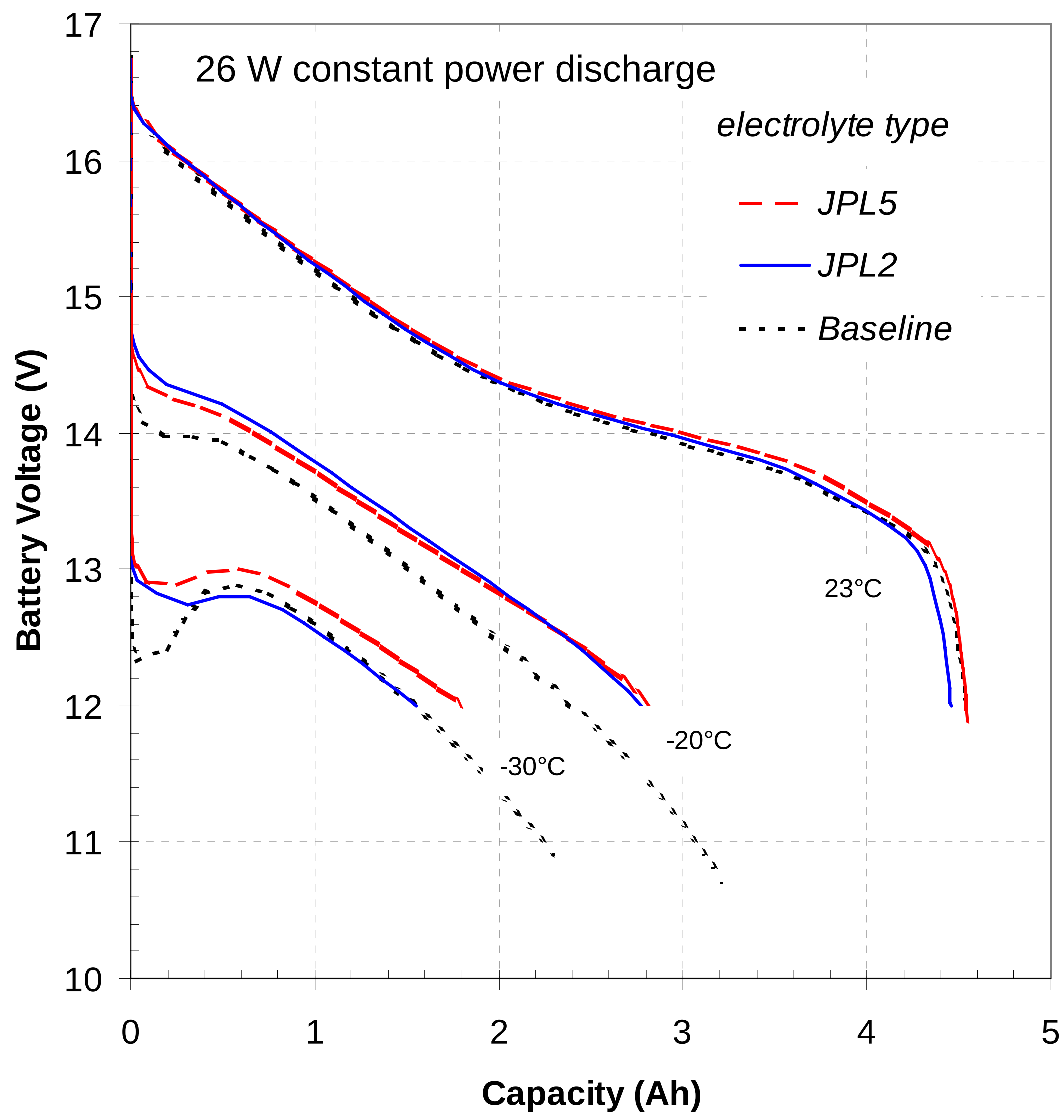
- three successful suit trials
- shielding reduced logger noise
- a fourth trial was abandoned when safety-circuit interfered with start-up (EMI?)

Laboratory Testing

Battery constant-power test

<u>Results at –30°C, 12V limit:</u>

- 40% of room temperature capacity
- ~20% improvement with JPL-5 electrolyte
- commercial battery does not function at –30°C



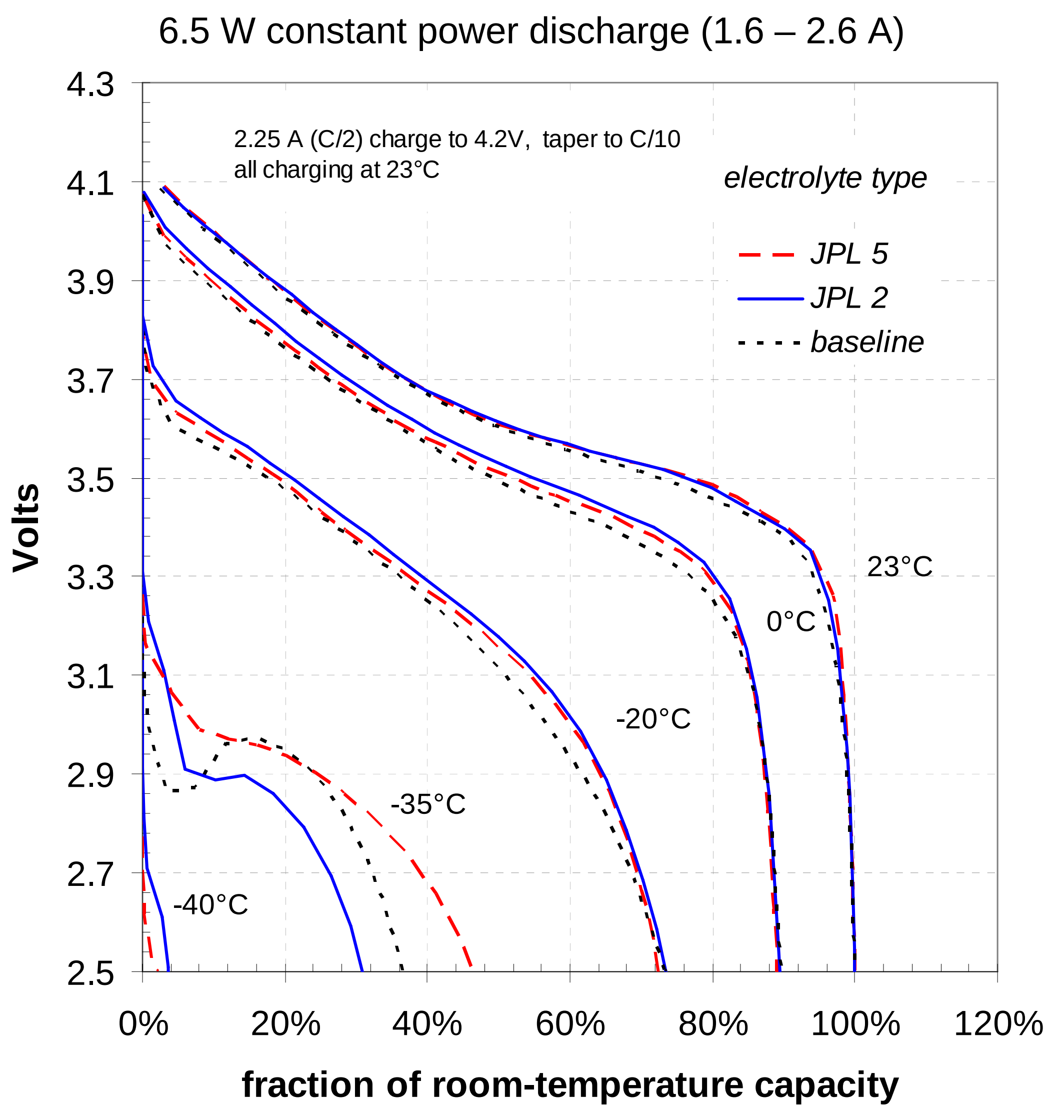
Laboratory Testing

Cell constant-power test

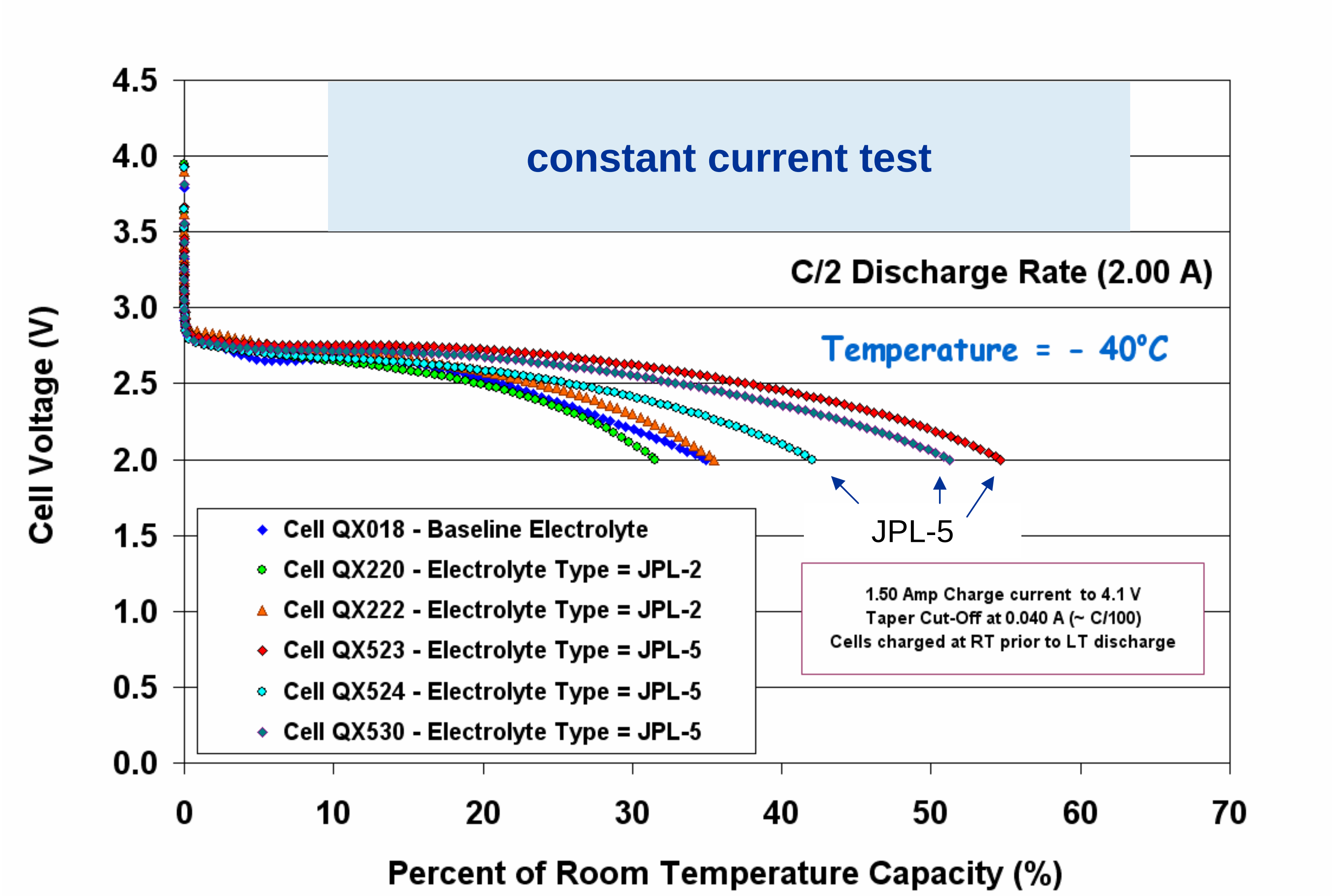
Preliminary results

- capacity improvement with JPL-5 at -35°C
- voltage recovery by self-heating benefits JPL-2 and baseline electrolyte cells
- -40°C temperature-limit under these conditions

testing at other load-profiles is under way



Laboratory Testing - JPL



data courtesy of Marshall Smart, JPL

Conclusions & Future Work

- Successful battery demonstration in six field-trials
  - expected battery capacity, temperature in limits
  - need to understand safety-circuit issues on start-up (EMI?)
  - logger data quality needs to be improved
- Good low-temperature function with all three electrolytes
- Some advantage with JPL-5 in constant-power testing
  - working to understand differences between JPL and GRC screening (load type, thermal environment etc.)

Acknowledgement

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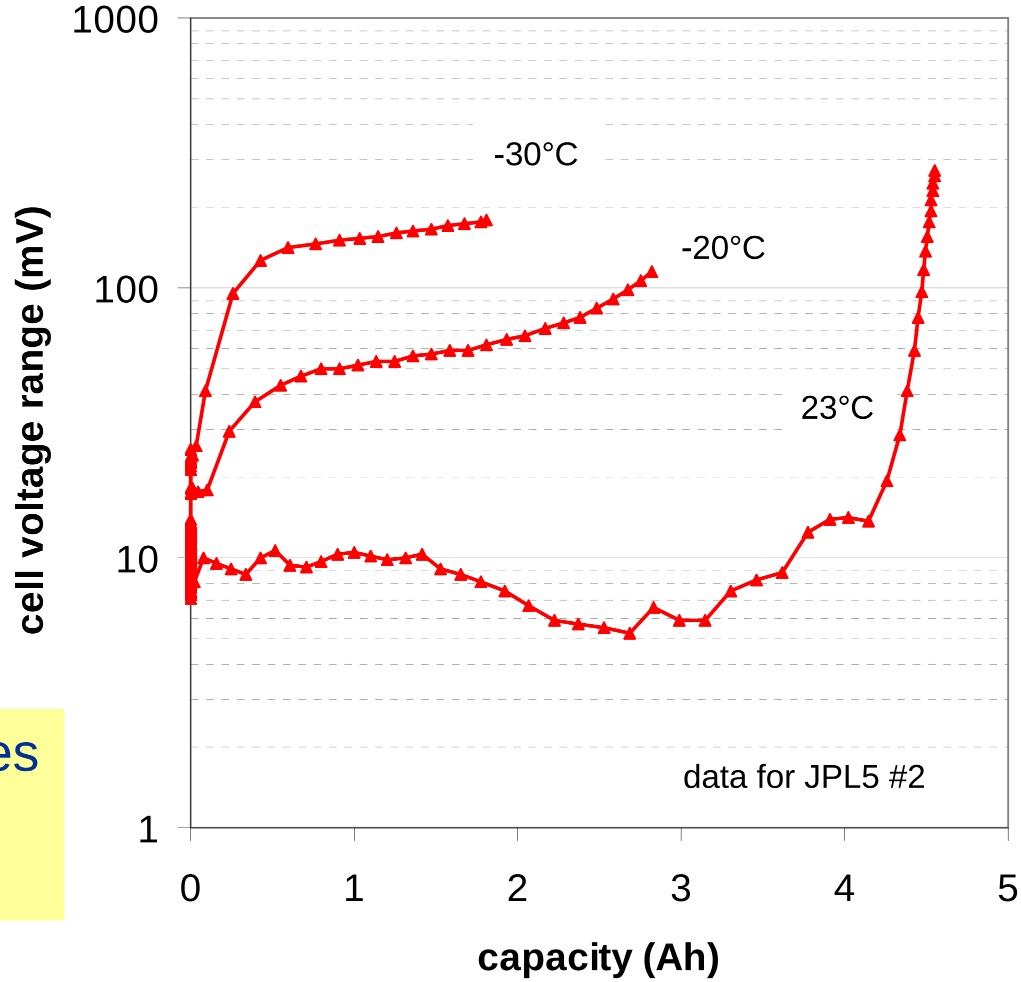
Paul Beach, Quallion

Vince Visco, Quallion

Backup Slides

Laboratory Testing

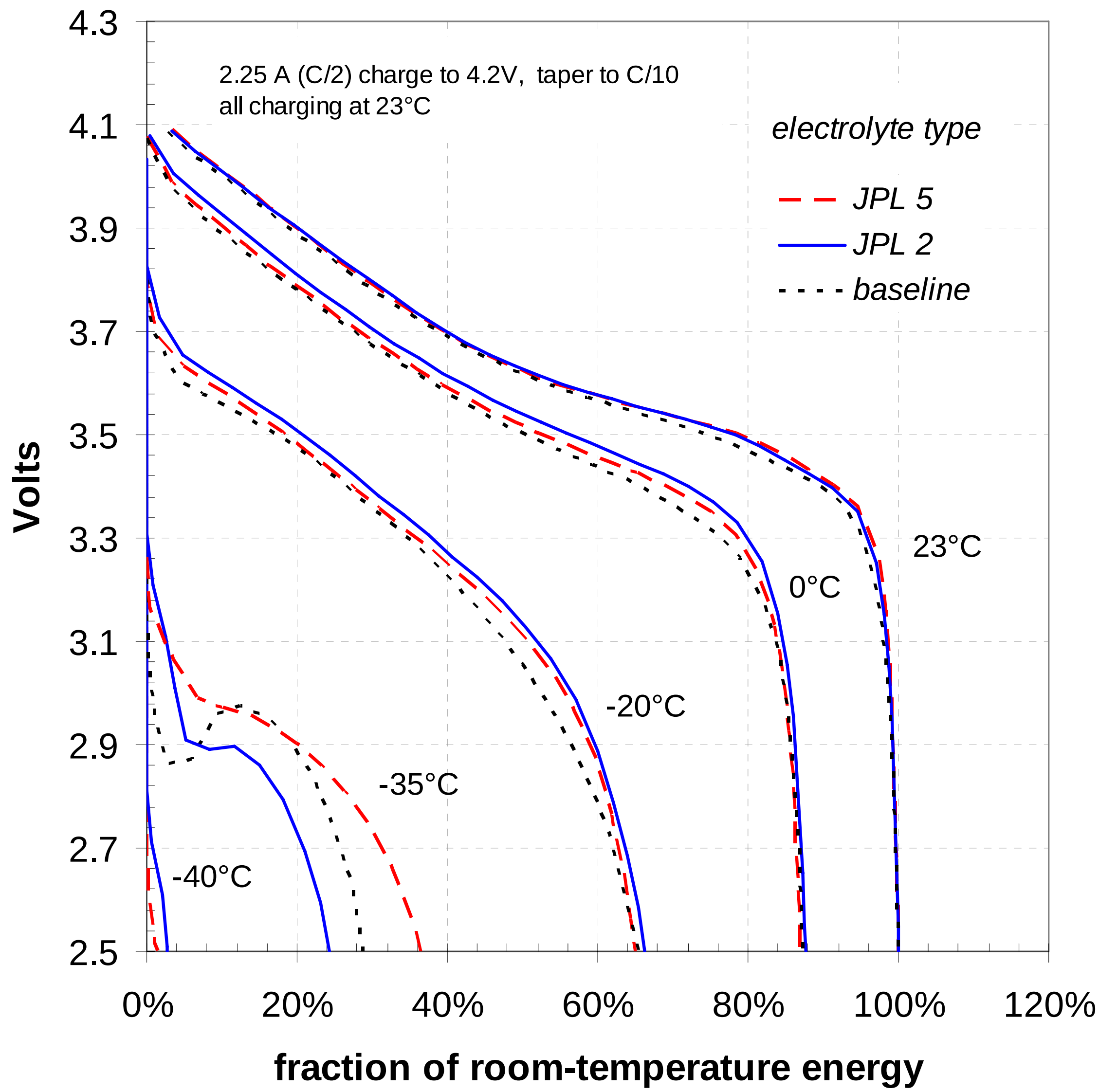
Battery cell-balance at low temperature



cell temperature gradient induces early separation of cell voltages at low temperature

Laboratory Testing

Cell energy at reduced temperature



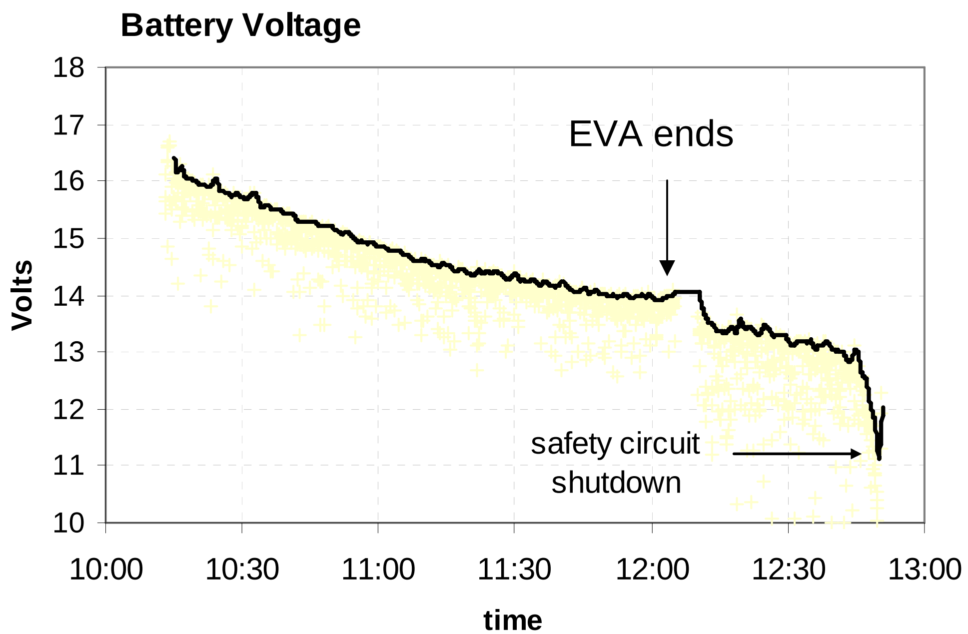
Dry Run Field-Trial Results

Day 4: Mark III suit indoor trial

•1.4-hour EVA time

•continue discharge after EVA to test over-discharge protection circuit

•2.6-hour total run time to safety circuit shutdown

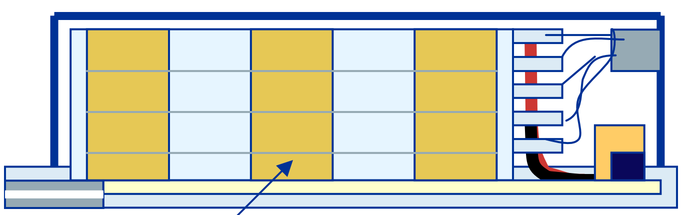


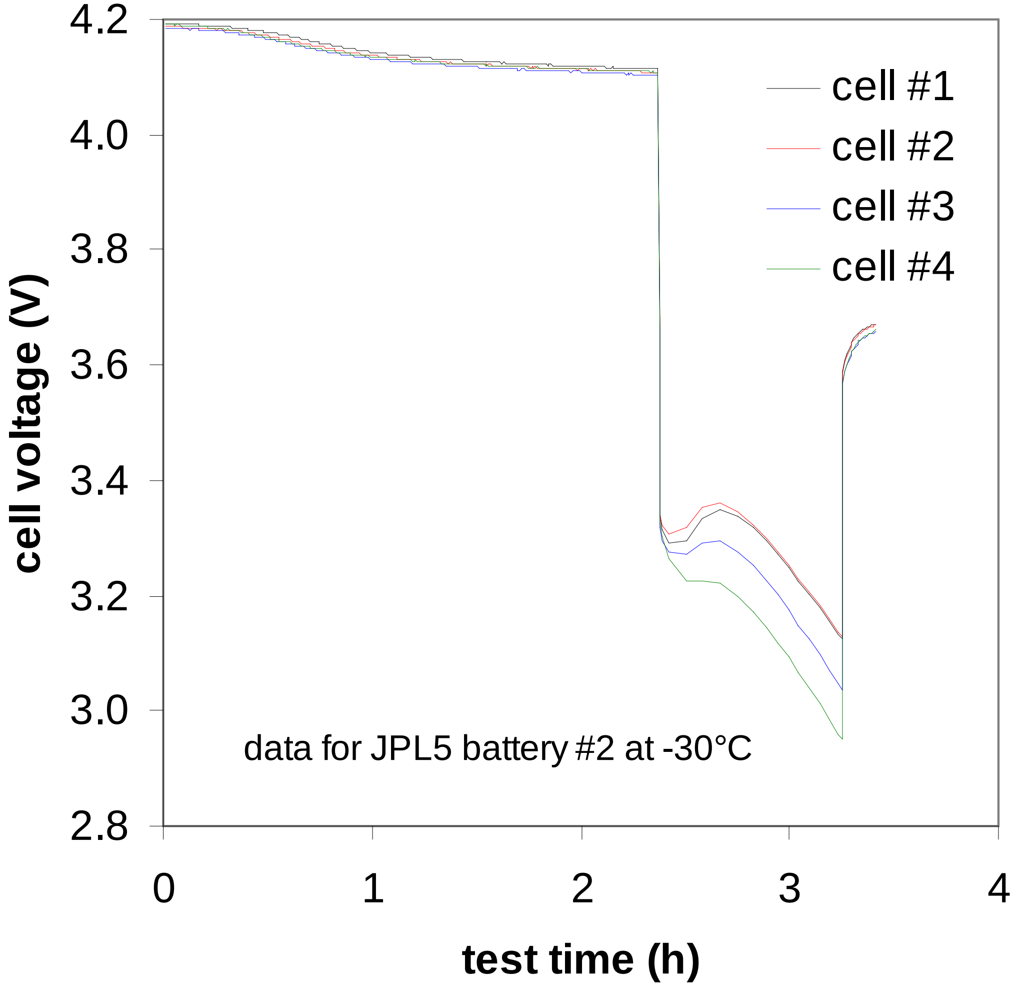
unshielded loggers are sensitive to EMI

Laboratory Testing

Battery cell voltage balance at low temperature

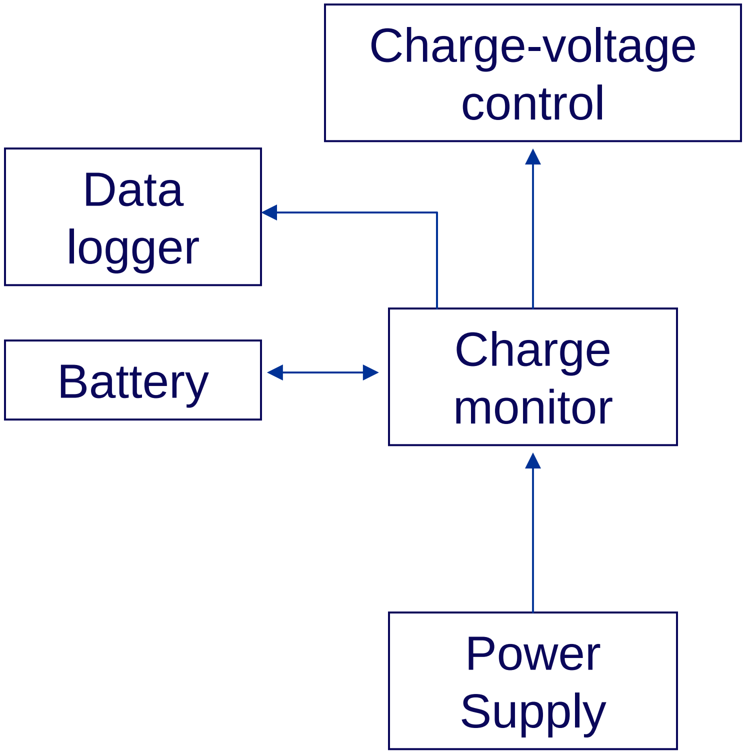
- trend in cell voltage correlates with position
- cell #1 benefits from greater self-heating





Battery Charging Elements

- power supply limits current/voltage (redundant fuse in monitor)
- battery housed in fire-proof enclosure
- keyed connections between equipment items make misconnection impossible
- charge monitor serves as redundant limiter for cell voltage control
- operator's record to monitor cell balance



Quallion Pouch Cell Abuse Testing Results

Quallion has performed extensive safety and abuse tests on this pouch cell design.

Per Quallion, no explosion, smoke or fire, indicating a thermal runaway situation, was observed during such tests

Fully-charged cell / heated to 150ºC and voltage drop to 3V after ~3 hours

Fully-charged cell / voltage drop and temperature rise recorded (an impact test deforms half of the cell's thickness)

Fully-charged cell / voltage drop and temperature rise recorded (test mimics an internal short-circuit event)

Fully-charged 7-cell stacks of Quallion pouch cells and $LiCoO_2$ pouch cells after bullet shot test

Battery Charge Monitor

- Five controllers monitor individual cell voltages and battery temperature
- Charge current supplied by 18 volt / 3 amp dc power supply
- Current to battery is interrupted if any monitored value falls out of range
- Requires operator action to reset
- Battery discharge uses 8 ohm 50 W resistor

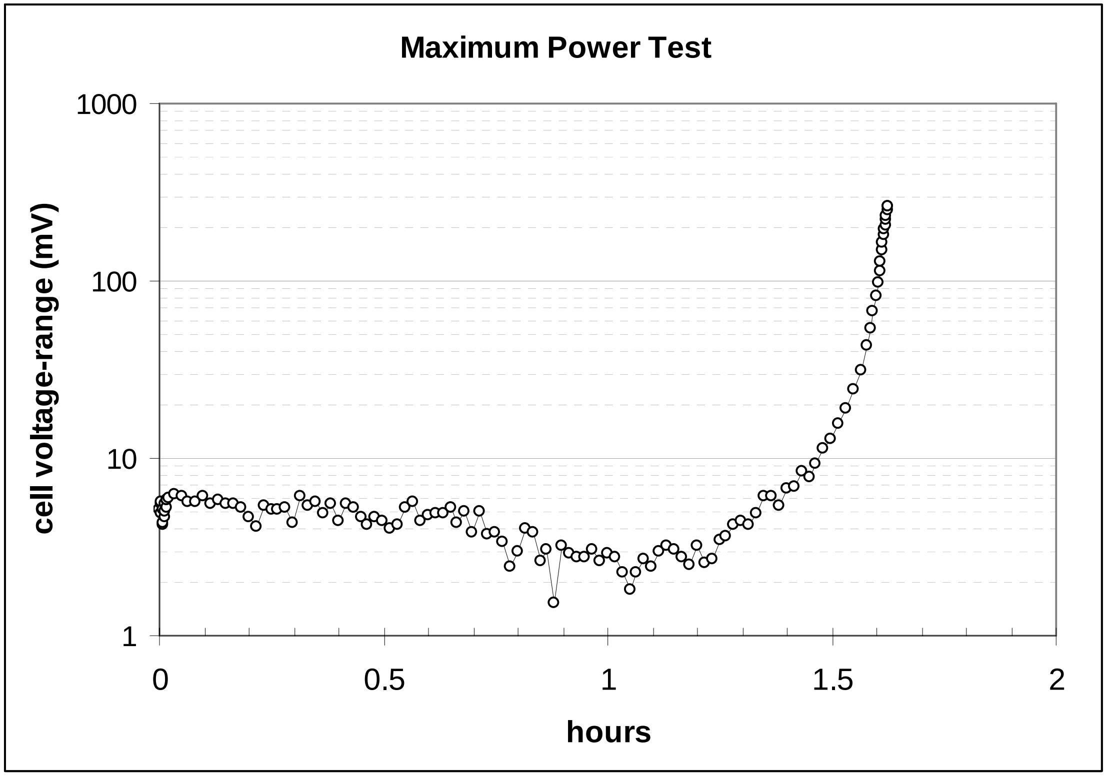
Protects battery if fault develops in the charge voltage control

Individual-Cell Charge-Voltage Control

- Automatically shunts current to limit upper cut-off voltage of individual cells
- Developed by Rob Button/GRC for Li-ion cell testing at Crane, Indiana
- Over 20 units have been operating successfully at Crane for over three years

Cell Balance

voltage range under worst-case drain test



individual cell capacity

Quall C1	4.469
Quall C2	4.459
Quall C3	4.468
Quall C4	4.474
JPL2-5	4.507
JPL2-7	4.467
JPL2-11	4.496
JPL5-10	4.529
JPL5-3	4.504
JPL5-8	4.496
JPL5-9	4.505
avg	4.488
min	4.459
max	4.529
range	0.070
range/avg	2%
c. of var.	0.50%

PLSS Battery Loads

- **Cryopac data system**
- **–Custom electronics supplied by Oceaneering.**
- **–8-24 VDC input (internal 5 VDC regulator).**
- **–2 Watts maximum total.**
- **Audio DSP**
- **–Custom electronics supplied by Kennedy Space Center.**
- **–Power box regulator 83% efficient: Power One P/N DFA6U12S12.**
- **–12 VDC input (internal 5 VDC regulator).**
- **–5 Watts maximum total.**
- **Pump**
- **–Greylor PQ-12 http://www.greylor.com/**
- **–Power box regulator 79% efficient: Power One P/N DFA20E12S12.**
- **–11 Watts nominal, 24 Watts maximum.**
- **–Voltage is varied to achieve desired flow rate.**
- **–Pump must continue to run during all cryogenic operations.**

Load elements (2 pump cases)

battery voltage 12 V

	net Watts	eff.	gross Watts	Amps at voltage	
data system	2	100%	2.0	0.167	
Audio DSP	5	83%	6.0	0.502	
Pump nominal	11	79%	13.9	1.160	
total	18	total	21.948	1.829	Amps nominal
data system	2	100%	2.0	0.167	
Audio DSP	5	83%	6.0	0.502	
Pump max	24	79%	30.4	2.532	
total	31	total	38.404	3.200	Amps max

expected battery current:

1.83 amp. nominal

3.20 amp. maximum

Current-carrying Capacities

cell maximum: 9 A (vendor limit)

maximum current to loads: 3.2 A

fuse rating: 4 A, 7A limit measured in laboratory

relay capacity (both poles): 4 A, switched

thermal fuse: 15 A