Operational Requirements for Applications of Li-ion Pouch Cells

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(Supported by NESC Battery Working Group)

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Background

- Pouch cell designs offer enhanced specific energy and energy densities compared to conventional deigns with metallic cell cases.
- Better form factor and packing efficiency.
- Attractive option for short-life missions.
- Limitation: Ability to maintain hermiticity of the cell through its lifetime
  - Electrolytes with high vapor pressure.
  - High temperature operations
  - Performance under hard vacuum.

Recommendations for Aerospace Applications of Pouch Cells

Objective:

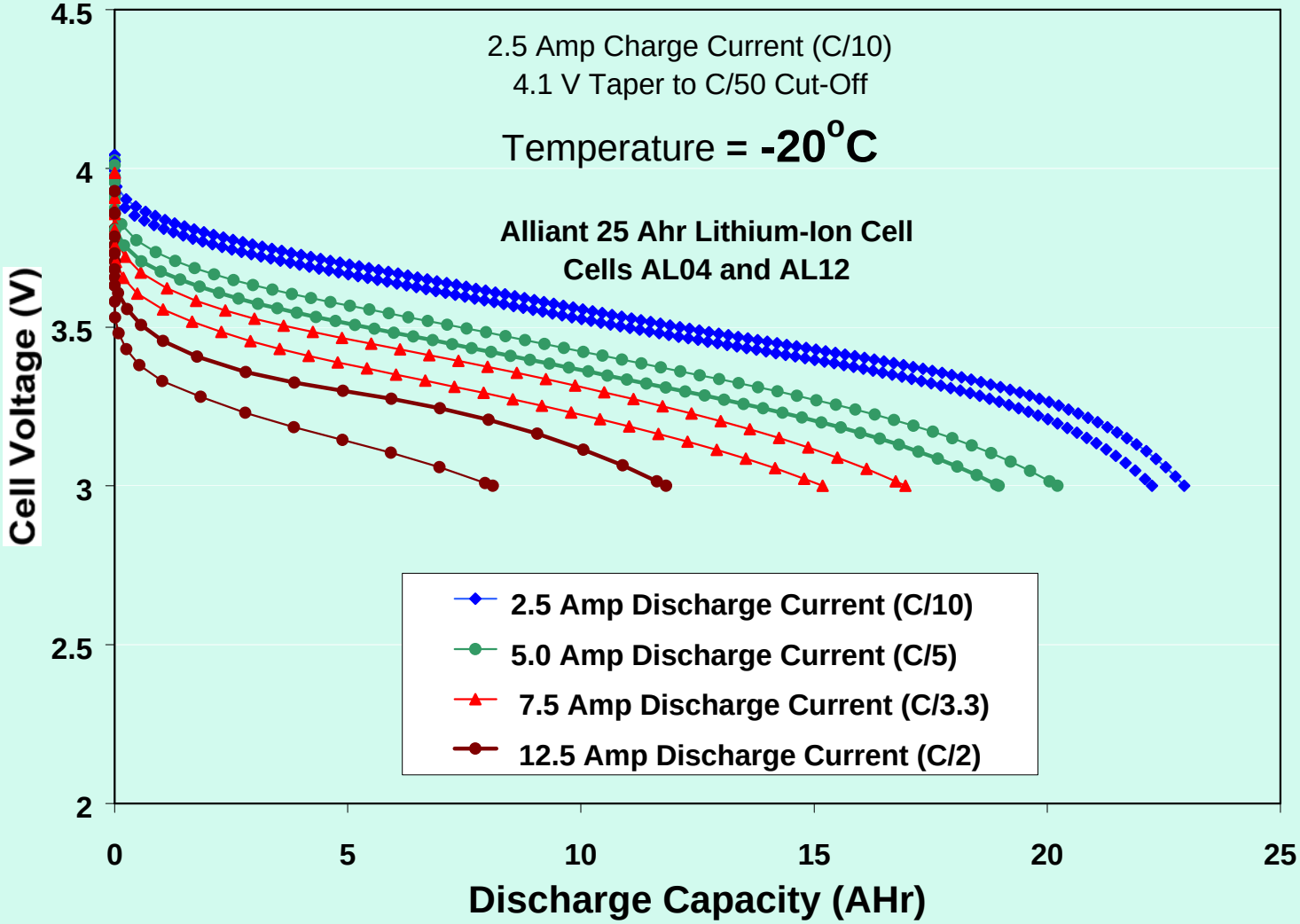
- Evaluate performance limitations related to thermal and vacuum environment

Approach:

- Perform focused research tasks to collect data related to corrosion of pouch materials in Li-Ion cells
- Generate recommendations for design considerations for pouch cells for aerospace applications
- Generate document outlining design, envelope requirements/limits for aerospace applications

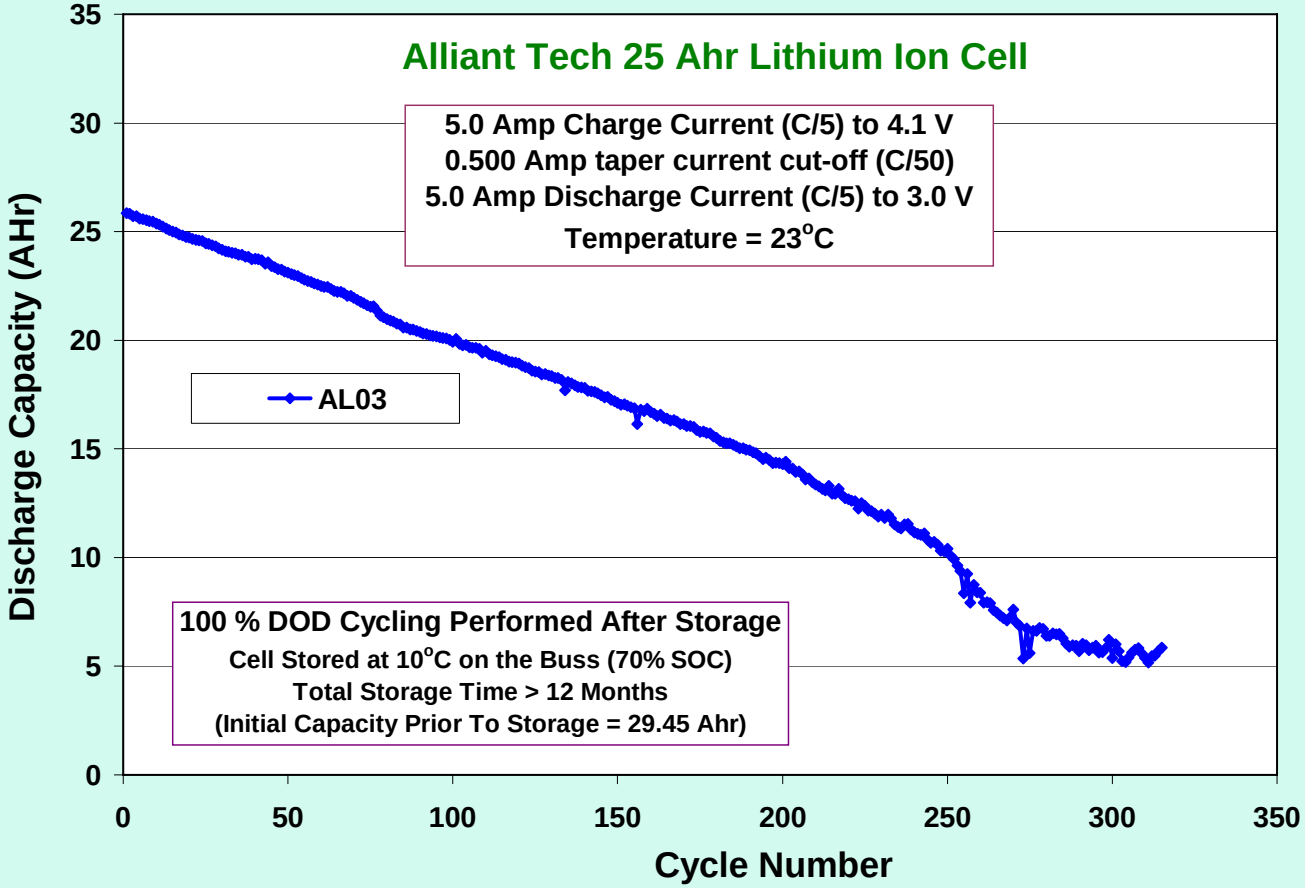
Alliant 25 Ah Lithium-Ion Polymer Cells for 2001 Mars Lander

Discharge Characterization at Low Temperature (-20°C)



Alliant 25 Ah Lithium-Ion Polymer Cells for 2001 Mars Lander

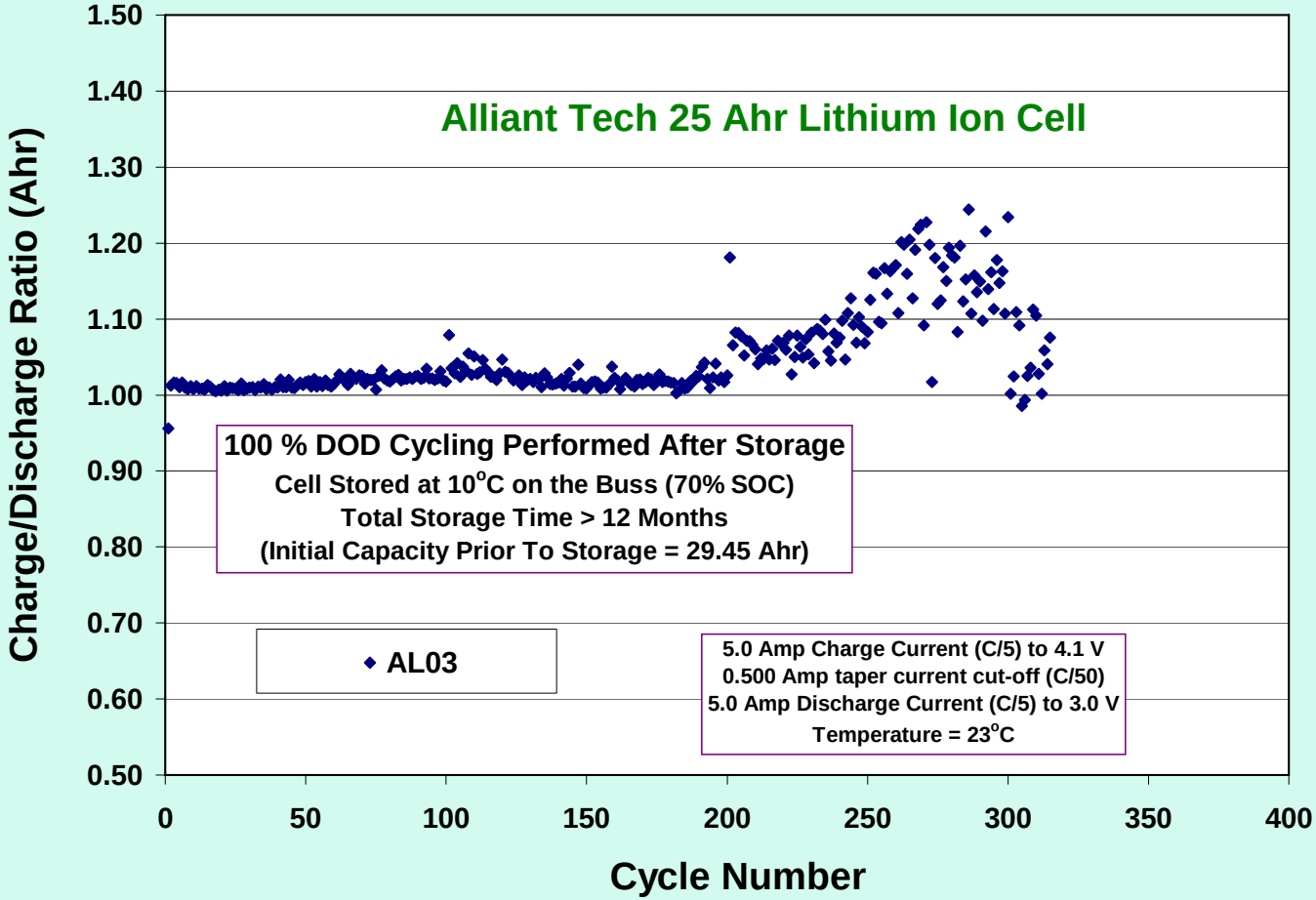
Cycle Life Performance at Room Temperature (23 ^{o}C)



* Alliant 25 AHr cell was observed to have a high capacity fade upon cycling
* Cell vented after 300 cycles (100% DOD)

Alliant 25 Ah Lithium-Ion Polymer Cells for 2001 Mars Lander

Cycle Life Performance at Room Temperature (23 ^{o}C)



* Prior to cell venting, cell performance characterized by dramatic increase in C/D ratio (suggesting parasitic reaction is occurring).

Planned Tests for Pouch Cell Tests

Manufacturer	Type	Chemistry		Tests	
			Chara-cterization	Thermal Vac	Cycling at 40°C
Quallion	Pouch Cells	ED2-LT electrolyte	1	LT Charge Rates	
	Pouch Cells	ED1-LT electrolyte	1		
SKC	Pouch Cells	Gel Polymer	2	2	1+1
Compact power	Pouch Cells	Gel Polymer	2	2	1+1
LTC	Pouch Cells	Li-ion	2	2	1+1
Electrovaya?	Pouch Cells	Li-ion	2	2	1+1
Another?	Pouch Cells	Li-ion	2	2	1+1

- **Additionally thermal acoustic IR tests (at MSA) if possible**

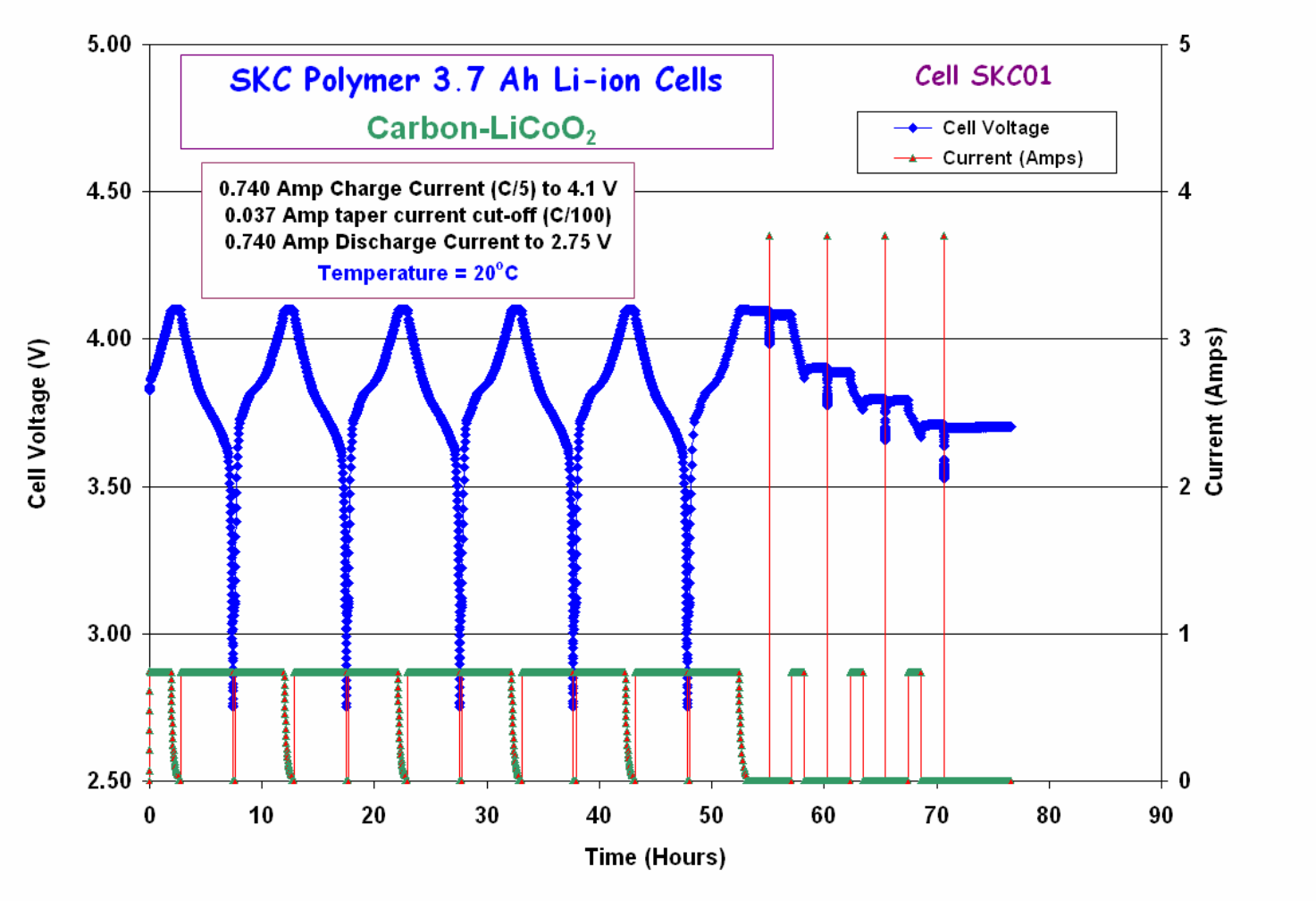
SKC Polymer 3.7 Ah Lithium-Ion Cells

Initial Characterization/Conditioning at 20°C

- Conditioning Cycling
  - 5 Cycles (100% DOD) performed at 20°C
    - C/5 Charge Rate (0.740 A) to 4.100 V
    - Charge taper current cut-off = C/100 (0.037 A)
    - C/5 Discharge Rate (0.740 A) to 2.750 V
  - Current-Interrupt Impedance Measurements
    - Performed at 4 different SOC (100, 75, 50 and 25% SOC)
    - Pulse Current = 3.70 A (1.0C discharge rate)
    - Pulse Duration = 60 Seconds
    - Rest period following pulse = 2 hrs
    - 25 % of capacity discharged between pulses (C/10 discharge rate)

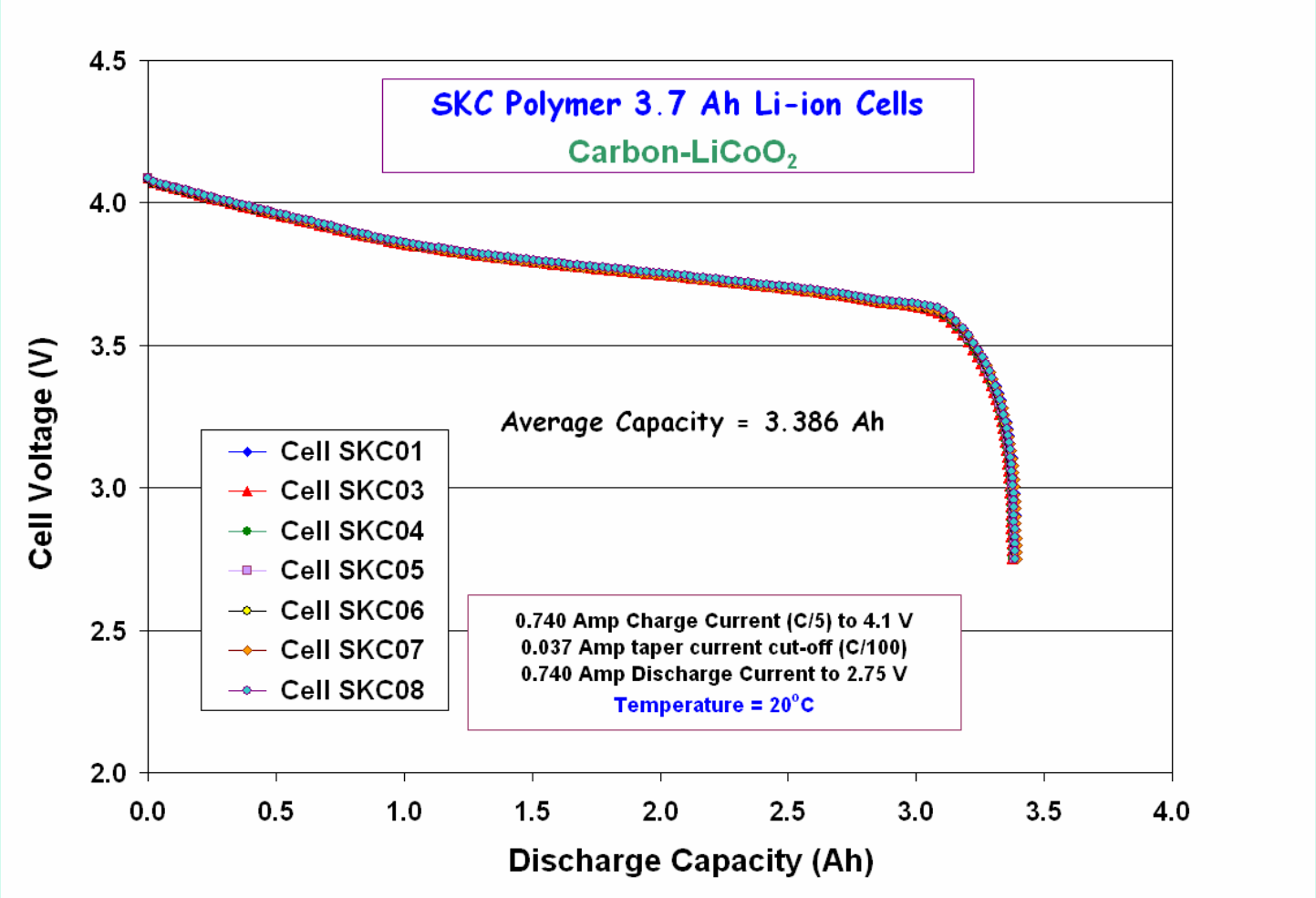
SKC Polymer 3.7 Ah Lithium-Ion Cells

Initial Characterization/Conditioning at 20°C (Cell SKC01)



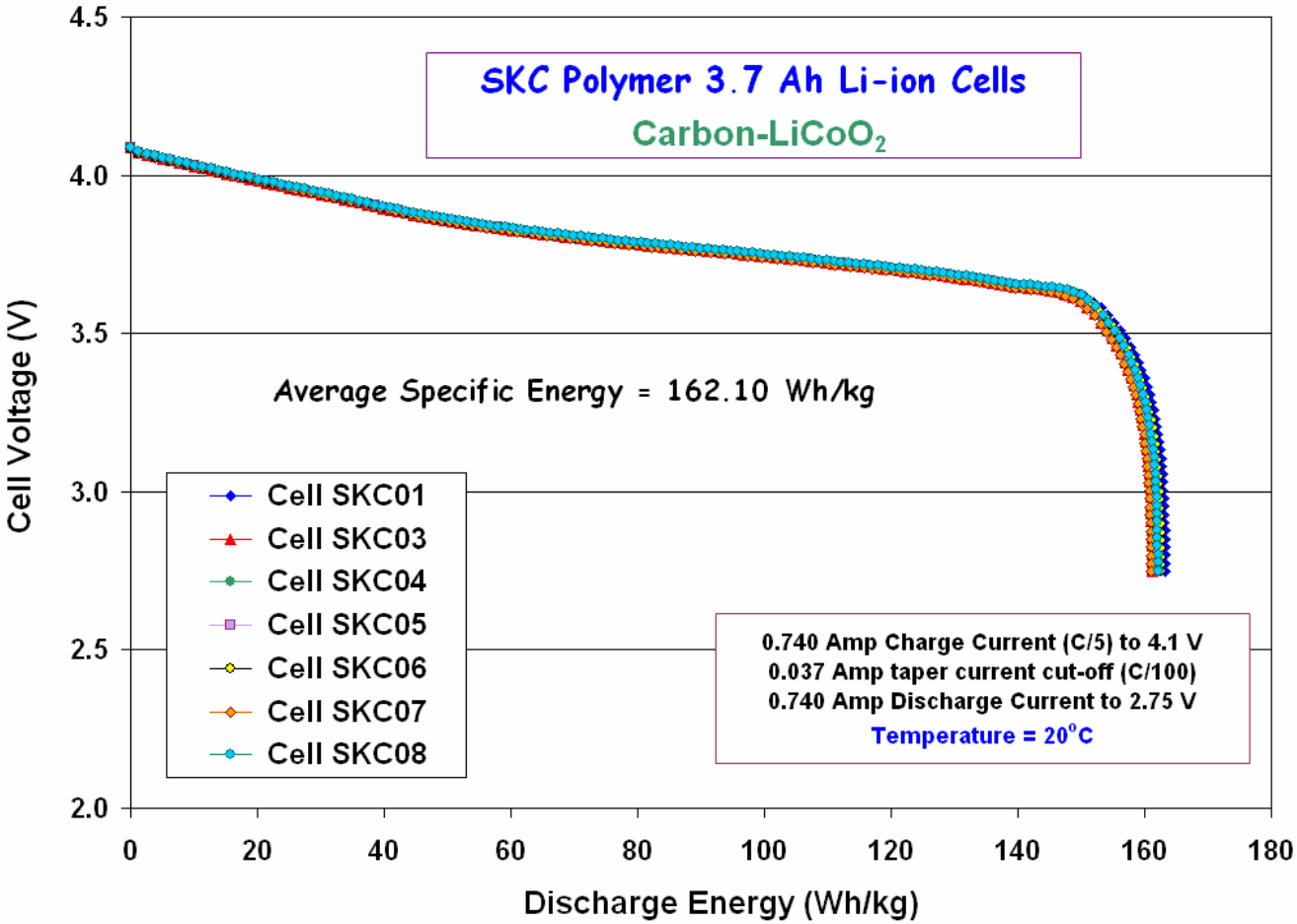
SKC Polymer 3.7 Ah Lithium-Ion Cells

Initial Characterization/Conditioning at 20ºC - Discharge Capacity (Ah)



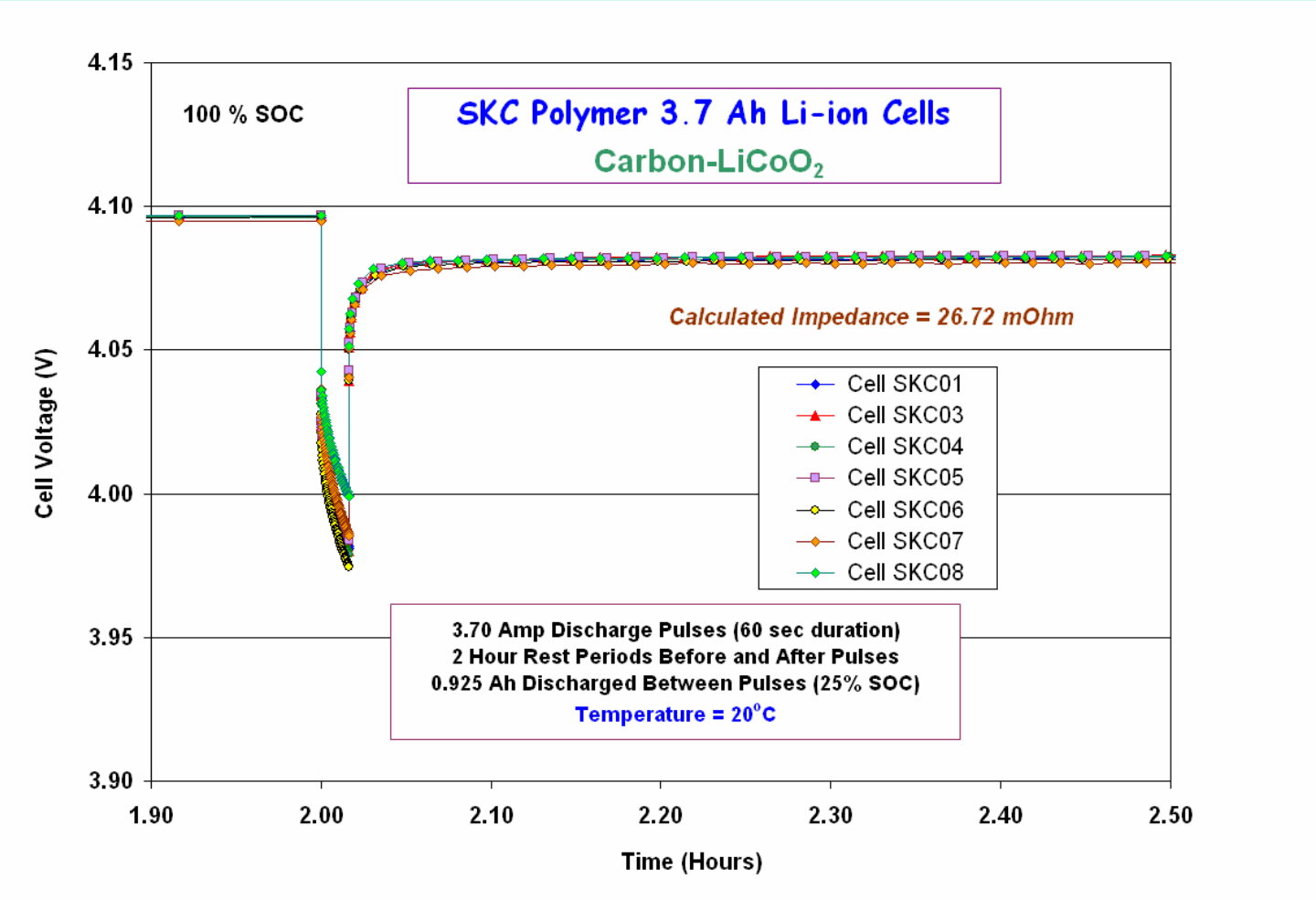
SKC Polymer 3.7 Ah Lithium-Ion Cells

Initial Characterization/Conditioning at 20ºC - Discharge Energy (Wh/Kg)



SKC Polymer 3.7 Ah Lithium-Ion Cells

Initial Characterization/Conditioning at 20ºC- Current-Interrupt Impedance (100 % SOC)



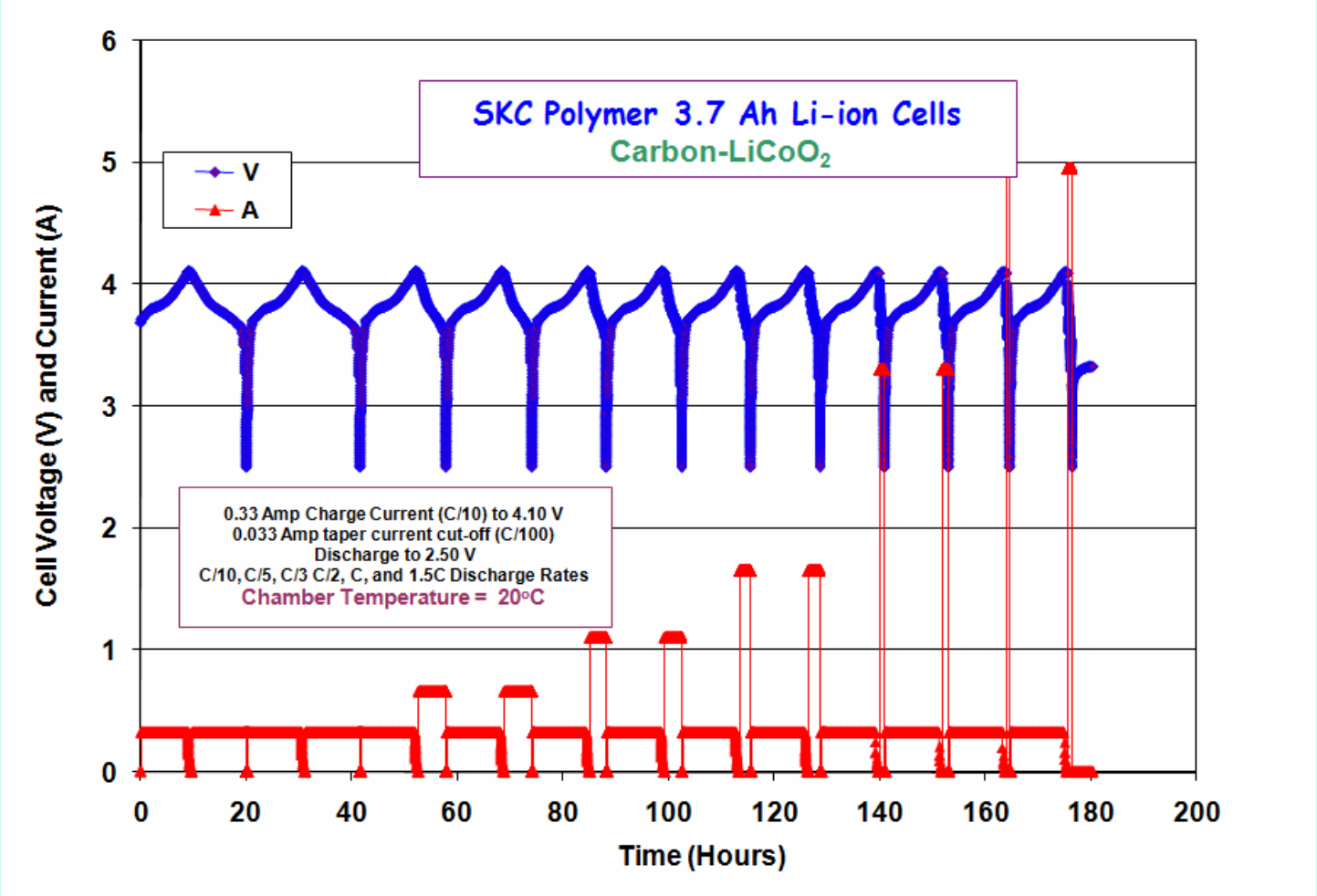
SKC Polymer 3.7 Ah Lithium-Ion Cells

Initial Characterization/Conditioning at 20ºC-Summary (Seven Cells)

Cell ID	Cell Weight (Grams)	Cell Weight (kg)	Initial Voltage	Initial Capacity (Ah)	Initial Watt-Hours	Initial Wh/kg	Calculated Impedance (mOhms) (100% SOC)	Calculated Impedance (mOhms) (75% SOC)	Calculated Impedance (mOhms) (50% SOC)
SKC01	78.56	0.0786	3.824	3.3940	12.825	163.25	27.30	30.81	36.95
SKC03	79.03	0.0790	3.826	3.3729	12.744	161.26	27.88	31.34	38.02
SKC04	78.68	0.0787	3.825	3.3783	12.764	162.22	28.08	31.18	37.24
SKC05	78.95	0.0790	3.826	3.3834	12.791	162.02	26.72	29.94	35.76
SKC06	78.67	0.0787	3.825	3.3878	12.797	162.67	29.03	32.62	38.81
SKC07	79.63	0.0796	3.820	3.3958	12.825	161.06	25.53	28.91	35.14
SKC08	79.05	0.0791	3.828	3.3873	12.821	162.19	22.52	28.83	29.82
Average	78.94	0.079	3.825	3.386	12.795	162.10	26.72	30.52	35.96

SKC Polymer 3.7 Ah Lithium-Ion Cells

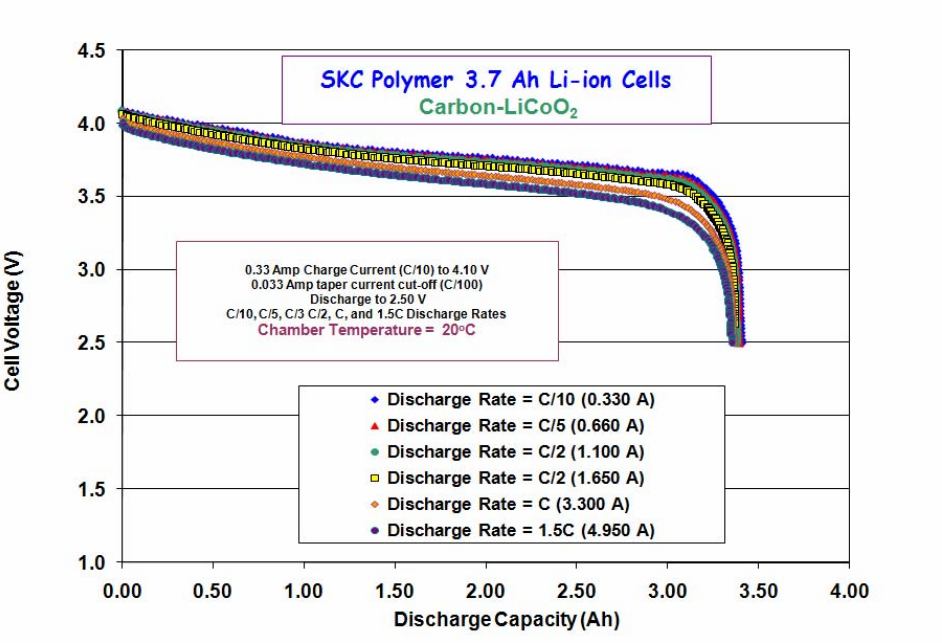
Discharge Rate Characterization at 20°C



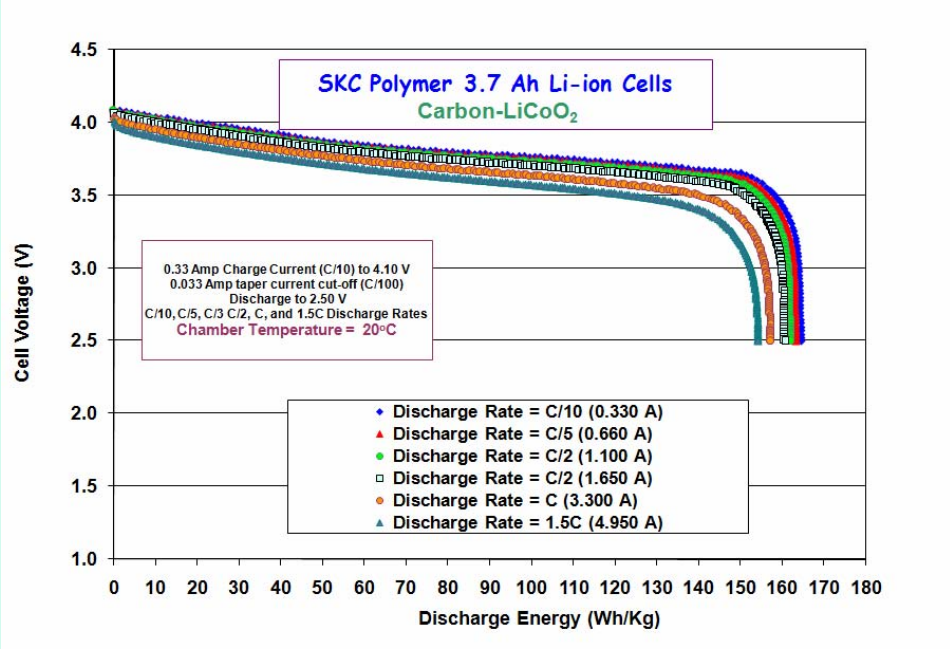
SKC Polymer 3.7 Ah Lithium-Ion Cells

Discharge Rate Characterization at 20ºC

Discharge Capacity (Ah)



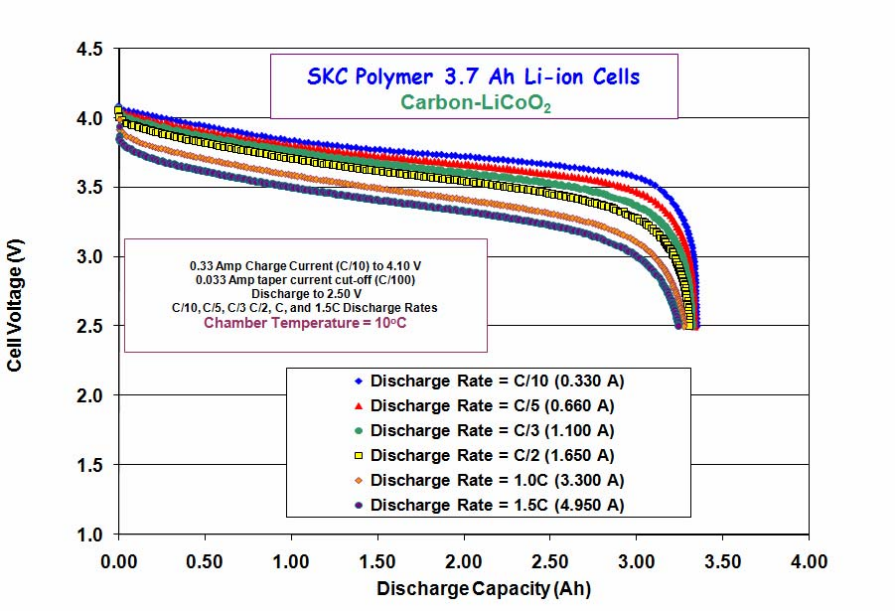
Discharge Energy (Wh/kg)



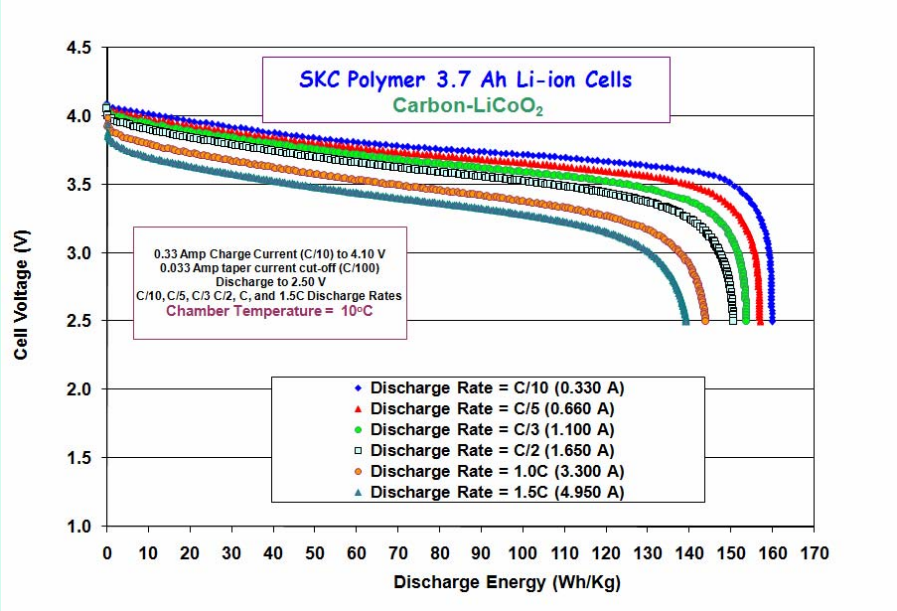
SKC Polymer 3.7 Ah Lithium-Ion Cells

Discharge Rate Characterization at 10ºC

Discharge Capacity (Ah)



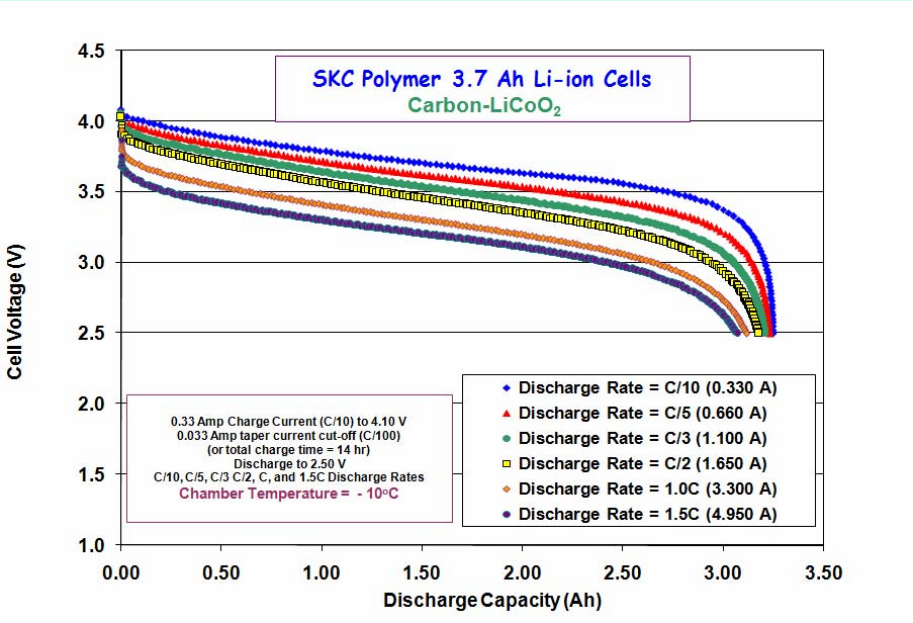
Discharge Energy (Wh/kg)



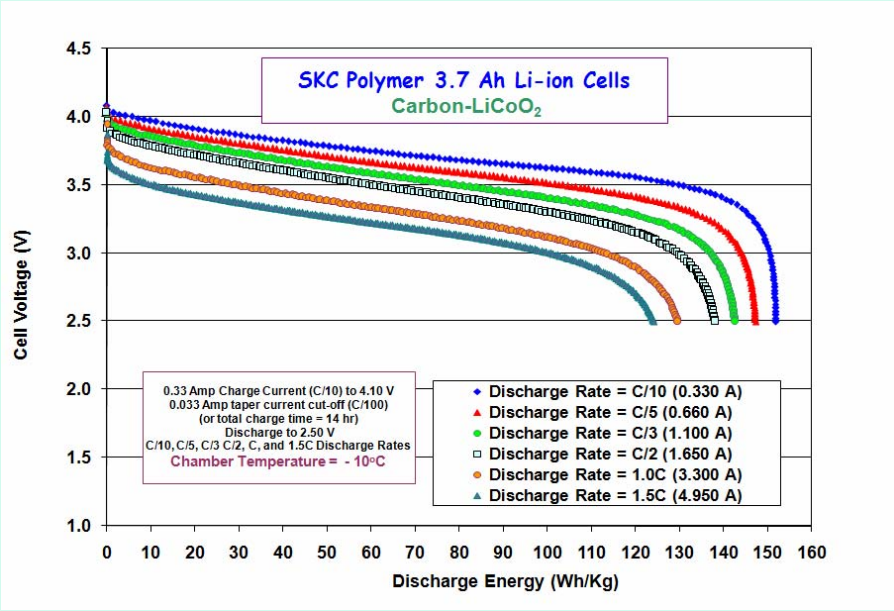
SKC Polymer 3.7 Ah Lithium-Ion Cells

Discharge Rate Characterization at - 10ºC

Discharge Capacity (Ah)



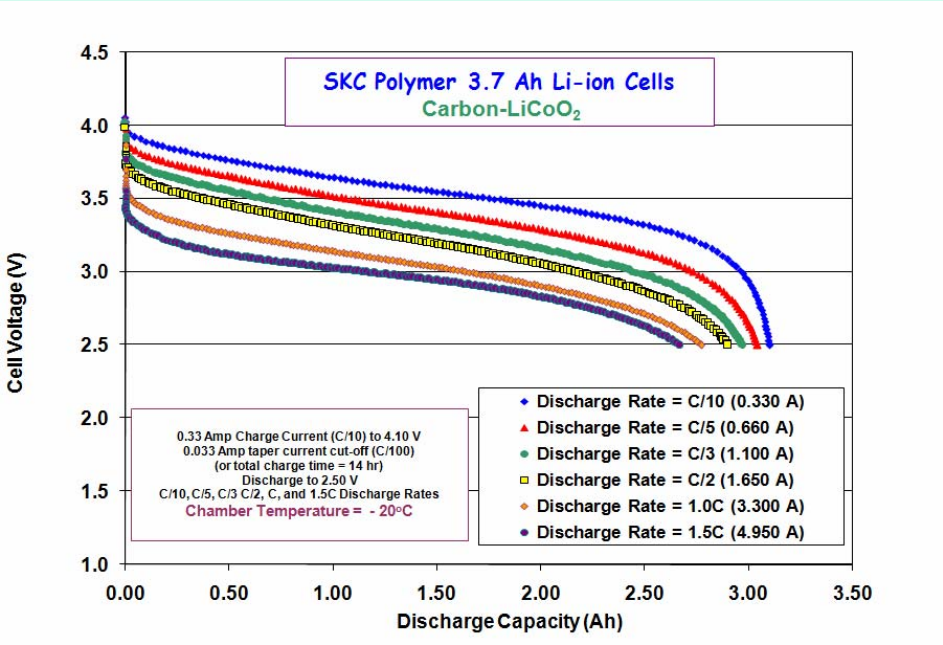
Discharge Energy (Wh/kg)



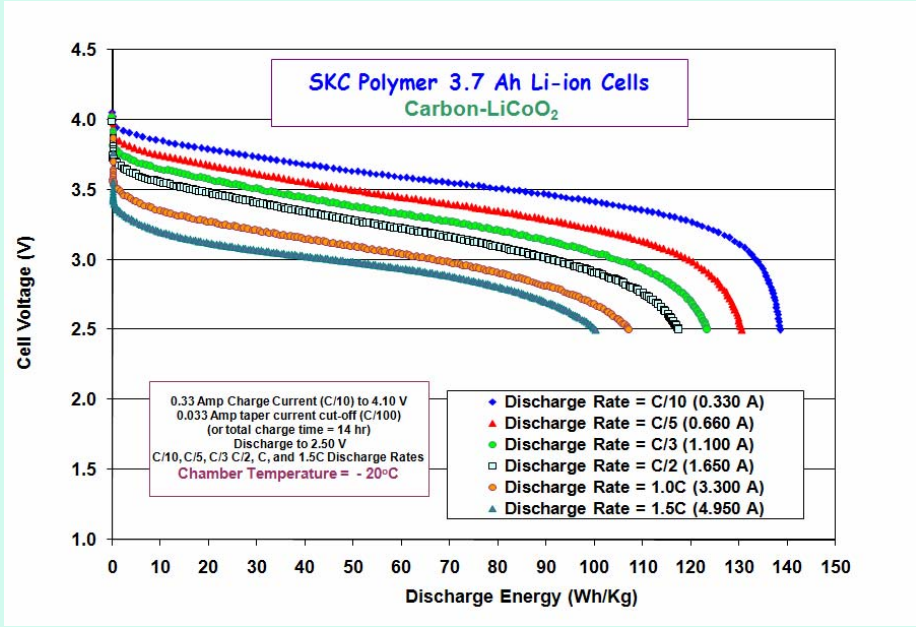
SKC Polymer 3.7 Ah Lithium-Ion Cells

Discharge Rate Characterization at - 20°C

Discharge Capacity (Ah)



Discharge Energy (Wh/kg)



SKC Polymer 3.7 Ah Lithium-Ion Cells

Charge Rate Characterization at Various Temperatures

			SKC Polymer 3.70 Ah Li-Ion Cell (Cell SKC01)							SKC Polymer 3.70 Ah Li-Ion Cell (Cell SKC01)						
Temp	Discharge Rate	Discharge Current (A)	Charge Capacity (Ah)	Charge Time (Hours)	Percent C/10 Capacity	Percent C/10 Capacity at 20°C	Charge Watt Hr (Wh)	Discharge Watt-Hr (Wh)	Watt Hour Efficiency (%)	Charge Capacity (Ah)	Charge Time (Hours)	Percent C/10 Capacity	Percent C/10 Capacity at 20°C	Charge Watt-Hr (Wh)	Discharge Watt-Hr (Wh)	Watt Hour Efficiency (%)
20°C	C/10	0.370	3.658	10.251	100.00	100.00	14.228	14.079	98.95	3.806	10.573	100.00	100.00	14.770	14.595	98.81
	C/5	0.740	3.679	5.496	100.57	100.57	14.378	14.121	98.21	3.804	5.586	99.94	99.94	14.822	14.588	98.42
	C/3	1.233	3.686	3.637	100.78	100.78	14.495	14.137	97.53	3.806	3.483	100.00	100.00	14.908	14.578	97.79
	C/2	1.850	3.691	2.750	100.91	100.91	14.616	14.150	96.81	3.797	2.663	99.77	99.77	14.955	14.561	97.37
	C	3.700	3.692	1.928	100.93	100.93	14.885	14.144	95.02	3.794	1.777	99.69	99.69	15.178	14.543	95.81
0°C	C/10	0.370	3.650	10.950	100.00	99.79	14.366	13.798	96.05	3.747	10.943	100.00	98.45	14.687	14.235	96.92
	C/5	0.740	3.641	6.599	99.75	99.54	14.528	13.737	94.55	3.740	6.321	99.83	98.28	14.831	14.192	95.70
	C/3	1.233	3.634	5.103	99.56	99.35	14.704	13.696	93.15	3.736	4.635	99.70	98.16	14.992	14.163	94.47
	C/2	1.850	3.628	4.519	99.39	99.19	14.851	13.644	91.87	3.732	3.843	99.59	98.05	15.138	14.130	93.34
	C	3.700	3.613	4.452	98.98	98.77	15.088	13.512	89.55	3.725	3.319	99.43	97.89	15.435	14.078	91.20
-10°C	C/10	0.370	3.511	12.606	100.00	95.97	14.133	12.799	90.56	3.669	10.239	100.00	96.41	14.599	13.645	93.47
	C/5	0.740	3.450	8.715	98.27	94.31	14.146	12.517	88.49	3.662	7.798	99.80	96.22	14.819	13.596	91.75
	C/3	1.233	3.356	6.528	95.58	91.73	13.941	12.088	86.71	3.652	6.744	99.52	95.95	14.983	13.535	90.33
	C/2	1.850	3.281	6.160	93.45	89.68	13.739	11.742	85.47	3.632	6.646	98.98	95.43	15.060	13.392	88.92
	C	3.700	3.200	6.346	91.16	87.49	13.437	11.432	85.08	3.578	6.555	97.51	94.01	14.998	13.119	87.47
-20°C	C/10	0.370	3.168	12.706	100.00	86.59	12.960	11.171	86.20	3.357	12.910	100.00	88.20	13.694	11.660	85.14
	C/5	0.740	3.095	9.469	97.70	84.60	12.897	10.823	83.92	3.259	8.557	97.08	85.63	13.540	11.476	84.76
	C/3	1.233	3.024	9.266	95.48	82.68	12.680	10.542	83.14	3.182	7.843	94.79	83.61	13.323	11.178	83.90
	C/2	1.850	2.959	9.459	93.42	80.89	12.422	10.307	82.97	3.109	7.912	92.61	81.68	13.043	10.912	83.66
	C	3.700	2.901	9.532	91.57	79.29	12.182	10.108	82.98	3.038	8.024	90.51	79.83	12.760	10.671	83.63
- 30°C	C/10	0.370	2.485	14.000	100.00	67.93	10.406	8.091	77.75	2.705	14.000	100.00	71.09	11.308	8.929	78.96
	C/5	0.740	2.460	14.000	99.02	67.26	10.330	7.980	77.25	2.680	14.000	99.05	70.41	11.247	8.814	78.36
	C/3	1.233	2.411	14.000	97.02	65.91	10.126	7.799	77.02	2.620	14.000	96.83	68.83	11.001	8.609	78.26
	C/2	1.850	2.377	14.000	95.64	64.97	9.982	7.730	77.44	2.554	14.000	94.41	67.11	10.727	8.385	78.16
	C	3.700	2.348	14.000	94.50	64.19	9.863	7.597	77.03	2.507	14.397	92.69	65.89	10.532	8.225	78.10
- 40°C	C/10	0.370	0.242	1.521	100.00	6.61	0.867	0.426	49.12	1.259	7.491	100.00	33.09	4.499	3.559	79.11
	C/5	0.740	0.112	0.735	46.22	3.06	0.403	0.278	68.95	1.193	6.435	94.76	31.36	4.285	3.377	78.82
	C/3	1.233	0.088	0.589	36.53	2.42	0.318	0.237	74.44	1.139	6.220	90.46	29.93	4.099	3.228	78.75
	C/2	1.850	0.085	0.565	34.95	2.31	0.304	0.224	73.48	1.084	5.808	86.07	28.48	3.902	3.082	78.98
	C	3.700	0.094	0.659	38.92	2.57	0.339	0.237	69.94	1.032	5.587	81.95	27.12	3.715	2.894	77.90

Data discussed in detail in the companion presentation “Safe Charge Rates in Lithium-Ion Cells”

Quallion 4 Ah Lithium-Ion Pouch Cells

- Quallion 4 Ah Prismatic 7 Ah Li-ion Cells
  - 20 Cells Received Total (12 cells under D-RATS Program)
  - Five different electrolyte types
    - Quallion Low Temperature Electrolyte (“ED-1”) *4 Cells*
    - Quallion Low Temperature Electrolyte (“ED-2”) *4 Cells*
    - Quallion Baseline Electrolyte (“ED-1”) *2 Cells*
    - JPL Low Temperature Electrolyte (JPL-2)
    - JPL Low Temperature Electrolyte (JPL-5)
- Completed the following initial characterization tests:
  - 5 Cycles at 20°, 0°, and -20°C
  - C/5 Charge current (1.40 A) to 4.1V, 0.070 A Taper current cut-off (C/100)
  - C/5 Discharge current (1.40 A) to 2.75 V
  - Current-interrupt pulse measurements performed vs. SOC
- Initiated the following initial characterization tests:
  - Charge Characterization vs. Temperature
  - Low Temperature Discharge Characterization

Quallion 4 Ah Lithium-Ion Pouch Cells

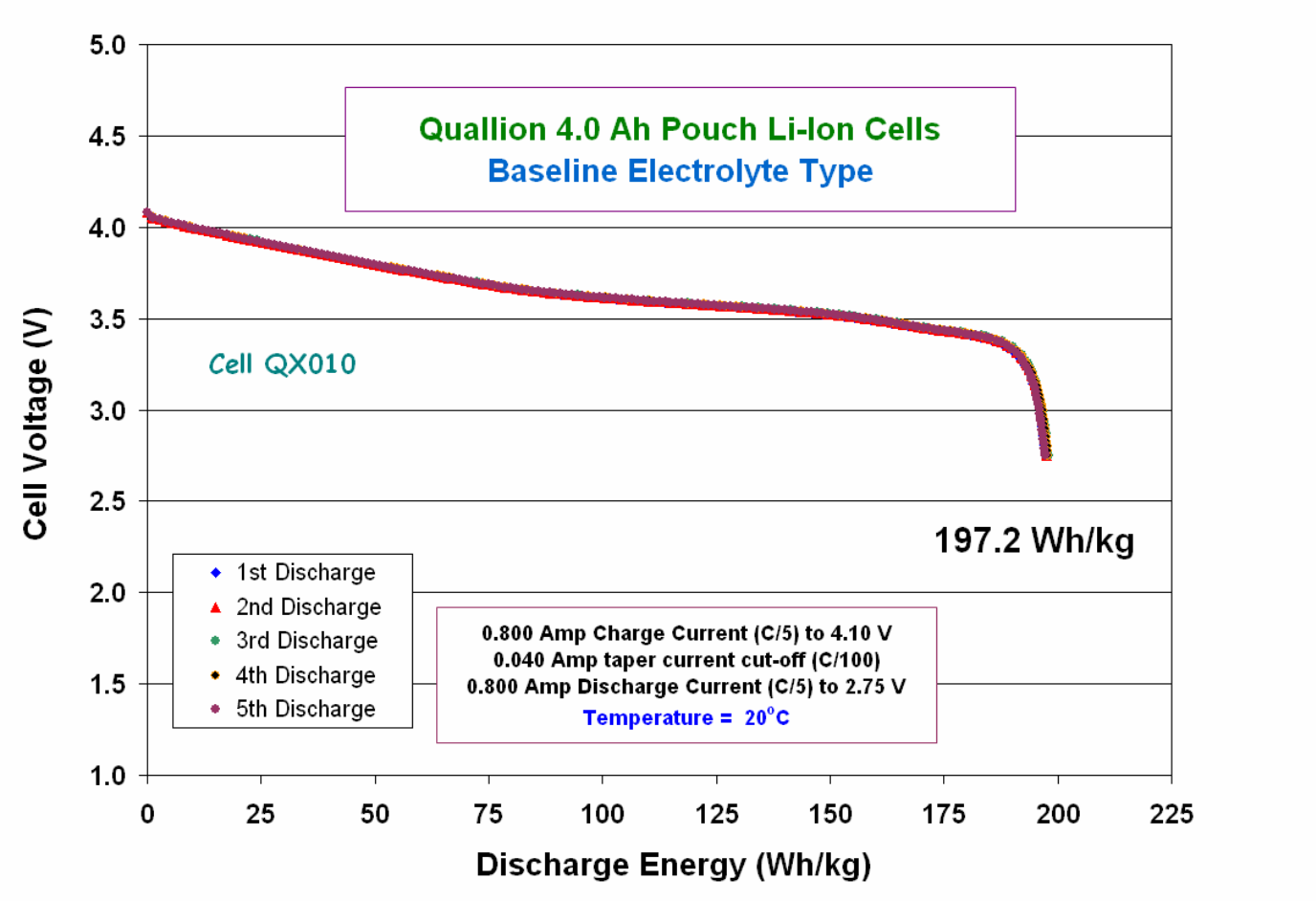
Initial Characterization/Conditioning at 20°C

Summary of Conditioning Results

Cell ID	Cell Weight (Grams)	Cell Weight (kg)	Initial Voltage	Initial Capacity (Ah)	Initial Watt-Hours	Initial Wh/kg	Calculated Impedance (mOhms) (100% SOC)	Calculated Impedance (mOhms) (80% SOC)	Calculated Impedance (mOhms) (60% SOC)	Electrolyte Type
QA05	79.18	0.0792	3.426	4.3847	16.009	202.19	29.98	39.52	30.44	ED-1
QA06	78.39	0.0784	3.446	4.3864	16.019	204.34	29.83	39.22	29.68	ED-1
QA07	79.11	0.0791	3.451	4.3714	15.951	201.63	30.98	40.74	33.88	ED-1
QA08	79.92	0.0799	3.703	4.3750	15.963	199.73	32.88	42.50	34.10	ED-1
QB04	78.47	0.0785	3.477	4.2974	15.626	199.14	35.86	45.93	37.16	ED-2
QB05	78.69	0.0787	3.461	3.5360	12.640	160.63	65.23	77.21	68.67	ED-2
QB06	79.28	0.0793	3.480	4.2537	15.477	195.22	35.48	47.46	37.92	ED-2
QB07	79.07	0.0791	3.483	4.2530	15.492	195.93	31.43	42.65	32.20	ED-2
QX010	80.31	0.0803	3.431	4.3436	15.818	196.96	33.88	44.10	34.49	Baseline Electrolyte
QX018	79.66	0.0797	3.4176	4.3172	15.712	197.24	34.56	45.93	35.78	Baseline Electrolyte
Average	79.21	0.08	3.48	4.25	15.47	195.30	36.01	46.53	37.43	

Quallion 4 Ah Lithium-Ion Pouch Cells

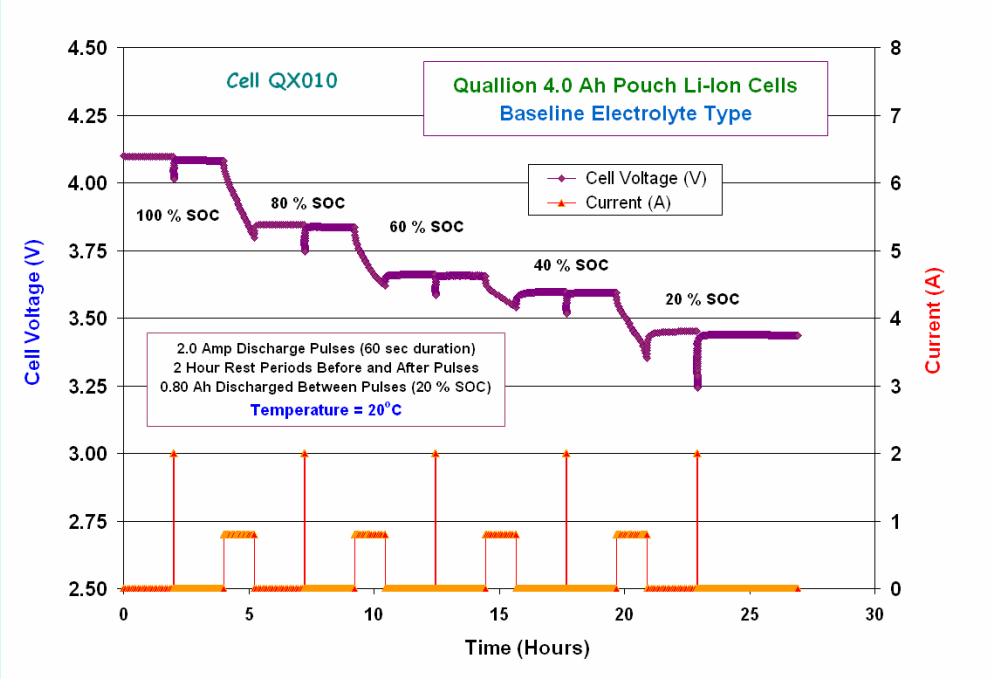
Initial Characterization/Conditioning at 20ºC - Discharge Energy (Wh/Kg)



- High specific energy observed (195-205 Wh/kg) with cells at 20ºC

Quallion 4 Ah Lithium-Ion Pouch Cells

Initial Characterization/Conditioning at 20°C - Impedance Characteristics

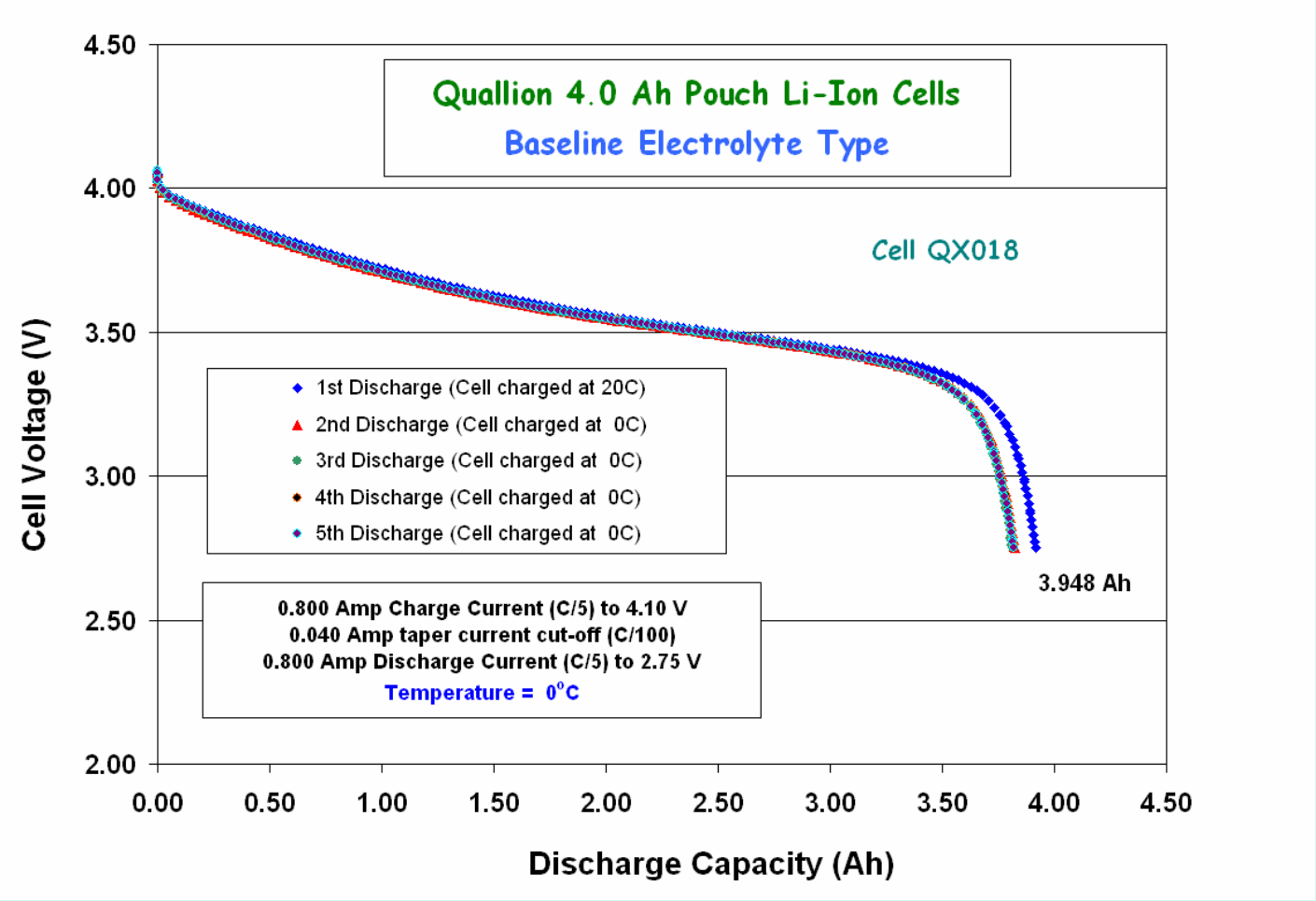


- Current interrupt impedance measurements performed at varying states-of-charge (SOC)

	100 % SOC		80 % SOC		60 % SOC		40 % SOC		20 % SOC	
Time (Minutes)	Cell Voltage	Cell Impedance (Ohms)	Cell Voltage	Cell Impedance (Ohms)	Cell Voltage	Cell Impedance (Ohms)	Cell Voltage	Cell Impedance (Ohms)	Cell Voltage	Cell Impedance (Ohms)
Initial V	4.09812		3.84527		3.66018		3.59792		3.45052	
Low V	4.01404		3.74472		3.58480		3.51675		3.24239	
5	4.08408	0.03502	3.83566	0.04547	3.65423	0.03471	3.58877	0.03601	3.42947	0.09354
15	4.08469	0.03532	3.83703	0.04616	3.65606	0.03563	3.59167	0.03746	3.43526	0.09644
30	4.08438	0.03517	3.83749	0.04639	3.65621	0.03571	3.59274	0.03799	3.43771	0.09766
60	4.08316	0.03456	3.83658	0.04593	3.65637	0.03578	3.59380	0.03853	3.43908	0.09834
120	4.08011	0.03304	3.83566	0.04547	3.65606	0.03563	3.59442	0.03883	3.43816	0.09789

Quallion 4 Ah Lithium-Ion Pouch Cells

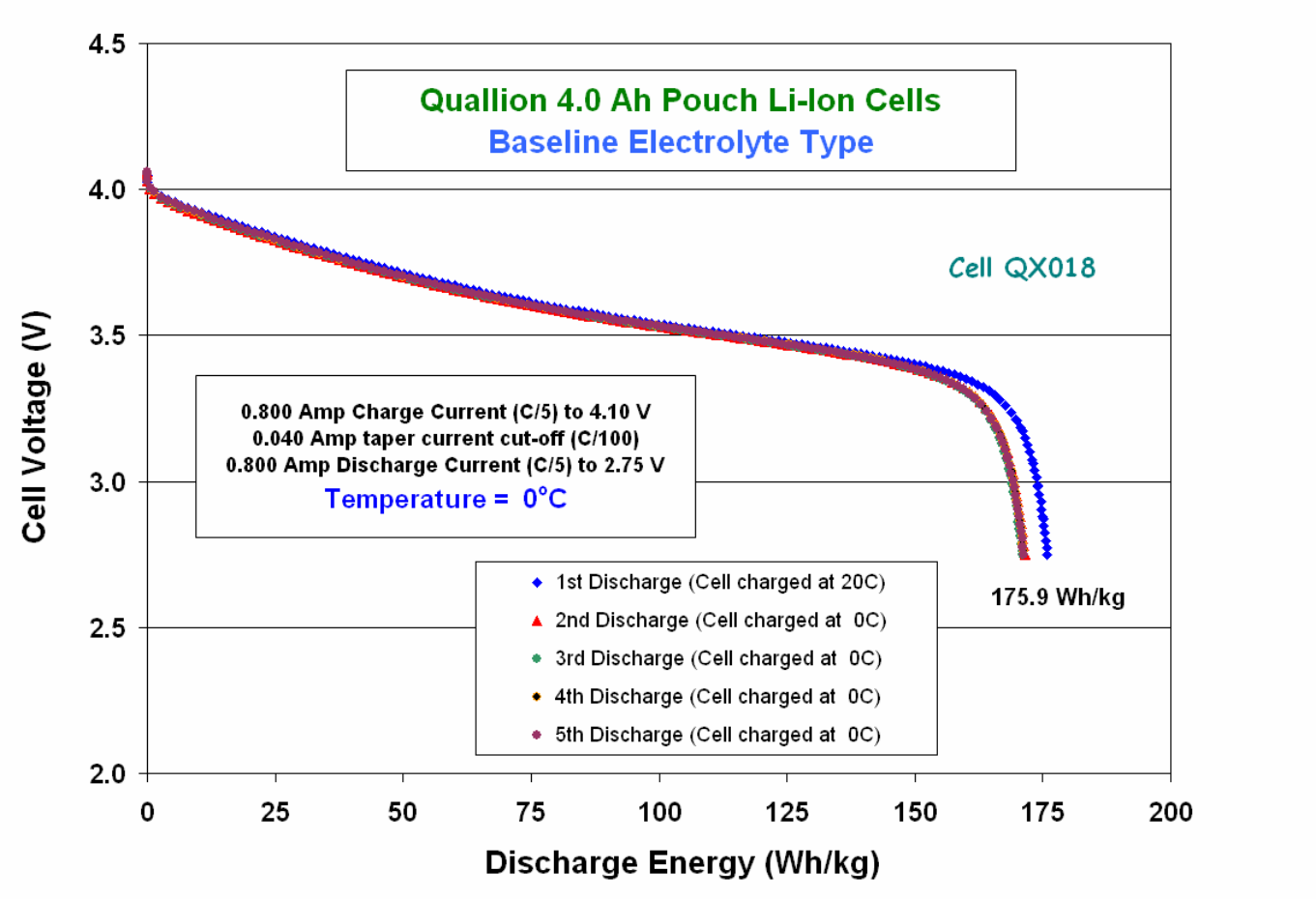
Initial Characterization/Conditioning at 0°C - Discharge Capacity (Ah)



Quallion Baseline Electrolyte

Quallion 4 Ah Lithium-Ion Pouch Cells

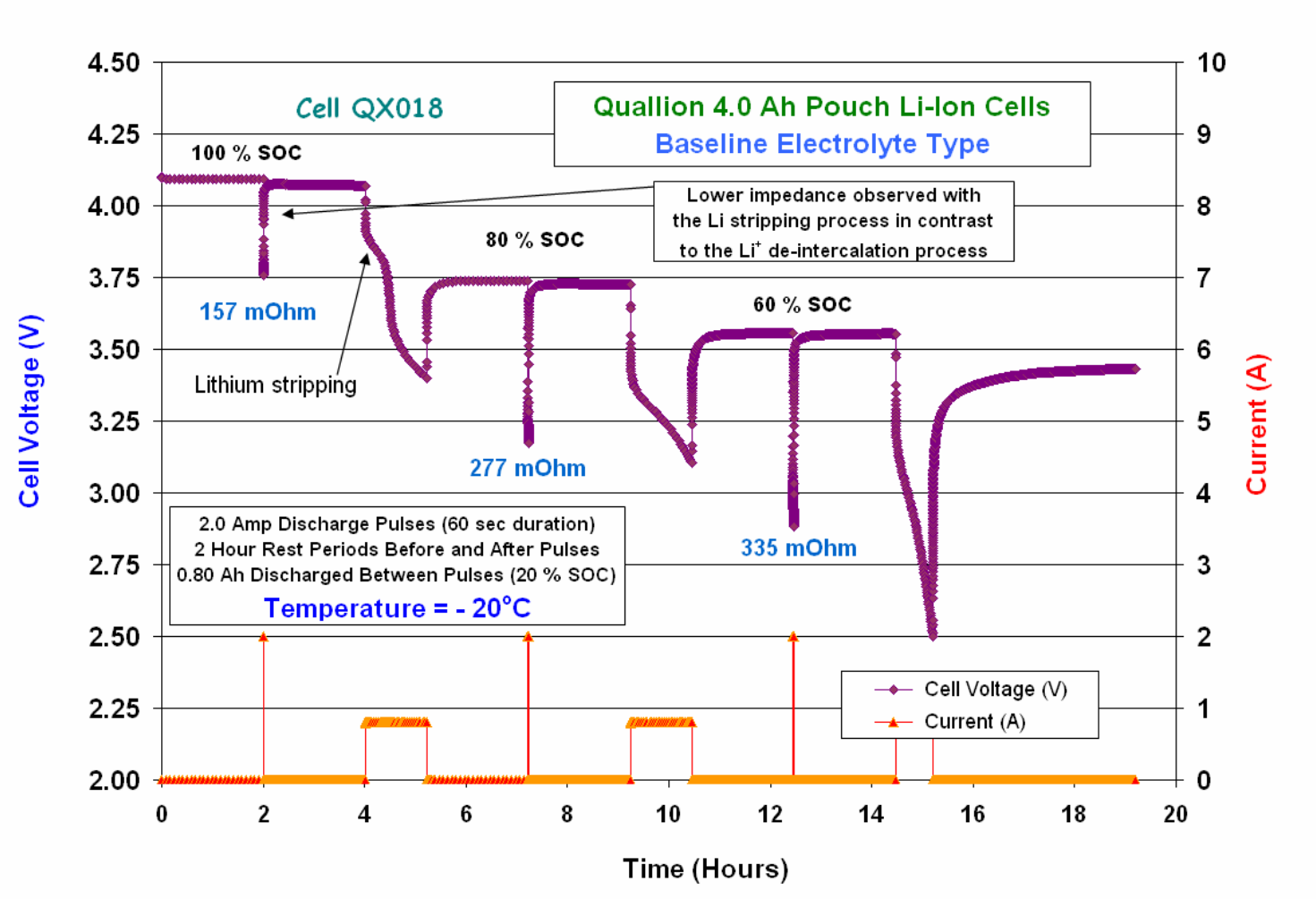
Initial Characterization/Conditioning at 0°C - Discharge Energy (Wh/Kg)



- High specific energy also observed with cells at 0°C

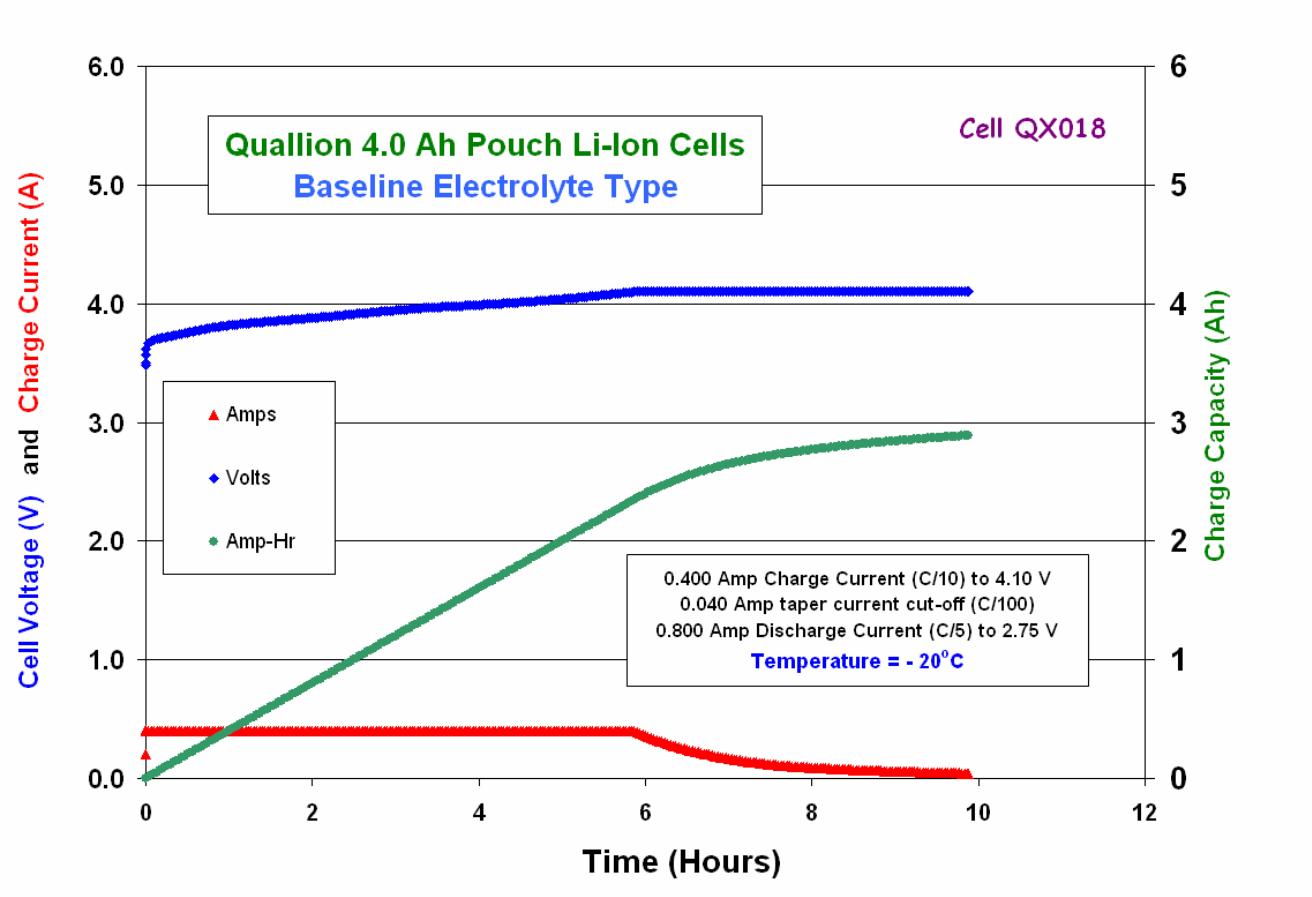
Quallion 4 Ah Lithium-Ion Pouch Cells

Initial Characterization/Conditioning at - 20ºC - Impedance Characteristics



Quallion 4 Ah Lithium-Ion Pouch Cells

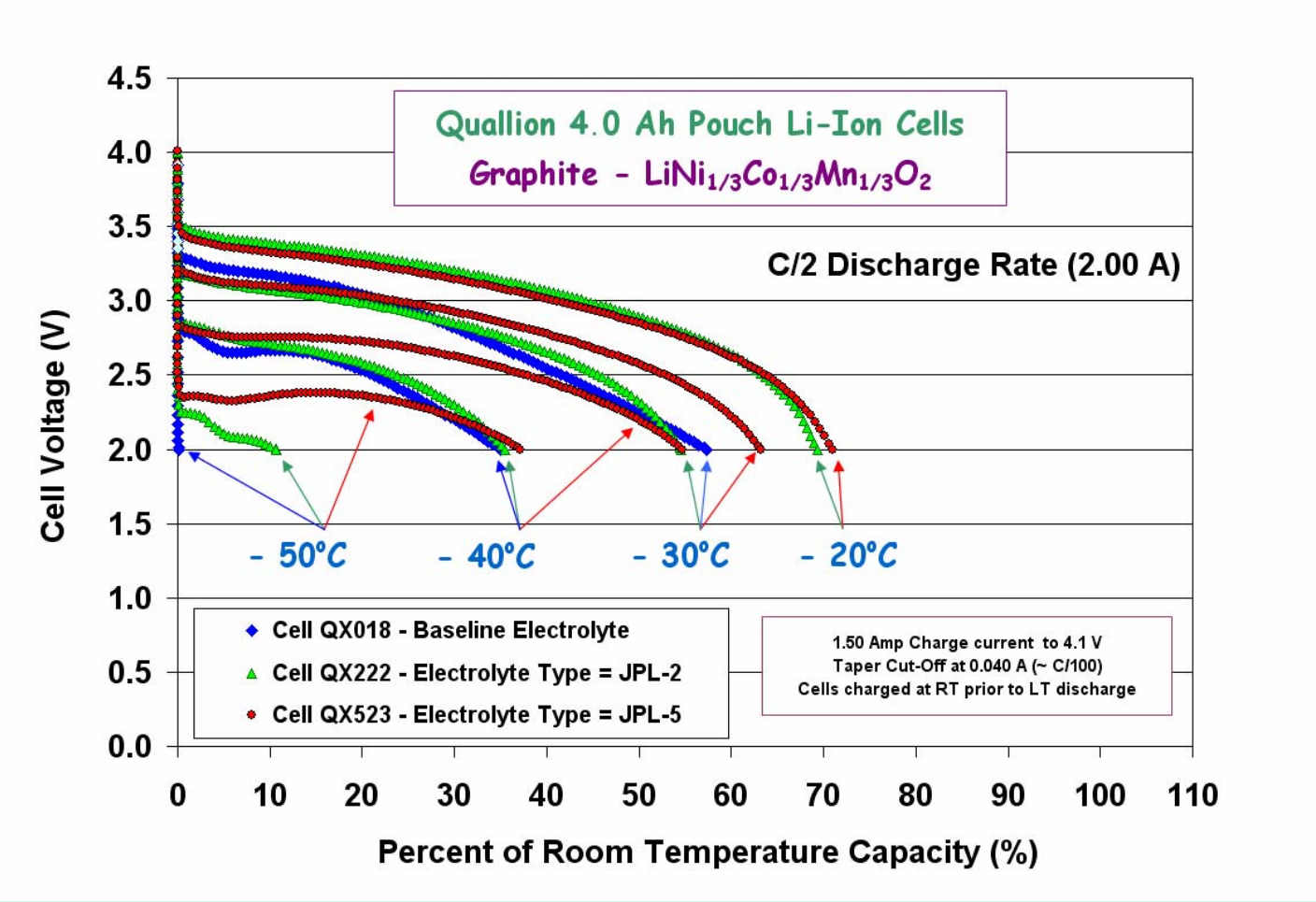
Initial Characterization/Conditioning at - 20°C - Charge Behavior at -20°C



No indications for Li plating during the preceding charge at -20°C

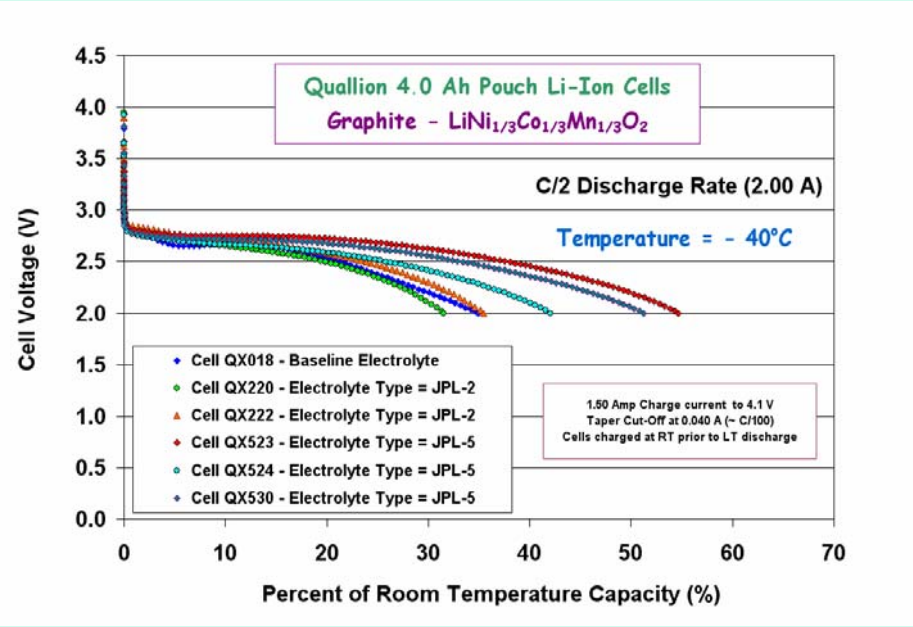
Quallion 4 Ah Lithium-Ion Pouch Cells

Discharge Performance (C/2 Rate) at Various Temperatures

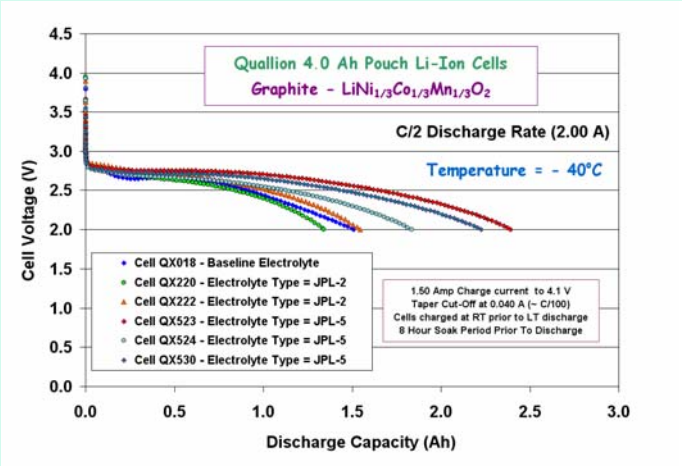


Quallion 4 Ah Lithium-Ion Pouch Cells
Discharge Performance (C/2 Rate) at - 40°C

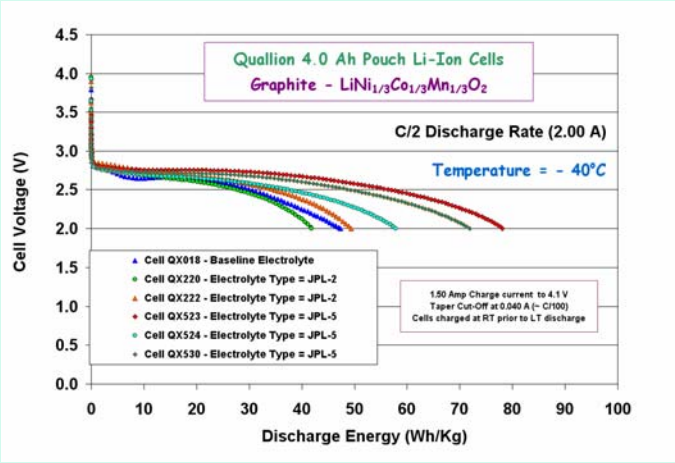
Percent of Room Temp Capacity (%)



Discharge Capacity (Ah)

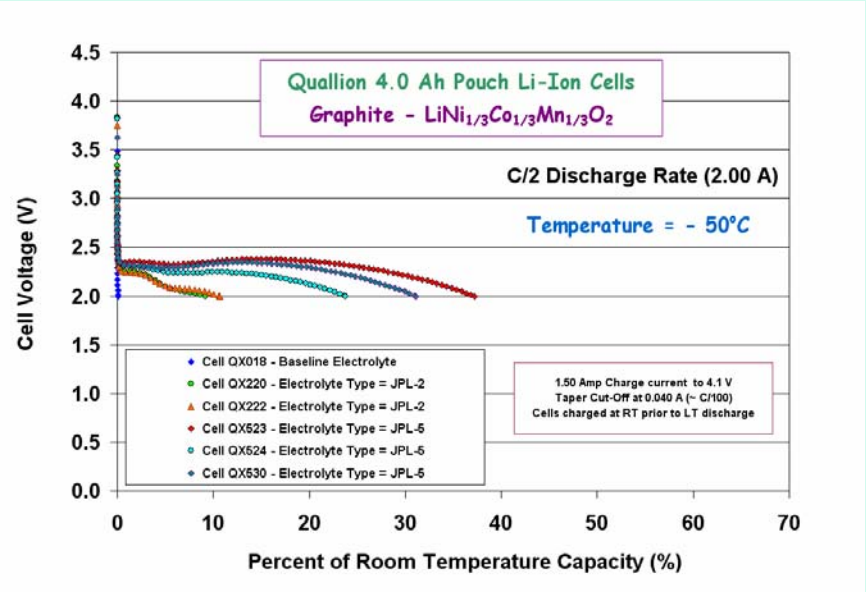


Discharge Energy (Wh/Kg)

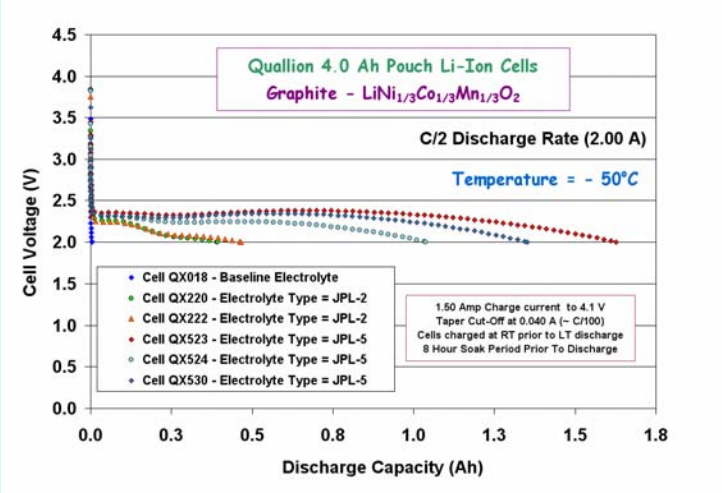


Quallion 4 Ah Lithium-Ion Pouch Cells
Discharge Performance (C/2 Rate) at - 50°C

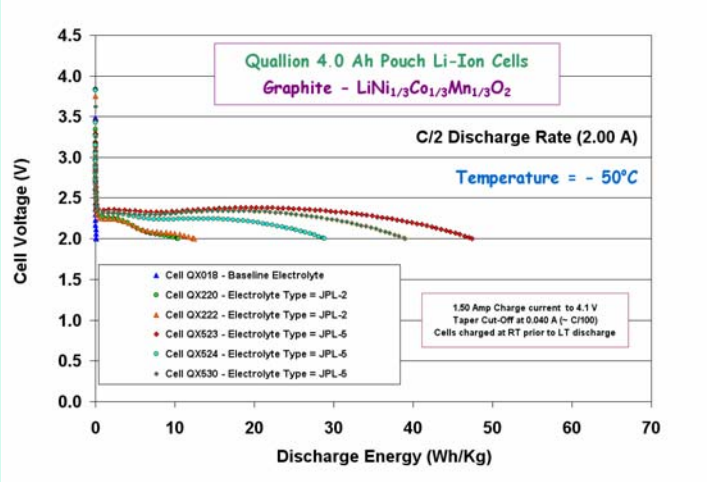
Percent of Room Temp Capacity (%)



Discharge Capacity (Ah)

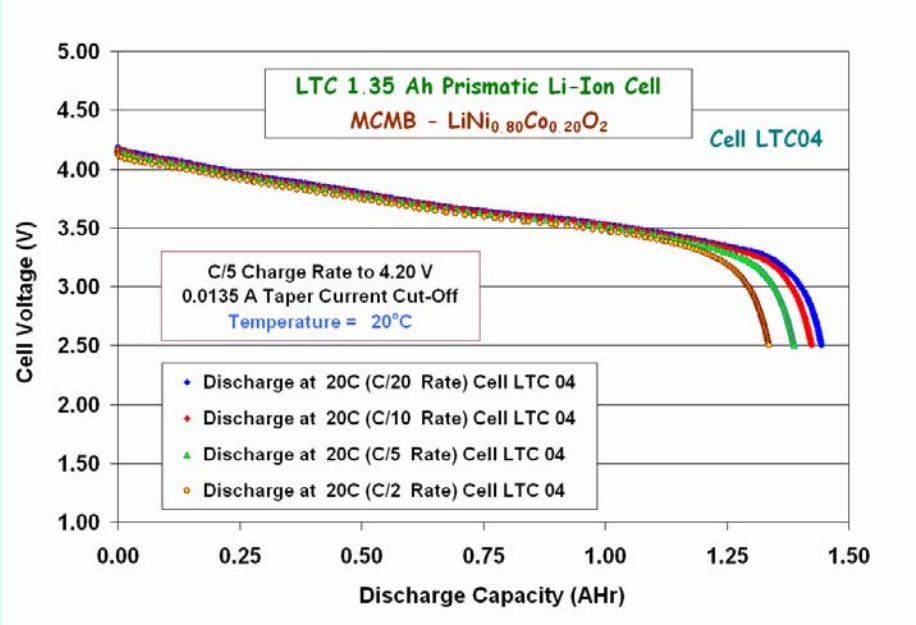


Discharge Energy (Wh/Kg)

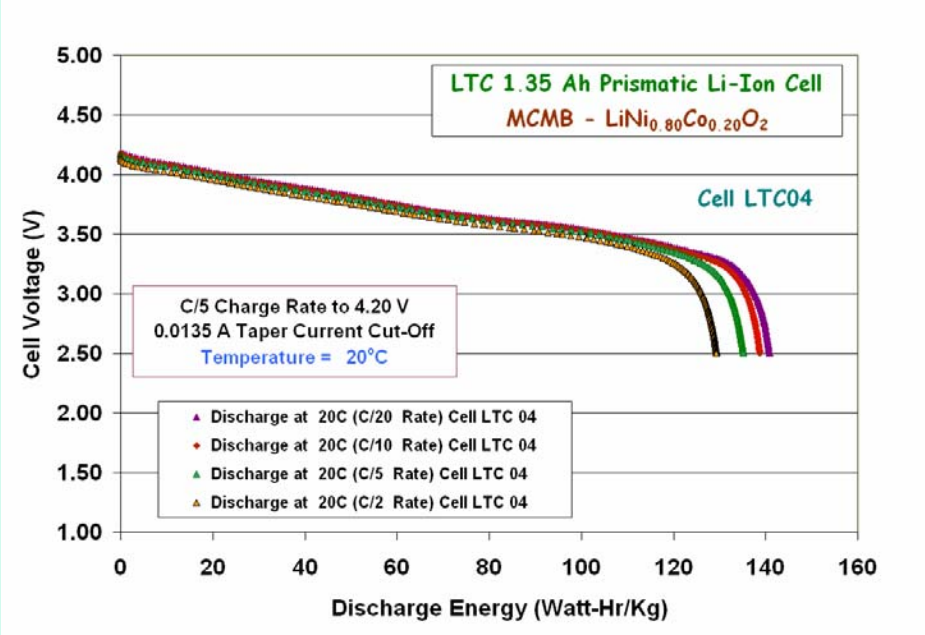


LTC-Gaia 1.35 Ah Prismatic Li-Ion Cells Discharge Rate Performance at 20°C

Discharge Capacity (Ah)

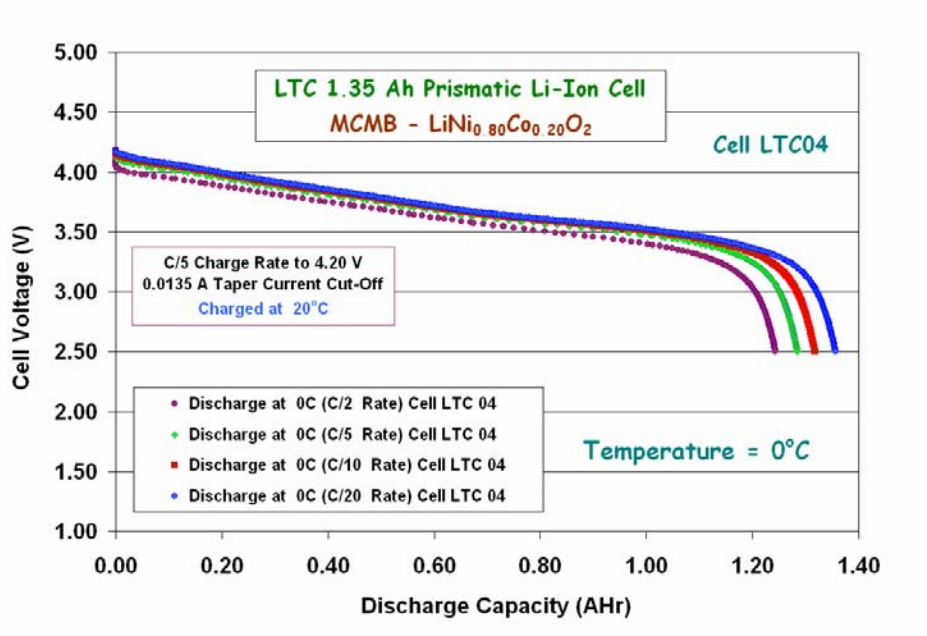


Discharge Energy (Wh/Kg)

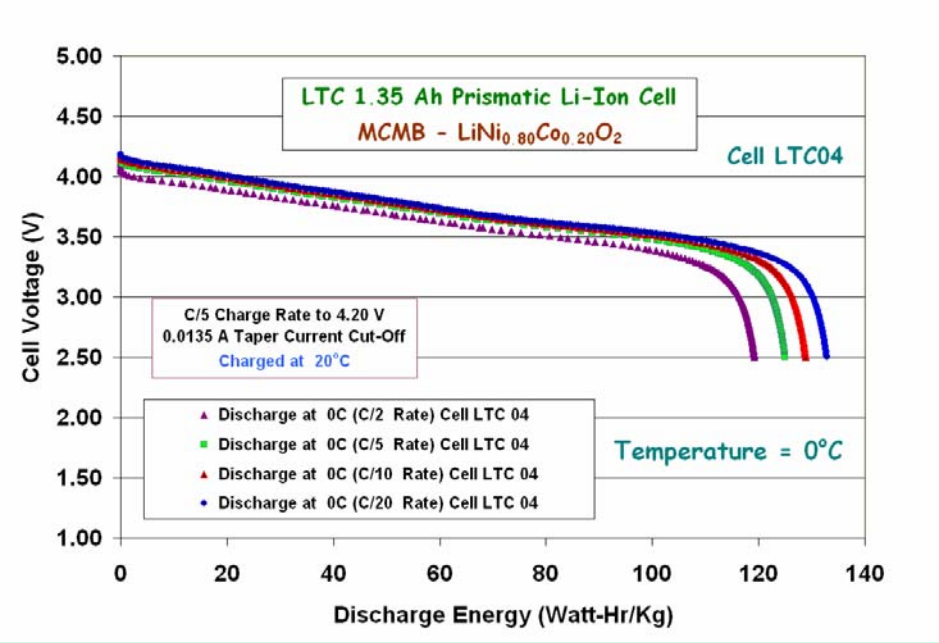


LTC-Gaia 1.35 Ah Prismatic Li-Ion Cells Discharge Rate Performance at 0°C

Discharge Capacity (Ah)

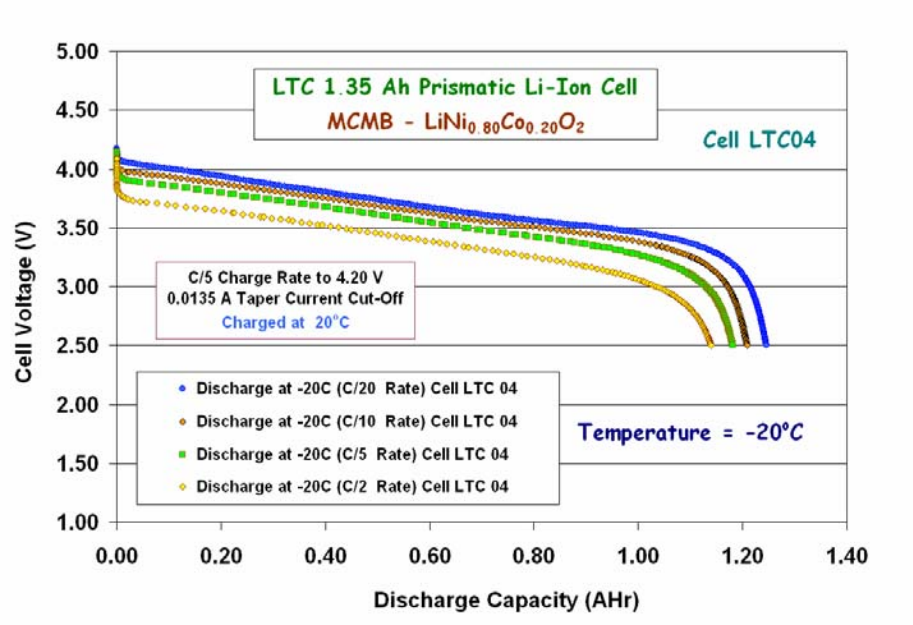


Discharge Energy (Wh/Kg)

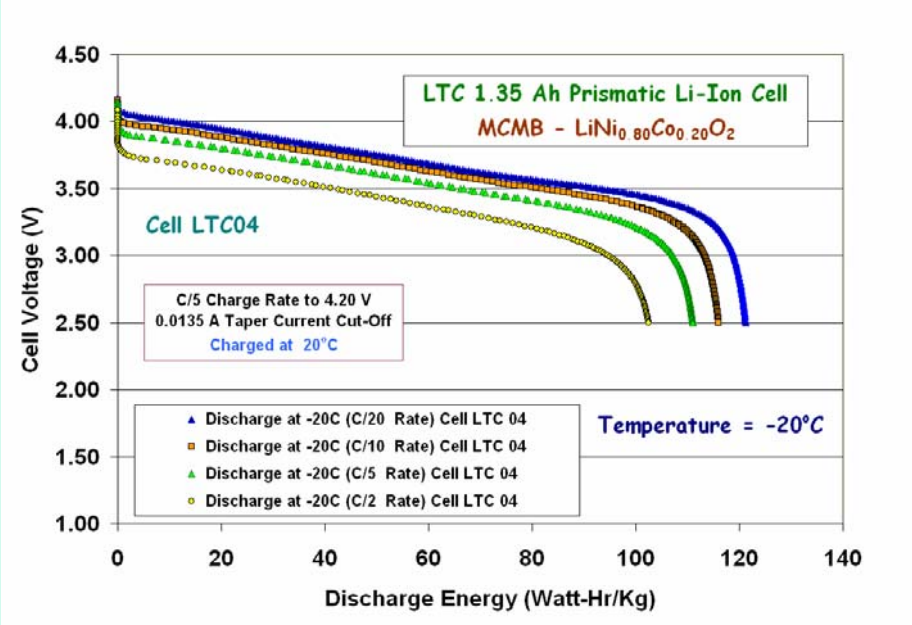


LTC-Gaia 1.35 Ah Prismatic Li-Ion Cells
Discharge Rate Performance at - 20°C

Discharge Capacity (Ah)

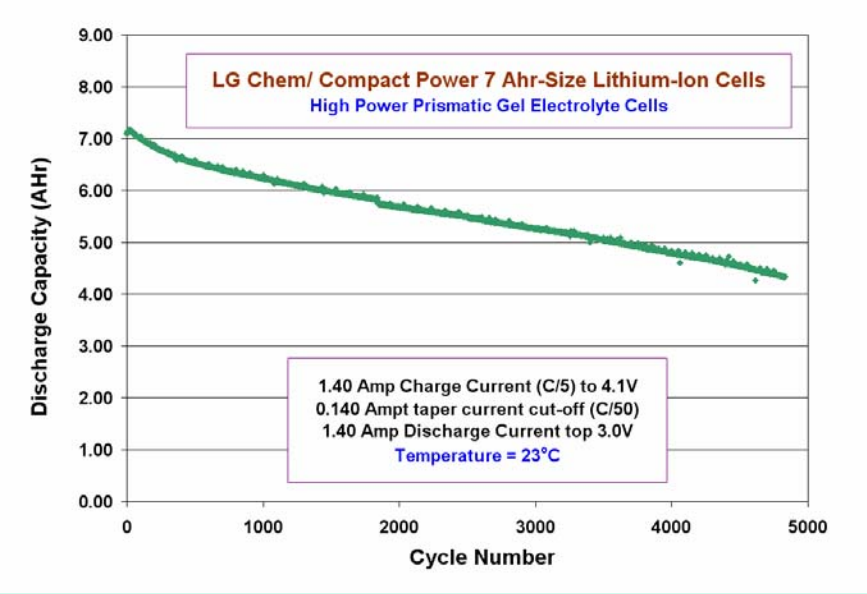


Discharge Energy (Wh/Kg)

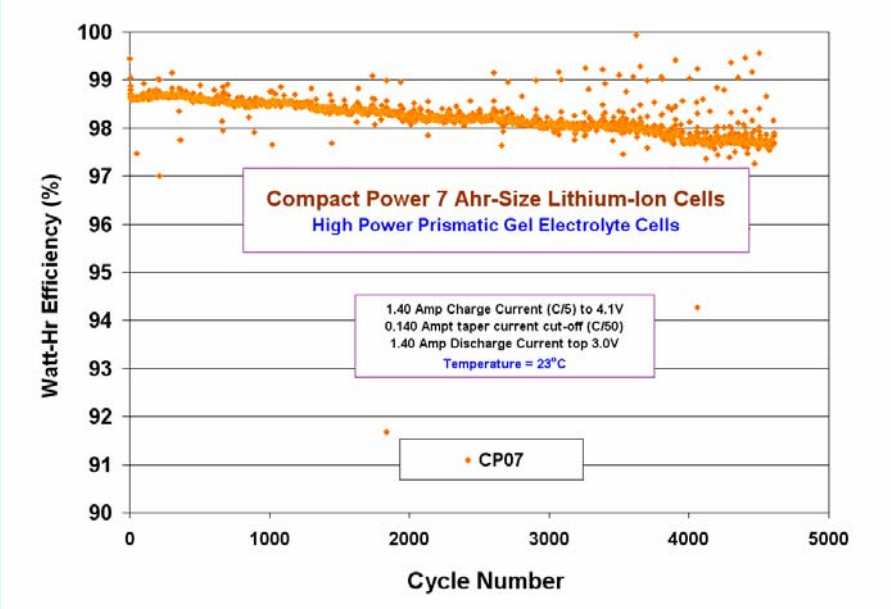


Performance Testing of High Rate, Gel Polymer Electrolyte Li-Ion Cells Cycle Life Performance at Room Temperature (100% DOD)

Discharge Capacity (Ah)



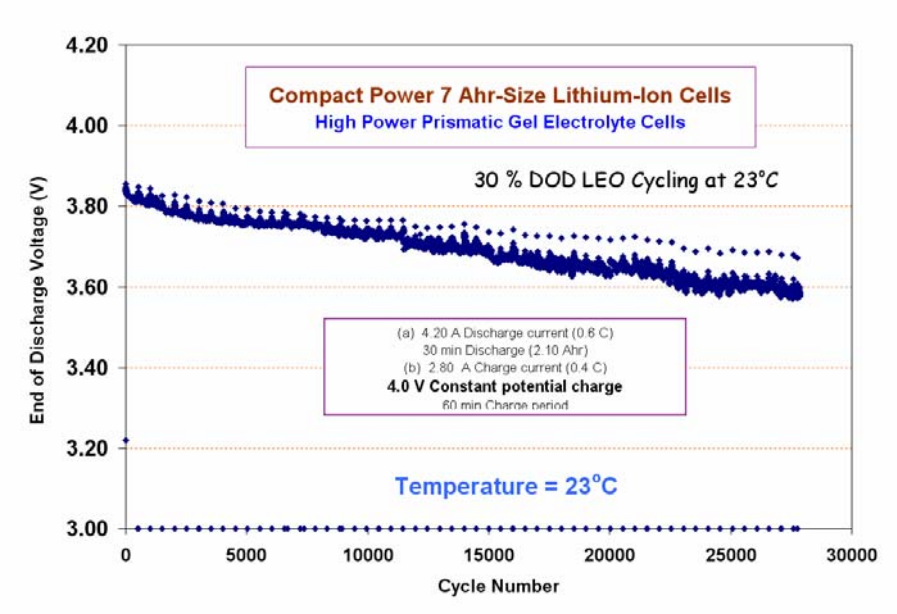
Watt-Hour Efficiency (%)



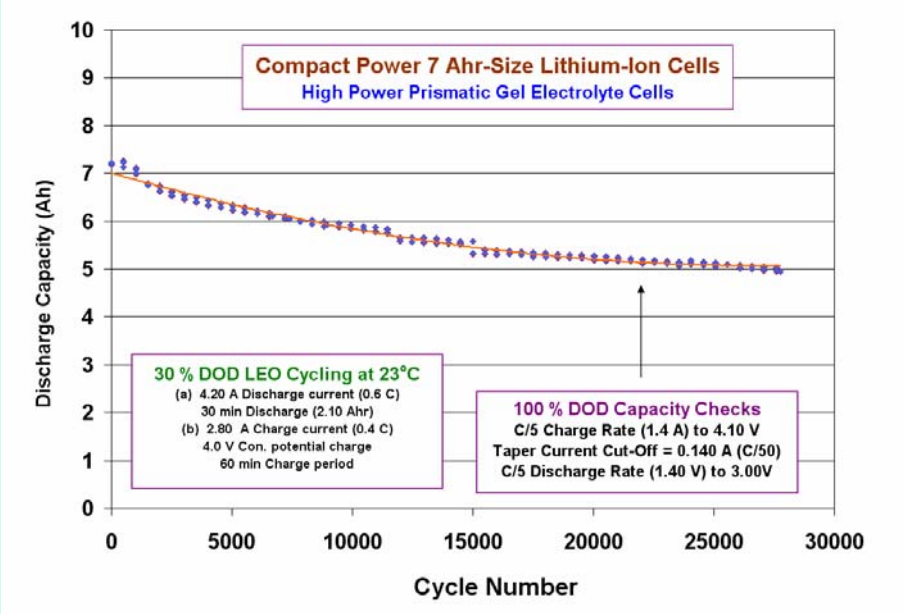
- Over 4,800 deep discharge cycles have been demonstrated with minimal capacity fade (100 % DOD, 3.0-4.1V) (~ 61 % of initial capacity)
- Very high, and stable, watt-hour efficiency observed (~97%) throughout cycling attributable to stable chemistry and cell design.
- On test since Feb. 2002 (> 5.0 years)

Performance Testing of High Rate, Gel Polymer Electrolyte Li-Ion Cells Cycle Life Performance at Room Temperature (30% DOD)

End-of-Discharge Voltage (EODV)



100% DOD Capacity Checks

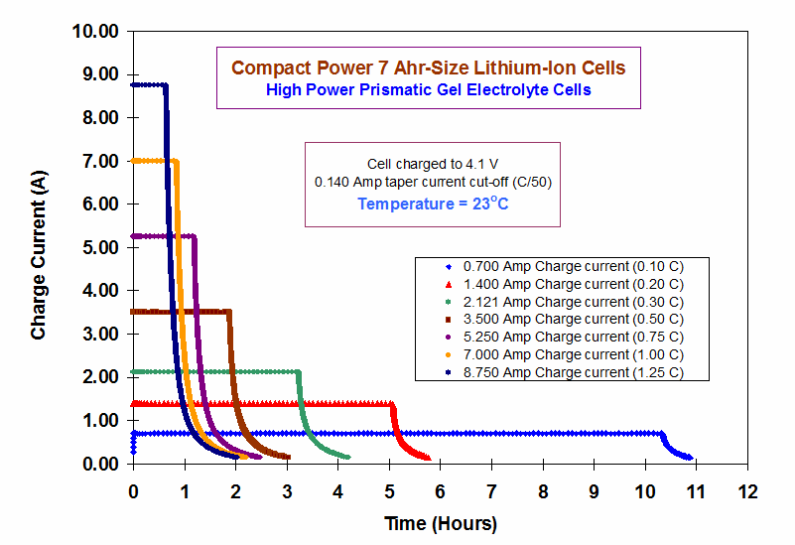


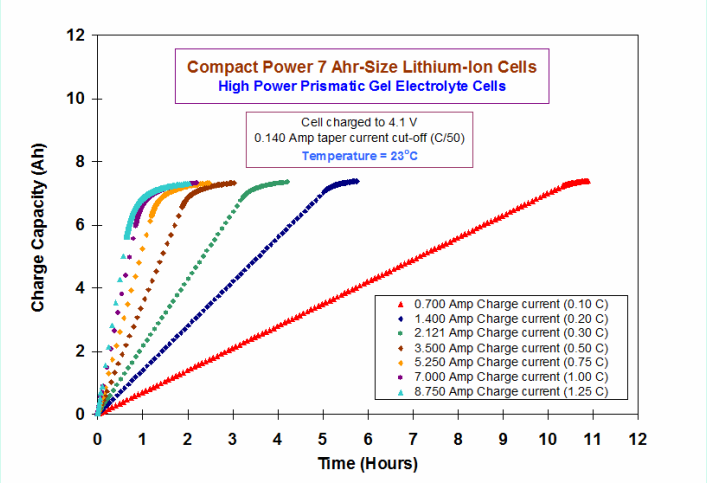
- **Over 28,000 30% DOD cycles have been demonstrated (LEO test) to-date**
  - **100 % DOD capacity checks taken every 500 cycles**
  - **> 70% of initial capacity observed after 27,000 cycles**
  - **Minimal change in EODV observed**
  - **On test since March. 2002 (> 5.0 years)**

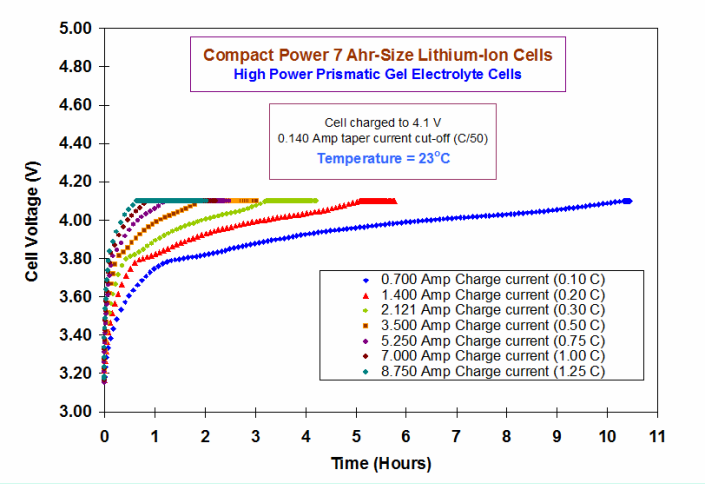
Compact Power Gel Polymer Electrolyte Li-Ion Cells

Charge Rate Characterization Tests

Performance at 23°C







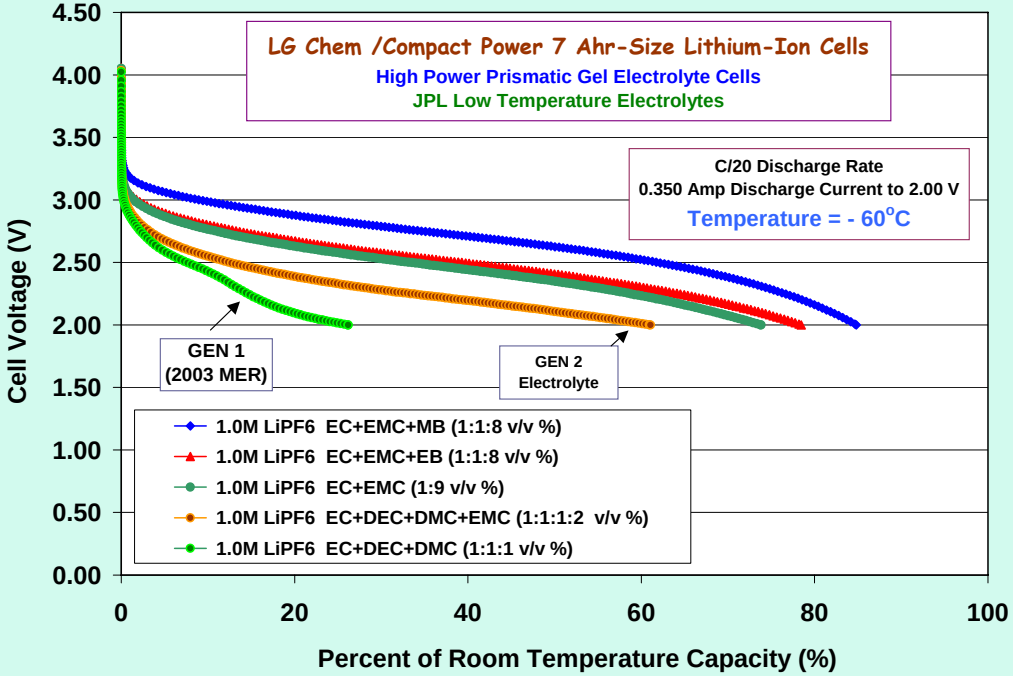
Performance Testing of High Rate, Gel Polymer Li-Ion Cells with Ester-Based Electrolytes at Low Temperatures

- **High power 7 Ah cells fabricated by Compact Power,Inc. (LG Chem) containing JPL developed Low temperature electrolytes:**
  - **1.0 M $LiPF_6$ EC+EMC (1:9 v/v %)**
  - **1.0 M $LiPF_6$ EC+EMC+EB (1:1:8 v/v %)**
  - **1.0 M $LiPF_6$ EC+EMC+MB (1:1:8 v/v %)**
  - **1.0 M $LiPF_6$ EC+DEC+DMC+EMC (1:1:1:2 v/v %)**
  - **1.0 M $LiPF_6$ EC+DEC+DMC+EMC (1:1:1:3 v/v %)**
  - **1.0 M $LiPF_6$ EC+DEC+DMC (1:1:1) (Baseline – 2003 MER Rover Electrolyte)**

M. C. Smart, B. V. Ratnakumar, A. Behar, L.D. Whitcanack, J.-S. Yu, M. Alamgir, “Gel Polymer Electrolyte Lithium-Ion Cells with Improved Low Temperature Performance”, ***J. Power Sources***, **165 (2)**, 535-543 (2007).

Performance Testing of High Rate, Gel Polymer Li-Ion Cells with Ester-Based Electrolytes at Low Temperatures

Discharge Performance at –60°C (C/20 Rate)

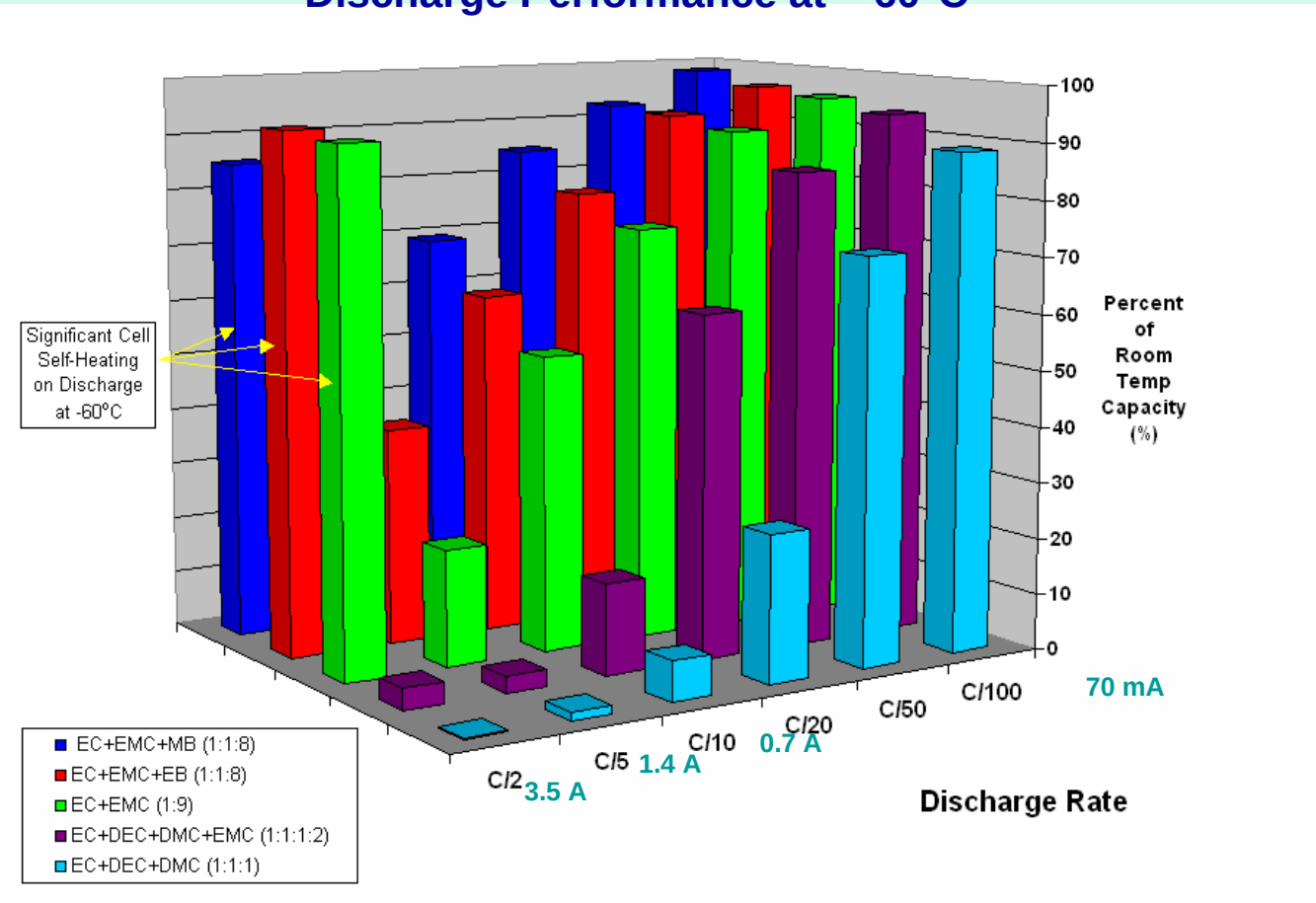


- **Over a threefold improvement in the low temperature performance of ester-based electrolytes compared with earlier generation ternary mixture (MER 2003 Rover electrolyte)**

M. C. Smart, B. V. Ratnakumar, L.D. Whitcanack, Ji-Sang Yu, Mohamed Alamgir, "Low Temperature Ester-Based Electrolytes and their Demonstration in High Power, Gel Polymer Electrolyte Lithium-ion Cells" , 207th Meeting of the Electrochemical Society, Quebec City, Canada, May. 19, 2005.

Performance Testing of High Rate, Gel Polymer Li-Ion Cells with Ester-Based Electrolytes at Low Temperatures

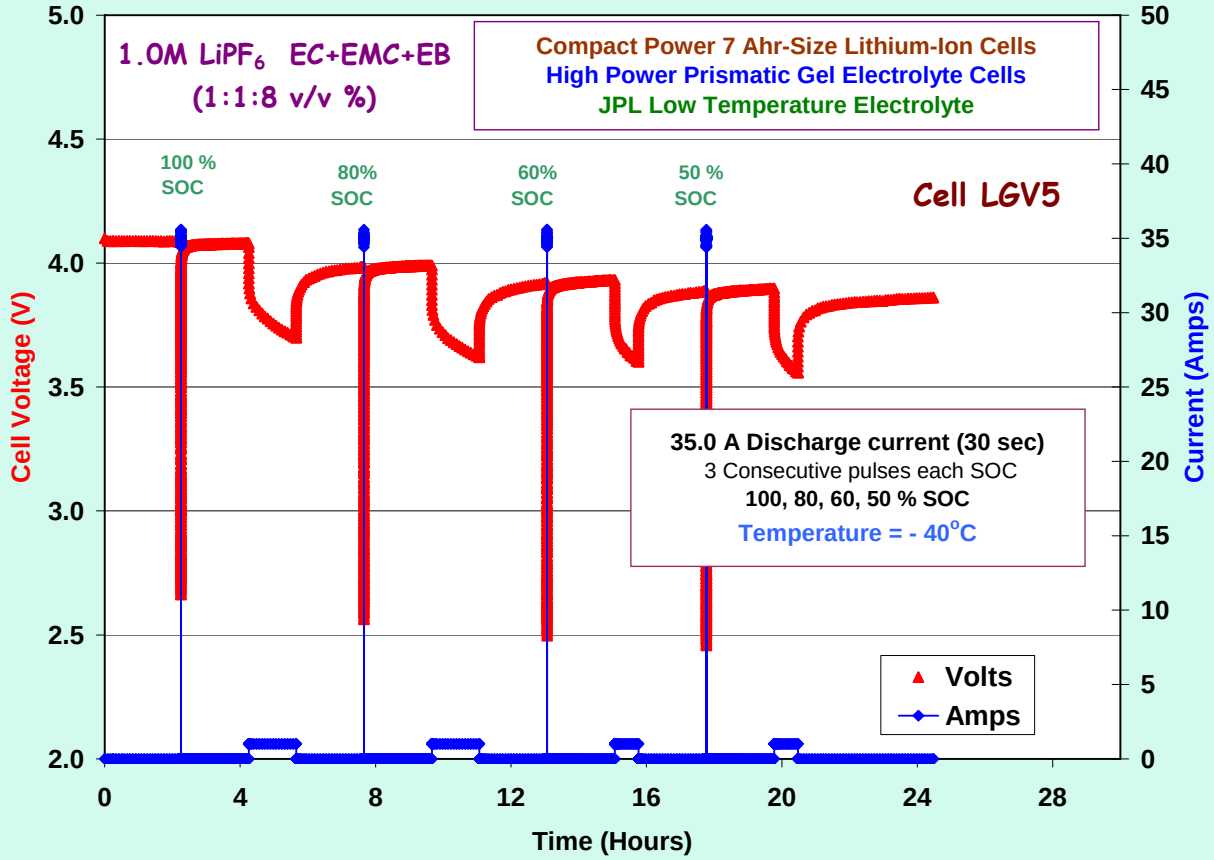
Discharge Performance at – 60ºC



- **Nearly full capacity was delivered with the methyl-butyrate (MB) containing electrolyte at –60ºC using low rates (C/100) and still delivered ~ 85% of the room temperature capacity using higher rates (C/20).**

Performance Testing of High Rate, Gel Polymer Li-Ion Cells with Ester-Based Electrolytes at Low Temperatures

Discharge Performance at – 40°C (MB-Based Electrolyte)



- **High discharge pulses supported at -40°C (e.g., 5C rates as in HEV Load profile for "cold cranking" requirements**

Summary

- Pouch cells from different manufacturers, e.g., SKC (gel polymer), Quallion, Compact Power (gel polymer) and LTC Li-ion cells have been well characterized at different temperatures for their capacities as function of charge and discharge rates and impedance from DC current-interrupt method. These data will serve as baseline for the thermal vac/high temperature cycling tests.
- The specific energies of the pouch cells are indeed 20-30% higher than the conventional metal-cased cells
- Plans are underway to perform EIS measurements as well before initiating thermal vac, high temperature cycling and possibly variable temperature cycling, in addition to room temperature cycling to assess the integrity of the plastic enclosures.
- Also plans are underway to include other pouch cells (eg., Saehan)

Acknowledgments

The work described here was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, for the NESC Advanced Battery Technology Program, under contract with the National Aeronautics and Space Administration (NASA).