Improved Wide Operating Temperature Range of High Rate Nano-Lithium Iron Phosphate Li-Ion Cells with Methyl Butyrate-Based Electrolytes

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Outline

- Objectives and Approach
- Introduction
- *Performance of COTS A123 $LiFePO_4$-Based Li-Ion Cells*
  - 100% DOD Cycle Life Performance
  - Partial DOD LEO Cycle Life Performance
  - Discharge Rate Capability at Different Temperatures
- *A123 $LiFePO_4$-Based Li-Ion Cells with JPL Electrolytes*
  - Discharge Rate Capability at Low Temperatures
  - Cycle Life Performance at Room Temperature
  - Cycle Life Performance at High Temperatures (up to 60oC)
  - Variable Temperature Cycling
  - Charge Characteristics at Low Temperatures
- Conclusions
- Acknowledgement

Outline

- **DOE desires Li-ion batteries than can operate over a wide temperature range *(i.e., -30 to +60°C).* and provide good life characteristics for HEV and PHEV applications**
- **NASA also desires Li-ion batteries than can operate over a wide temperature range for future planetary lander and rover applications.**

Objectives and Approach

- ***Develop advanced Li-ion electrolytes that enable cell operation over a wide temperature range (i.e., -30 to +60°C).***
- **Improve the high temperature stability and lifetime characteristics of wide operating temperature electrolytes.**
- **Define the performance limitations at low and high temperature extremes, as well as, life limiting processes.**
- **Demonstrate the performance of advanced electrolytes in large capacity prototype cells.**

Why Battery Performance Degrades at Low Temperatures?

- Increased cell and electrode polarizations in general
  - Ohmic, kinetic as well as mass transfer
- Increased Ohmic polarization
  - Mainly contributed by the electrolyte
    - Reduced Ionic mobility in electrolyte.
      - Slow diffusion of ions mainly due to increased viscosity of solvent components
    - Reduced ionic strength due to lower solubility at low temperatures.
- Slower electrode kinetics
  - Slower charge transfer at the electrodes governed by Arrhenius dependence.
  - Charge-transfer over film-covered electrodes?
- Enhanced mass transfer polarization
  - Slow diffusion of (Li^+) ion in solution caused by increased electrolyte viscosity
  - Slower diffusion of reactant/product species in the electrode lattices (bulk diffusion).
  - Surface films complicating the charge transfer and diffusion process.
- Likelihood of lithium plating is possible at high charge rates at low temperatures

Low Temperature Lithium Ion Electrolytes

Electrolyte Development: Approach/Background

General Approaches to Improve Low Temperature Performance of SOA Electrolytes

- Optimization of linear carbonate type and concentration
- Optimization of cyclic carbonate concentration (i.e., EC content)
- Use of aggressive low viscosity co-solvents
- Optimization of electrolyte salt type and concentration
- Use of "SEI promoting" additives

- These approaches are often used in conjunction to achieve desired result.
- In addition, the specific application can influence low temperature electrolyte selection (i.e., low temperature requirement, life requirement, or the need for high temperature resilience, etc.).

Low Temperature Lithium Ion Electrolytes

Background: Use of Ester-Based Solvents

- **Ohta, and coworkers (Matsushita): have investigated the use of MA-, EP-, and MP-based systems (i.e., EC+DEC+MP)**

(1) A. Ohta, H. Koshina, H. Okuno, and H. Murai, *J. Power Sources*, **54 (1)**, 6-10 (1995).

- **At JPL, we have previously studied coworkers have studied MF-, EA-, MA-, EP-, and EB-based systems:**

(2) M.C. Smart, C.-K. Huang, B.V. Ratnakumar, and S. Surampudi,, Proceedings of the 37th Power Sources Conference, 239-242 (1996).

(3) M. C. Smart, B. V. Ratnakumar, S. Surampudi, Y. Wang, X. Zhang, S. G. Greenbaum, A. Hightower, C. C. Ahn, and B. Fultz., *J. Electrochem. Soc*., **146**, 3963 (1999).

(4) M.C. Smart, B.V. Ratnakumar, S. Greenbaum, and S. Surampudi, 194th Electrochemical Society Meeting, Abst. # 159, Boston, Mass, Nov. 4, 1998.

(5) M. C. Smart, B. V. Ratnakumar, and S. Surampudi, *J. Electrochem. Soc*., **149 (4)**, A361-A370 (2002)

- **Herreyre and coworkers have studied EA- and MB-based systems (SAFT): (EC+DMC+EA, EC+DMC+MB, PC+DMC+MB)**

(6) S. Herreyre, O. Huchet, S. Barusseau, F. Perton, J. M. Bodet, and Ph. Biensan, *J. Power Sources*, **97-98**, 576 (2001).

- **Shiao and coworkers have studied EA- and MA-based systems (Maxpower):** [EC+EMC+MA (1:1:1 v/v %) and EC+DMC+MA (1:1:1 v/v %)]

(7) H. –C. Shiao, D. Chua, H. –P., Lin, S. Slane, and M. Solomon, *J. Power Sources*, **87**, 167-173 (2000).

- **Sazhin and coworkers have studied EP- and MA-based systems (Samsung):** [EC–DEC–EP (30:35:35), and EC–EMC–EP (30:30:40)]

(8) S. V. Sazhin, M. Y. Khimchenko, Y. N. Tritenichenko, and H. S. Lim, *J. Power Sources*, **87**, 112-117 (2000).

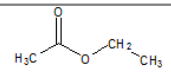
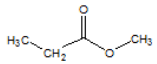
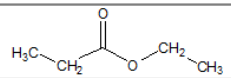
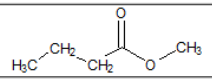
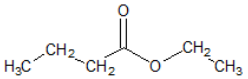
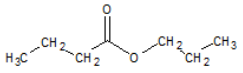
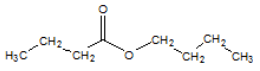
- **Jow and coworkers have studied EA- and GBL-based systems (Army Res. Lab.):** [LiBOB in EC–DMC-GBL–EA]

(9) T. R. Jow, K. Xu, M. S. Ding, S. S. Zhang, J. L. Allen, and K. Amine, *Journal of The Electrochemical Society*, 151, A1702-A1706 (2004).

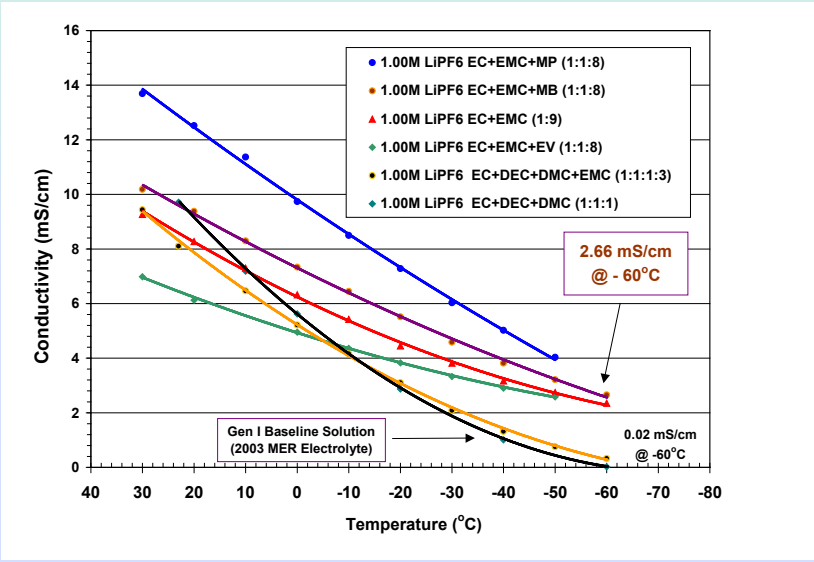
Low Viscosity, Low Melting Electrolyte Co-Solvents

Candidate High Molecular Weight Ester-Based Co-Solvents

Properties of Ester Co-Solvents

Chemical Structure	Name	m.p.	b.p	Viscosity (25°C)	Density	Dielectric Constant
	Ethyl acetate	-84°C	77°C		0.902	
	Methyl propionate	-87.5°C	79.8°C	0.431 cP	0.915	6.200
	Ethyl propionate	-73°C	99°C		0.888	
	Methyl butyrate	-85.8°C	102.8°C	0.541 cP	0.898	5.48
	Ethyl butyrate	-93°C	120°C	0.639 cP	0.878	5.18
	Propyl butyrate	-95.2°C	143°C		0.873	4.3
	Butyl butyrate	-91.5°C	164°C		0.829	

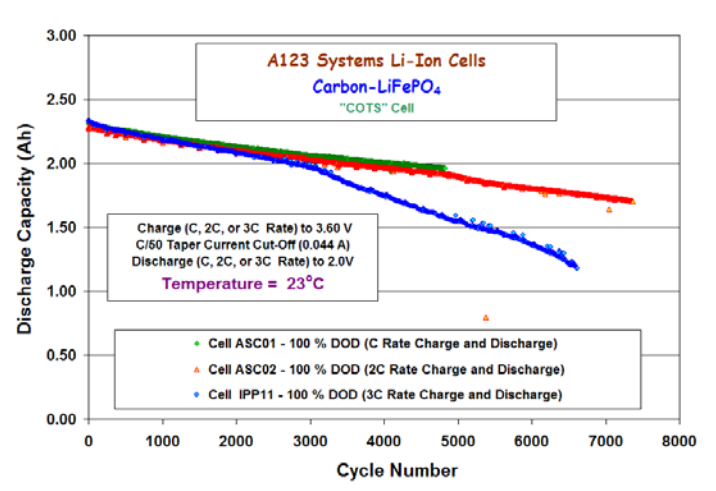
Ionic Conductivity of Ester Based Electrolytes

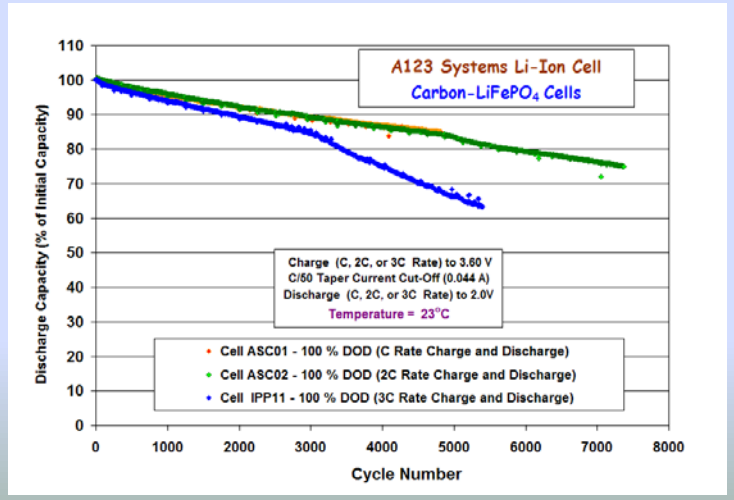


A123 2.20Ah High Power COTS Lithium-Ion Cells

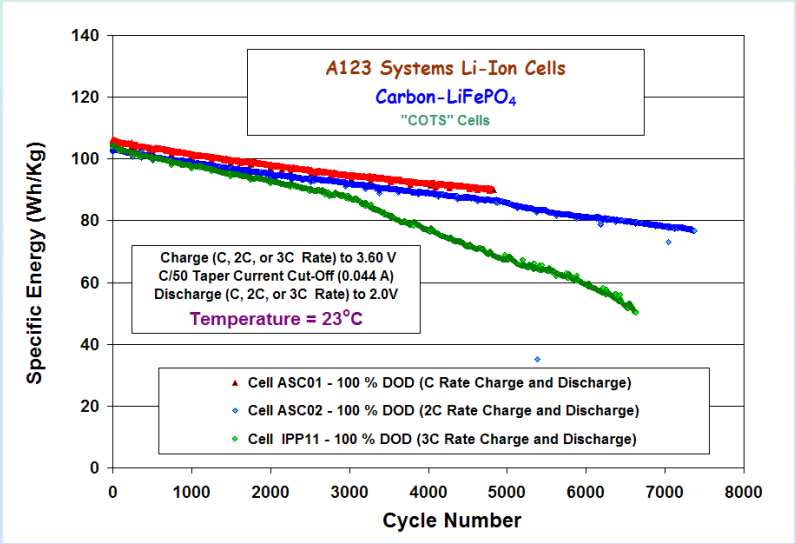
100 % DOD Cycle Life Performance at 23°C

Discharge Capacity (Ah)





Discharge Energy (Wh/Kg)

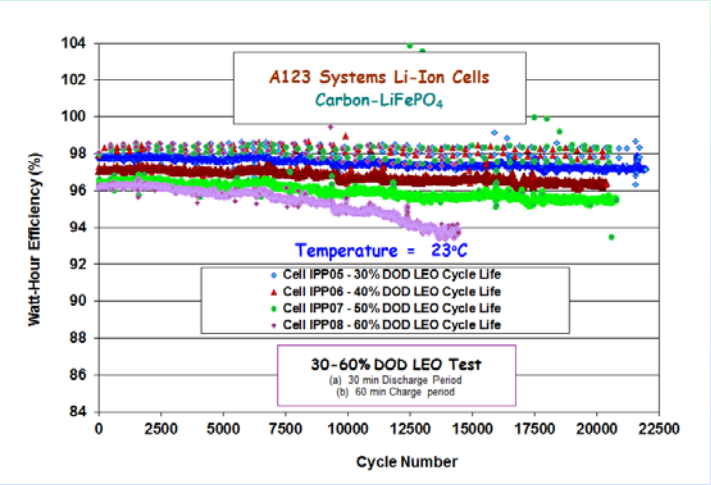


- Excellent life characteristics have been displayed thus far, even when using aggressive rates (i.e., 3C charge and discharge).
- Over 90% of original capacity displayed after > 2,000 full discharge cycles.

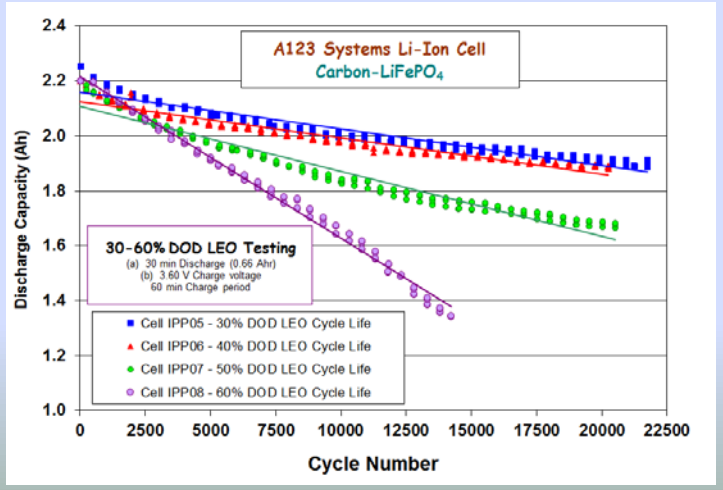
A123 2.20 Ah High Power Lithium-Ion Cells

Low Earth Orbit (LEO) Cycle Life Performance

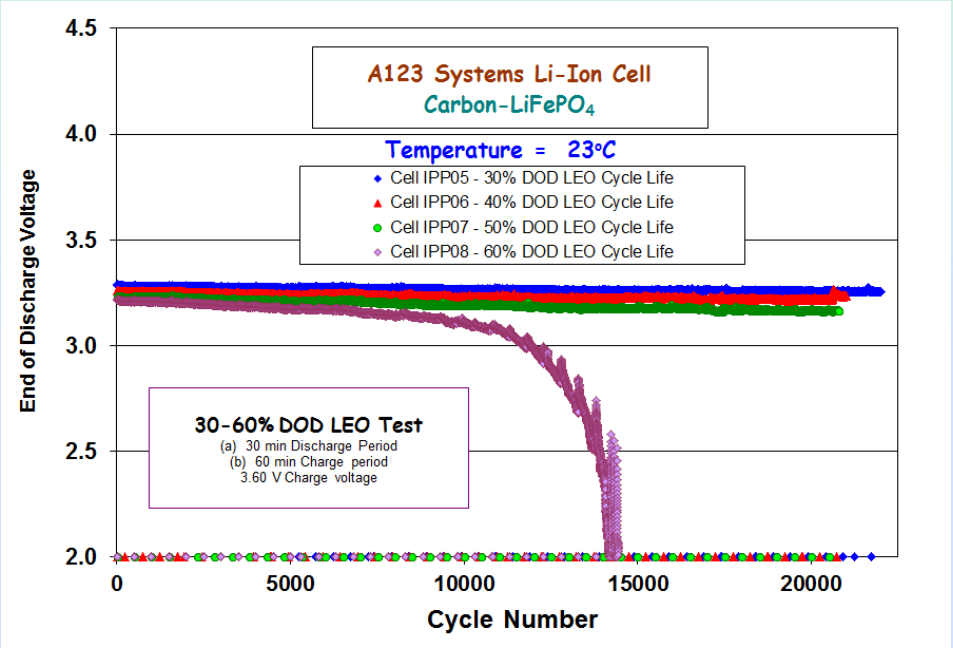
Watt-Hour Efficiency (%)



Capacity Loss During Cycling



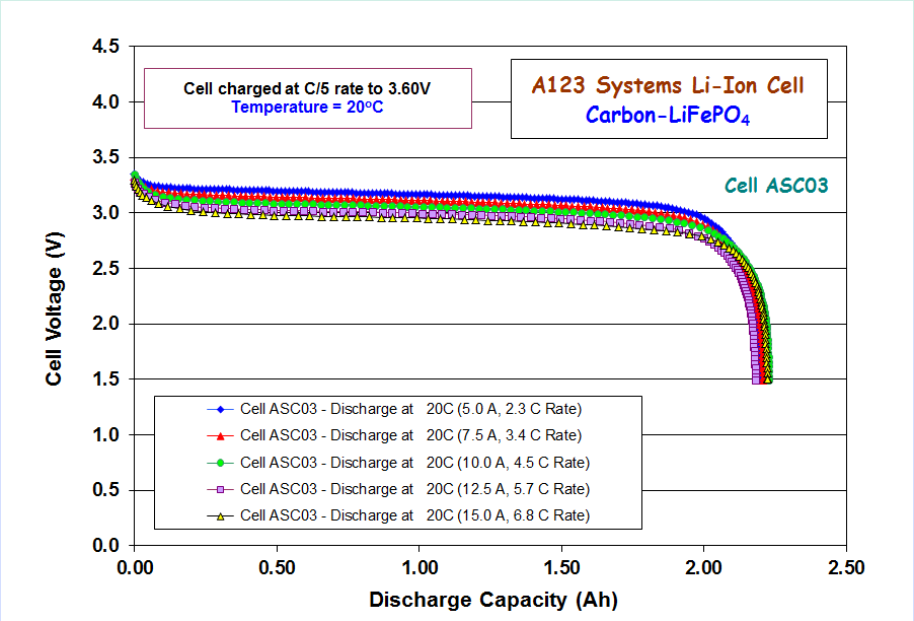
End of Discharge Voltage (EODV)



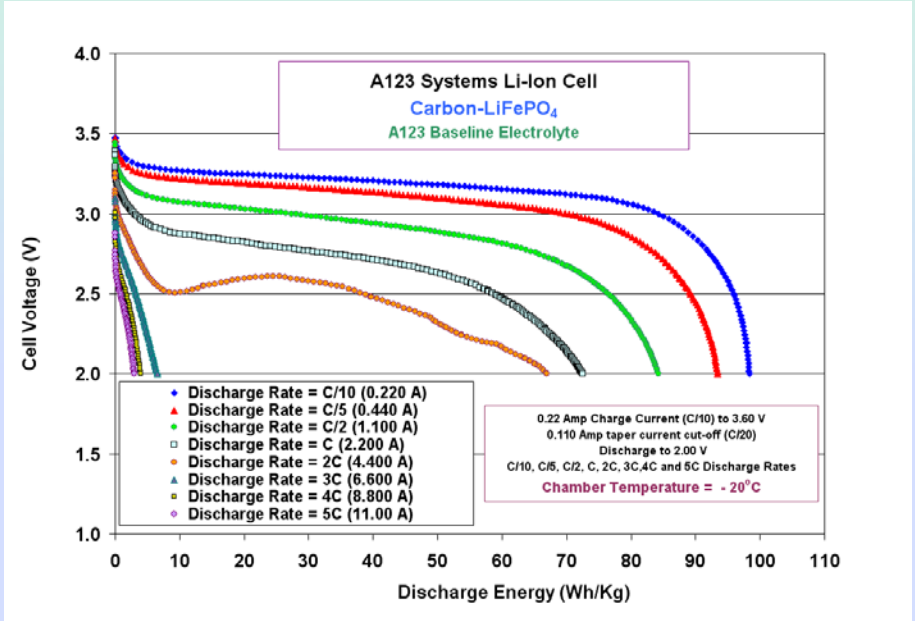
- ***Excellent performance observed to-date, even when aggressive DOD's are employed (i.e., up to 50 % DOD)***
- ***Data represents over 4 years of cycling***

A123 2.20 Ah High Power Lithium-Ion Cells
Discharge Rate Performance of COTS Cells

Rate Characterization Test at 23°C
Discharge Energy (Wh/kg)



Rate Characterization Test at -20°C
Discharge Energy (Wh/kg)



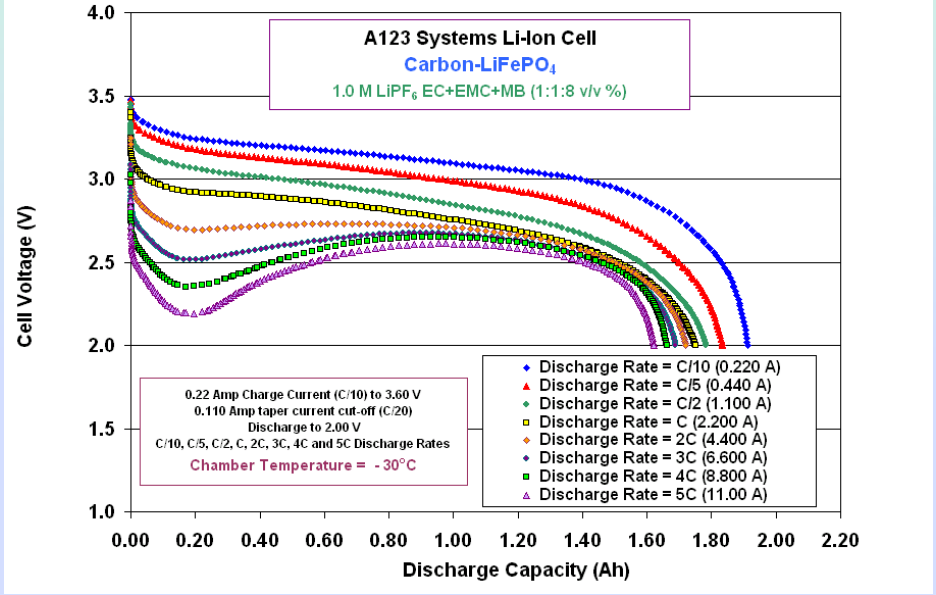
- **Low voltage loss and capacity decrease even at high rates of > 6C indicative of high power capability**
- **Encouraging low temperature performance capability (cell charged at -20°C)**

One intent is to improve the low temperature performance, while still preserving the excellent high temperature stability.

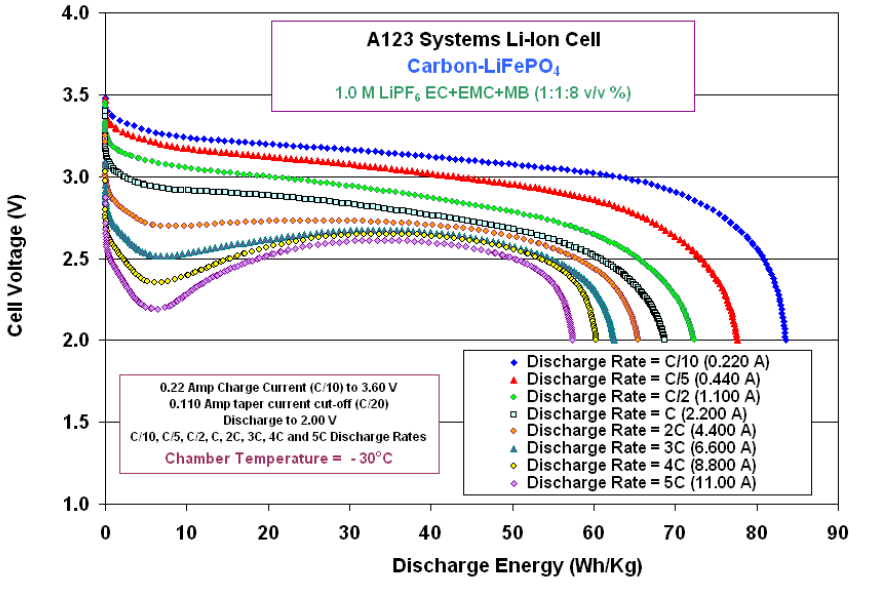
A123 2.20 Ah High Power Lithium-Ion Cells

Discharge Rate Characterization Testing at - 30°C

Discharge Capacity (Ah)



Discharge Energy (Wh/Kg)

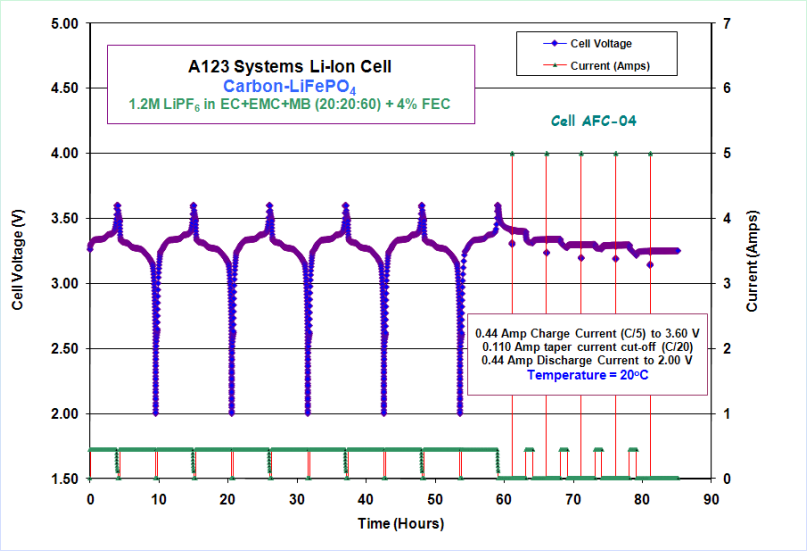


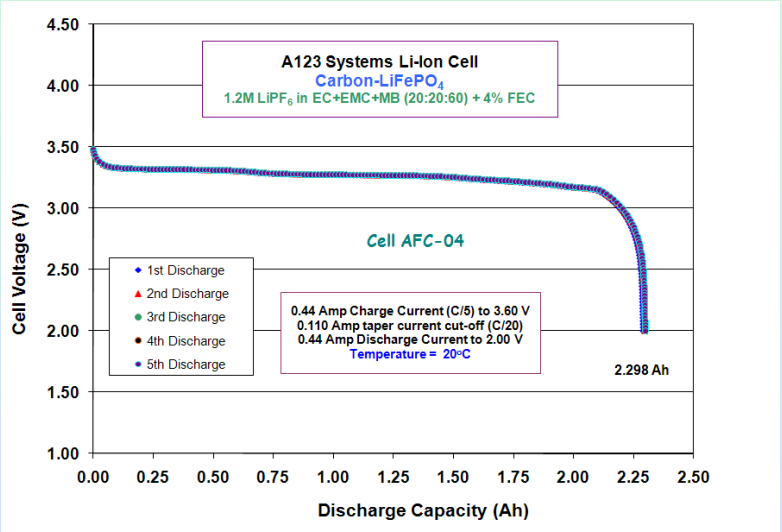
- 1.4M $LiPF_6$ in EC+EMC+MB (10:10:80)
- Cell both charged and discharge at -30°C

M. C. Smart, B. V. Ratnakumar, L. D. Whitcanack, A. S. Gozdz, and S. Mani, 214th Meeting of ECS, Honolulu, HI , Oct. 15th 2008.

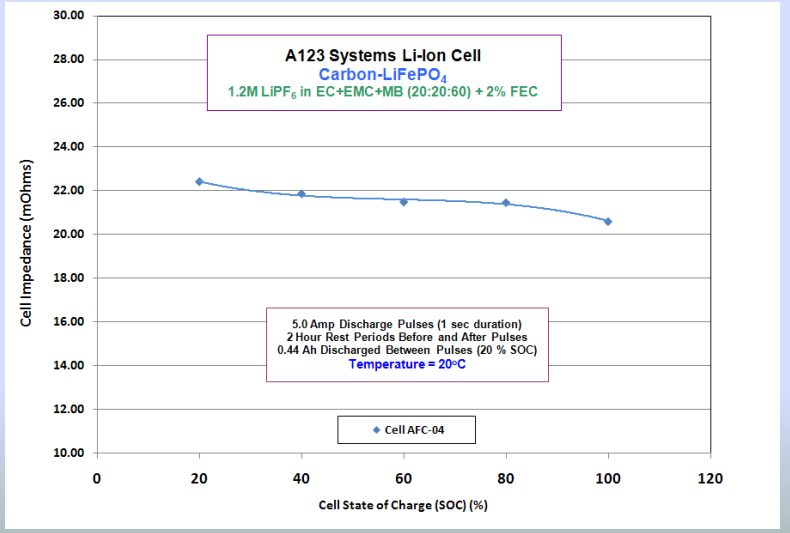
A123 LiFePO4-Based Lithium-Ion Cells

Results of Initial Characterization





- **Cells obtained from A123 Systems contains promising JPL developed electrolytes, namely**
  1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 vol %) + 4% FEC and
  1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 vol %) + 2% VC
- **A123 Systems is actively developing Li-ion batteries for automotive applications**
- **Currently testing technology over a wide range of conditions (i.e., -60 to +60°C).**



A123 LiFePO4-Based Lithium-Ion Cells

Results of Initial Characterization

Cell Series	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)	Calculated Impedance (mOhms) (40% SOC)	Calculated Impedance (mOhms) (20% SOC)
TWJ00095	ACC-01	75.5	0.0755	3.300	2.1845	7.079	93.77	12.73	13.06	13.24	13.55	14.13
TWJ00095	ACC-02	75.5	0.0755	3.292	2.1287	6.882	91.16	12.97	13.18	13.31	13.70	14.19
TWJ00095	ACC-03	76.2	0.0762	3.292	2.2123	7.187	94.32	11.81	12.21	12.33	12.63	13.03
TWJ00095	ACC-04	76.2	0.0762	3.300	2.2122	7.194	94.40	10.10	10.19	10.38	10.59	11.02
TWJ00095	ACC-05	75.8	0.0758	3.309	2.2422	7.284	96.10	13.35	14.11	14.16	14.33	14.83
TWJ00095	ACC-06	76.0	0.0760	3.311	2.2020	7.162	94.23	12.24	12.76	12.85	13.06	13.58
TWJ00095	ACC-07	75.6	0.0756	3.309	2.2146	7.202	95.26	12.12	12.82	12.85	13.09	13.52
TWJ00095	ACC-08	76.2	0.0762	3.307	2.2495	7.308	95.91	12.70	13.46	13.37	13.70	14.10
TWJ00095	AVC-01	71.2	0.0712	3.386	2.3674	7.666	107.67	21.00	21.64	21.94	22.31	22.86
TWJ00095	AVC-02	71.0	0.0710	3.388	2.3605	7.645	107.67	20.51	21.12	21.36	21.82	22.34
TWJ00095	AVC-03	71.0	0.0710	3.390	2.3649	7.668	108.00	19.99	21.09	21.18	21.52	22.13
TWJ00095	AVC-04	71.0	0.0710	3.387	2.3458	7.602	107.07	20.63	21.61	21.85	22.16	22.80
TWJ00095	AVC-05	71.2	0.0712	3.389	2.3800	7.712	108.31	19.58	20.28	20.42	20.78	21.30
TWJ00095	AVC-06	71.2	0.0712	3.390	2.3413	7.585	106.53	19.87	20.29	20.57	20.90	21.48
TWJ00095	AVC-07	71.0	0.0710	3.388	2.3637	7.660	107.89	19.78	20.66	20.94	22.25	21.48
TWJ00095	AVC-08	70.8	0.0708	3.384	2.3433	7.591	107.22	17.76	18.43	18.65	19.01	19.59
TWJ00096	AFC-01	71.0	0.0710	3.373	2.3226	7.511	105.79	18.71	19.10	19.47	19.75	20.29
TWJ00096	AFC-02	71.0	0.0710	3.376	2.3115	7.490	105.50	19.50	19.99	20.05	20.48	21.00
TWJ00096	AFC-03	71.0	0.0710	3.376	2.3055	7.474	105.27	19.20	20.05	20.17	20.48	21.00
TWJ00096	AFC-04	71.0	0.0710	3.377	2.2986	7.452	104.96	20.60	21.45	21.48	21.85	22.40
TWJ00096	AFC-05	71.0	0.0710	3.376	2.3167	7.505	105.70	19.13	19.70	19.82	20.16	20.77
TWJ00096	AFC-06	71.0	0.0710	3.375	2.4605	7.974	112.31	20.57	20.87	21.00	21.27	21.85
TWJ00096	AFC-07	71.0	0.0710	3.376	2.3363	7.570	106.62	19.29	19.90	20.08	20.36	20.97
TWJ00096	AFC-08	70.8	0.0708	3.363	2.3376	7.573	106.97	17.49	18.13	18.19	18.65	19.07
Average		72.63	0.07	3.35	2.30	7.46	102.86	17.15	17.75	17.90	18.27	18.74

Baseline Electrolyte

1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 vol %) + 2% VC

1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 vol %) + 4% FEC

A123 2.20 Ah High Power Lithium-Ion Cells

Discharge Rate Characterization Testing

Temperature Range - 20 to - 50°C; Cells Discharged to 0.50V

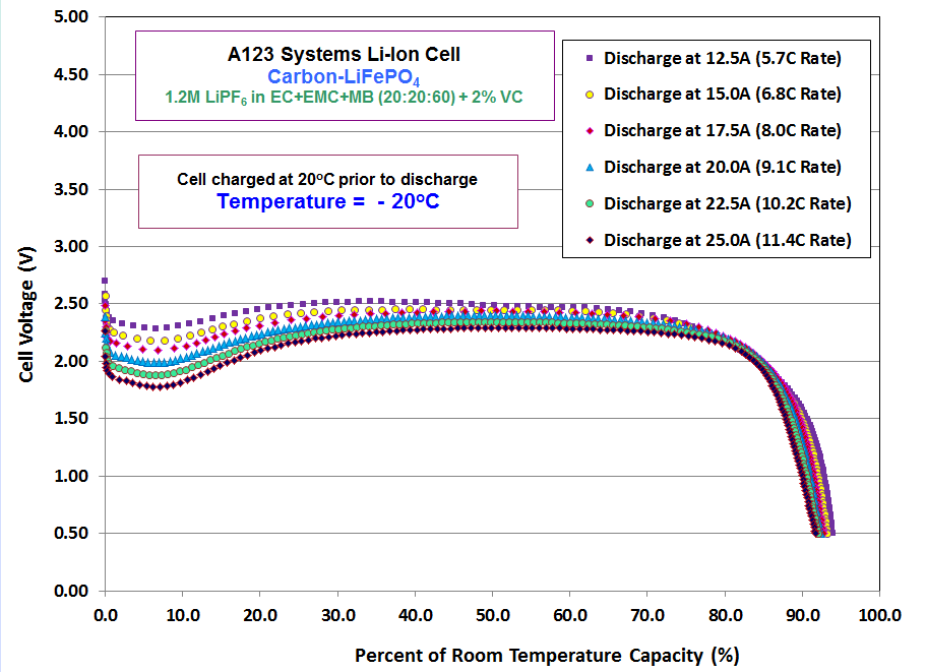
			ACC-05				AVC-05				AFC-05			
			BASELINE Electrolyte				1.2M LiPF6 in EC+EMC+MB (20:20:60 v/v %) + 2% VC				1.2M LiPF6 in EC+EMC+MB (20:20:60 v/v %) + 4% FEC			
Temperature (°C)	Rate	Current (A)	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp
20°C (Initial)	C/5	0.400	2.2422	7.284	102.59	100	2.380	7.712	108.31	100.00	2.3167	7.505	105.70	100
- 20°C	11.40C	25.0	0.0561	0.0792	1.116	2.50	2.1834	4.5665	64.136	91.74	2.1342	4.2968	60.52	92.12
	10.20C	22.5	0.0626	0.0921	1.297	2.79	2.1889	4.7069	66.108	91.97	2.1406	4.6829	65.96	92.40
	9.1C	20.0	0.0717	0.1101	1.550	3.20	2.1977	4.8495	68.111	92.34	2.1470	4.8679	68.56	92.67
	8.0C	17.5	0.0836	0.1335	1.880	3.73	2.2072	4.9812	69.961	92.74	2.1528	5.0226	70.74	92.93
	6.8C	15.0	0.0954	0.1562	2.201	4.26	2.2182	5.0652	71.140	93.20	2.1644	5.1671	72.78	93.42
	5.7C	12.5	2.1367	4.7826	67.360	95.30	2.2356	5.1980	73.006	93.93	2.1729	5.2893	74.50	93.79
- 30°C	11.40C	25.0	0.0133	0.012	0.169	0.59	2.1742	4.2765	60.063	91.35	2.1335	4.1116	57.91	92.09
	10.20C	22.5	0.0134	0.012	0.175	0.60	2.1781	4.3645	61.299	91.52	2.1416	4.4236	62.30	92.44
	9.1C	20.0	0.0169	0.017	0.240	0.75	2.1842	4.4827	62.959	91.77	2.1476	4.5831	64.55	92.70
	8.0C	17.5	0.0209	0.023	0.326	0.93	2.1899	4.5847	64.392	92.01	2.1518	4.7165	66.43	92.88
	6.8C	15.0	0.0258	0.031	0.440	1.15	2.2029	4.6949	65.940	92.56	2.1592	4.8436	68.22	93.20
	5.7C	12.5	0.0326	0.043	0.609	1.45	2.1857	4.6835	65.780	91.84	2.1313	4.8215	67.91	92.00
	4.5C	10.0	0.0422	0.062	0.868	1.88	2.2301	4.8821	68.569	93.70	2.1745	5.0710	71.42	93.86
	3.4C	7.5	0.0575	0.092	1.295	2.56	2.2530	4.9692	69.793	94.66	2.1892	5.1815	72.98	94.49
	2.3C	5.0	2.1277	4.044	56.957	94.89	2.2823	5.0549	70.996	95.89	2.2066	5.2904	74.51	95.25
- 40°C	11.40C	25.0	0.0000	0.000	0.000	0.00	0.0971	0.0623	0.875	4.08	2.1463	4.0134	56.53	92.65
	10.20C	22.5	0.0000	0.000	0.000	0.00	2.1838	4.0748	57.231	91.76	2.1537	4.1968	59.11	92.96
	9.1C	20.0	0.0000	0.000	0.000	0.00	2.1846	4.1430	58.188	91.79	2.1507	4.2987	60.55	92.84
	8.0C	17.5	0.0000	0.000	0.000	0.00	2.1842	4.2071	59.089	91.77	2.1494	4.3991	61.96	92.78
	6.8C	15.0	0.0000	0.000	0.000	0.00	2.1916	4.2578	59.800	92.08	2.1534	4.4934	63.29	92.95
	5.7C	12.5	0.0016	0.0011	0.016	0.07	2.1912	4.2981	60.366	92.07	2.1365	4.5392	63.93	92.22
	4.5C	10.0	0.0060	0.0051	0.072	0.27	2.1763	4.2646	59.896	91.44	2.1500	4.6114	64.95	92.80
- 50°C	11.40C	25.0	0.0000	0.000	0.000	0.00	0.0002	0.0001	0.002	0.01	0.0009	0.0006	0.01	0.04
	10.20C	22.5	0.0000	0.000	0.000	0.00	0.0003	0.0002	0.003	0.01	0.0016	0.0011	0.02	0.07
	9.1C	20.0	0.0001	0.000	0.000	0.01	0.0007	0.0005	0.007	0.03	0.0029	0.0020	0.03	0.13
	8.0C	17.5	0.0000	0.000	0.000	0.00	0.0016	0.0011	0.015	0.07	0.0583	0.0346	0.49	2.52
	6.8C	15.0	0.0000	0.000	0.000	0.00	0.0033	0.0023	0.032	0.14	0.0898	0.0630	0.89	3.88
	5.7C	12.5	0.0000	0.000	0.000	0.00	0.0970	0.0675	0.949	4.07	2.1362	4.1794	58.86	92.21
	4.5C	10.0	0.0000	0.000	0.000	0.00	2.1843	3.8318	53.818	91.77	2.1596	4.2429	59.76	93.22
	3.4C	7.5	0.0000	0.000	0.000	0.00	2.1551	3.6314	51.003	90.55	2.1456	4.1495	58.44	92.61
	2.3C	5.0	0.0000	0.000	0.000	0.00	2.1350	3.4121	47.923	89.70	2.1602	4.1228	58.07	93.25

A123 2.20 Ah High Power Lithium-Ion Cells

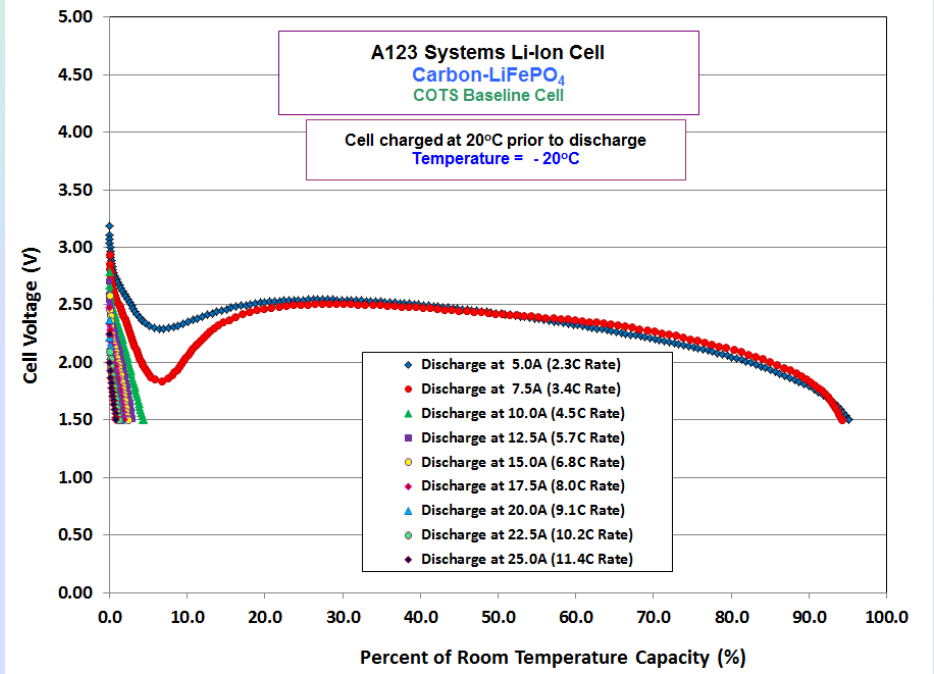
Discharge Rate Characterization Testing

Temperature = -20°C; Cells Discharged to 0.50V

MB-Based Electrolyte



Baseline Electrolyte

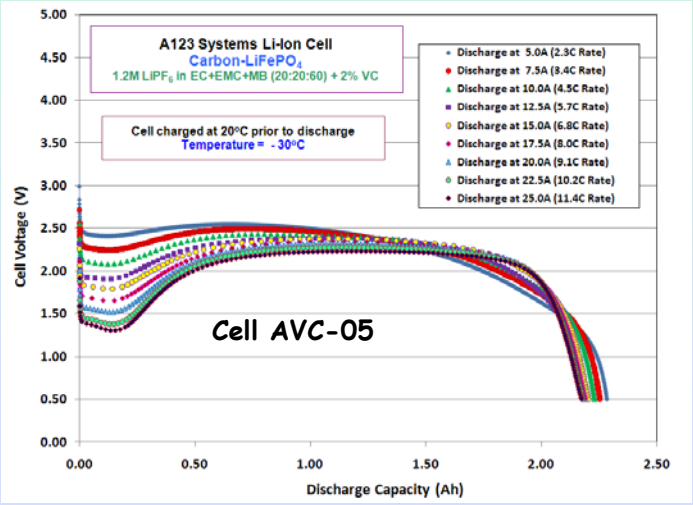


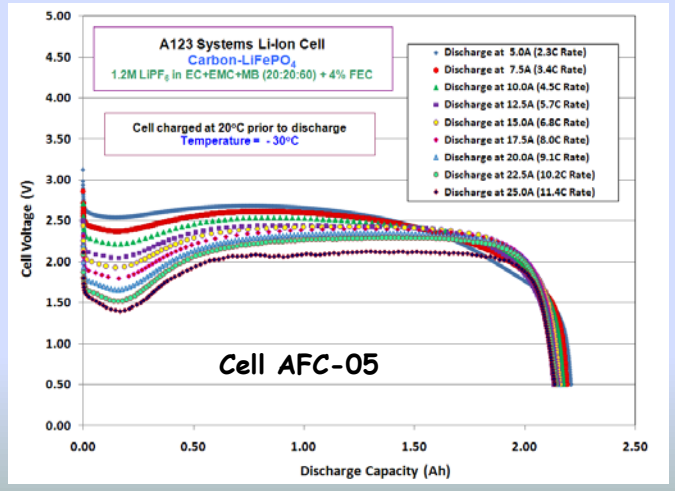
- The MB-based systems are capable of supporting greater than 11C discharge rates at -20°C, with over 90% of the room temperature capacity being delivered.
- Whereas, only moderate rates can be support with baseline system under similar conditions.

A123 2.20 Ah High Power Lithium-Ion Cells

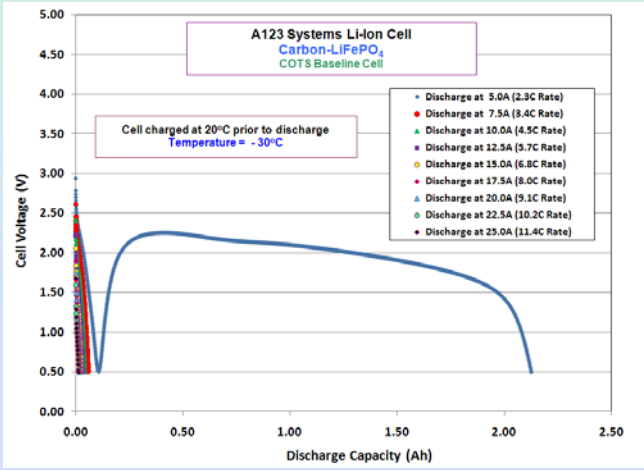
Discharge Rate Characterization Testing

Temperature = -30°C; Cells Discharged to 0.50V





Baseline Electrolyte

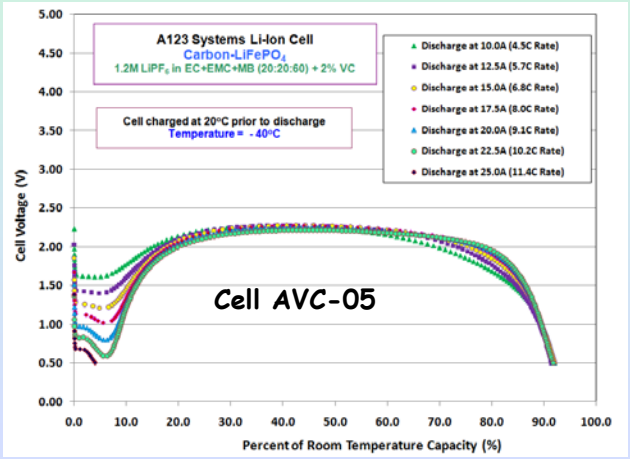


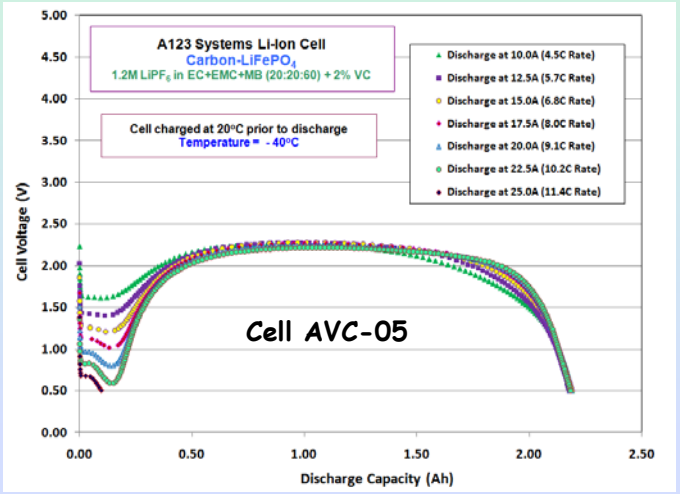
- The MB-based systems are capable of supporting greater than 11C discharge rates at -30°C, with over 90% of the room temperature capacity being delivered.
  - Whereas, negligible capacity delivered with the baseline system under similar conditions.

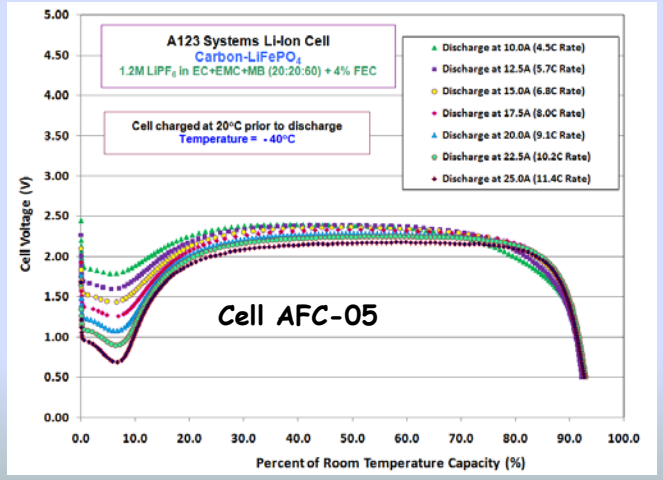
A123 2.20 Ah High Power Lithium-Ion Cells

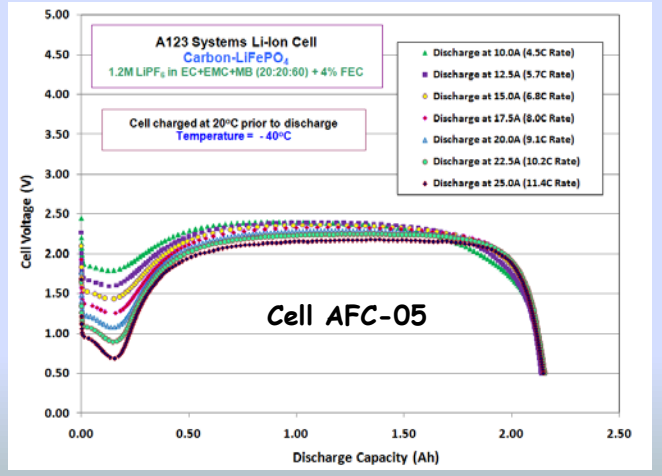
Discharge Rate Characterization Testing

Temperature = -40°C; Cells Discharged to 0.50V









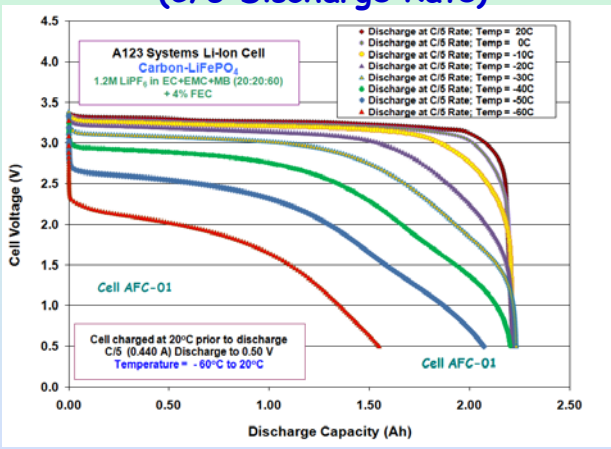
A123 2.20 Ah High Power Lithium-Ion Cells

Discharge Rate Characterization Testing : Cell Discharged to 0.50V

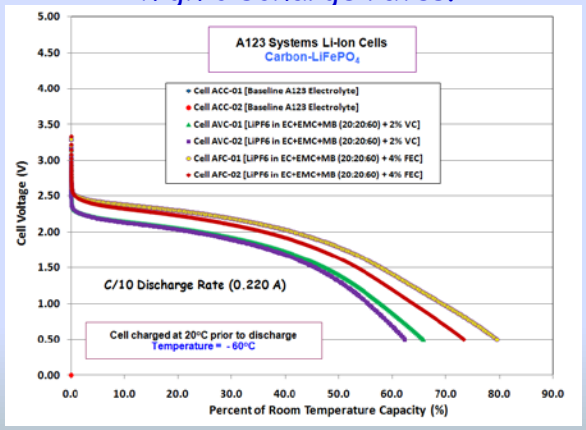
			ACC-01				ACC-02				AVC-01			
			BASELINE Electrolyte				BASELINE Electrolyte				1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 v/v %) + 2% VC			
Temperature (oC)	Rate	Current (A)	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp
20°C (Initial)	C/5	0.400	2.1845	7.079	99.7	100	2.1287	6.882	96.9299	100	2.367	7.666	107.67	100.00
- 50°C	2.0C	4.4	0.0003	0.000	0.003	0.02	0.0009	0.001	0.009	0.04	2.1920	3.6872	51.787	92.59
	1.0C	2.200	0.0071	0.007	0.098	0.32	0.0065	0.006	0.089	0.31	2.0991	3.3378	46.879	88.67
	C/2	1.100	0.0206	0.028	0.396	0.95	0.0200	0.027	0.377	0.94	1.9076	3.2225	45.259	80.58
	C/5	0.440	0.0529	0.091	1.282	2.42	0.0528	0.091	1.276	2.48	1.9441	3.6606	51.412	82.12
	C/10	0.220	0.1101	0.211	2.968	5.04	0.2543	0.344	4.846	11.95	2.0913	4.3253	60.749	88.34
	C/20	0.110	0.1978	0.406	5.714	9.06	0.8887	1.202	16.930	41.75	2.2267	4.9607	69.673	94.06
- 60°C	2.0C	4.400	0.0000	0.000	0.000	0.00	0.0000	0.000	0.000	0.00	0.0776	0.0523	0.735	3.28
	1.0C	2.200	0.0000	0.000	0.000	0.00	0.0000	0.000	0.000	0.00	1.7678	2.1979	30.870	74.67
	C/2	1.100	0.0000	0.000	0.000	0.00	0.0000	0.000	0.000	0.00	1.1856	1.7511	24.594	50.08
	C/5	0.440	0.0000	0.000	0.000	0.00	0.0000	0.000	0.000	0.00	1.2975	2.0892	29.343	54.81
	C/10	0.220	0.0000	0.000	0.000	0.00	0.0000	0.000	0.000	0.00	1.5576	2.6671	37.459	65.79
	C/20	0.110	0.0000	0.000	0.000	0.00	0.0000	0.000	0.000	0.00	1.6461	3.0460	42.781	69.53

			AVC-02				AFC-01				AFC-02			
			1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 v/v %) + 2% VC				1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 v/v %) + 4% FEC				1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 v/v %) + 4% FEC			
Temperature (oC)	Rate	Current (A)	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp
20°C (Initial)	C/5	0.400	2.361	7.645	107.37	100.00	2.3226	7.511	105.79	100	2.3115	7.490	105.50	100
- 50°C	2.0C	4.4	2.2605	4.3563	61.184	95.76	2.1547	3.9919	56.22	92.77	2.0616	3.3731	47.51	89.19
	1.0C	2.200	2.2465	4.0824	57.337	95.17	2.1368	3.8107	53.67	92.00			0.00	0.00
	C/2	1.100	2.1434	3.8110	53.525	90.80	2.0841	3.8386	54.07	89.73	1.8740	3.3751	47.54	81.07
	C/5	0.440	2.0374	3.9063	54.863	86.31	2.0728	4.1971	59.11	89.25	2.0055	4.0077	56.45	86.76
	C/10	0.220	2.1145	4.4063	61.886	89.58	2.1403	4.7116	66.36	92.15	2.1213	4.6323	65.24	91.77
	C/20	0.110	2.2219	4.9761	69.890	94.13	2.2079	5.1914	73.12	95.06	2.2089	5.1795	72.95	95.56
- 60°C	2.0C	4.400	2.2216	3.5010	49.172	94.11	0.6380	1.0049	14.15	27.47	1.8806	2.353	33.14	81.36
	1.0C	2.200	1.4061	1.5815	22.212	59.57	1.8368	2.6085	36.74	79.08	1.3663	1.6266	22.91	59.11
	C/2	1.100	0.9061	1.2827	18.015	38.39	1.6426	2.4223	34.12	70.72	0.9161	1.4289	20.13	39.63
	C/5	0.440	1.1637	1.8289	25.686	49.30	1.5480	2.6287	37.02	66.65	1.2838	2.1715	30.58	55.54
	C/10	0.220	1.4723	2.5295	35.527	62.37	1.8468	3.3788	47.59	79.52	1.6963	3.0543	43.02	73.39
	C/20	0.110	1.5755	2.9099	40.870	66.75	1.9478	3.8672	54.47	83.86	1.8801	3.6737	51.74	81.34

Discharge Capacity vs. Temperature (C/5 Discharge Rate)



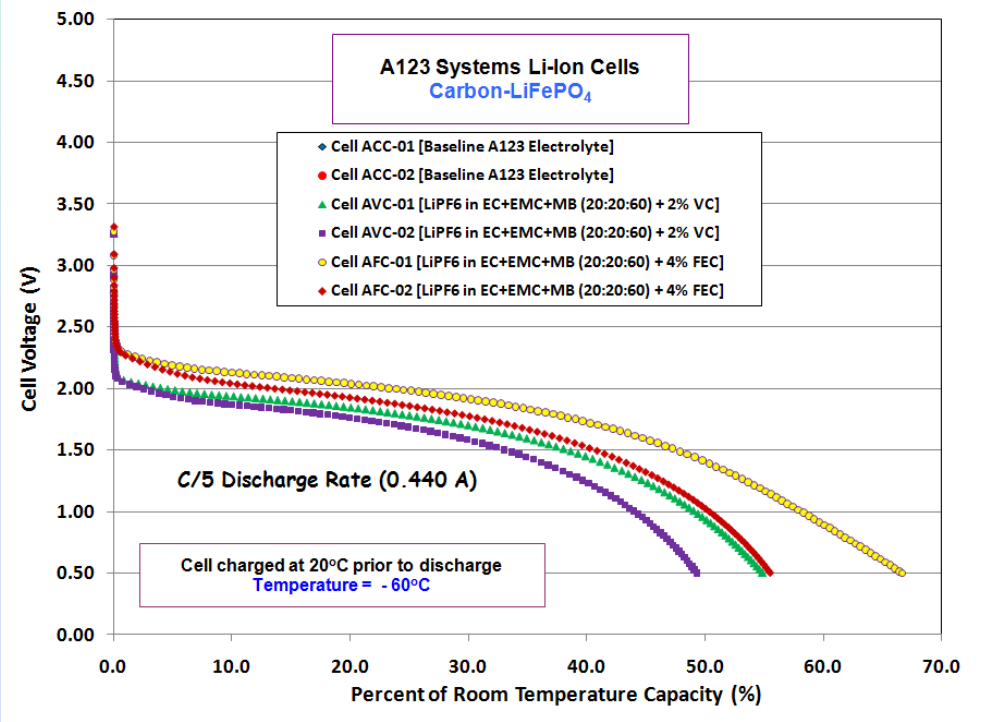
- The MB-based containing FEC was observed to deliver good performance down to -60°C, being able to support high discharge rates.

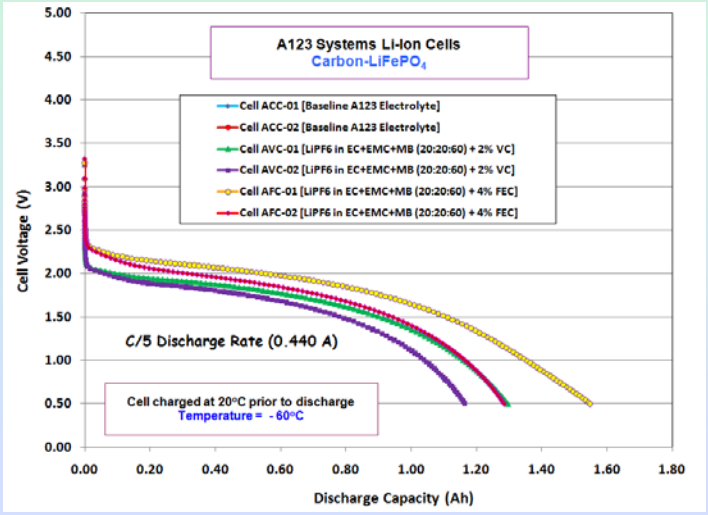


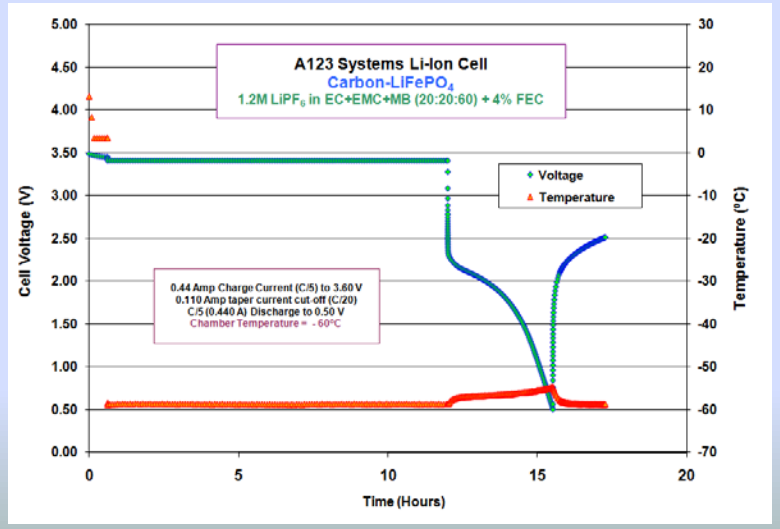
A123 2.20 Ah High Power Lithium-Ion Cells

Discharge Rate Characterization Testing

Temperature = - 60°C; Rate = C/5; Cells Discharged to 0.50V





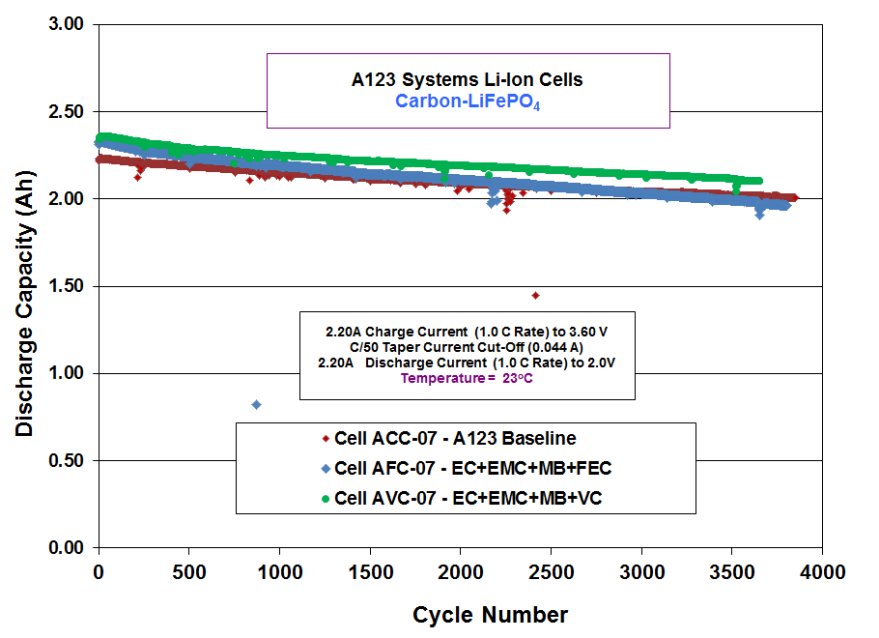


A123 2.20 Ah High Power Lithium-Ion Cells

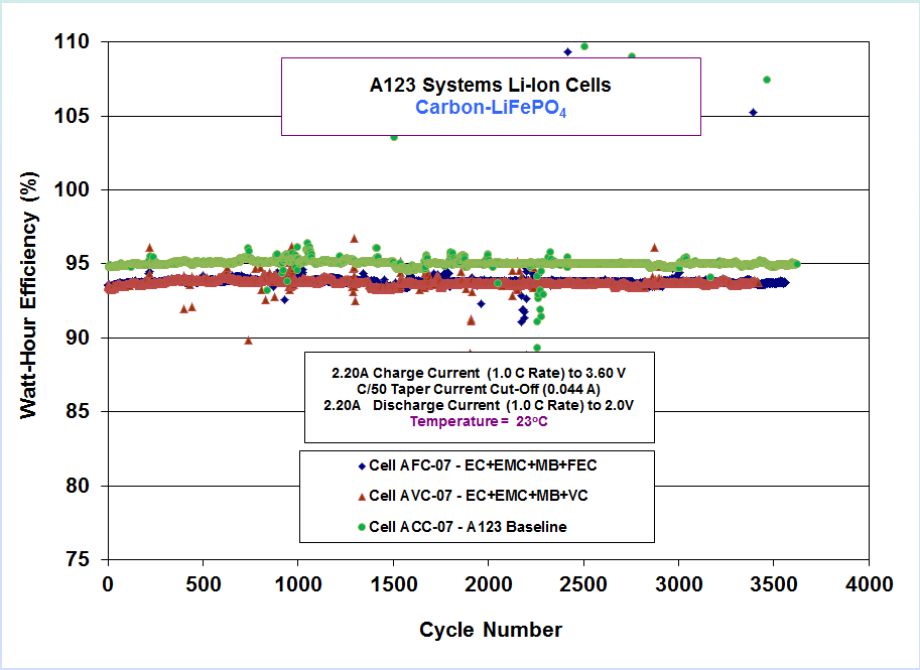
100% DOD Cycle Life Characterization Testing at 23°C

Test Articles (Three Different Electrolyte Variations)

Discharge Capacity (Ah)



Watt-Hour Efficiency (%)



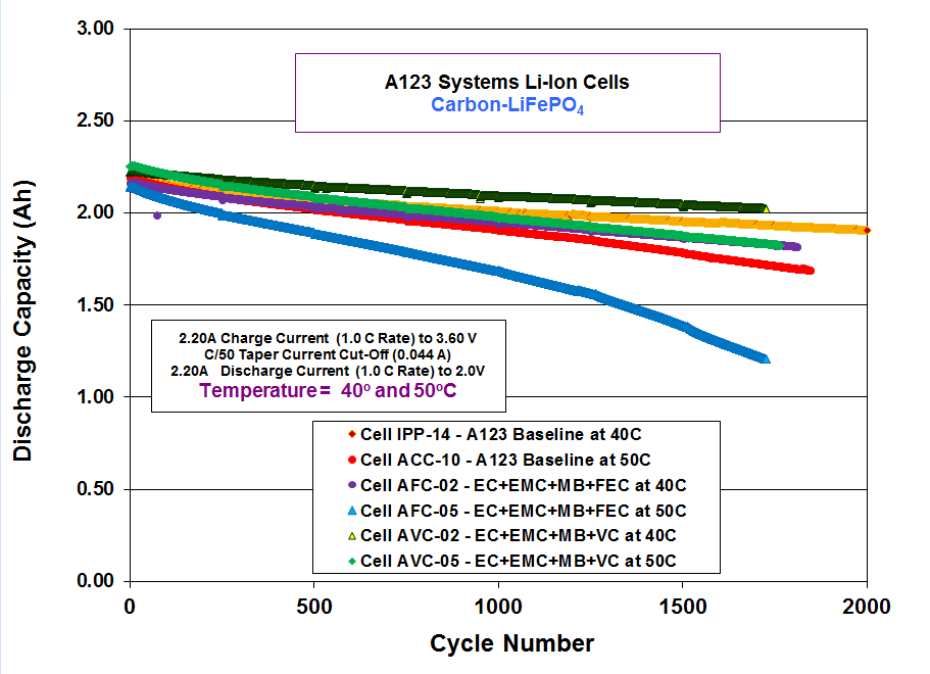
- Although modestly higher capacity fade rates were observed with the MB-based electrolytes compared with the baseline, generally good cycle life characteristics were observed (i.e., over 90% of the initial capacity after 2,000 cycles).
- Observed trend (in increasing capacity fade rate): Baseline < MB+VC < MB+FEC

A123 2.20 Ah High Power Lithium-Ion Cells

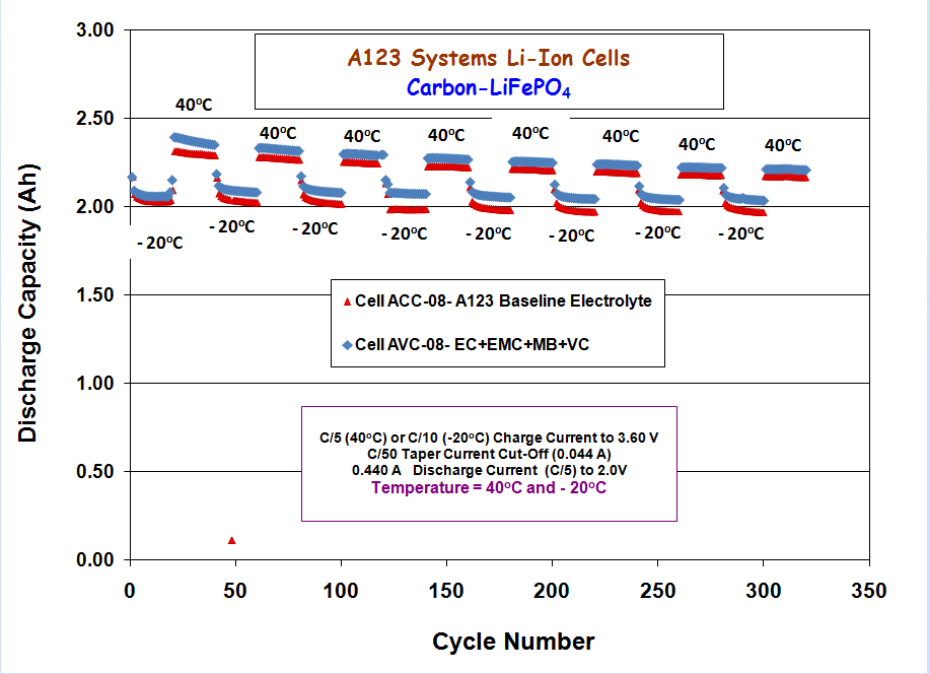
100% DOD Cycle Life Characterization Testing at 40 and 50°C

Test Articles (Three Different Electrolyte Variations)

Cycling at High Temperature



Variable Temperature Cycling



- Generally good resilience to high temperature cycling observed with the MB+VC and MB+FEC systems.
- Good resilience to low temperature charging also observed (no apparent lithium plating).

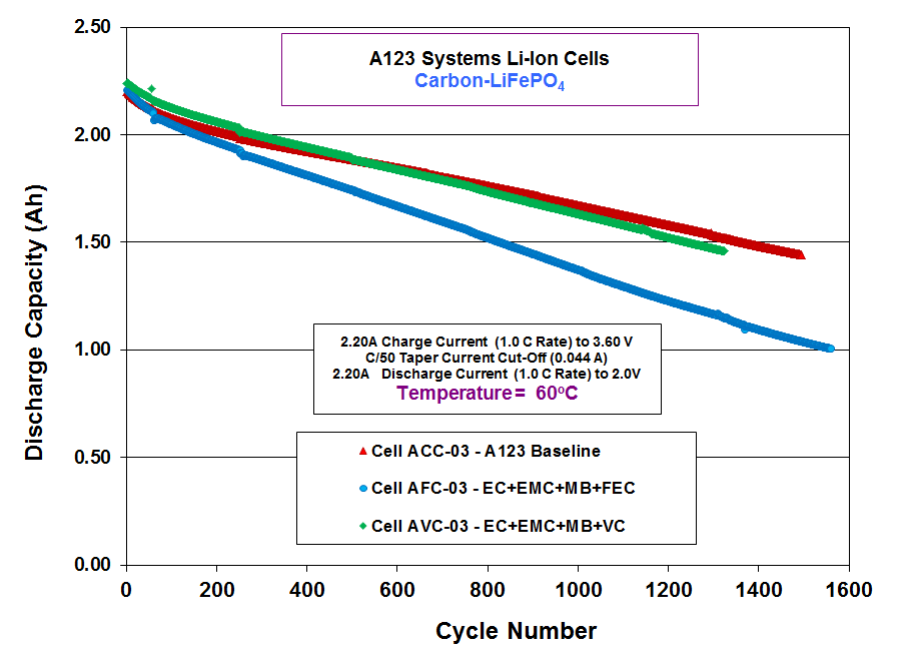
Testing involves alternating between performing 20 cycles at -20°C (using C/10 charge and C/5 discharge) and performing 20 cycles at 40°C (using C/5 charge and C/5 discharge) .

A123 2.20 Ah High Power Lithium-Ion Cells

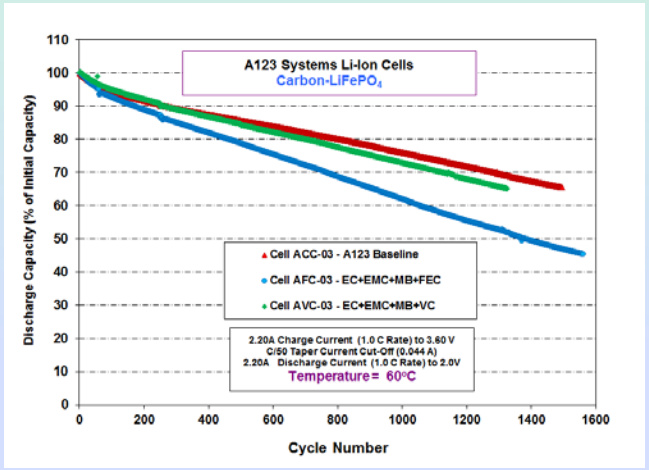
100% DOD Cycle Life Characterization Testing at 40 and 50°C

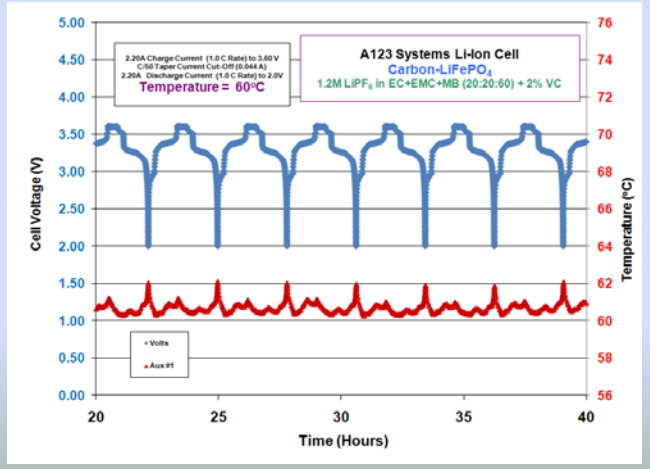
Test Articles (Three Different Electrolyte Variations)

Discharge Capacity at 60°C



Percent of Initial Capacity at 60°C





- Good performance has been demonstrated thus far when cycling continuously at +60°C
- SOA aerospace cells do not operate well at such temperatures without rapid capacity fade with the possibility of venting.

SUMMARY and CONCLUSIONS

- ***Performance of COTS A123 Li-ion Cells***
  - ***Excellent cycle life performance has been obtained to-date under a number of conditions (i.e., 100 % DOD Life at various temperatures and LEO cycling using different DODs)***
    - ***Over 7,000 cycles demonstrated with a 100% DOD cycle life test using 2C rates***
    - ***Excellent, stable LEO cycle life performance exhibited thus far.***
  - ***Excellent rate capability demonstrated at the cell and battery level***

- ***Performance of A123 Cells Containing Low Temperature Electrolytes***
  - **Demonstrated good cycle life and improved low temperature of A123 Systems $LiFePO_4$-based cells using methyl butyrate-based electrolytes:**
    - **1.2M $LiPF_6$ EC+EMC+MB (20:20:60) + 4% FEC**
    - **1.2M $LiPF_6$ EC+EMC+MB (20:20:60) + 2% VC**
  - ***Demonstrated operational capability over a wide temperature range (-60^o to +60^{o}C)***
  - ***Systems are capable of supporting >11C discharge rates at -30^{o}C, with over 90% of the room temperature capacity being delivered.***
  - ***The cells were observed to perform well down to -60^{o}C, with 80% of the room temperature capacity being delivered using a C/10 rate.***

Acknowledgments

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