Development of Novel Electrolytes for Use in High Energy Lithium-Ion Batteries with Wide Operating Temperature Range

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Overview

Timeline

- Start Date = October 2009
- End Date = October 2014
- Percent complete = 10%

Budget

- Total project funding
  - 875K total (~ 175K/year)
  - Contractor share = 0K
- Funding received

  FY'09 = 0 K

  FY'10 = 175K

Barriers

- Barriers addressed
  - Enhance low temperature performance
  - Define performance limitations that limit life
  - Develop long life systems stable at high voltage

Partners

- Univ. Rhode Island (Brett Lucht)
  (Analysis of harvested electrodes, on-going collaborator)
- Argonne Nat. Lab (Khalil Amine)
  (Source of electrodes, on-going collaborator)
- Material Methods, LBNL (John Kerr)
  (Evaluation of novel salt, ex-situ analysis)
- A123 Systems, Inc.
  (Electrolyte development, on-going collaborator)
- Quallion, LCC.
  (Electrolyte development, on-going collaborator)
- Yardney Technical Products
  (Electrolyte development, on-going collaborator)
- Saft America, Inc.
  (Collaborator, industrial partner under NASA program)
- NREL (Smith/Pesaran)
  (Supporting NREL in model development by supplying data)

Objectives

- **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.**
- **Improve the high voltage stability of these candidate electrolytes systems to enable operation up to 5V with high specific energy cathode materials.**
- **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.**

Milestones

Month/Year	Milestone or Go/No-Go Decision
March 2010	Milestone: Prepare and characterize $LiPF_6$-based carbonate blend electrolytes containing novel additives.
Sept 2010	Milestone: Prepare and characterize experimental laboratory cells containing Gen-1 electrolytes and identify performance limiting characteristics at different temperatures.
Sept. 2010	Milestone: Demonstrate improved performance of Gen-I electrolyte over a wide temperature range compared with the baseline electrolyte (*i.e.*, 1 M $LiPF_6$ in EC:DEC 1:2), especially at -30°C, in experimental and prototype cells

Technical Approach

- **Electrolyte Development Approach:**
  - Optimization of carbonate solvent blends
  - Use of low viscosity, low melting ester-based co-solvents
  - Use of fluorinated esters and fluorinated carbonates as co-solvents
  - Use of novel "SEI promoting" and thermal stabilizing additives
  - Use of novel non-fluorine based salts (with Materials Methods, LBNL)
- **Electrolyte Characterization Approach:**
  - Ionic conductivity and cyclic voltammetry measurements
  - Performance characteristics in ~ 400 mAh three electrode cells
    - MCMB /$LiNi_{0.8}Co_{0.2}O_2$ cells, Graphite /$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ cells
    - Use of high specific energy electrode materials (from in-house NASA program)
    - Electrochemical Impedance Spectroscopy (EIS) Measurements as function of temperature, high temperature storage, and cycle life
    - DC Tafel and linear (micro) polarization measurements on electrodes
    - Ex-situ analysis of harvested electrodes (URI and LBNL)
  - Performance characteristics in coin cells
    - Evaluation of electrolytes in conjunction with high voltage cathodes
- **Performance evaluation in prototype cells**
  - Yardney, A123, Saft, and/or Quallion Cells (0.300 mAh to 7 Ah size prototype cells)
  - Cells will be procured and/or obtained through on-going collaborations

Summary of Technical Accomplishments

1) **Demonstrated improved performance with wide operating temperature electrolytes containing ester co-solvents (i.e., methyl propionate and ethyl butyrate) in Quallion prototype cells.**
   - At -40^{o}C, the JPL developed MP-based electrolyte was demonstrated to deliver over 60% of the room temperature capacity using a 5C rate.
2) **Investigated a number of electrolyte additives to improve the performance of methyl propionate and methyl butyrate-based blends in MCMB-$LiNiCoO_2$ cells.**
   - Formulations possessing mono-fluoroethylene carbonate (FEC), LiBOB, lithium oxalate, and vinylene carbonate have shown promise in experimental cells.
   - Performed extensive electrochemical characterization to determine the degradation modes when subjected to extreme temperatures.
3) **Investigated the use of methyl propionate-based electrolyte containing additives in conjunction with $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ and $Li(Li_{0.17}Ni_{0.25}Mn_{0.58})O_2$ cathode materials in experimental cells.**

4) **Investigated the use of lithium dinitramide (LiDNA) as a potential electrolyte additive. Preliminary results suggest efficient SEI formation is occurring with good reversibility.**

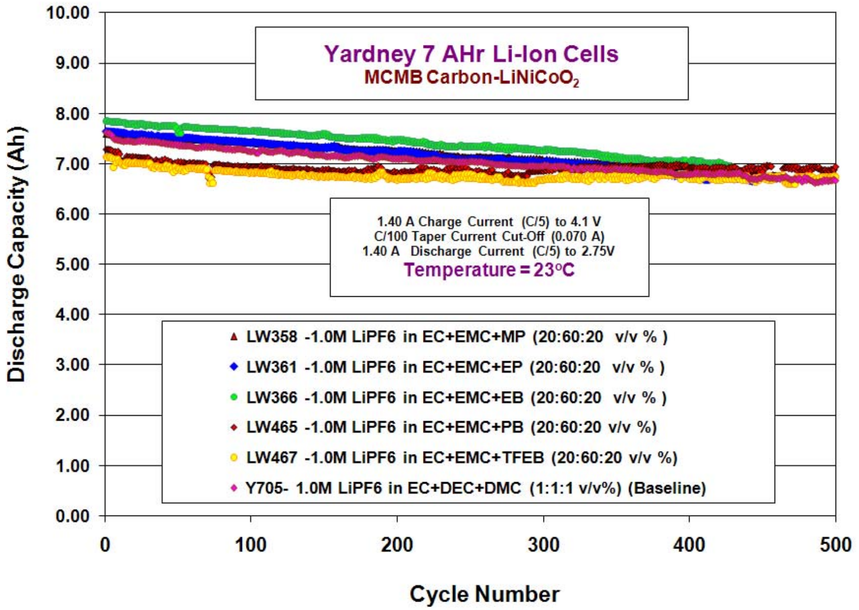
Technical Accomplishments

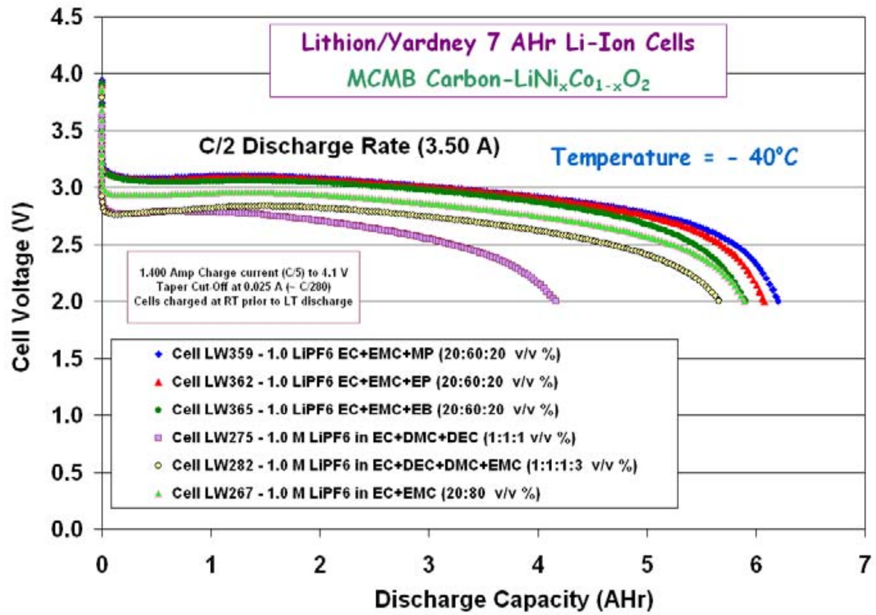
Yardney 7 Ah Prismatic Li-Ion Cells

Characterization of Cells Containing Advanced Electrolytes

100 % DOD Cycle Life Testing at Room Temperature

Discharge Capacity (Ah) at 20°C





- Cells containing an electrolytes with ester co-solvents display comparable 100% DOD life characteristics compared to the all carbonate baseline electrolyte.
  - Addition of small proportions of ester co-solvents improved the rate capability at low temperatures.

➢ *Early development effort supported by NASA ESMD Program.*

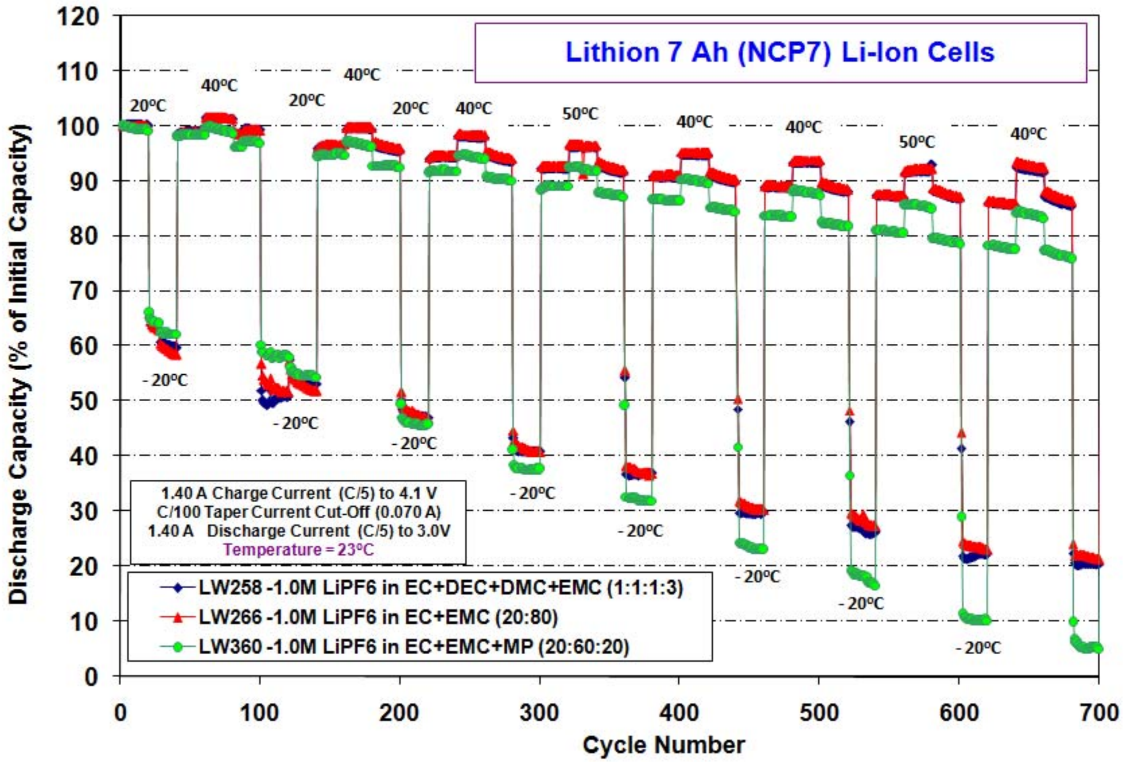
Technical Accomplishments

Yardney 7 Ah Prismatic Li-Ion Cells

Characterization of Cells Containing Advanced Electrolytes

100 % DOD Variable Temperature Cycling

Percentage of Initial Capacity (%)



Variable temperature cycling between a wide range of temperatures (i.e., +50°C to -20°C) represents a stressful test resulting in decreased low temperature capabilities.

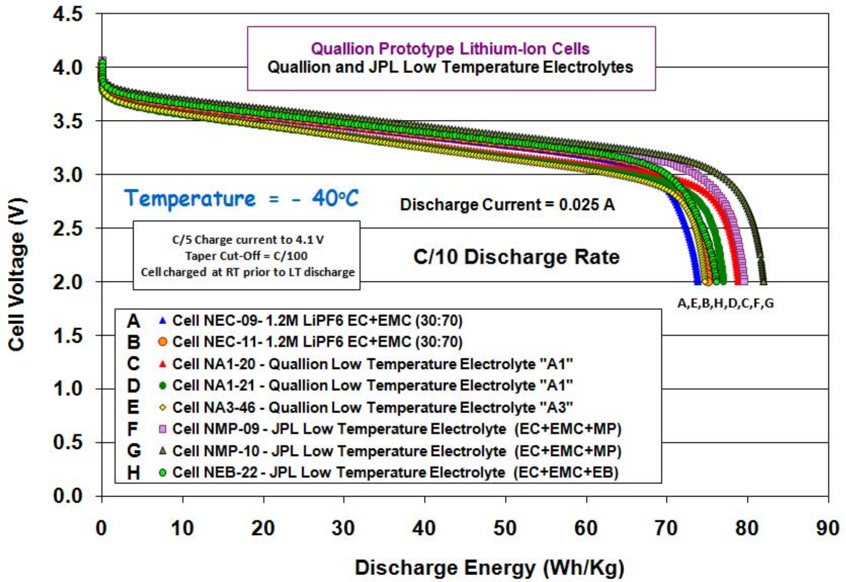
The ester-based solutions display decreased tolerance to high temperature excursions.

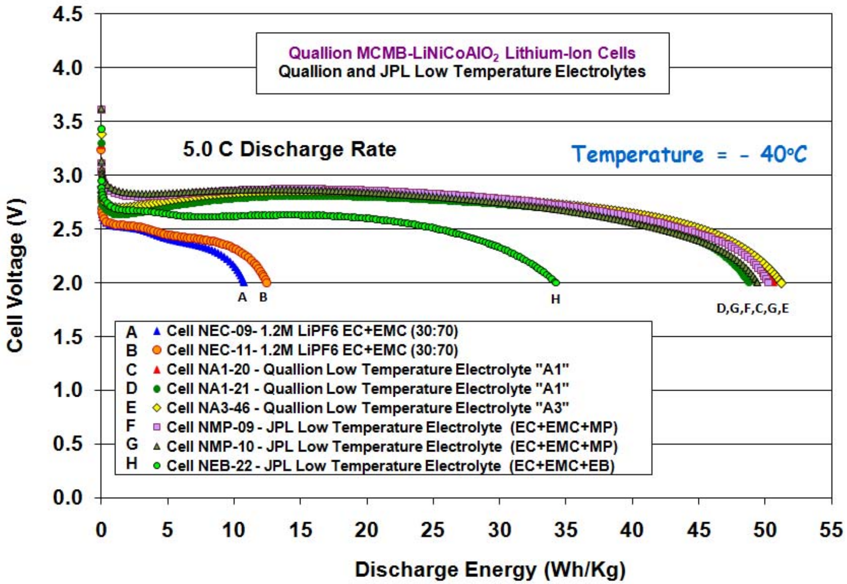
Desire to improve the high temperature resilience of ester based formulations.

Technical Accomplishments

Quallion Prototype Li-Ion Cells
Wide Operating Temperature Electrolytes

Discharge Characterization at Various Temperatures





Methyl propionate containing electrolytes have displayed dramatically improved rate capability compared to the baseline DOE formulation (i.e., 1.2M $LiPF_6$ in EC+EMC (30:70).

Quallion developed electrolytes also display impressive improvements at low temperatures.

- *Quallion collaboration supported by NASA SBIR Program.*
  (H. Tsakamoto, M. Tomcsi, M. Nagata, and V. Visco)

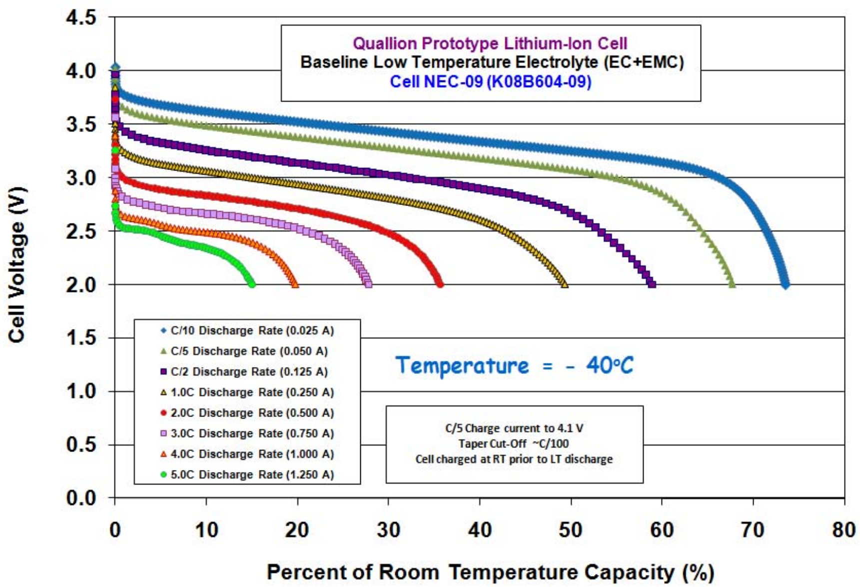
Technical Accomplishments

Quallion Prototype Li-Ion Cells

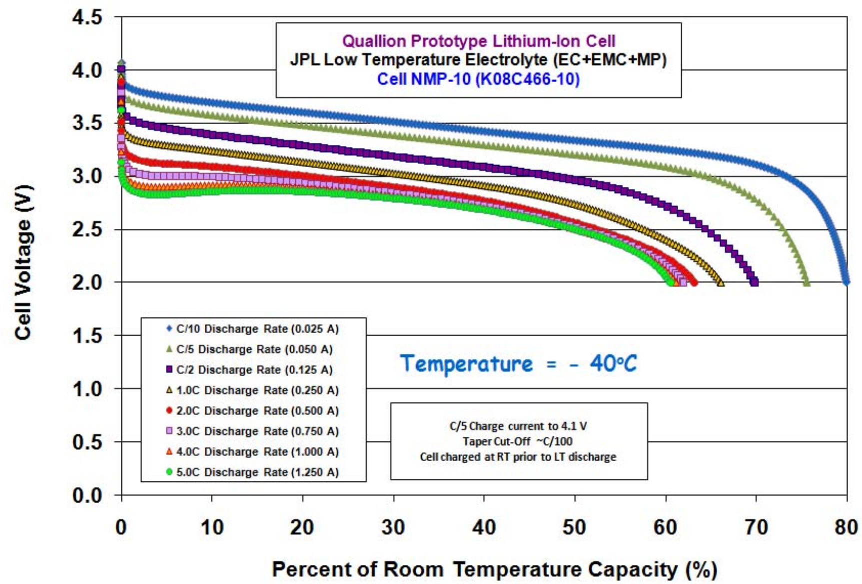
Wide Operating Temperature Electrolytes

Discharge Characterization at -40°C

Baseline Electrolyte



MP-Based Electrolyte



Methyl propionate containing electrolytes have displayed dramatically improved rate capability at -40°C compared to the baseline DOE formulation (i.e., 1.2M $LiPF_6$ in EC+EMC (30:70).

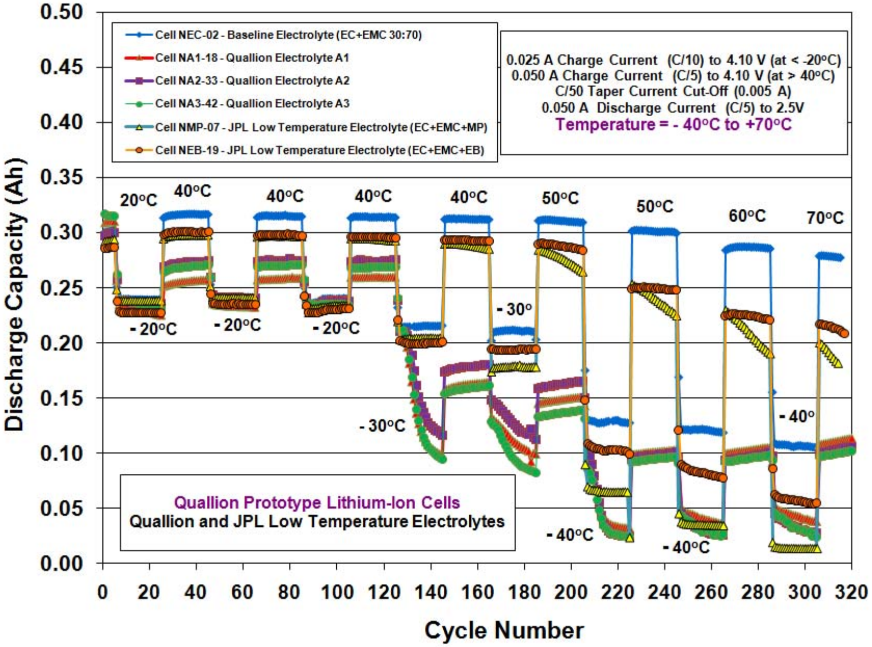
Significantly higher capacity and operating voltage delivered at high rate .

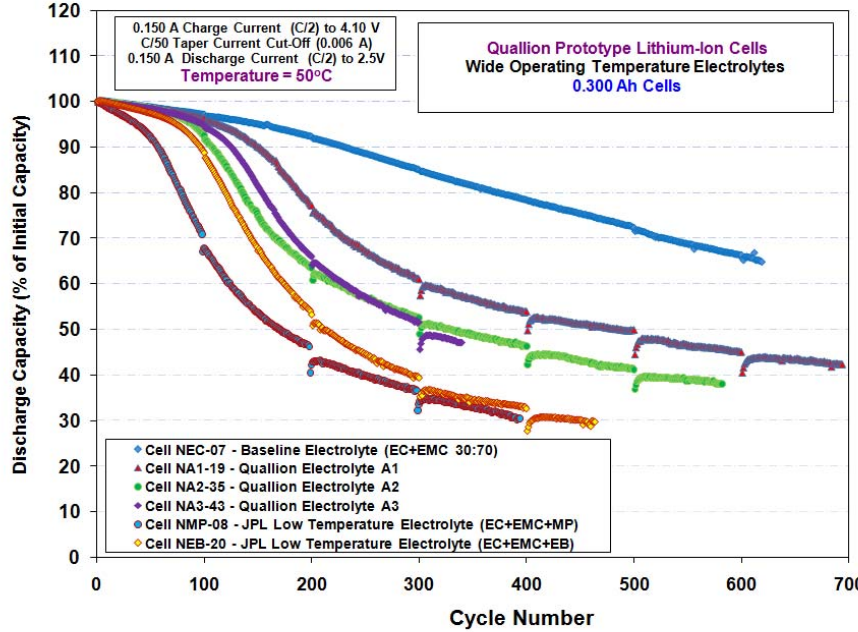
Technical Accomplishments

Quallion Prototype Li-Ion Cells

Wide Operating Temperature Electrolytes

Variable Temperature Cycling over a Wide Temperature Range





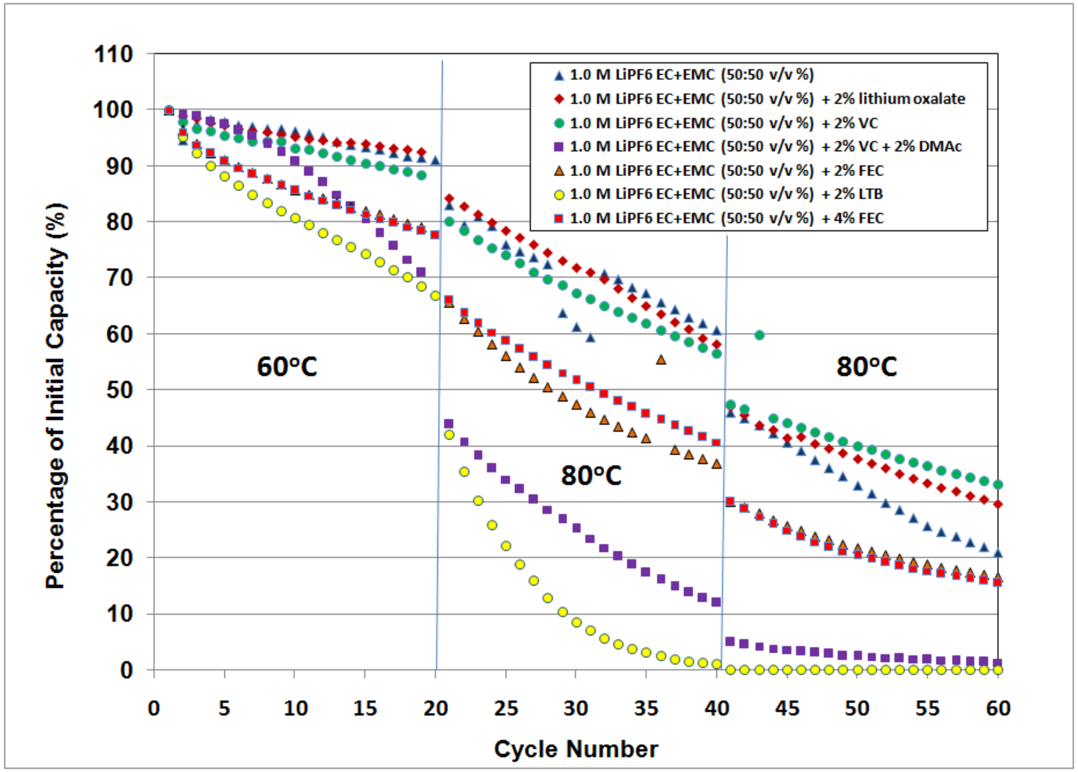
Both JPL and Quallion developed electrolyte display wide operating temperature range (-40 to +70^{o}C).
There is room for improvement with regard to the high temperature resilience.

Although reasonable cycle life is observed at 50^{o}C, the advanced wide operating temperature Electrolyte display higher capacity fade compared to DOE baseline chemistry.

Technical Accomplishments

Performance of High Temperature Resilient Li-Ion Electrolytes

- Experimental lithium-ion cells (MCMB-$LiNiCoO_2$) fabricated with electrolytes containing various additives.

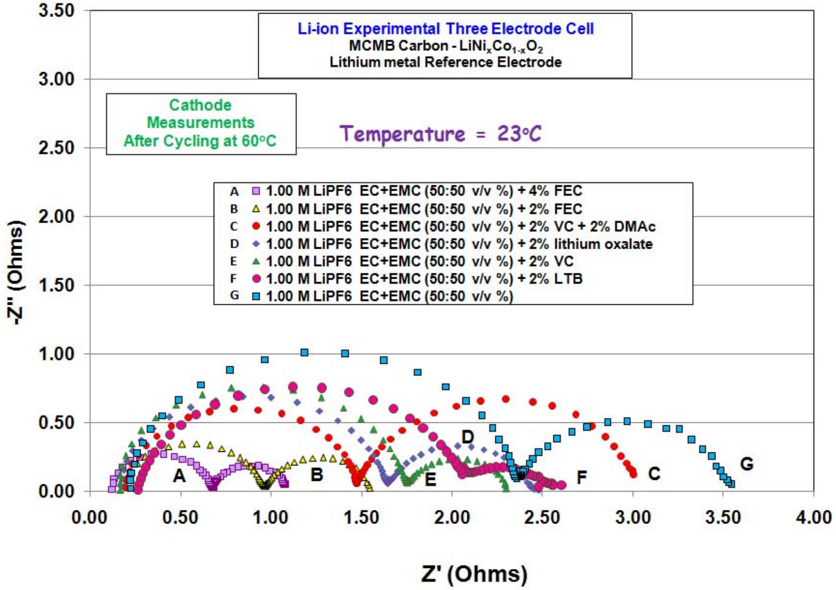


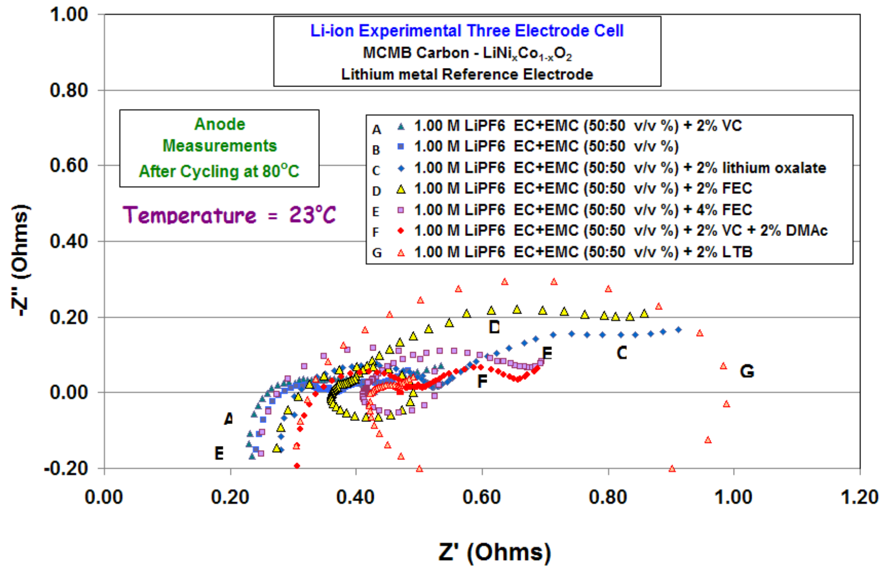
- **A number of electrolyte additives were explored in a robust solvent system (EC+EMC) with the intent of improving high temperature resilience**
- **After being subjected to high temperature cycling, the electrolytes containing the VC and the lithium oxalate additives yielded the best performance.**

Technical Accomplishments

Performance of High Temperature Resilient Li-Ion Electrolytes

- Experimental lithium-ion cells (MCMB-$LiNiCoO_2$) fabricated with electrolytes containing various additives.

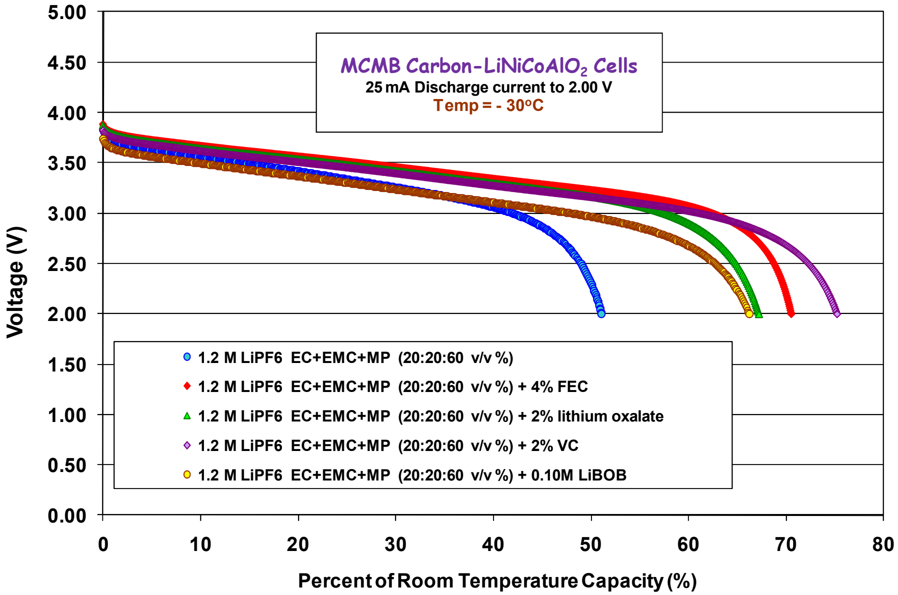


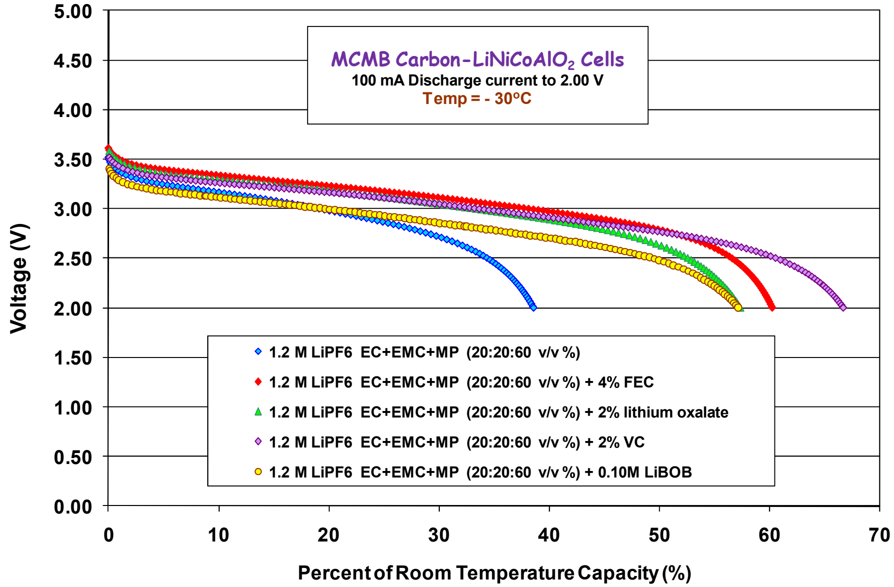


- *The degradation of the anode kinetics was slowed most dramatically by the incorporation of VC and lithium oxalate into the electrolytes*
- *The greatest retention in the cathode kinetics was observed in the cell containing the electrolyte with FEC added.*
- *Studies are also focused upon determining the high temperature resilience of these solutions in relation to other all electrolyte mixtures designed for wide temperature range of operation.*

Technical Accomplishments

Experimental lithium-ion cells (MCMB-$LiNiCoAlO_2$) fabricated with methyl propionate–based electrolytes containing various additives.



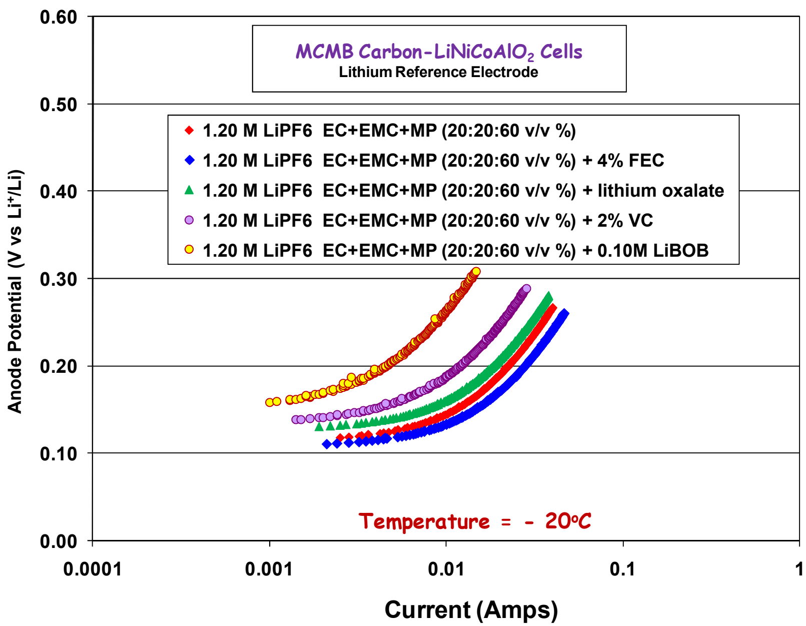


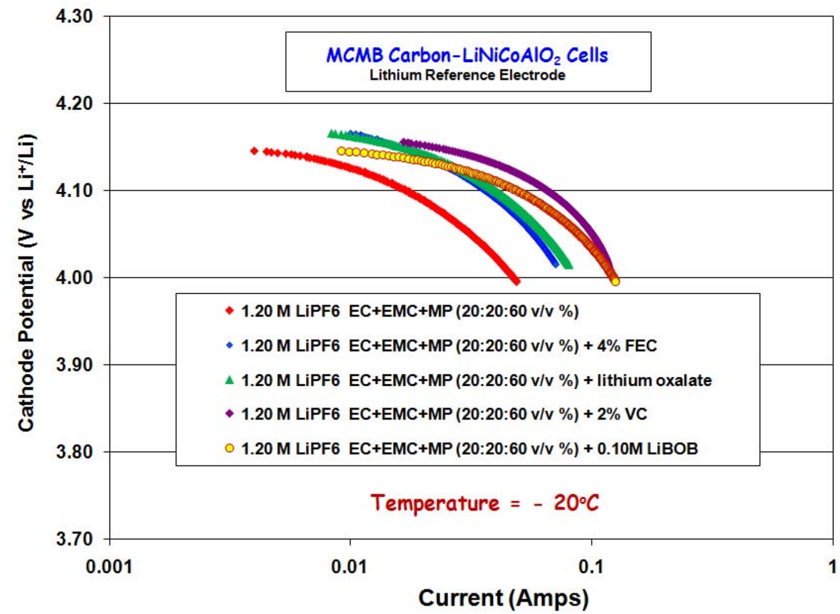
- ***At low temperatures, the best performance was obtained with the addition of VC and FEC to the MP-based electrolyte formulations.***

- ***The polarization of the cell containing LiBOB was more pronounced that the other cells with additives, presumably due to the filming process at the anode.***

Technical Accomplishments

Experimental lithium-ion cells (MCMB-$LiNiCoAlO_2$) fabricated with methyl propionate–based electrolytes containing various additives.





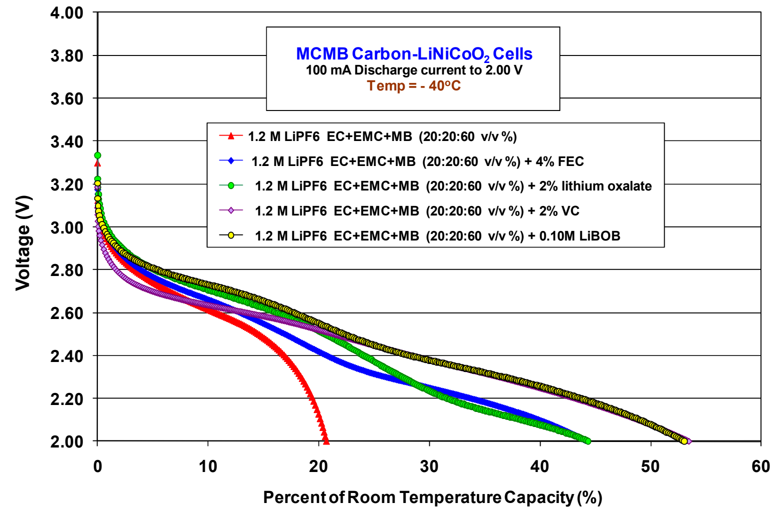
➢ **Promising electrolyte additives were explored in a wide operating temperature range solvent systems (EC+EMC+MP) with the intent of improving high temperature resilience**

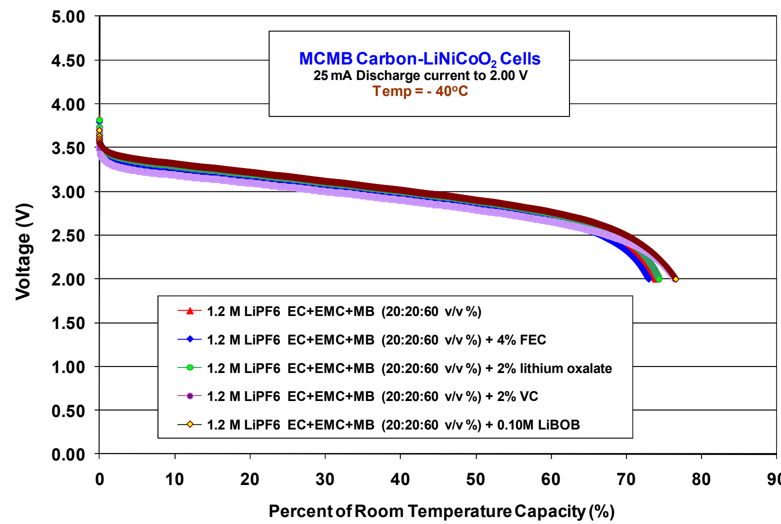
- *FEC was observed to enhance the lithium kinetics of the MCMB anode, whereas the other additives appeared to impede the kinetics (especially LiBOB).*
- *VC and LiBOB were observed to most dramatically enhance the kinetics of the cathode at low temperatures. All additives appeared to improve the kinetics somewhat.*

Technical Accomplishments

Experimental lithium-ion cells (MCMB-$LiNiCoO_2$) fabricated with **methyl butyrate**–based electrolytes containing various additives.

Electrolyte Type		1.2 M LiPF6 EC+EMC+MB (20:20:60 v/v %)		1.2 M LiPF6 EC+EMC+MB (20:20:60 v/v %) + 4% FEC		1.2 M LiPF6 EC+EMC+MB (20:20:60 v/v %) + 2% lithium oxalate		1.2 M LiPF6 EC+EMC+MB (20:20:60 v/v %) + 2% VC		1.2 M LiPF6 EC+EMC+MB (20:20:60 v/v %) + 0.10M LiBOB	
Temperature	Current (mA)	Capacity (Ahr)	Percent (%)	Capacity (Ahr)	Percent (%)	Capacity (Ahr)	Percent (%)	Capacity (Ahr)	Percent (%)	Capacity (Ahr)	Percent (%)
23°C	25 mA	0.3973	100.00	0.3825	100.00	0.3850	100.00	0.3868	100.00	0.3969	102.62
0°C	25 mA	0.3514	88.46	0.3355	87.71	0.3431	89.12	0.3558	91.98	0.3549	89.40
	50 mA	0.3484	87.70	0.3300	86.29	0.3384	87.90	0.3534	91.37	0.3503	88.26
	100 mA	0.3376	84.99	0.3177	83.06	0.3269	84.91	0.3432	88.72	0.3409	85.87
	150 mA	0.3269	82.27	0.3048	79.70	0.3178	82.55	0.3329	86.06	0.3296	83.03
-20°C	25 mA	0.3438	86.53	0.3236	84.60	0.3299	85.70	0.3484	90.06	0.3502	88.23
	50 mA	0.3226	81.19	0.3022	79.01	0.3104	80.64	0.3285	84.92	0.3268	82.32
	100 mA	0.3051	76.79	0.2842	74.30	0.2967	77.05	0.3140	81.19	0.3149	79.32
	150 mA	0.2906	73.14	0.2714	70.96	0.2863	74.36	0.3011	77.84	0.3016	75.97
-30°C	25 mA	0.3179	80.01	0.3001	78.46	0.3030	78.71	0.3230	83.51	0.3289	82.86
	50 mA	0.2990	75.27	0.2808	73.43	0.2930	76.11	0.3090	79.88	0.3113	78.44
	100 mA	0.2704	68.07	0.2535	66.28	0.2730	70.91	0.2873	74.29	0.2879	72.52
	150 mA	0.2233	56.20	0.2095	54.78	0.2502	65.00	0.2642	68.31	0.2604	65.60
-40°C	25 mA	0.2938	73.95	0.2792	73.00	0.2861	74.32	0.2956	76.43	0.3038	76.53
	50 mA	0.2348	59.10	0.2355	61.57	0.2530	65.71	0.2634	68.09	0.2660	67.01
	100 mA	0.0823	20.71	0.1690	44.18	0.1709	44.39	0.2068	53.48	0.2106	53.04
	150 mA	0.0501	12.60	0.0388	10.14	0.0606	15.74	0.1104	28.54	0.0705	17.76
-50°C	25 mA	0.0709	17.83	0.0497	12.99	0.0939	24.40	0.1031	26.66	0.1694	42.69
	50 mA	0.0463	11.64	0.0310	8.11	0.0532	13.83	0.0450	11.63	0.0396	9.97
	100 mA	0.0203	5.12	0.0104	2.72	0.0285	7.41	0.0107	2.76	0.0167	4.21

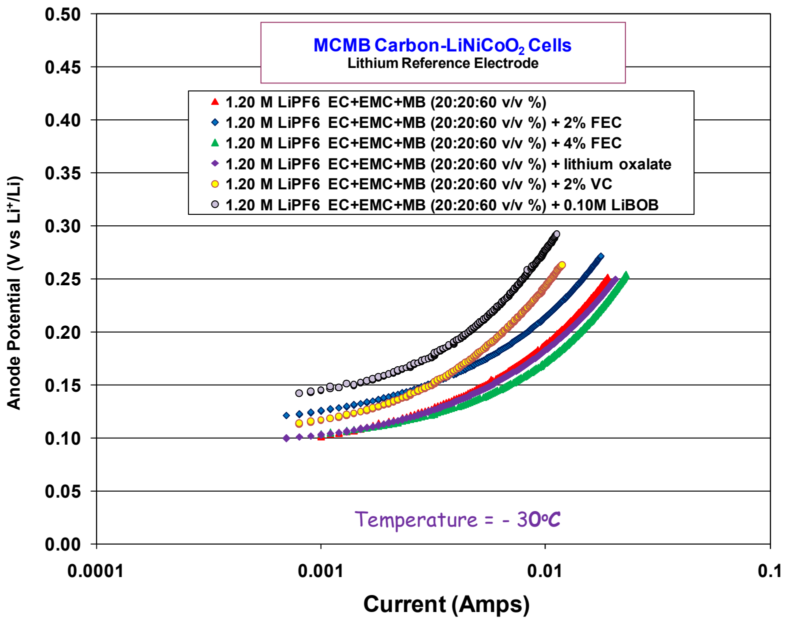


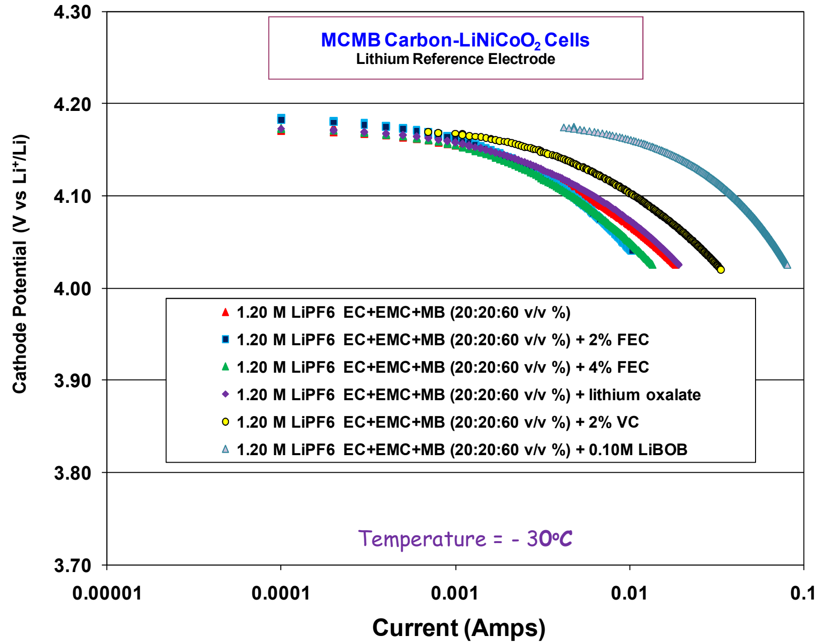


- LiBOB was observed to improve the low temperature performance.
- The benefit of LiBOB was determined to be due to improved kinetics at the cathode.

Technical Accomplishments

Experimental lithium-ion cells (MCMB-$LiNiCoO_2$) fabricated with methyl butyrate–based electrolytes containing various additives.





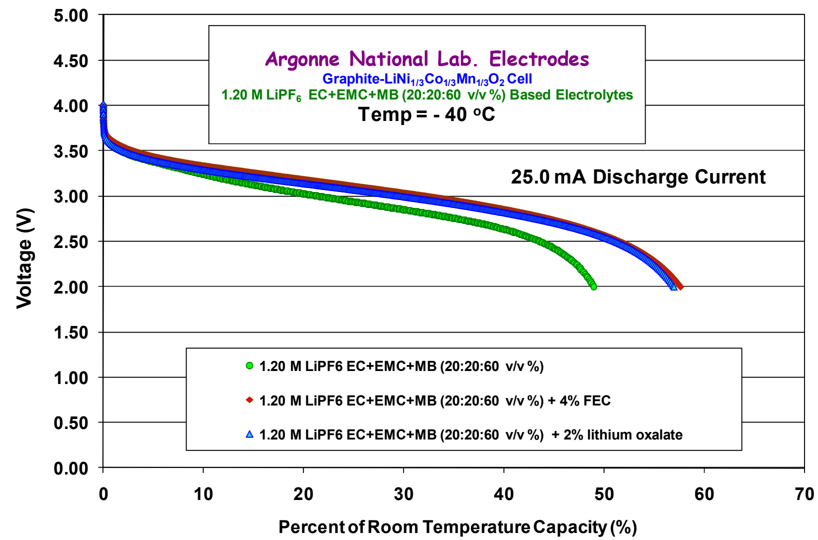
- **Promising electrolyte additives were explored in a wide operating temperature range solvent systems (EC+EMC+MB) with the intent of improving high temperature resilience.**
- **Some additives have the beneficial effect of improving the lithium kinetics through the formation of desirable SEI layers on both electrodes.**

Technical Accomplishments

Experimental lithium-ion cells (Graphite-$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$) fabricated with methyl butyrate–based electrolytes containing various additives.

			1.20 M LiPF6 in EC+EMC+MB (20:20:60 v/v %)		1.20 M LiPF6 in EC+EMC+MB (20:20:60 v/v %) + 4% FEC		1.20 M LiPF6 in EC+EMC+MB (20:20:60 v/v %) + 2% lithium oxalate	
Temperature (°C)	Current (mA)	Rate	Capacity (Ah)	Percent (%)	Capacity (Ah)	Percent (%)	Capacity (Ah)	Percent (%)
23°C	25.00	C/5	0.10655	100.00	0.11486	100.00	0.10794	100.00
- 20°C	6.25	C/16	0.07743	72.67	0.09486	82.59	0.09734	90.18
	8.33	C/12	0.07191	67.49	0.09237	80.42	0.09607	89.00
	12.50	C/8	0.06533	61.31	0.08757	76.24	0.09084	84.16
	25.00	C/4	0.06143	57.65	0.08334	72.56	0.08515	78.89
	41.67	0.42 C	0.05703	53.53	0.07851	68.35	0.07858	72.80
	62.50	0.63 C	0.04341	40.74	0.07153	62.28	0.07216	66.85
- 40°C	6.25	C/16	0.07796	73.17	0.08384	73.00	0.08243	76.37
	8.33	C/12	0.05455	51.19	0.07379	64.24	0.06930	64.21
	12.50	C/8	0.05985	56.17	0.07287	63.44	0.07160	66.33
	25.00	C/4	0.05212	48.92	0.06611	57.56	0.06146	56.94
	41.67	0.42 C	0.01584	14.87	0.04761	41.45	0.02495	23.12
	62.50	0.63 C	0.00854	8.02	0.02444	21.28	0.01410	13.06
- 50°C	6.25	C/16	0.03944	37.01	0.06311	54.95	0.04852	44.95
	8.33	C/12	0.03098	29.07	0.06107	53.17	0.04824	44.69
	12.50	C/8	0.02135	20.04	0.05437	47.33	0.04157	38.51
	25.00	C/4	0.00766	7.19	0.03567	31.06	0.02348	21.75
	41.67	0.42 C	0.00312	2.93	0.00796	6.93	0.00555	5.14
- 60°C	6.25	C/16	0.00827	7.76	0.02632	22.91	0.01275	11.81
	8.33	C/12	0.00399	3.74	0.00878	7.65	0.01411	13.07
	12.50	C/8	0.00162	1.52	0.00315	2.74	0.00792	7.33

C/4 Discharge at -40°C

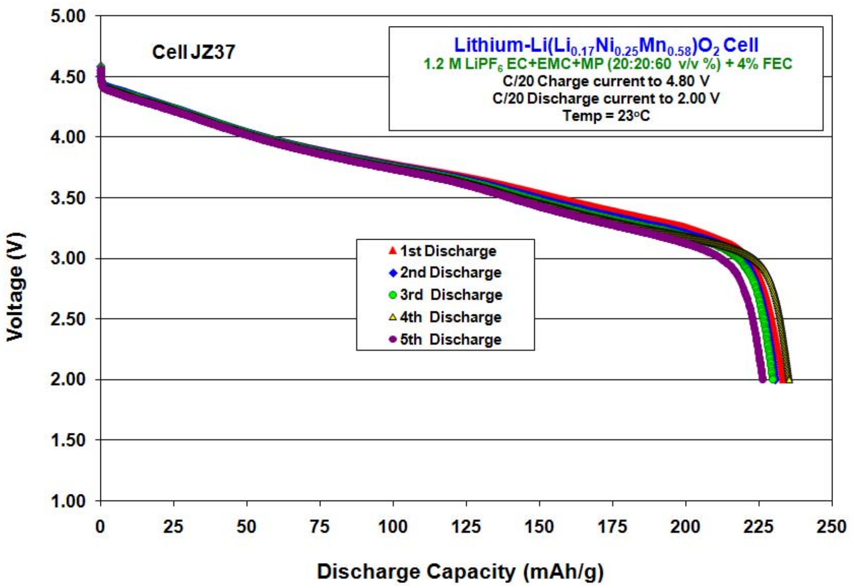


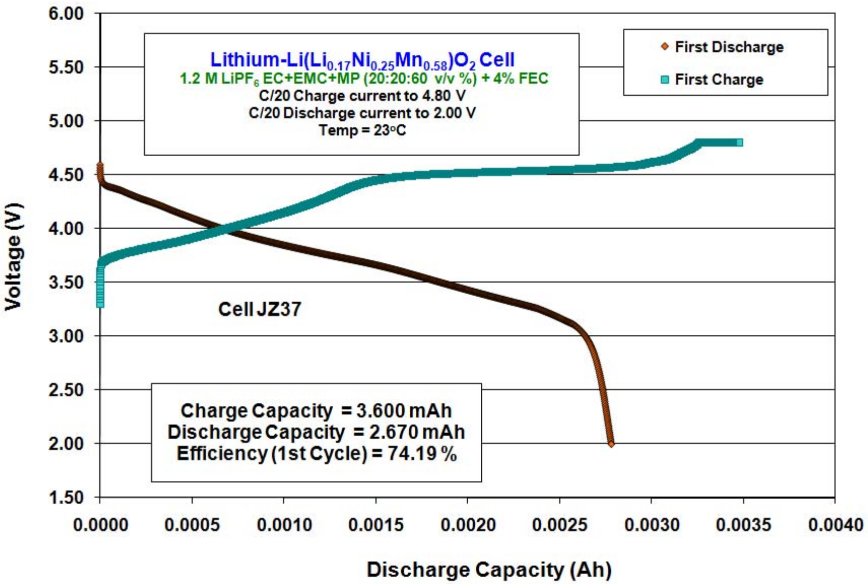
- Electrodes provide by Khalil Amine (Argonne National Lab.)

Technical Accomplishments

Electrolytes With Operating Temperature Performance and High Voltage Stability

Formation Characteristics in Li-Li($Li_{0.17}Ni_{0.25}Mn_{0.58}$)$O_2$ cells





- **A promising wide operating temperature range electrolyte formation (EC+EMC+MP+ FEC) was evaluated with high voltage, high specific energy cathode materials.**
- **Formation characteristics very comparable to all carbonate baseline electrolytes.**

Technical Accomplishments

Electrolytes With Operating Temperature Performance and High Voltage Stability

Rate Capability at Low Temperature

		1.0 M $LiPF_6$ EC+DEC+ DMC (1:1:1 v/v %)						1.2 M LiPF6 EC+EMC+MP (20:20:60 v/v %) + 4% FEC					
		Cell JZ35			JZ36			Cell JZ37			JZ38		
Temp (°C)	Discharge Rate	mAh	mAh/g	% of C/20 Capacity (mAh/g)	mAh	mAh/g	% of C/20 Capacity (mAh/g)	mAh	mAh/g	% of C/20 Capacity (mAh/g)	mAh	mAh/g	% of C/20 Capacity (mAh/g)
23°C	C/20	2.721	226.77	100	2.709	227.28	100	2.678	224.67	100	2.556	223.45	100
	C/10	2.636	219.64	96.86	2.626	220.34	96.94	2.602	218.26	97.15	2.487	217.40	97.29
	C/5	2.510	209.18	92.25	2.500	209.72	92.27	2.488	208.70	92.89	2.381	208.13	93.14
	C/2	2.283	190.28	83.91	2.122	178.00	78.32	2.283	191.49	85.23	2.183	190.80	85.39
0°C	C/20	2.147	178.92	78.90	2.102	176.34	77.59	2.118	177.66	79.08	2.043	178.62	79.9378
	C/10	2.051	170.94	75.38	1.993	167.17	73.55	2.017	169.20	75.31	1.948	170.26	76.19
	C/5	1.881	156.73	69.11	1.678	140.80	61.95	1.845	154.75	68.88	1.780	155.57	69.62
	C/2	1.416	118.04	52.05	0.877	73.55	32.36	1.535	128.77	57.32	1.494	130.57	58.43
-10°C	C/20	1.947	162.25	71.55	1.876	157.41	69.26	1.925	161.46	71.86	1.865	163.02	72.95
	C/10	1.744	145.30	64.08	1.651	138.51	60.94	1.717	144.05	64.12	1.666	145.63	65.17
	C/5	1.410	117.47	51.80	1.065	89.31	39.29	1.475	123.71	55.06	1.435	125.40	56.12
	C/2	0.658	54.84	24.18	0.651	54.59	24.02	0.889	74.59	33.20	1.057	92.37	41.34

Cells containing an electrolyte containing methyl propionate and mono-fluoroethylene carbonate perform well with a high voltage cathode, delivering improved rated capability at lower temperatures.

Technical Accomplishments

JPL Data (Three Electrode 0.400Ah Cells)

Formation Characteristics of Three Electrode MCMB-$LiNi_xCo_{1-x}O_2$ Cells

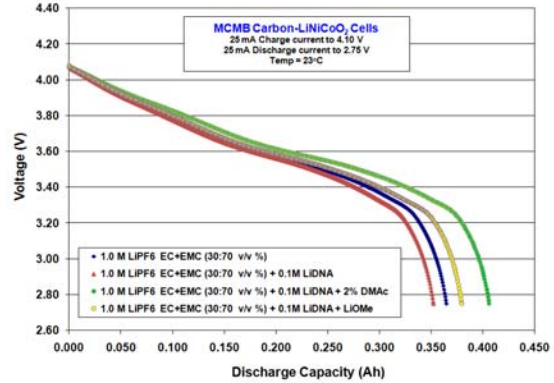
Electrolyte Type	Charge Capacity (Ah) 1st Cycle	Discharge Capacity (Ah) 1st Cycle	Irreverisible Capacity (1st Cycle)	Couloumbic Efficiency (1st Cyle)	Charge Capacity (Ah) 5th Cycle	Reversible Capacity (Ah) 5th Cycle	Specific Capacity of LiNiCoO2 (mAh/g)	Cummulative Irreverisible Capacity (1st-5th Cycle)	Couloumbic Efficiency (5th Cycle)	Anode Active Material Mass (g)	Cathode Active Material Mass (g)
1.0M $LiPF_6$ EC+EMC (30:70 vol %)	0.4729	0.3725	0.100	78.77	0.3728	0.3650	153.8	0.1427	97.92	1.864	2.374
1.0M $LiPF_6$ EC+EMC (30:70 vol %) + 0.10M LiDNA	0.4301	0.3542	0.076	82.35	0.3644	0.3523	146.3	0.1323	96.68	1.892	2.408
1.0M $LiPF_6$ EC+EMC (30:70 vol %) + 0.10M LiDNA + 2% DMAc	0.5118	0.4097	0.102	80.05	0.4146	0.4059	168.0	0.1429	97.92	1.902	2.416
1.0M $LiPF_6$ EC+EMC (30:70 vol %) + 0.10M LiDNA + LiOMe	0.4659	0.3847	0.081	82.56	0.3941	0.3795	157.3	0.1425	96.29	1.866	2.413

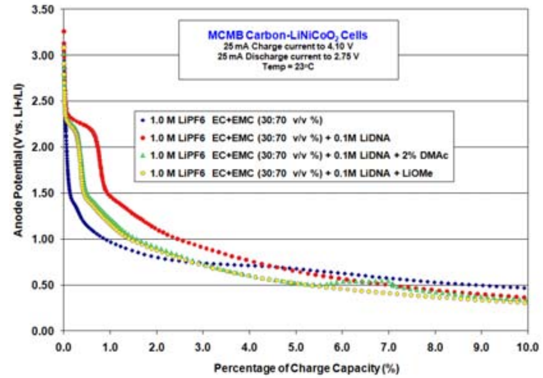
- **Lithium dinitramide was investigated as a potential electrolyte additive, with the intent of producing robust, protective SEI layers on carbon.**
- **Study performed in collaboration with Steve Jaffe (Material Methods)**

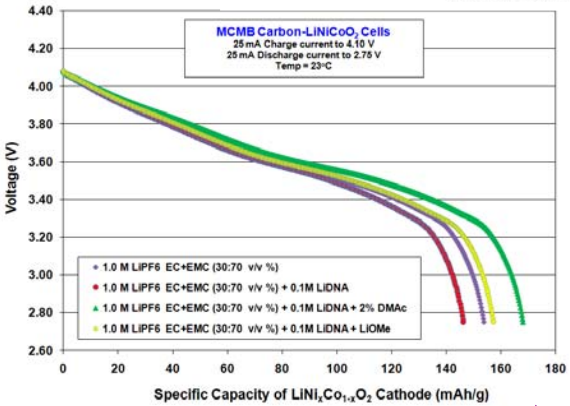
Technical Accomplishments

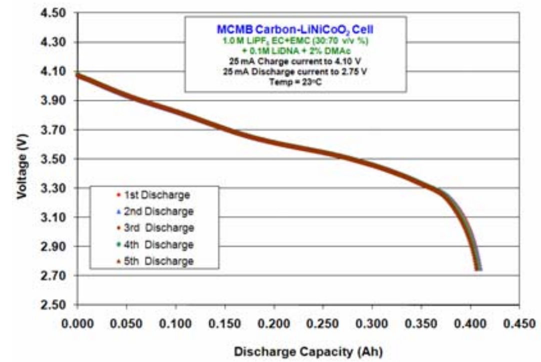
Formation Characteristics of Three Electrode MCMB-$LiNi_xCo_{1-x}O_2$ Cells

Comparison of Electrolytes: Reversible Capacity After Formation Cycling









- *Preliminary results suggest that the LiDNA salt in conjunction with a Lewis base (i.e., dimethyl acetamide, DMAc) can result in higher reversible capacity compared with the baseline formulation.*
- *It appears as though the LiDNA is participating (and possibly the Lewis Base) in formation of the SEI layer, with the onset of decomposition occurring at ~ 2.0 – 2.5V / Li^+*
- *Excellent reversibility displayed over the first five formation cycles*

Summary

- Met programmatic milestones for program.
- Demonstrated improved performance with wide operating temperature electrolytes containing ester co-solvents (i.e., methyl propionate and ethyl butyrate) in Quallion prototype cells:
  - At -40°C, the JPL developed MP-based electrolyte was demonstrated to deliver over 60% of the room temperature capacity using a 5C rate.
  - Demonstrated cycle life over a wide temperature range (-40 to +70°C)
- Developed a number of methyl propionate and methyl butyrate containing electrolyte that contain various additives intended to improve the high temperature resilience:
  - Demonstrated improved low temperature performance with many formulations.
  - Improved low temperature electrode kinetics observed with many additives.
  - Studied degradation modes when exposed to high temperature cycling.
  - Formulations possessing mono-fluoroethylene carbonate (FEC), LiBOB, lithium oxalate, and vinylene carbonate have shown promise in experimental cells.
  - Investigated with many chemistries (i.e., $LiNiCoO_2$, $LiNiCoAlO_2$, $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$, $Li(Li_{0.17}Ni_{0.25}Mn_{0.58})$)
- Investigated the use of lithium dinitramide (LiDNA) as a potential electrolyte additive. Preliminary results suggest efficient SEI formation is occurring with good reversibility.

Future Work

- ***Continue the investigation of the use of additives in conjunction with ester-based wide operating temperature range electrolytes.***
  - *Expand study to include other potential additives.*
  - *Study the cycle life behavior and high temperature resilience more thoroughly.*
  - *Correlate trends in electrochemical data with charge/discharge behavior*
  - *Identify performance limiting aspects at extreme temperatures*
- ***Continue the investigation of LiDNA as an electrolyte additive.***
  - *Investigate the life characteristics.*
  - *Explore the utility of the salt in conjunction with alternate solvent mixtures.*
  - *Explore concentration effects.*
- ***Investigate the performance of candidate wide operating temperature electrolytes using different chemistries.***
  - *Demonstrate the performance with high voltage mixed metal oxides.*
- ***Demonstrate the performance of advanced electrolytes in prototype cells.***
  - *A123 26650 (2.2 Ah) Cells (LiFePO4 Chemistry).*
  - *Yardney 7 Ah Cells ($LiNiCoO_2$ Chemistry).*
  - *Quallion Prototype Cells ($LiNiCoO_2$ Chemistry).*

Collaborations

- Quallion, LCC: Provided prototype cells , on-going collaborator (NASA SBIR Phase II)
- A123 Systems, Inc. : Provided prototype cells with DOE developed electrolyte, on-going collaborator
- Argonne Nat. Lab (Khalil Amine): ANL provided electrodes for evaluation (on-going collaborator)
- Material Methods, LBNL (John Kerr): Mat Methods provided novel lithium dinitrimide salt
- Yardney Technical Products: Electrolyte development, on-going collaborator)
- Univ. Rhode Island (Brett Lucht): Analysis of harvested electrodes, (on-going collaborator)
- Saft America, Inc.: Collaborator, industrial partner under NASA program
- NREL (Smith/Pesaran): Supporting NREL in model development by supplying prototype cell data.

Publications and Presentations

M. C. Smart, B. V. Ratnakumar, A. S. Gozdz, and S. Mani, "The Effect of Electrolyte Additives upon the Lithium Kinetics of Li-Ion Cells Containing MCMB and $LiNi_xCo_{1-x}O_2$ Electrodes and Exposed to High Temperatures", *ECS Transactions*, In press. (From ECS 216th Meeting of the ECS, Vienna, Austria).

S. M. Jaffe, A. A. Gorkovenko, M. C. Smart, and F. C. Krause, "Lithium Dinitramide in Secondary Lithium Batteries", 27th International Battery Seminar, Ft. Lauderdale, Florida, March 18, 2010.

M. C. Smart, B. V. Ratnakumar, F. C. Krouse, W. C. West, and L. W. Whitcanack, "The Development of Li-Ion Electrolytes with Improved Operating Temperature Range and Safety Characteristics", 2010 Space Power Workshop, Manhattan Beach, CA, April 22, 2010.

M. Tomcsi, M. Nagata, H. Tsukamoto, M. C. Smart, and B. V. Ratnakumar, "Li-Ion Battery with Wide (-42^{o}C to +71^{o}C) Operational Temperature Range", 2010 Space Power Workshop, Manhattan Beach, CA, April 22, 2010.

M. C. Smart, B. V. Ratnakumar, M. R. Tomcsi, M. Nagata, V. Visco, and H. Tsukamoto, "Performance of Wide Operating Temperature Range Electrolytes in Quallion Prototype Li-Ion Cells", 2010 Power Sources Conference, Las Vegas, NV, June 16, 2010.

Acknowledgments

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