Lithium batteries for electric vehicles applications: Energy density, power capability, cycle life, and pack design considerations

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Outline of the presentation

1. Introduction
2. Batteries available
3. Battery characteristics and sizing
4. Test data for lithium-ion cells and modules
5. Test data for fast charging of cells
6. Pack design considerations
7. Battery operating conditions and limits
8. Cycle life considerations
9. Summary and conclusions

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Emerging Lithium Battery Technologies

(neg)

- Graphite/NiCo and Mn spinel (pos)
- Iron phosphate (positive)
- Lithium titanate oxide (negative)
- Cylindrical vs. prismatic cells

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Summary of the performance characteristics of Lithium-ion batteries of various chemistries

Battery Developer/ Cell type	Electrode chemistry	Voltage range	Ah	Resist. mOhm	Wh/kg	W/kg 90% effic.*	Wgt. (kg)	Density gm/cm3
Enerdel HEV	Graphite/ Ni MnO2	4.1-2.5	15	1.4	115	2010	.445	----
Enerdel EV/PHEV	Graphite/ Ni MnO2	4.1-2.5	15	2.7	127	1076	.424	----
Kokam prismatic	Graphite/ NiCoMnO2	4.1-3.2	30	1.5	140	1220	.787	2.4
Saft Cylind.	Graphite/ NiCoAl	4.0-2.5	6.5	3.2	63	1225	.35	2.1
GAIA Cylind.	Graphite/ NiCoMnO2	4.1-2.5	40 7	.48 3.6	96 78	2063	1.53	3.22
A123 Cylind.	Graphite/Iron Phosph.	3.6-2.0	2.2	12	90	1393	.07	2.2
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	11	2.2	70	990	.34	1.83
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	3.8	1.15	35	2460	.26	1.91
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	1.8	60	144	577	.043	2.6
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	2.3	72	170	445	.047	2.8
EIG prismatic	Graphite/ NiCoMnO2	4.2-3.0	20	3.1	165	1278	.41	----
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	113	1100	.42	---
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	46	395	1.04	1.8

* power density $P = Eff.*(1-Eff.)\, Voc^2/R$

exmple

Energy storage requirements for various transportation applications

- energy stored (kWh), peak power (kW), system voltage
- pack voltage set by motor/electronics
- pack weight (kg) and volume (L)
- cell characteristics: Ah, resistance, geometric shape
- Wh/kg, Wh/L, W/kg
- initial cost ($/kWh)
- cycle and calendar life

Battery cell and pack sizing

Vehicle energy useage and range   wh/mi and miles

Energy stored   Wh = Wh/mi x miles/ fraction used

Cell size required

Number cells = system V/Vcell (in series)

Ahcell = Whstored/ (Ncells x Vcell) (in parallel)

Cell weight (kg) = Whstored/ Wh/kg cell

Cell volume (L) = cell weight / cell density kg/L

Example Iron phosphate

A/C Drive

Vehicle energy useage and range 275 wh/mi and 100 miles

27.5 kWh useable

Energy stored Wh = 275Wh/mi x 100miles/ .7 = 39 kWh

Number cells = system V/Vcell = 300/ 3.2 = 94 in series

Ahcell = Whstored/ (Ncells x Vcell) = 39000/(94 x 3.2) = *130*

Cell weight (kg) = Whstored/ Wh/kg cell = 39000/110 = *355 kg*

Cell volume (L) = cell weight / cell density kg/L = 355/2.2=161 L

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Pack size and cost

Pack weight (kg) = cell weight/ weight packaging factor

Pack volume (L) = cell volume/ volume packaging factor

$/Whcell = $/cell / Ah x Vcell

$ pack = Whstored x $/Wh cell

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Example Iron phosphate (cont.)

Pack weight (kg) = cell weight/ weight packaging factor

= 355/.8 = 444 kg

Pack volume (L) = cell volume/ volume packaging factor

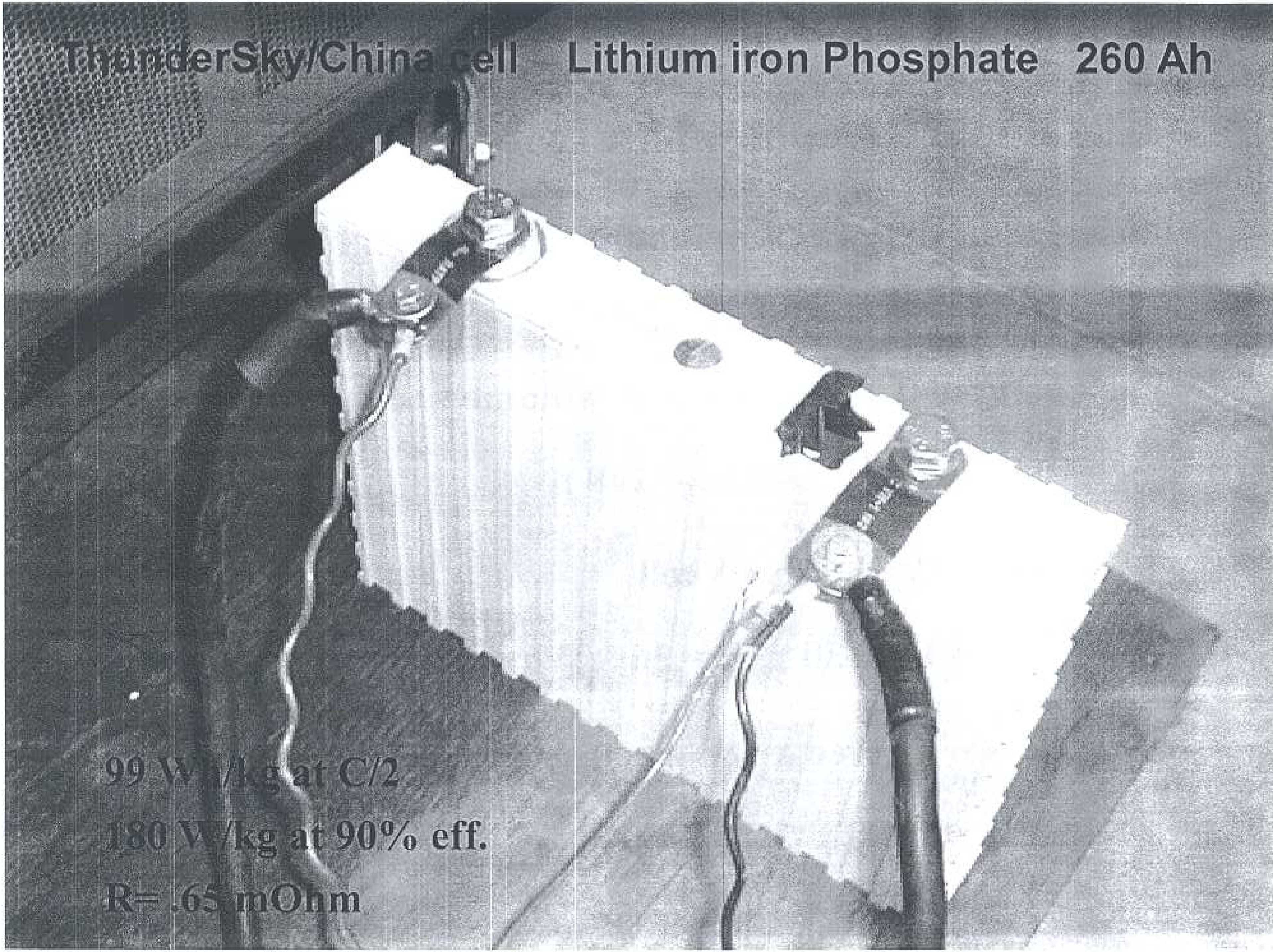
= 161/.65 = 248 L

$/Whcell = $/cell / Ah x Vcell

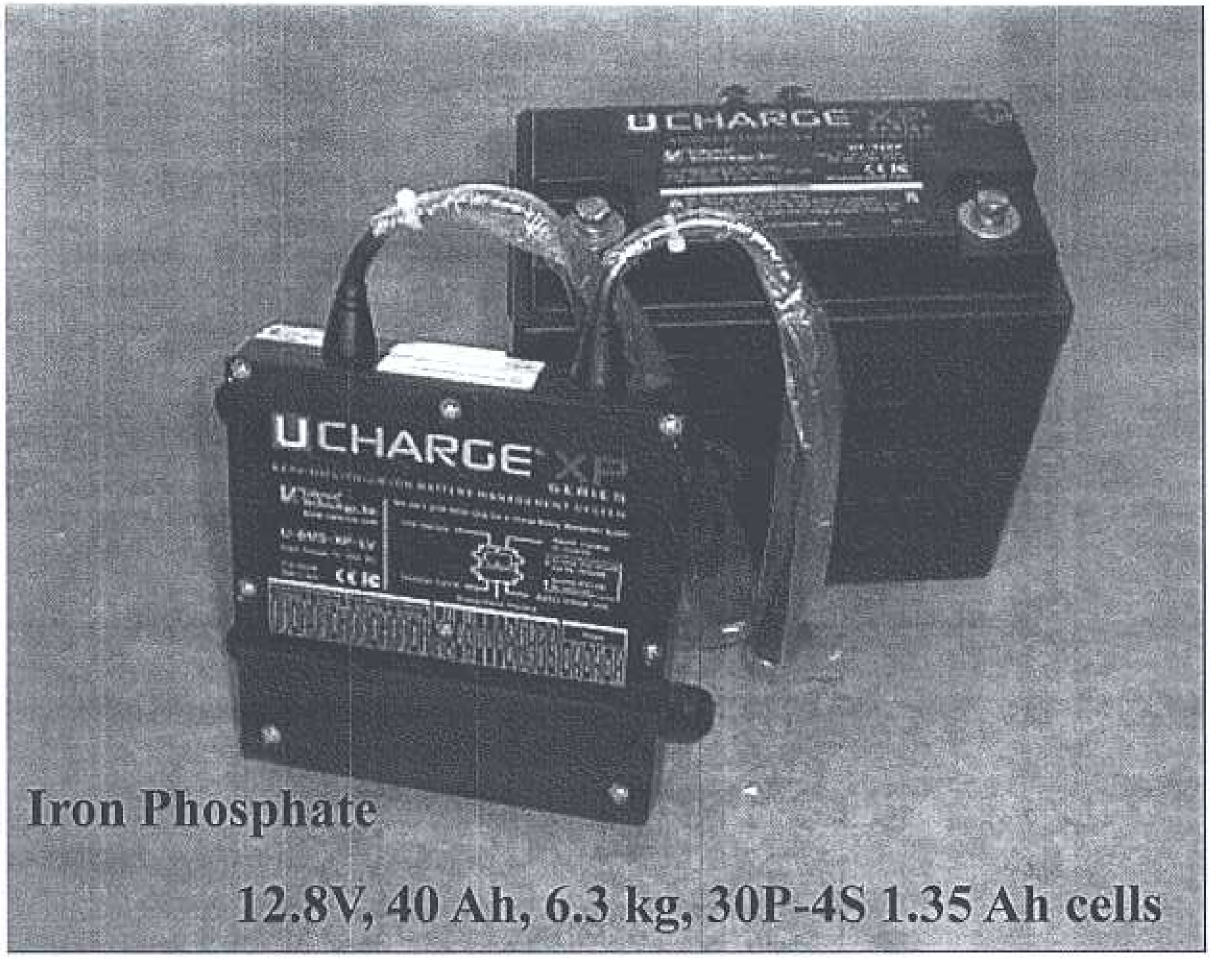
= 150/130 x3.2 =.36 $/Wh = 360 $/kWh

$ pack = Whstored x $/Wh cell

= 390000 x .36 = $14040


ThunderSky/China cell Lithium iron Phosphate 260 Ah
99 W /kg at C/2
180 W/kg at 90% eff.
R= .65 mOhm

12V Module from Valence

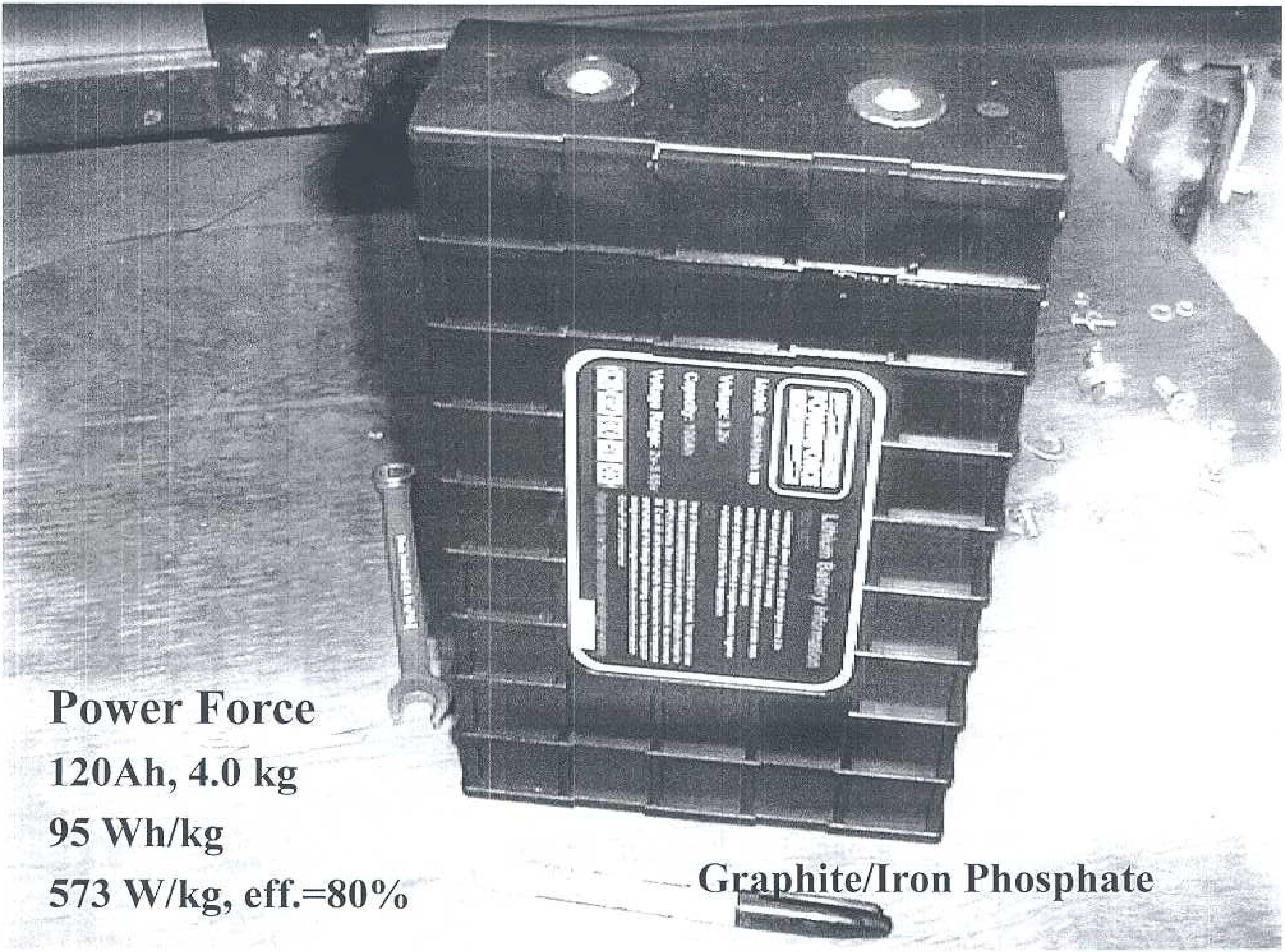


89 Wh/kg based on cell weight

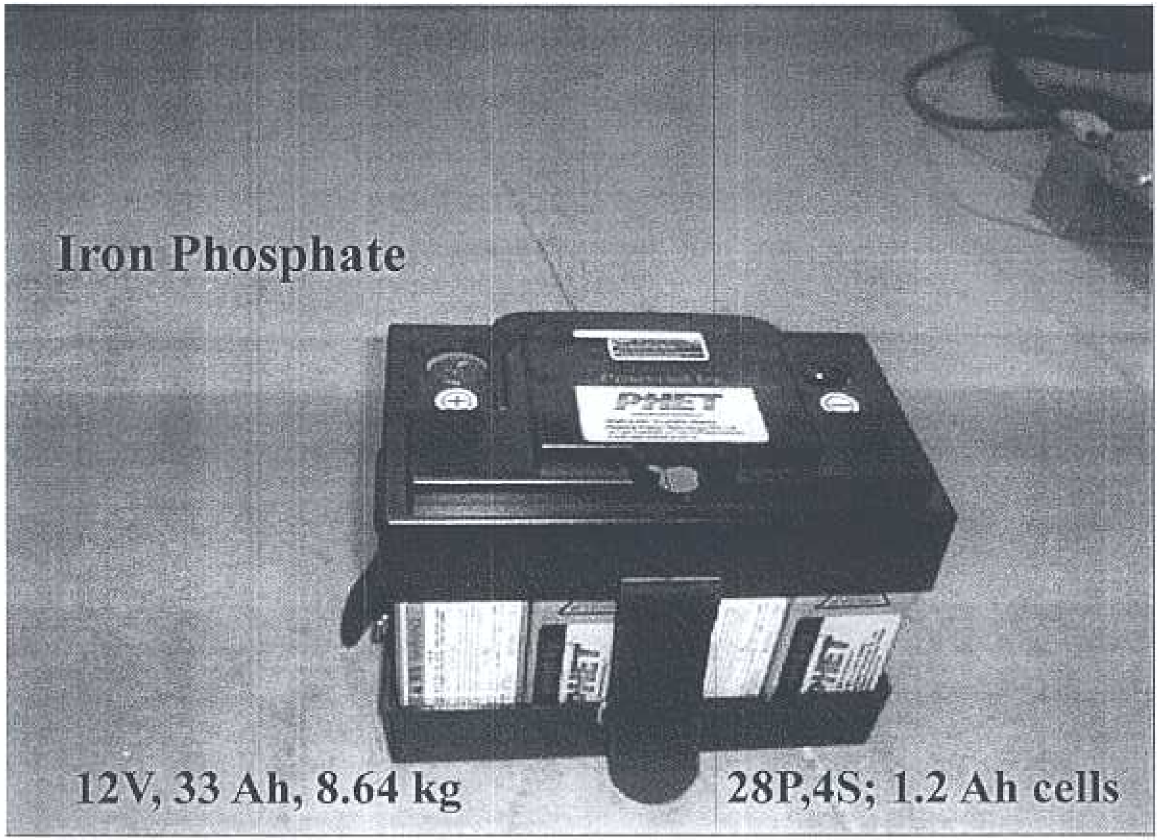
79 Wh/kg based on module weight

530 W/kg at 80% eff. based on module weight

good


Power Force
120Ah, 4.0 kg
95 Wh/kg
573 W/kg, eff.=80%
Graphite/Iron Phosphate

PHET 12V module



90 Wh/kg based on cell weight

44 Wh/kg based on module weight BAP

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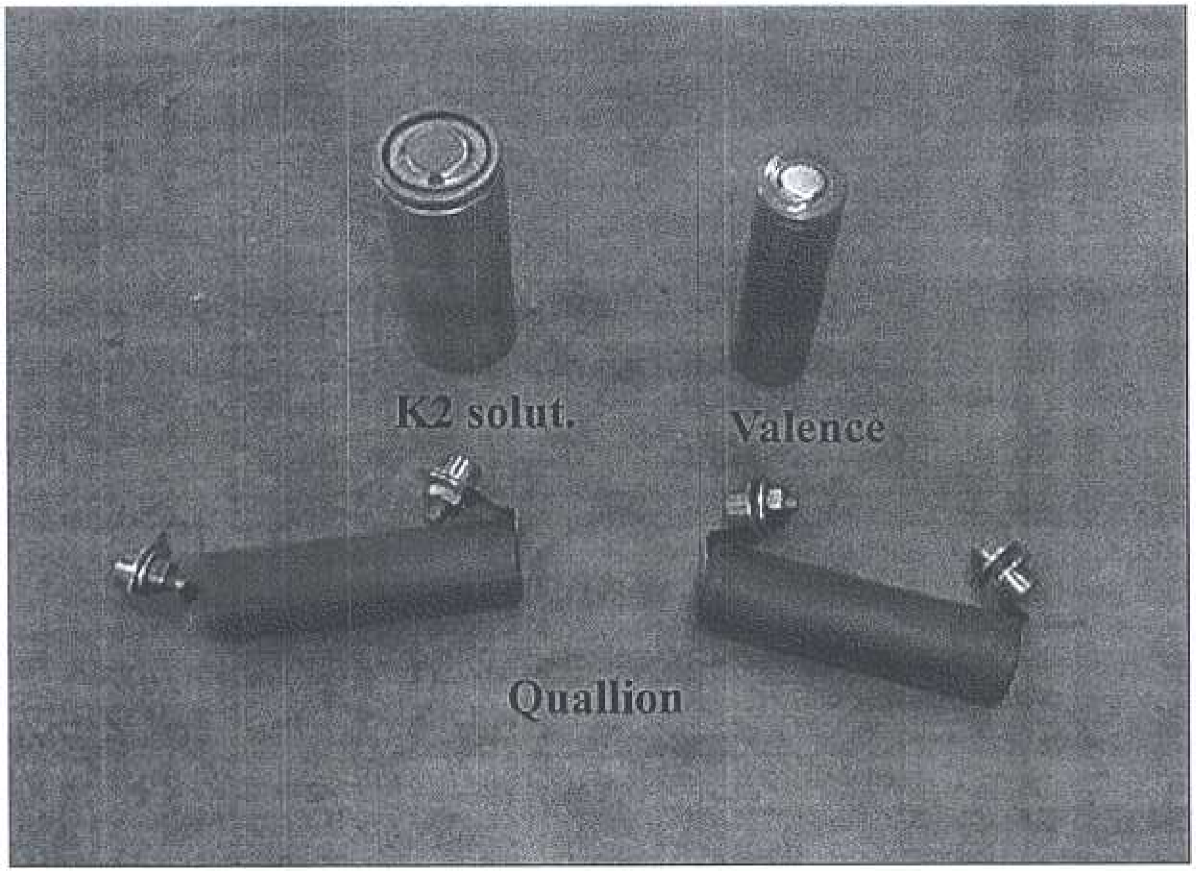
Selected cylindrical Lithium cells



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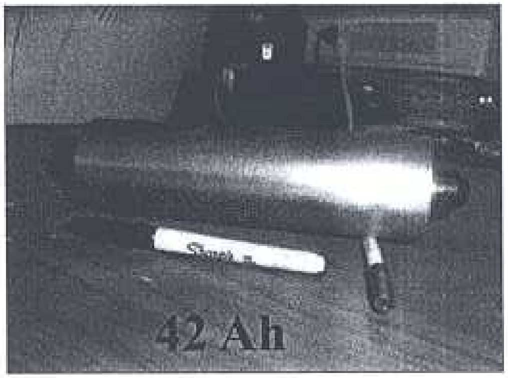
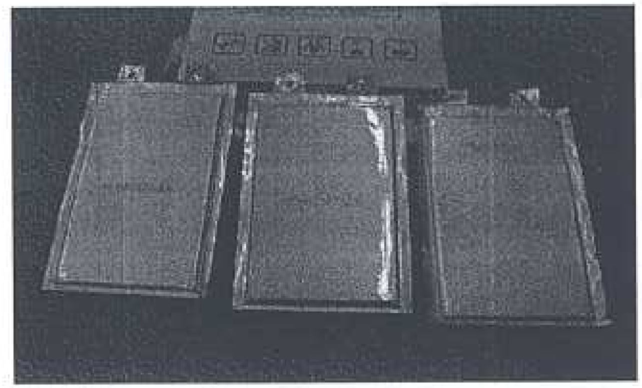
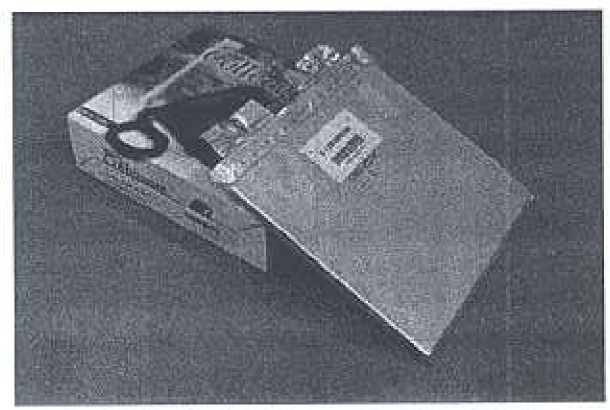


GAIA Cells

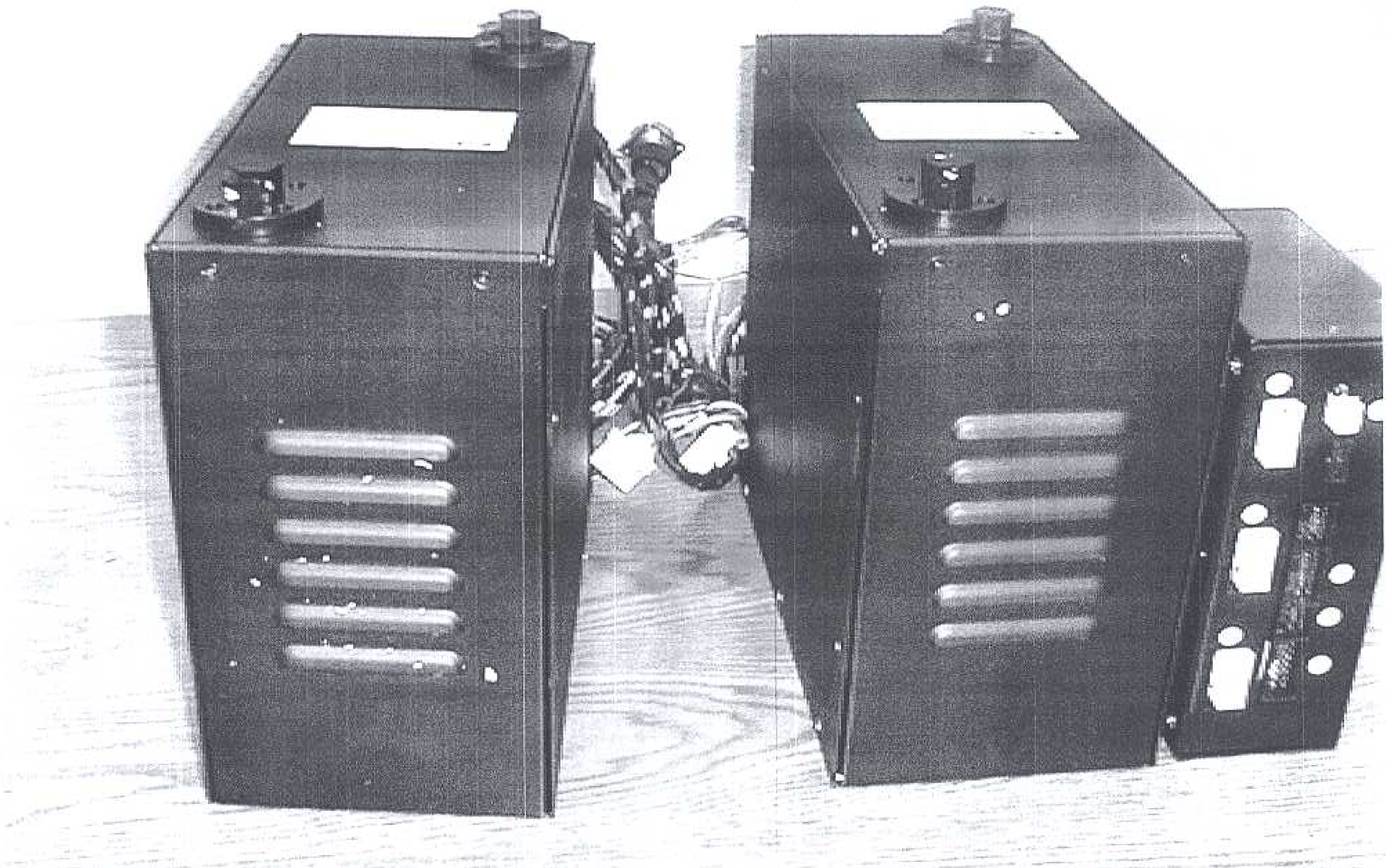


EIG cells



Altairnano cells

EIG 72V Modules NiCoMnO2 and iron phosphate



Modules include cooling fans and battery management hardware/software

Characteristics of lithium-ion batteries using various chemistries

Chemistry Anode/cathode	Cell voltage Max/nom.	Ah/gm Anode/cathode	Energy density Wh/kg	Cycle life (deep)	Thermal stability
Graphite/ $NiCoMnO_2$	4.2/3.6	.36/.18	100-170	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	.36/.11	100-120	1000	fairly stable
Graphite/ $NiCoAlO_2$	4.2/3.6	.36/.18	100-150	2000-3000	least stable
Graphite/ iron phosphate	3.65/ 3.25	.36/.16	90-115	>3000	Stable
Lithium titanate/ Mn spinel	2.8/2.4	.18/.11	60-75	>5000	most stable

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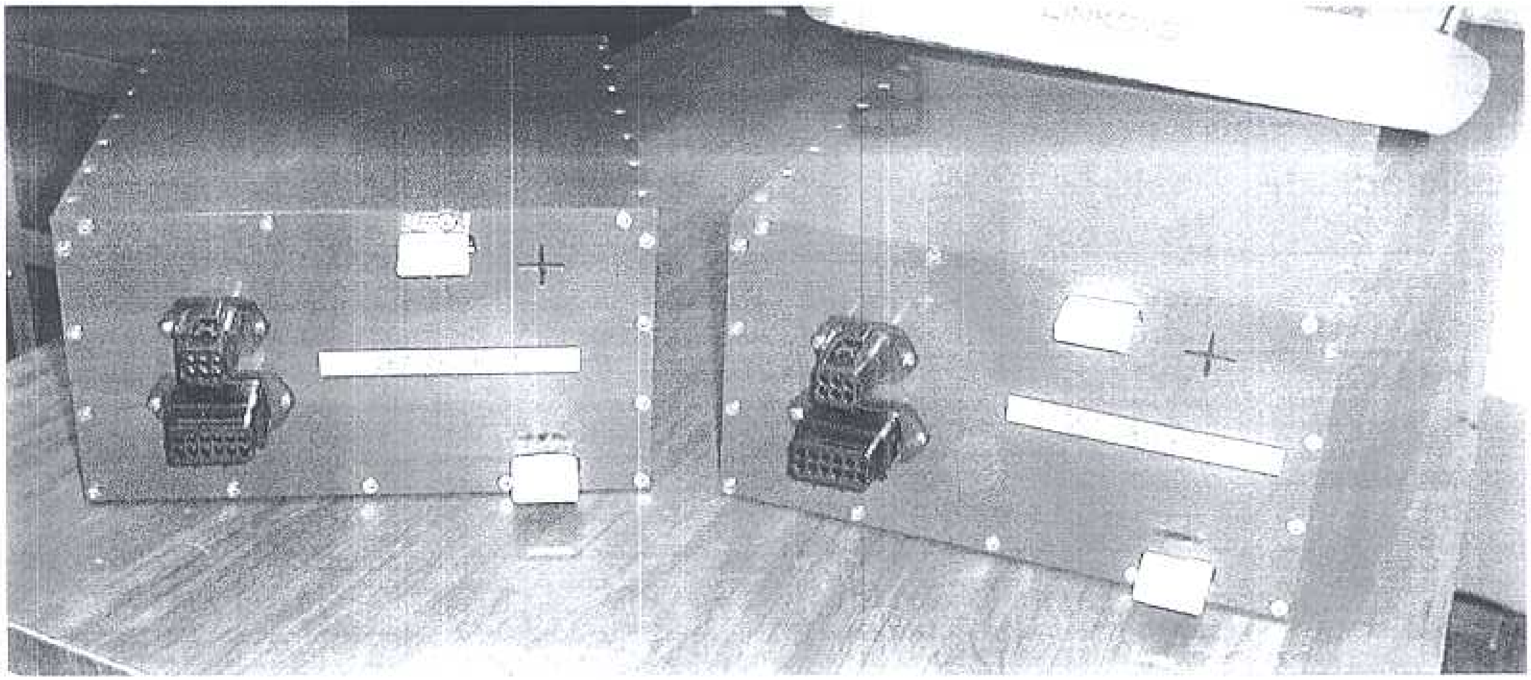

24V Module of the Alairnano 50Ah cells
(Lithium Titanate Oxide)

Normalized resistance characteristics of various cells

Battery developer	Configuration Type	Ah	Resistance mOhm	Wh/kg	Ah-mOhm	Weight kg
Iron phosphate	3.6V/cell					
Power Force	*Prismatic*	*120*	*.93*	*98*	*113*	*3.86*
Tenergy	Prismatic	105	1.5	87	158	3.5
Tenergy	Prismatic	76	2.1	99	160	2.27
Thundersky	Prismatic	260	.65	99	169	8.3
A123	Cylindrical	2.2	12	90	26	.07
K2 Solutions	Cylindrical	2.3	16	88	37	.082
EIG	Prismatic	15	2.5	113	38	.42
Graphite/ NiCoMnO2	4.1V/cell					
Enerdel	Prismatic	15	2.7	127	41	.424
Kokam	Prismatic	30	1.5	140	45	.787
Quallion	Cylindrical	1.8	60	144	108	.043
Quallion	Cylindrical	2.3	72	170	166	.047
EIG	Prismatic	20	3.1	165	62	.41

Summary of the performance characteristics of Lithium-ion batteries of various chemistries

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Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	46	395	1.04	1.8

* power density $P = \text{Eff.}^*(1-\text{Eff.})\, V_{oc}^2/R$

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Thundersky battery tests at UC Davis

(Iron phosphate chemistry   8.3 kg/cell)

Discharged at 130A from 4.2V to 2.5V
7200 sec   260Ah at C/2   99 Wh/kg

400A, 5 sec pulse at $V_{oc} = 3.27V$
Resistance = .65 mOhm   peak power 400 W/kg

Suitable for use in EVs

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Test procedures and approach

- Start with cells, then modules, then packs
- Constant current and then constant power
- Pulse tests at various SOC
- Testing with battery management/monitoring units
- Pulse power cycle (driving simulation) tests – CD, CS
- Life cycle tests
- Fast charging

Test data for the 12V Valence module (iron phosphate)

Constant current tests*

Current A	Time sec	Ah	C/n
20	7054	39.2	C/1.96
40	3525	39.2	C/.98
60	2379	39.6	C/.66
80	1782	39.6	C/.5
100	1441	40	C/.4

* module consists of 30-1.35 cells in parallel and 4 in series charged at 20A to 14.6V and tapered to 2A . discharged to a cut-off voltage of 10V

Constant power tests

Power W	W/kg *	Time sec	Wh	Wh/kg
300	47	6025	502	79
600	94	2949	492	77
900	142	1929	482	76
1200	189	473	473	74

* module weight 6.36 kg, cell weight 5.7 kg

Pulse tests *

		Resistance mOhm	
Current A		discharge	charge
100		9.3	9.3
150		9.2	9.3
200		9.3	9.3

* 5 sec pulses, voltage read at 2 sec to calculate the resistance; 530 W/kg at 80% eff.

Test results for the 100 Ah Tenergy cell from China

Cell is rated at 100Ah, weighs 3.5 kg, and is the iron phosphate chemistry

Constant current

I (A)	Ah
25	106.1
50	103.1
100	100.9
150	100.0

Constant power

W	W/kg	sec	Wh	Wh/kg	max T °C	delta T °C
182	52	6009	304	87	29	5
352	100	2967	290	83	41	15

Pulse tests

I(A)	mohms	
300	1.5	5 sec discharge pulse
300	1.4	5 sec charge pulse
400	1.5	5 sec discharge pulse

Calculation of the peak pulse power

90% efficiency at SOC=50%

$P = .1x.90x\,(3.28)^2/R$

$P = .1x.90x\,(10.76)/.0015 = 645$ W, 184 W/kg (low power cell)

Test data for the K2 iron phosphate cylindrical cell

Constant current discharge data

I(A) *	C rate	Time (sec) to 2.5V	Time (sec) to 2.0V	Ah to 2.5V	Ah to 2.0V
2.5	1	3345	3381	2.33	2.35
5	2	1710 1775 **	1748 1814	2.38 2.46	2.43 2.52
10	4	835	877	2.32	2.44
15	6	560	582	2.33	2.43
20	8	420	435	2.33	2.42
25	10	326	346	2.26	2.40
30	12	260	284	2.17	2.37

* charge at 2.5A to 3.65 V, taper to .1A; rest for 120 sec

** second cell tested

Constant power discharge data-K2 cells

Power W	W/kg	Time to 2.5V	Time to 2.0V	Wh to 2.5V	Wh to 2.0V	Wh/kg to 2.0V
12.6	154	2040	2071	7.14	7.25	88.4
32.2	392	770	791	6.88	7.07	86.2
42.4	517	574	591	6.76	6.96	84.9
52.2	636	440	459	6.38	6.66	81.2
62.4	761	360	378	6.24	6.550	79.9

Weight 82 gm

Pulse resistance data-K2 cells

		Cell #1		Cell#2	
State-of-charge	Open-circuit voltage	Resistance for a discharge pulse mOhm (1)	Resistance for a charge pulse mOhm	Resistance for a discharge pulse mOhm (1)	Resistance for a charge pulse mOhm
100%	3.55	16	15	16	15.3
80%	3.33	16.3	15.4	16	14.7
60%	3.27	16.8	17.3	17.4	17.2
40%	3.25	18.0	17.8	18.7	17.9
20%	3.21	20	18.8	20.8	20.0

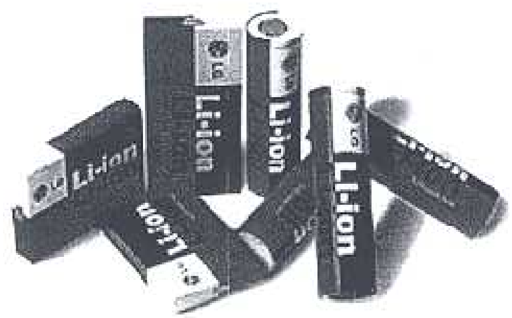
(1) Average of resistance for a 2 sec pulse

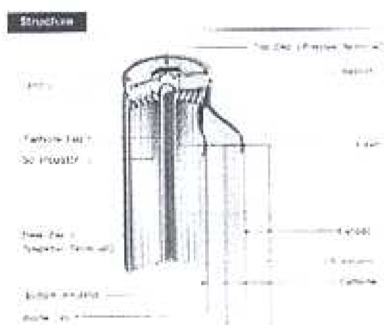
(2) Peak power 780 W/kg at 60% SOC for 90% effic.

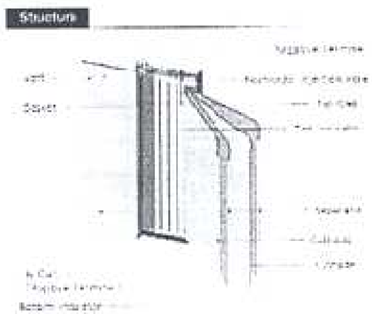
Products Info

LG Li-ion Battery

CYLINDRICAL/PRISMATIC







CYLINDRICAL/PRISMATIC

Model		CP853448	CP633067	CP633450	CP633048	CP673450	ICP423450	ICP423048	ICR[illegible]	ICR[illegible]
Nominal Capacity		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Minimum Capacity		[illegible]	[illegible]	860mAh	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Nominal Voltage		3.7V	3.7V	3.7V	3.7V	3.7V	3.7V	3.7V	[illegible]	3.7V
Standard Charge Conditions	Constant Current	[illegible]	[illegible]	490mA	425mA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Constant Voltage	4.2V	4.2V	4.2V	4.2V	4.2V	4.2V	4.2V	[illegible]	4.2V
	Cut-off Current	[illegible]	50mA	50mA	50mA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Ending Time	5hrs	5hrs	5hrs	[illegible]	5hrs	5hrs	5hrs	[illegible]	[illegible]
	Temperature	[illegible]	[illegible]	23°C	23°C	[illegible]	23°C	23°C	23°C	23°C
Standard Discharge Conditions	Constant Current	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Cut-off Voltage	3.0V	3.0V	3.0V	[illegible]	3.0V	3.0V	3.0V	[illegible]	3.0V
	Temperature	23°C	23°C	23°C	23°C	[illegible]	23°C	23°C	23°C	[illegible]
Maximum Charge Current		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Maximum Discharge Current		2300mA	2100mA	1960mA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Operating Temperature	Charge	0 ~ 45°C	0 ~ 45°C	0 ~ 45°C	0 ~ 45°C	0 ~ 45°C	0 ~ 45°C	0 ~ 45°C	0 ~ 45°C	0 ~ 45°C
	Discharge	-20 ~ 60°C	-20 ~ 60°C	-20 ~ 60°C	-20 ~ 60°C	-20 ~ 60°C	-20 ~ 60°C	-20 ~ 60°C	[illegible]	[illegible]
	Storage	[illegible]	[illegible]	-20 ~ 60°C	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dimensions (mm)	Max Thickness	8.5	6.5	6.5	6.5	6.4	4.6	4.6	18.4	18.4
	Max Width	[illegible]	[illegible]	34.0	[illegible]	34.0	34.0	30.0		

LG Chem

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Kokam High Power Cells (graphite/NiCoMnO2)

Constant current discharges   4.1V to 3.2V

Current (A)	Time (sec)	Ah	nC
15	7417	30.9	.485
30	3611	30.1	1.0
60	1728	28.8	2.08
100	976	27.1	3.69
150	603	25.1	5.97

Charge at 31A to 4.2V and taper to 1.5A

Constant power discharges   4.1V to 3.2V

Power (W)	Time (sec)	Wh	Wh/kg	W/kg
43	9806	117.1	148.8	55
82	4835	110.1	139.8	104
162	2355	106.0	137.7	206
242	1509	101.4	128.9	308
321	1097	97.8	124.3	408
402	854	95.4	121.2	511
482	674	90.2	114.6	612

Cell weight   787 g

Test data for the Power Force 120 Ah cell (iron phosphate)

Constant current (A)	Time sec	Ah		Pulse resistance	mOhm
60	7327	122		100 A	.85
120	3638	121		150A	.93
200	2176	121		200A	.95
Constant power	Time sec	Wh		Wh/kg	W/kg
200	6815	379		98	52
400	3305	367		95	104
800	1559	346		90	207

Charge at 60A to 3.65V, taper to 2A; weight 3.86 kg
Discharge from 3.65V to 2.0V

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Pulse resistance of the 30 Ah Kokam cell

		Current initiation** Resistance (mOhm)				Current interruption*** Resistance (mOhm)		
SOC (%)	V_{oc}	100A	150A	200A		100A	150A	200A
80	3.9	1.8	1.7	1.8		1.8	1.7	1.7
60	3.72	1.8	---	1.7		1.7	---	1.7
40	3.6	1.8	1.7	1.7		1.6	1.7	1.7
20	3.51	2	---*	---*		2	2	---*

* Pulse voltage fell to minV (3.2V) in less than 5 sec

** resistance calculated from the voltage at 2 sec

*** resistance calculated from the voltage at the end of a 5 sec discharge pulse and the voltage 5 sec after the current interruption

Pulse test data for the 31Ah Kokam Cell

Cell resistance based on pulse tests 5 sec pulses, V at 2 sec

State-of-charge	Current (A)	Resistance (mOhm)
80%	150A disch	1.6
$V_{oc} = 3.94$	200A disch	1.6
	310A disch	1.55
	50A charge	1.6
	100A charge	1.6
	150A charge	1.53
		1120 W/kg at 90% eff.
60%		
$V_{oc} = 3.75$	150A disch	1.53
	200A disch	1.5
	310A disch	1.45
	50A charge	1.6
	100A charge	1.5
	150A charge	1.53
40%		
$V_{oc} = 3.64$	150A disch	1.53
	200A disch	1.5
	310A disch	1.42
	50A charge	1.6

GOOD BATTERY

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Test data for the EIG graphite/ NiCoMnO2 cell

	Weight .45kg	4.2V-3.0V		
Power (W)	W/kg	Time (sec)	Wh	Wh/kg
50	111	4560	63.0	140.7
90	200	2486	62.1	138.0
120	267	1906	63.5	141
Current (A)	Time (sec)	Ah	Crate	
20	3242	18	1.1	
40	1602	17.8	2.2	
60	1065	17.8	3.3	
Resistance	3 sec pulses			
	mOhm			
SOC Voc	100A	250A	$(W/kg)_{90\%eff.}$	
100% 4.11	3.2	3.12	1069	
50 % 3.67	2.9	3.12	895	
20% 3.52	3.6	3.3	718	

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Pulse Power Capability of the Kokam 30Ah cell

Matched impedance power $P = V^2/4R = 16/4x\ .00155 = 2580\ W,\ 3280\ W/kg$

Power at specified pulse efficiency $P = EF\ (1\text{-}EF)\ V^2/R$

95%	$P = .95x.05x\ 16/.00155 = 490W,\ 623\ W/kg$
90%	$P = .9x.10x\ 16/.00155 = 929W,\ 1180\ W/kg$
80%	$P = .8x.20x\ 16/.00155 = 1651W,\ 2099\ W/kg$

Two cells were tested and the data from the two cells were almost identical. The difference in the weight of the cells was only 2 grams.

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Test data for the 15 Ah EIG iron phosphate cell

Iron Phosphate				
FO 15A	Weight .424kg	3.65-2.0V		
Power (W)	W/kg	Time (sec)	Wh	Wh/kg
62	142	2854	49.5	117
102	240	1694	48.0	113
202	476	803	45.1	106
302	712	519	43.5	103
401	945	374	41.7	98
Current (A)	Time (sec)	Ah	Crate	Resistance mOhm
15	3776	15.7	.95	
30	1847	15.4	1.95	2.5
100	548	15.2	6.6	
200	272	15.1	13.2	
300	177	14.8	20.3	

W/kg=869 at 90% effic.

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Pulse characteristics of the CO20Acell at 250A at various states-of-charge

Voc	DOD %	$V_{2\ sec}$	Effic. %	R mOhm	Power W	W/kg
4.12	0	3.33	80.8	3.16	833	1850
3.98	10	3.24	81.4	2.96	810	1800
3.88	20	3.14	80.9	2.96	785	1744
3.78	30	3.06	81.0	2.88	765	1700
3.72	40	2.98	80.1	2.96	745	1655
3.67	50	2.90	79.0	3.08	725	1611
3.63	60	2.84	78.2	3.16	710	1578
3.59	70	2.74	76.3	3.4	685	1522
3.54/100A	80	3.18	89.8	3.6	318	706
3.48/100A	90	2.96	85.1	5.2	296	658

SOC=80%, 1003 W/kg at 90% eff.

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Test data for the 15 Ah EIG iron phosphate cell

Iron Phosphate				
FO 15A	Weight .424kg	3.65-2.0V		
Power (W)	W/kg	Time (sec)	Wh	Wh/kg
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100	548	15.2	6.6	
200	272	15.1	13.2	
300	177	14.8	20.3	

W/kg=869 at 90% effic.

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Fast charging of iron phosphate and lithium titanate oxide cells

Test data for the Altairnano 11Ah lithium titanate oxide cell

Constant current test data (2.8-1.5V)

I(A)	nC	Time (sec)	Ah	Resistance mOhm
10	.8	4244	11.8	--
20	1.7	2133	11.9	--
50	4.5	806	11.2	2.2
100	9.2	393	10.9	2.1
150	15.3	235	9.8	--
200	---	116	6.4	--

W/kg =849 at 90% eff.

Resistance based on 5 sec pulse tests

Constant power test data (2.8-1.5V)

Power W	W/kg	Time sec	nC	Wh	Wh/kg
30	88	2904	1.2	24.2	71.2
50	147	1730	2.1	24.0	70.7
70	206	1243	2.9	24.2	71.0
100	294	853	4.2	23.7	69.7
150	441	521	6.9	21.7	63.8
170	500	457	7.9	21.6	63.5
260	764	255	14	18.4	54.2
340	1000	103	35.0	9.7	28.6

Mass: .34 kg

Continous power capability

We can estimate continuous power from the batteries of the 66 Ah cells.
V_{oc} = 344, 66 Ah cells, 2.5 kg per cell, $R_{66\ Ah\ cell}$ = 2.3 mOhm, 105 cells in series,
$(c_p)_{mat}$ = .84 kJ/kg degK

I (A)	V	P(kW)	delta V	EF	delta T deg C/hr	**Q (W)heat gen.**
25	338	8.45	6	.982	2.5	152
50	332	16.6	12	.965	6.5	581
75	326	24.5	18	.948	20.8	1274
100	320	32.0	24	.930	36.5	2240

The simulations of the vehicle indicated that the battery power is 10.7 kW for 65 mph. and about 20 kW at 80 mph. Clearly cooling of this battery pack is required for high speed travel for long distances.

$P_{dissip} = I^2 R$, eff. = delta V/ V_{oc}

$(C_p)_{pack} = (c_p)$mat. x Weight pack

Delta T degC /hr. = $Q/(C_p)_{pack}$ x 3600/1000

Constant power tests of the Tenergy 66 Ah cell

We did constant power tests at 180 and 350W. We were planning tests at higher power, but the cell heated up to over 40 deg C during the 350W tests so we did not do higher powers.

W	W/kg	time-sec	Wh	Wh/kg	max T	delta T
182	52	6009	304	87	29	5
352	100	2967	290	83	41	15

100 W/kg with the 66 Ah cells (105 in series) corresponds to 26 kW continuous power. It seems clear that serious consideration must be given to cooling of this battery in the car to achieve reasonably high continuous power.

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Battery pack weight and peak power characteristics for various battery technologies

Battery	Vnom	Ah	kg	R mOhm	Wh/kg	W/kg 80% ***	Wgt. kg 25kWh ****	Max. Power kW
Thnder sky *	3.5	260	8.3	.65	99	363	253	92
Tenergy	3.5	105	3.5	1.5	87	373	287	107
Tenergy	3.5	76	2.3	2.1	99	406	253	103
Power Force	3.5	120	4.0	.93	95	527	263	139
EIG	3.5	15	.42	2.5	113	1866	221	>300
Enerdel**	3.75	15	.42	2.7	127	1984	197	>300
Kokam	3.75	30	.79	1.5	140	1898	179	>300
EIG	3.75	20	.41	3.1	165	1770	152	269

* graphite/iron phosphate
** graphite/NiCoMno2

*** $P_{max} = .2 \times .8 \times Vnom.^2/R$, eff.=80%
**** cell weight only, battery packaging not included

Calculation of the peak pulse power (100 Ah Tenergy cell)

I will do the calculation for 75% efficiency and 50% SOC. This corresponds to a pulse voltage of 258V.

$P = .75x.25x\ (3.28)^2\ /R$

$P = .75x.25x\ (10.76)/.0015 = 1345\ W$

If we have 105 cells, the peak pulse power would be 141 kW using the 100 Ah cells.

P = Eff x (1-Eff) x (Voc)2 /R : Eff = Vpulse/Voc
Voc and R depend on SOC

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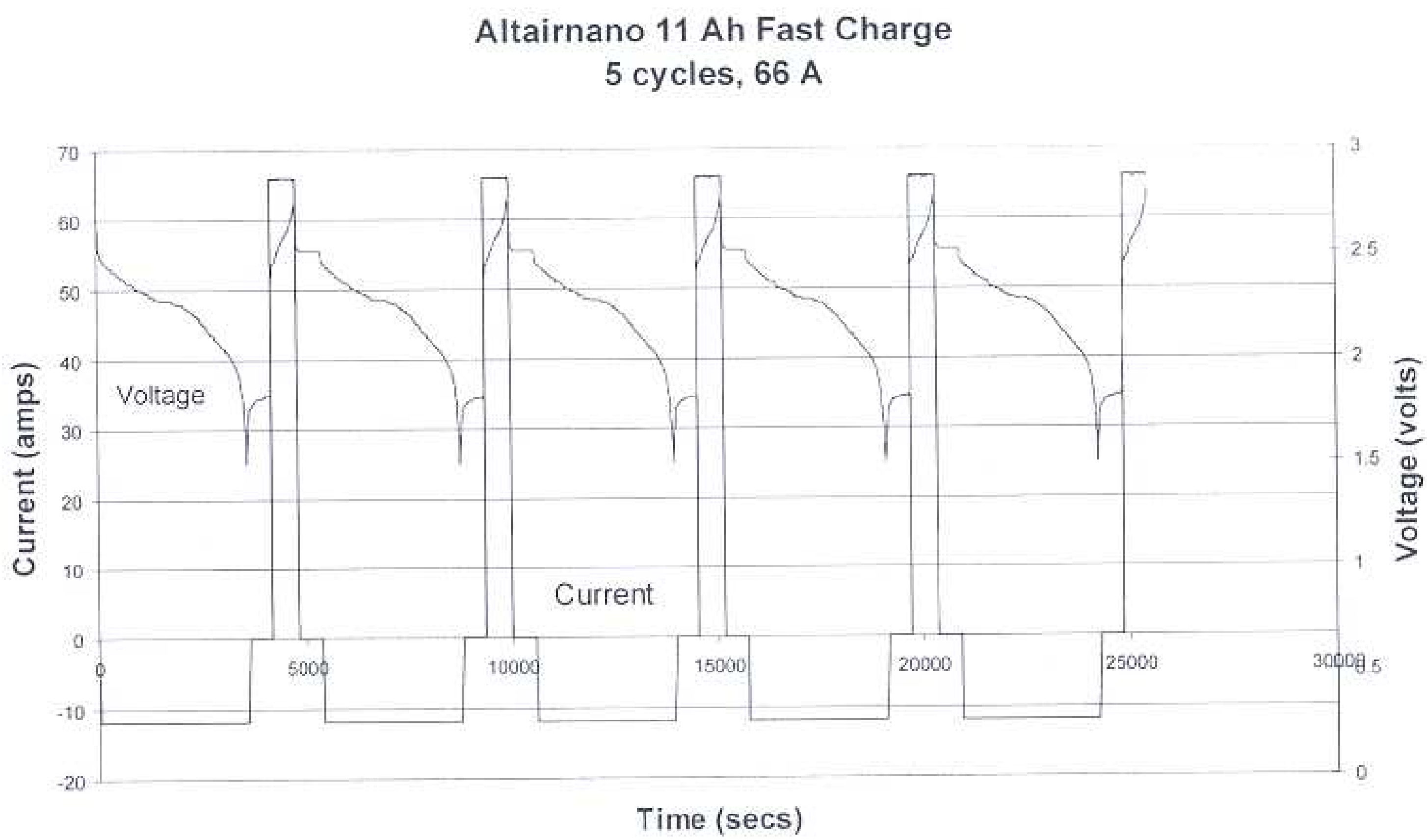
Five cycle fast charge of the Altairnano 11 Ah cell



Fast charge test data for lithium-ion chemistries

EIG iron phosphate 15 Ah cell

Charge Current (Amps)	Time to Cutoff (secs)	Taper Time (secs)	Charge to Cutoff (Amp-hrs)	Total Charge (Amp-hrs)	Discharge (Amp-hrs)	Temp Rise During Cha Initial Temp (C)	Temp Change (C)
15	3630	210	15.2	15.4	15.50	22.5	0
30	1770	210	14.7	15.4	15.45	22.5	1.5
45	1140	199	14.2	15.4	15.38	22.5	3
60	840	172	13.9	15.3	15.30	23.5	4.5
75	630	184	13.1	15.3	15.29	25.5	5.5
90	480	219	11.9	15.2	15.17	23	7
120	240	316	7.9	15.2	15.16	25	9
No Taper							
60	780.4		12.9		12.99		
90	464.8		11.6		11.60		

Altairnano titanate oxide 11 Ah cell

Charge Current (Amps)	Time to Cutoff (secs)	Taper Time (secs)		Charge (Amp-hrs)	Discharge (Amp-hrs)	Temp Rise During Cha Initial Temp (C)	Temp Change (C)
11	3920	81	11.9	12.0	12.00	22.5	0
22	1950	68.5	11.9	12.0	12.00	22	0.5
33	1300	57.7	11.9	12.0	12.00	22.5	1.5
44	970	59.2	11.8	12.0	12.01	23	2.5
55	760	74.8	11.6	12.0	11.97	21.5	4
66	620	83	11.3	12.0	11.97	22.5	4.5
88	440	103.1	10.7	12.0	11.97	24	6.5

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Detailed calculations of pack performance limits

- Energy stored kWh What is useable?
- Peak power for acceleration kW
- Max power for steady speed kW Cooling requirements (W)
- Pack weight (kg) and volume (L)
- Cycle life
- Voltage and temperature limits
- Battery management (voltage and temperature)
- Cost

Repeated fast charging cycles for the 11Ah lithium Titanate oxide cell

66 Amps charge to 2.8V 12A discharge to 1.5V no active cooling

Cycle Charge or Discharge	Time to Cutoff (secs)	charge Amp-hrs	Discharge Amp-hrs	Initial Temp (C)	Highest Temp (C)
1 Chg	614.4	10.24		21.5	26
2 Dischg			11.19	24	22
2 Chg	614.7	10.25		21.5	26.5
3 Dischg			11.18	24	22
3 Chg	614.5	10.24		21.5	26
4 Dishcg			11.18	24	22
4 Chg	614.1	10.24		21.5	26
5 Dischg			11.17	23.5	22
5 Chg	614.1	10.24		21.5	26

Characteristics of battery electric vehicles (EV) of various types

Vehicle type	Vehicle test weight kg	Battery Wgt. kg (1)	Battery kWh stored (2)	Electric motor kW (3)	Required Battery pulse power W/kg (4)	Wh/mi from battery (5)	0-60 mph Sec
Cars							
Compact	1373	168	20.2	65	387	202	11.3
Mid-size	1695	208	24.9	102	490	249	8.9
Full	1949	238	28.5	122	513	285	8.6
SUV							
Small	2103	266	31.9	128	481	319	9.6
Mid-size	2243	278	33.3	143	514	333	9.3
Full	2701	317	38.0	160	501	380	9.6

(1) Lithium-ion battery with an energy density of 120 Wh/kg
(2) All vehicles have a range of 100 miles
(3) Peak motor power
(4) Peak pulsed power required from the battery at 90% efficiency
(5) Average energy consumption on the FUDS and FHWAY drive cycles

$P = IE$
120×240

240
120
4800
240
$\overline{}$00

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Energy storage requirements for various transportation applications

- energy stored (kWh), peak power (kW), system voltage
- pack weight (kg) and volume (L)
- cell characteristics: Ah, resistance, geometric shape
- Wh/kg, Wh/L, W/kg
- initial cost ($/kWh)
- cycle and calendar life

Temperature limits

- Depend primarily on the properties of the electrolyte and salt added (LiPF6)
- At low temperatures, issue is performance due to the high viscosity and high resistance of the electrolyte. Lower limit is -10 to -20 deg C for electrolytes using EC.
- At high temperatures, it is cycle life due to the PF6- ion being unstable in the electrolyte above about 60 deg C. The iron phosphate chemistry seems to have the best high temperature stability by about 10 deg C.

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Voltage and temperature limits for battery operation

Voltage limits for charge and discharge – cell basis

Iron phosphate

- charge to 3.65 V/cell and taper at constant V
- cells charge at the 1C rate very well
- discharge to 2.0V/cell

NiCoMnO2

- charge to 4.2 V/cell and taper at constant V
- cells charge at the 1C rate very well
- discharge to 3.0V/cell

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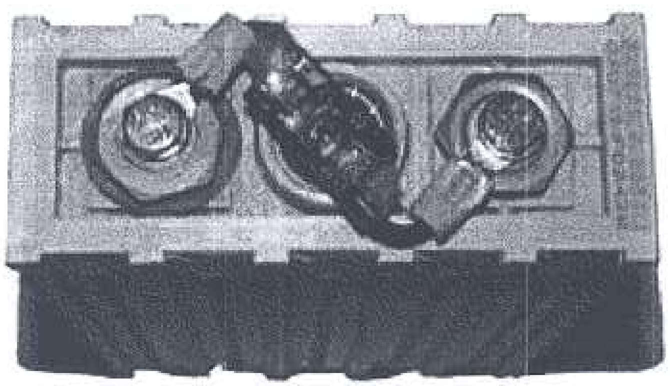
Regulators / Equalizers / Balancers

Regulators (also called "equalizers" or "balancers") are sometimes used in Li-Ion packs as a simple protection against overcharging. A regulator is required across each cell.

A regulator performs balancing during charging by bypassing charging current from the fully charged cells, so that other cells in the battery can finish charging.



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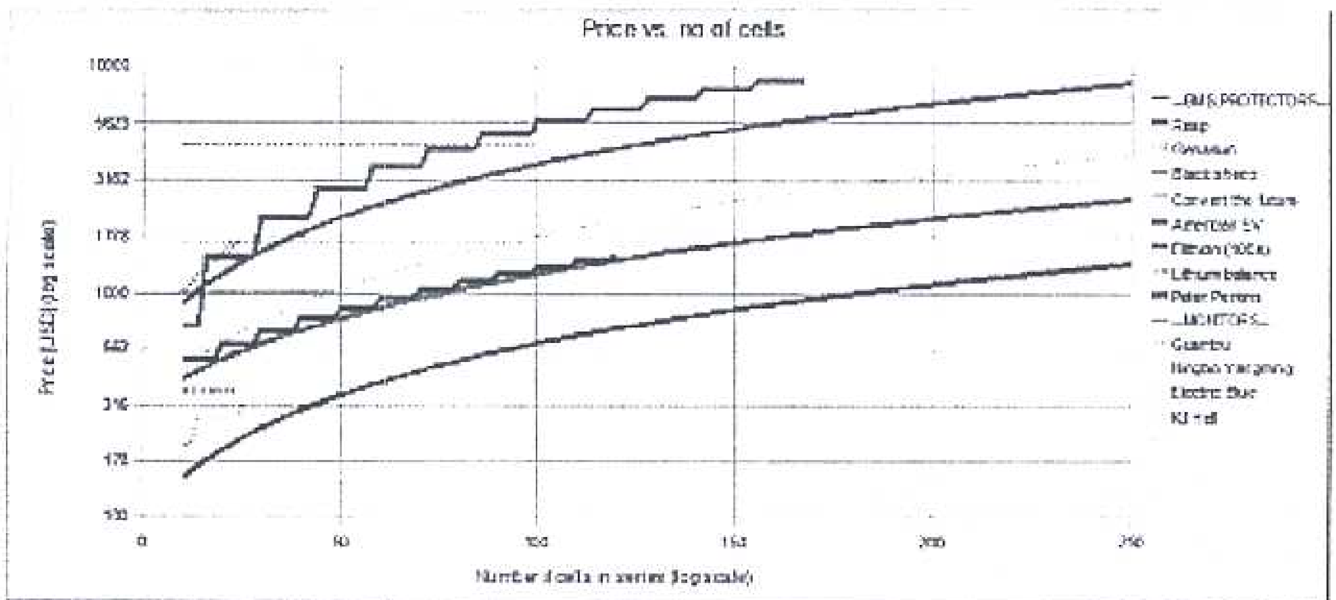
Price of battery management hardware



Protectors (thick dotted line), Balancers (thick line), Monitors and displays (thin dotted line).

Note: log scales. Sources: [15]

Battery management units

		Reports individual cell voltages	Balances the battery	Requests that battery be switched off	Includes switch to turn off battery
Digital	Protector	☐	☐	☐	☐
	Balancer	☐	☐	☐	
	Monitor	☐		☐	
	Display	☐			
Analog	Protector		☐	☐	☐
	Balancer		☐	☐	
	Monitor			☐	
	Regulator		☐		

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Discharge of an Iron Phosphate cell at the 1C rate at various temperatures

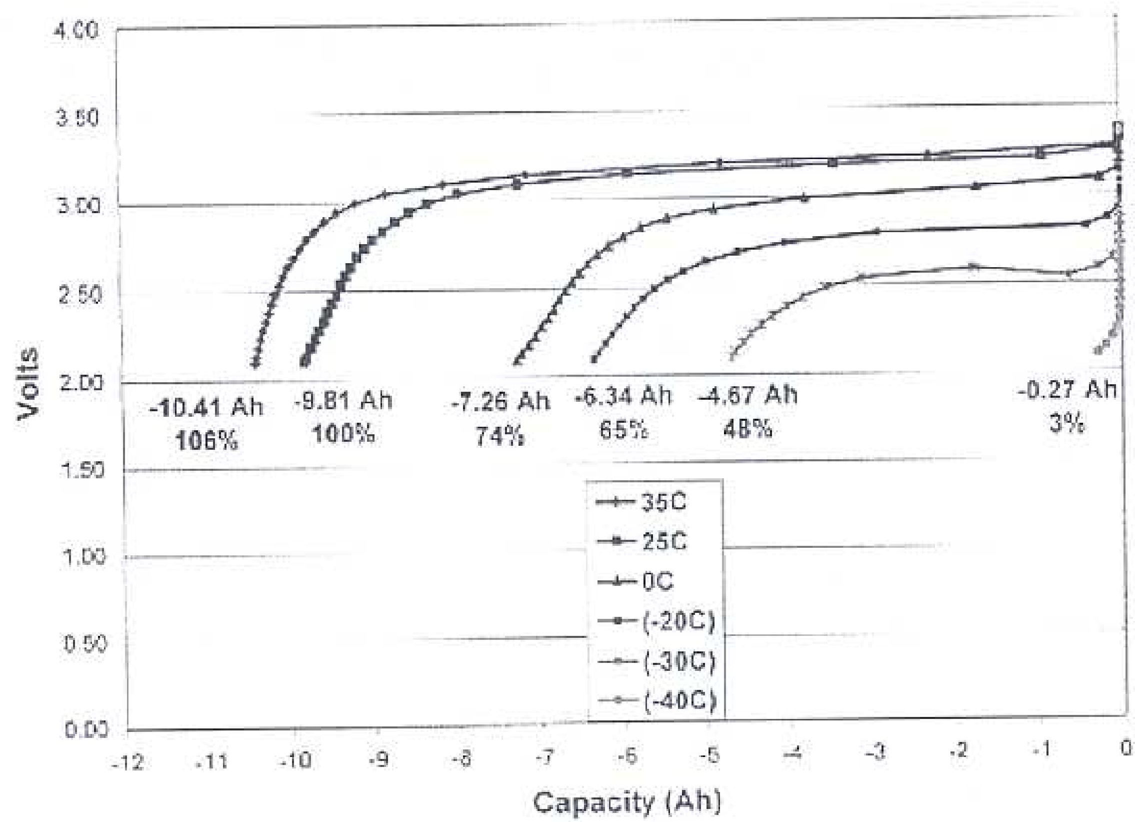
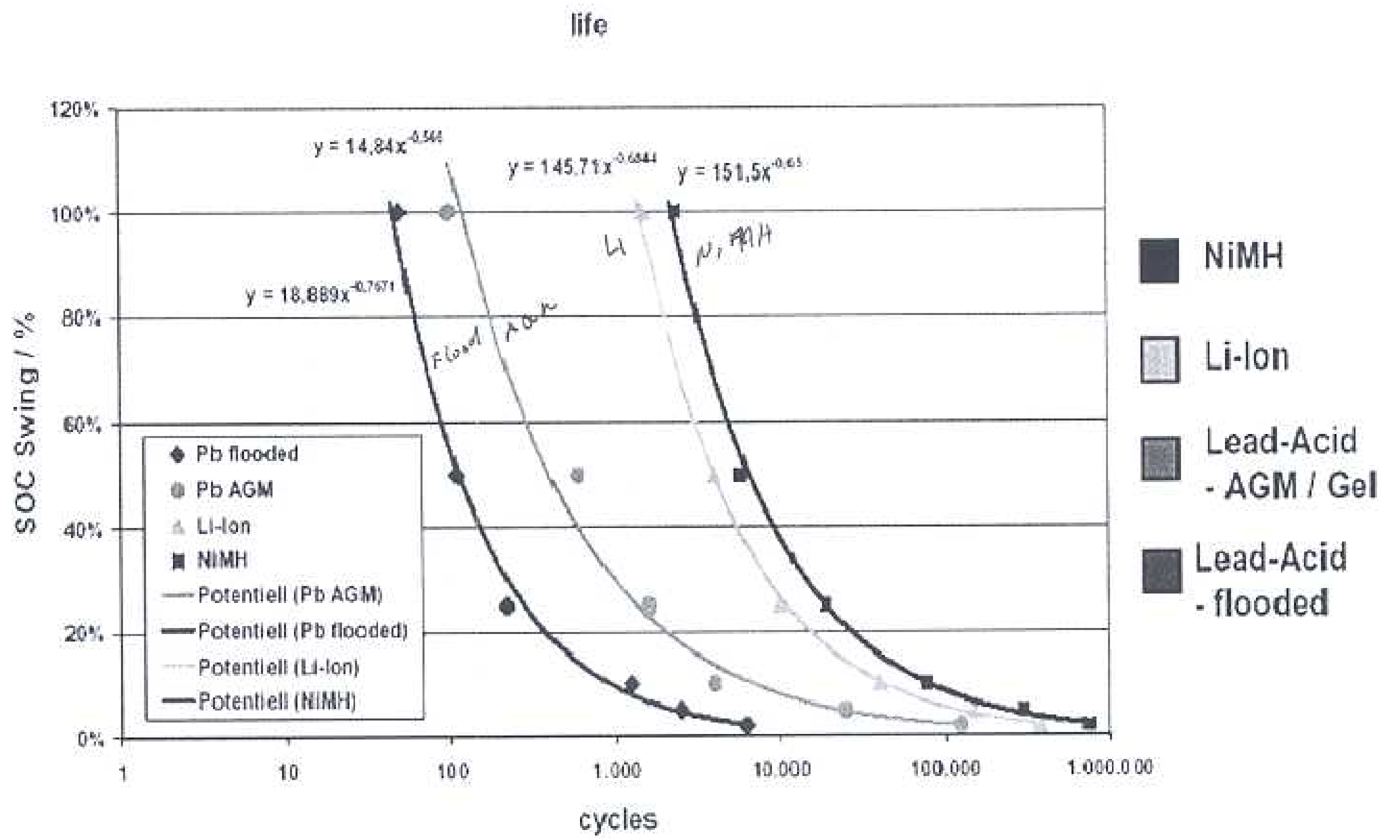


Figure 10. Capacity vs. Temperature at 10A.

Sandia NL data

Cycle life correlations for various types of batteries



y = SOC swing, x=number of cycles   data compiled by NREL

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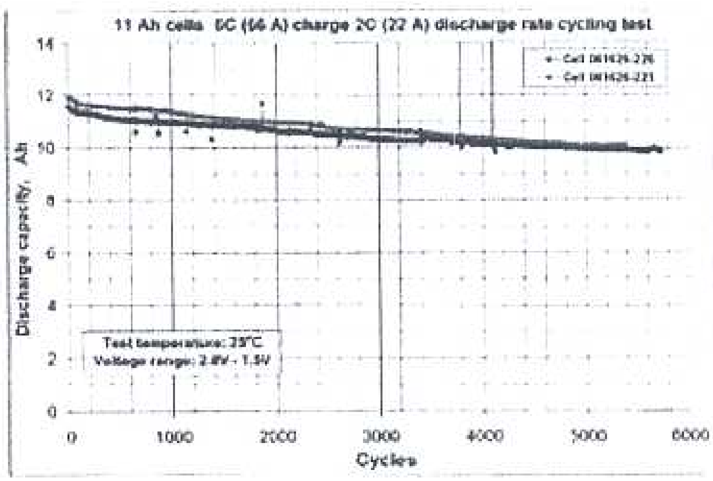
Cycle life considerations

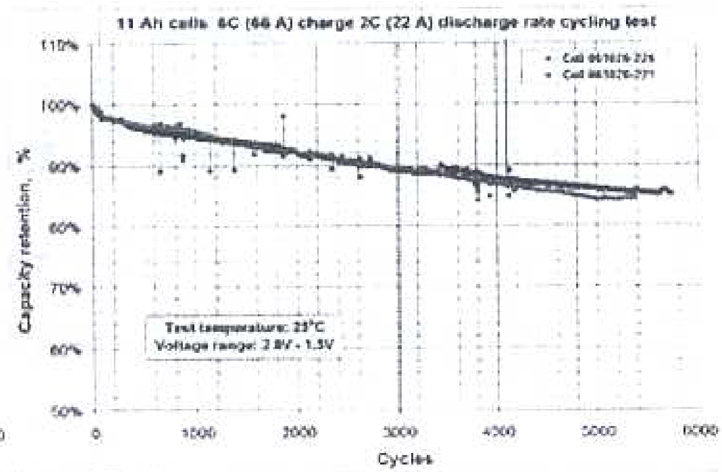
Limited data available for cells

Almost no data on modules and testing at elevated temperatures

No information on the effect of the cell performance and life cycle statistics on packs consisting of hundreds or thousands of cells

- Altairnano 11 Ah energy storage cells cycling test at 6C (10 min) charge & 2C (30 min) discharge rate
  - Multi-metal oxide positive elctrode
  - Cell used in Phoenix SUT





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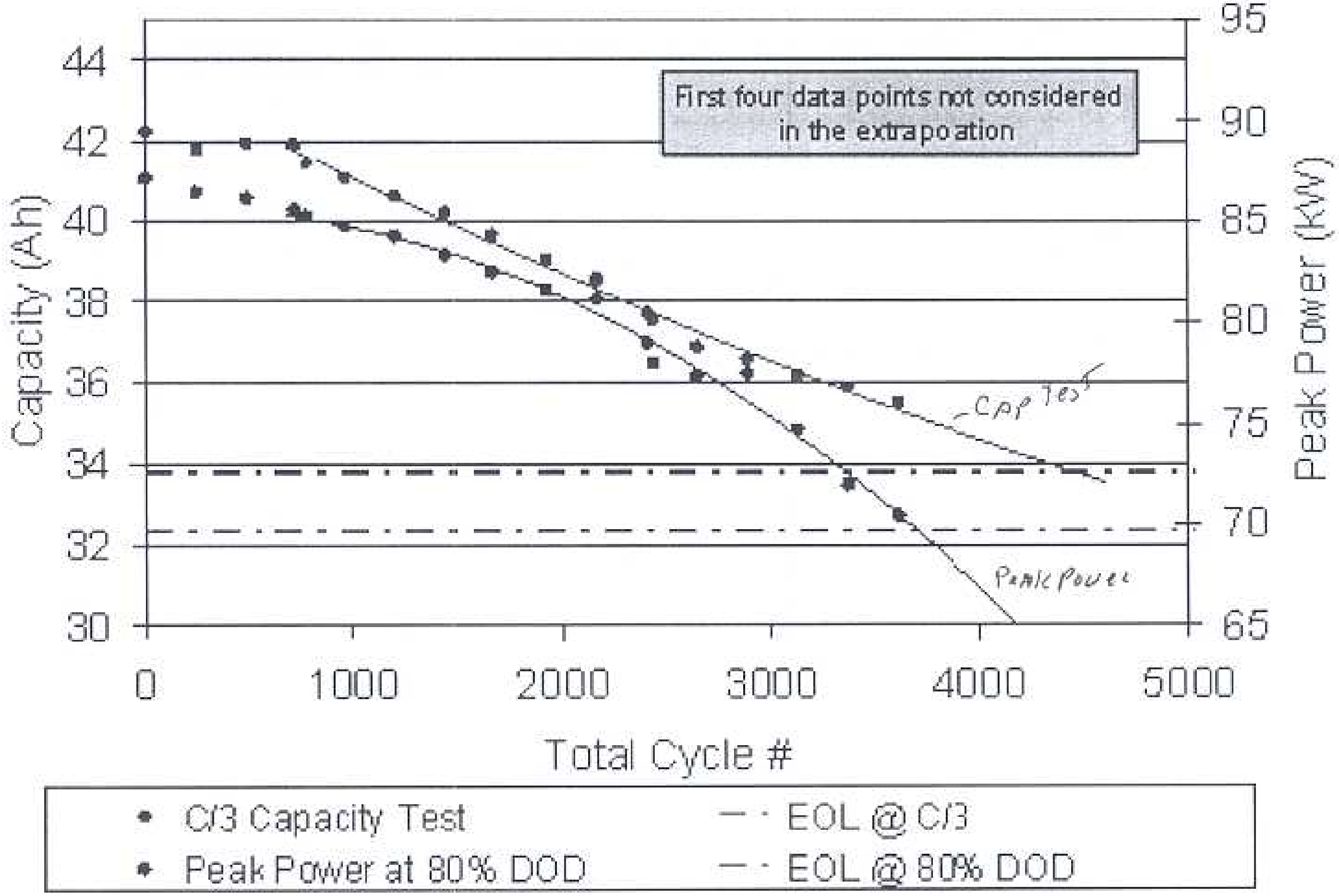
Life Cycle Tests of the Saft lithium-ion battery (NiCoAl)



Southern California Edison data Sprinter PHEV project

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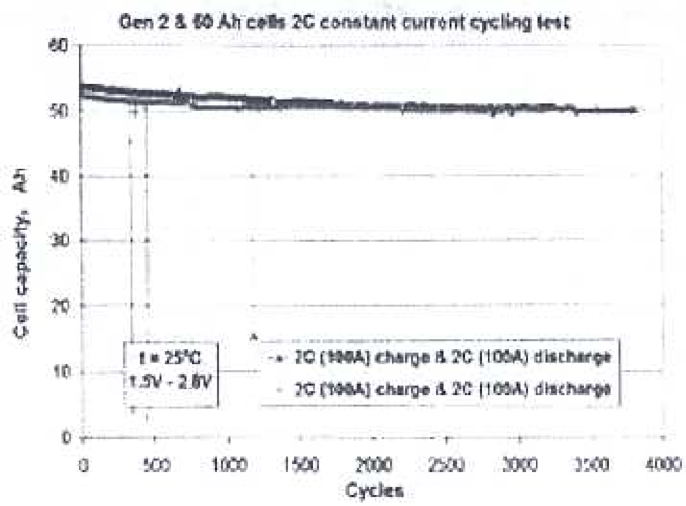
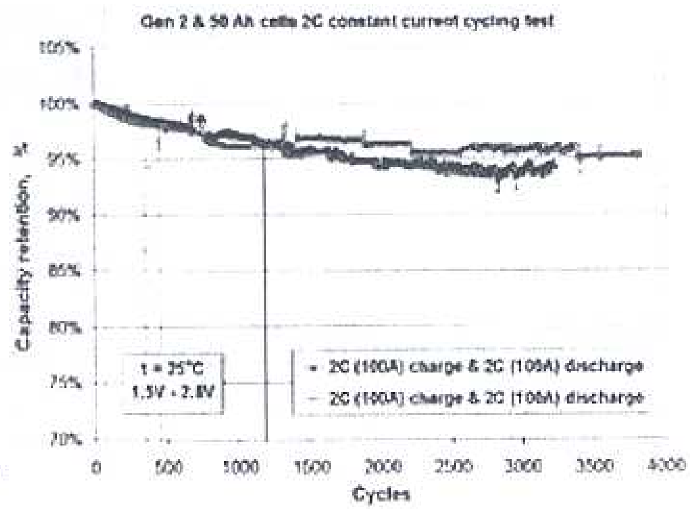
Comments on Cycle life

- I have no cycle life data on the large format cells from China. They appear to be robustly packaged, but their quality control is questionable.
- Since the cells from China are relatively low power capability, cooling and battery management are very important when using them.
- Most of the good cycle life data for lithium cells are attained at or near room temperature. Cycle life begins to decrease markedly at temperatures greater than about 50 deg C.
- Iron phosphate lithium batteries are thought to have good cycle life, but very little data are available that demonstrate the long cycle life of 2000-3000 cycles.

Altairnano 50Ah cells cycling performance at 25°C & 1.5 – 2.8 V voltage window





Battery cost issues

Present lithium-ion battery costs

- Most individuals and small companies purchase lithium batteries from China at a delivered cost per cell of $300-400/kWh.

- Batteries from most non-Chinese battery companies not for sale except to large auto companies.

- Cells/modules from EIG are available for $800-1000/kWh w/o battery management system

- Present cost of cells in high volume are thought to be about $500/kWh

$$\begin{array}{r} 300 \\ \underline{28} \\ 2400 \\ \underline{600} \\ 8400 \end{array}$$

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Summary of battery performance and cost projections for various lithium battery chemistries using the Argonne National Laboratory cost model

NiCoAl	kWh	kW	kg	Wh/kg	W/kg	$ cell Mat.	$ battery	$/kWh Cell mat.	$/kWh battery
available	5.1	50	44	116	1136	716	1890	140	371
energy	10.1	50	74	136	676	1156	2820	114	279
60%	20.2	76	143	141	531	2163	4143	107	205
LiFePhos.	kWh	kW	kg	Wh/kg	W/kg	$ cell Mat.	$ battery	$/kWh Cell mat.	$/kWh battery
available	4.8	50	47	102	1064	742	1943	155	405
energy	9.4	50	80	118	625	1148	2838	122	302
65%	18.7	76	149	126	510	2132	4147	114	222
LiTitanate	kWh	kW	kg	Wh/kg	W/kg	$ cell Mat.	$ battery	$/kWh Cell mat.	$/kWh battery
available	3.6	50	55	65	909	668	1855	186	515
energy	7.2	50	103	70	485	1196	2901	166	403
85%	14.4	76	201	72	378	2352	4458	163	310

$/Wh = {[($/gm)/Ah/gm] anode + [$/gm)/Ah/gm]cathode }/ Vnom.

Relative electrode material costs for various lithium battery chemistries

Chemistry Anode/cathode	Cell voltage Max/nom.	Electrode material $/kg Anode/cathode	Electrode material cost $/kWh	Cycle life (deep)
Graphite/ $NiCoMnO_2$	4.2/3.6	12/25	48	2000-3000
Graphite/ Mn spinel	4.0/3.6	12/8	30	1000
Graphite/ $NiCoAlO_2$	4.2/3.6	12/25	48	2000-3000
Graphite/ iron phosphate	3.65/ 3.25	12/20	49	>3000
Lithium titanate/ Mn spinel	2.8/2.4	25/8	88	>5000

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Key battery issues –
What do we know and what do we not know?

1) *Cell and module performance*
2) *Energy density and power capability and trade-offs*
3) Calendar and cycle life for various use patterns, including temperature and EV/PHEV useage
4) System safety and reliability with battery management hardware/software
5) *Slow and fast charging requirements* and effect on cycle life
6) Materials, cell, module, system costs in volume production
7) In-vehicle tests by consumers in various climates
8) Battery recycling including possible second-use

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The cost projections obtained using the ANL model indicate that in large scale production (at least 100,000 packs/year), battery costs to the OEM auto companies can be in the $300-400/ kWh range for plug-in hybrids of an all-electric range of 20-40 miles. On a cost basis, the emerging technologies – iron phosphate and lithium titanate oxide do not appear to be at a significant cost disadvantage compared to NiCoAl. The emerging chemistries do have significant advantages in the areas of safety and cycle life as discussed previously.

Key electric vehicle issues- EVs and PHEVs

All the rest are presently uncertain

1) *Cell and module performance*
2) *Energy density and power capability and trade-offs*
3) Calendar and cycle life for various use patterns, including temperature and EV/PHEV useage
4) System safety and reliability with battery management hardware/software
5) *Slow and fast charging requirements* and effect on cycle life
6) Materials, cell, module, system costs in volume production
7) In-vehicle tests by consumers in various climates
8) Battery recycling including possible second-use

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Conclusions

- There are significant trade-offs in energy density, power density, cycle life, and thermal stability between the various lithium battery chemistries
- In terms of battery performance, there are data available to evaluate the trade-offs
- Knowledge of the battery resistance is key to assessing the power characteristics. W/kg claimed by the manufacturer is not a reliable assessment of power
- There continues to be uncertainty concerning the differences in cycle life, power (efficiency), useable energy fraction, and safety (thermal stability) of the various chemistries
- Fast charging of both titanate oxide and iron phosphate lithium chemistries appears to be feasible