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Performance Characteristics of Lithium-ion Batteries of Various Chemistries for Plug-in Hybrid Vehicles

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Abstract

This paper is concerned with the testing and evaluation of various battery chemistries for use in PHEVs. Test data are presented for lithium-ion cells and modules utilizing nickel cobalt, iron phosphate, and lithium titanate oxide in the electrodes. The energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. The situation regarding the power capability (W/kg) of the different chemistries is not as clear because of the energy density/power capability trade-offs inherent in battery design.

Simulations of Prius plug-in hybrids were performed with **Advisor** utilizing lithium-ion batteries of the different chemistries. The UC Davis test data were used to prepare the battery input files needed in **Advisor**. Simulations were made for battery packs weighing 60 kg and 120 kg. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

Keywords: lithium-ion batteries, plug-in hybrid vehicles, energy density, pulse power

1 Introduction

It is well recognized that the key issue in the design of a plug-in hybrid-electric vehicle is the selection of the battery. The consensus view is the battery will be of the lithium-ion type, but which of the lithium-ion chemistries to use is still a major question. The selection will depend on a number of factors: useable energy density, useable power density, cycle and calendar life, safety (thermal stability), and cost. The most developed of the lithium-ion chemistries is that used in consumer electronics – that is carbon/graphite in the negative electrode and nickel cobalt and other metal oxides in the positive electrode. That chemistry yields the best performance (energy density and power density), but also has the greatest uncertainty concerning safety. The other chemistries (iron phosphate in the positive and lithium titanate in the

negative) being developed are known to have less favorable performance, but less concern regarding safety and longer cycle life. These latter chemistries have been evaluated in detail in the present study.

A number of companies world-wide are presently developing lithium-ion batteries utilizing the various electrode chemistries. Most of these companies are relatively small and are not well known in the battery business, but nevertheless their technologies are representative of the possibilities for the development of the emerging battery technologies. Hence a strong effort was made to obtain cells from a number of these companies for testing and evaluation. Reasonable success was achieved in obtaining lithium-ion cells from a number of sources for testing. This paper is concerned with analyzing the performance of the various cells/chemistries based on testing of the cells. In addition, simulation results are presented for a plug-in Prius-type vehicle using different battery technologies and their suitability for use in plug-in hybrids assessed.

2 Lithium-ion battery chemistries

The lithium-ion battery technology used for consumer electronics applications is reasonably mature and in 2008 over one billion, small (18650) cells were manufactured and sold. These cells utilized graphite/carbon in the negative and nickelate (LiNiCoAlO) in the negative. This is the baseline chemistry with which the other emerging chemistries are compared. The graphite/nickelate chemistry yields cells with the highest energy density and power capability of the chemistries being developed for vehicle applications primarily because the cell voltage and the specific charge (mAh/gm) of the positive electrode material are higher than for the other chemistries. The material and cell characteristics of the various chemistries are shown in Table 1. If performance of the cell was the only consideration, there would be little interest in developing cells/batteries with the other chemistries. However, cycle life and safety (thermal stability) as well as cost are important considerations in selecting batteries for vehicle applications. Unfortunately the graphite/nickelate chemistry has shown in the consumer electronics applications to have safety and cycle life limitations, which can become even more serious for the large cells/batteries needed for vehicle applications. Hence development is underway using lithium manganese spinel and iron phosphate for the positive electrodes and lithium titanate oxide for the negative electrode. As indicated in Table 1, these chemistries have significantly lower performance than the graphite/nickelate chemistry, but longer cycle life and higher thermal stability. It is more difficult to compare the power capability of the different chemistries, because there is the inherent trade-off between energy density and power capability via the design of the electrodes and choice of material properties (primarily particle size and surface area). Nevertheless, the cells with the higher cell voltage tend to have higher power capability. The goal of the developments of the other chemistries is to minimize the penalty in performance without significant sacrifice of the inherent advantages of the respective emerging chemistries.

Most of the cells for the consumer electronics applications are spiral wound packaged in a rigid container. Some cells are prismatic (thin, flat) in shape, but they are also packaged in a rigid container. All these cells (Figure 1) are small (1-3 Ah) and can be used in vehicle applications only if larger cells/modules are assembled by placing many of the small cells in parallel. This can be done, but it requires special attention to safety issues. For vehicle applications, larger cells (up to 100 Ah) are being developed so it is not necessary to assemble parallel strings of the cells in the modules. In all cases, the modules consist of a number of cells in series to attain a reasonably high module voltage. In some cases, the larger cells (Ah > 10 Ah) are packaged in a soft laminated pouch (see Figure 2), which are then placed in a rigid container to form a high voltage module. Some of the larger cells are spiral wound (see Figure 3), but the trend in cell development seems to be toward soft packaging. Whether this proves to be a wise trend remains to be seen as there are strong, well founded concerns about the robustness and reliability of the soft packaging for vehicle applications.

3 Battery testing

3.1 Test procedures and the batteries tested

Table 1: 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

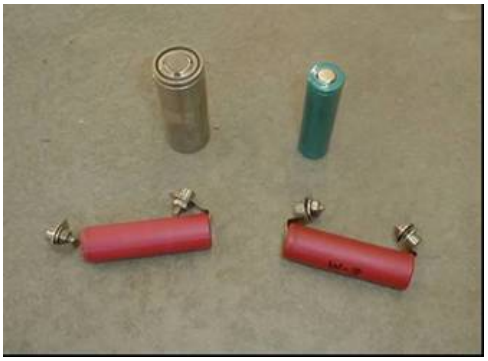


Figure 1: Small, spiral wound cells

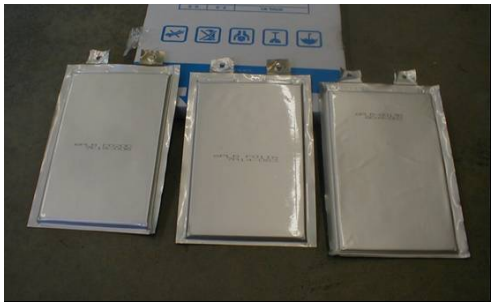
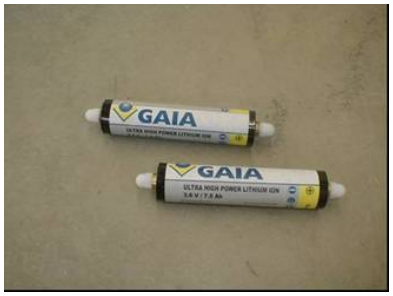


Figure 2: Pouch packaged cells

44 Ah cell



7.5 Ah

Figure 3: Spiral wound large cells

For each of the cells/modules, the following tests were performed:

1) **Constant current tests** starting at C/1 and up to currents at which the Ah capacity of the cell begins to show a significant decrease with rate.
2) **Constant power tests** starting at about 100 W/kg and up to powers (W/kg) at which the energy density (Wh/kg) begins to show a significant decrease with rate.
3) **5 sec pulse tests** at high currents (5-10C) at states of charge between 90% -10% to determine the open-circuit voltage and resistance from which the power capability of the cells can be calculated.

The power capability of the cells/modules was determined in the present study by determining the open-circuit voltage and resistance as a function of state-of-charge and calculating the pulse power using the following equation:

$$P = Eff\ (1-Eff)\ V_{oc}^{\ 2}/R$$

where Eff is the pulse efficiency, $Eff = V_{pulse}/V_{oc}$

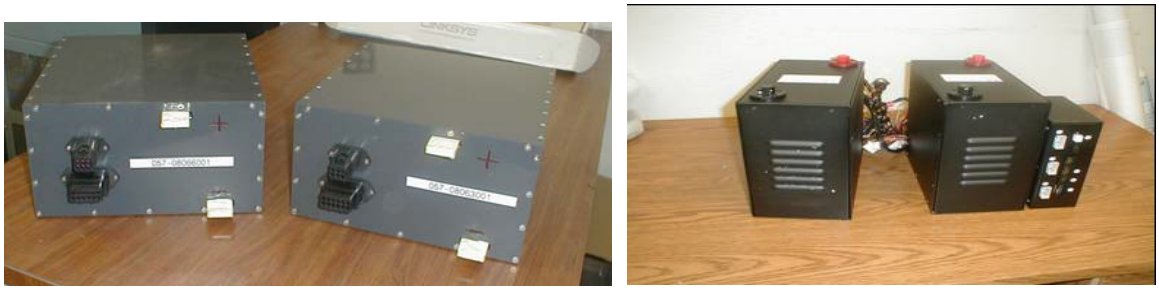
The power density is simply calculated as P/battery weight or volume. This method is not too different from that given in the USABC test manual for PHEV batteries and can be applied for

cells/modules independent of the vehicle in which they would be used.

The cells tested in the present study are listed in Table 2. As indicated in Table 3, modules were available for some of the batteries. Testing of the modules is still in progress. Photographs of a few of the cells and modules are shown in Figures 1- 4.

3.2 Test data for selected cells and modules

Detailed data were taken for all the cells listed in Table 2. Selected data for some of the cells are shown in Tables 3- 8 as illustrations of the performance of the iron phosphate and lithium titanate oxide cells.



24 V, 50 Ah modules from Altairnano 70V modules from EIG

Figure 4: Lithium-ion battery modules for testing

Table 2: Batteries tested -manufacturers, technology, and characteristics

Manufacturer	Technology type	Ah	Voltage range	Weight kg/ Volume L
K2	Iron phosphate	2.4	3.65-2.0	.083/.035
EIG	Iron phosphate	10.5 15.7	3.65-2.0	.325/.13 .424/--
A123	Iron phosphate	2.1	3.6-2.5	.07/--
Lishen	Iron Phosphate	10.2	3.65-2.0	----
EIG	Graphite/ Ni CoMnO2	18	4.2-3.0	.45/--
GAIA	Graphite/ LiNiCoO2	42	4.1-3.0	.32/--
Quallion	Graphite/ Mn spinel	1.8 2.3	4.2-3.0	.043/.017 .047/.017
Altairnano	Lithium Titanate	11 52	2.8-1.5	.34/-- 1.6/--
EIG	Lithium Titanate	12.0	2.7-1.5	

Table 3: Lithium-ion battery modules available for testing

Chemistry Anode/cathode	Developer	Voltage	Ah	Resistance mOhm	Weight kg pack.fact.	Volume L Pack.fact.
Nickel Cobalt	EIG	72	20	60	13.4 .67	11.3 .41
Iron Phosphate	EIG	74	14	55	13.6 .69	11.3 .34
Lithium titanate	Altairnano	16V	11	2	16.3 ----	11.4 ----
Lithium titanate	Altairnano	24V	50	10	21.4 .75	12.6

Table 3: 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	

Table 4: 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	--

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

Table 5: Test data for the Altairnano 50Ah lithium titanate oxide cell
Constant current discharges (2.8-1.5V)

Current A	nC	Time sec	Ah	Resistance mOhm
50	.96	3773	52.4	
100	1.95	1847	51.3	1.0
200	4.0	904	50.2	.95
300	6.1	588	49.0	1.0

Constant power discharge (2.8-1.5V)

Power W	W/kg	Time sec	nC	Wh	Wh/kg
100	62	3977	.9	111	69
200	125	1943	1.85	108	67
300	188	1244	2.9	102	64
400	250	849	4.2	94	59
500	313	636	5.66	88	55
600	375	516	7.0	86	54

weight: 1.6 kg

Table 6: Pulse characteristics of the EIG 20Ah NiCo cell at various states-of-charge

Voc	DOD %	$V_{2\ sec}$	Effic. %	R mOhm	Power W	W/kg
4.12/250A	0	3.33	80.8	3.16	833	1850
3.98/250A	10	3.24	81.4	2.96	810	1800
3.88/250A	20	3.14	80.9	2.96	785	1744
3.78/250A	30	3.06	81.0	2.88	765	1700
3.72/250A	40	2.98	80.1	2.96	745	1655
3.67/250A	50	2.90	79.0	3.08	725	1611
3.63/250A	60	2.84	78.2	3.16	710	1578
3.59/250A	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

Table 7: Pulse characteristics of the EIG 14Ah Iron phosphate cell at various states-of-charge

Voc	DOD %	$V_{2\ sec}$	Effic. %	R mOhm	Power W	W/kg
3.45/75A	0	3.08	89	4.9	231	711
3.3/75A	10	3.02	91.5	3.73	227	698
3.28/75A	20	3.0	91.5	3.73	225	692
3.26/75A	30	2.98	91.4	3.73	224	689
3.25/75A	40	2.96	91.0	3.87	222	683
3.25/75A	50	2.94	90.5	4.13	220	679
3.24/75A	60	2.91	89.8	4.4	218	672
3.21/75A	70	2.85	88.8	4.8	214	658
3.17/75A	80	2.74	86.4	5.7	206	632
2.58/75A	90	2.06	79.8	6.9	155	475

Table 8: Comparisons of the power characteristics of the EIG NiCo and iron phosphate cells

		90% effic.			80% effic.	
Cell	Wh/kg at C/1	10% DOD	80% DOD		10% DOD	80% DOD
NiCo 20Ah	140	1056 W/kg	696 W/kg		1875 W/kg	1238 W/kg
Iron phosphate 14 Ah	90	808 W/kg	488 W/kg		1437 W/kg	67 W/kg

The resistance of the cells was determined from pulse tests performed at various states-of-charge. Pulse data for the EIG iron phosphate and NiCo cells are shown in Tables 6 and 7. A comparison of the power characteristics of the NiCo and iron phosphate cells is given in Table 8.

Test data for a 16V module of the Altairnano 11Ah cells are shown in Table 9. The characteristics of the module follow directly from the characteristics of the 11Ah cells.

Table 9: Test data for the Altairnano 16V module)
Constant current discharge (8 cells in parallel, 6 in series)

I(A)	Time (sec)	nC	Ah	Resistance mOhm
50	6908	.52	95.9	
100	3419	1.05	95.0	
200	1704	2.11	94.7	1.95
300	1113	3.23	92.8	2.0
400	833	4.32	92.6	2.0

Cell mass: 16.3 kg, resistance based on 5 sec pulses of the module
90% efficiency pulse: 11.5 kW, 706 W/kg

Constant power discharges

Power (W)	(W/kg) cells	Time (sec)	kWh	(Wh/kg)cells
1000	61	4576	1.27	77.9
1500	92	2975	1.24	76.1
2000	122	2217	1.23	75.5
2500	250	1756	1.22	75.0
3000	184	1459	1.22	75.0
3500	215	1221	1.19	73.0
3600	221	1222	1.22	75.0

Charge at 88A to 16.3, discharge from 16.3 to 9V

Table 10: Summary of the performance characteristics of lithium-ion cells of different chemistries from various battery developers

Manufacturer	Technology type	Ah	Voltage range	Wh/kg at 300 W/kg	$(W/kg)_{90\%eff.}$ 50% SOC
K2	Iron phosphate	2.4	3.65-2.0	86	667
EIG	Iron phosphate	10.5 15.7	3.65-2.0	83 113	708 919
A123	Iron phosphate	2.1	3.6-2.5	88	1146
Lishen	Iron Phosphate	10.2	3.65-2.0	82	161
EIG	Graphite/ Ni CoMnO2	18	4.2-3.0	140	895
GAIA	Graphite/ LiNiCoO2	42	4.1-3.0	94	1742 at 70%SOC
Quallion	Graphite/ Mn spinel	1.8	4.2-3.0	144	491 at 60%SOC
		2.3	4.2-3.0	170	379 at 60%SOC
Altairnano	Lithium Titanate	11 52	2.8-1.5	70 57	684 340
EIG	Lithium Titanate	12.0	2.7-1.5	43	584

4 Comparisons of the performance of lithium-ion cells of the different chemistries from various battery developers

A summary of the data for the different chemistries is shown in Table 10. It is clear from the table that both the energy density and power capability of the cells vary over a wide range and that there are significant trade-offs between energy and power with all the chemistries. Energy density and power

capability are discussed separately the following sections.

4.1 Energy density

It is clear from Table 10 that the energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. Hence in terms of energy density, the rankings of the different chemistries are clear and the differences are significant: 1. NiCo, 2. iron phosphate, 3. lithium titanate oxide. The question of what fraction of the energy density is useable in a specific vehicle application could decrease the relative advantage of the different chemistries.

4.2 Power capability

The situation regarding the power capability (W/kg) of the different chemistries is not as clear as was the case for energy density because of the energy density/power capability trade-offs inherent in battery design. Further the question of the maximum useable power density is also application specific. In order to have a well-defined basis for comparing the different chemistries and cells, the power density (W/kg) for a 90% efficient pulse at 50% SOC is shown in Table 10 for most of the cells. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it seems possible to design high power batteries (500-1000 W/kg at 90% efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life. The data in Table 10 indicate that high power iron phosphate cells can be designed without a significant sacrifice in energy density. When power densities greater than 2000 W/kg for lithium-ion batteries are claimed, it is for low efficiency pulses. For example, for an efficiency of 65%, the 15Ah EIG iron phosphate battery has a pulse power of 2330 W/kg rather than the 919 value for a 90% efficient pulse.

5 Considerations for selecting batteries/energy storage for Plug-in Hybrid vehicles

The selection of the battery for plug-in hybrid vehicle is complicated process and depends on many factors. In simplest terms, the battery must meet the energy storage (kWh) and peak power (kW) requirements of the vehicle and fit into the space available. In addition, the battery must satisfy the cycle life requirements both for deep discharge cycles in the charge depleting mode and shallow cycling in the charge sustaining mode of operation. Further the battery unit must be designed to meet the thermal management, cell-to-cell monitoring, and safety requirements. The final considerations are concerned with the initial and life cycle costs of the battery.

This paper has dealt in detail with the performance of the lithium-ion batteries using different chemistries. Even though electrode chemistry has a significant effect on the performance of the battery, these differences alone are far from sufficient for selecting a battery for a PHEV. The other factors – cycle life and the effect on cycle life of depth-of-discharge, safety and thermal issues, and cost can be critical in influencing battery selection.

As indicated earlier in the paper, a primary reason for the present development of lithium-ion batteries of various chemistries is related to safety issues with the batteries using NiCo and other metal oxides in the positive electrode. There have been some instances in which those cells/batteries have experienced thermal runaway events and as a result, the NiCo based battery systems are treated with considerable caution. They incorporate extensive cell monitoring circuitry as protection against possible destructive thermal events.

Cells using iron phosphate in the positive electrode are thought to be much less prone to thermal runaway both because they are less energetic (significantly lower energy density) and do not produce oxygen on overcharge which can react exothermically with the graphite in the negative electrode. Cells using lithium titanate oxide (LTO) in the negative are even less energetic (lower energy density) than cells using iron phosphate and in addition the LTO replaces the graphite in the negative electrode removing a combustible substance in the cell. Hence both the iron

phosphate and lithium titanate chemistries are inherently safer than the NiCo chemistry.

Another important issue in evaluating lithium-ion battery chemistries is cycle life and calendar life. In a plug-in hybrid vehicle, a battery life of at least ten years is thought to be necessary. This means that the battery must be able to sustain about 3000 deep discharge cycles in the charge depleting mode and several hundred thousand shallow cycles at low states-of-charge in the charge sustaining mode. Hence a PHEV battery must have the life cycle characteristics of an EV battery and a HEV battery. Whether any of the lithium battery chemistries can meet these life cycle requirements has not yet been determined.

It is expected that both the iron phosphate and lithium titanate chemistries will have significantly longer cycle life than the NiCo chemistry. This is especially true of the lithium titanate chemistry. Life cycle testing of cells done by Altairnano as part of their development program have indicated a very long cycle life of greater than 5000 cycles even for fast charge and discharge rates (Reference 1).

Little information is available on the relative cost ($/kWh) of lithium-ion batteries of the different chemistries. Further it is difficult to get good information on the costs of the various materials used in the batteries. If such information were available, it is relatively simple to estimate the differences in the electrode material costs for the different chemistries. This could be done using the following equation to estimate the $/Wh for each chemistry:

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

Values for the Ah/gm and Voc are given in Table 1. Calculated values for the electrode material costs ($/kWh) are shown in Table 11 for the assumed unit costs of the various materials. The material unit costs used in the calculations are based on inquiries made of several sources involved with the manufacture of lithium batteries (References 2 and 3). The results shown in Table 11 indicate the relative electrode material costs of the various chemistries and also that electrode material costs should not dominate the total battery cost. Note that in general the higher cost lithium battery chemistries have the potential for longer cycle life which on a life cycle cost basis can compensate for the higher initial cost of those chemistries. This is especially true of the lithium titanate chemistry.

6 Plug-in hybrid vehicle simulations using various battery chemistries

Simulations of Prius plug-in hybrids have been performed with **Advisor** utilizing lithium-ion batteries of the different chemistries (References 4 and 5). The UC Davis test data were used to prepare the battery input files needed in **Advisor**. Simulations were made for battery packs weighing 60 kg and 120 kg. The results of the simulations are given in Table 12. Note from Table 12 that plug-in hybrids can be designed using the various lithium-ion batteries as well as a nickel metal hydride battery. However, the charge depleted (CD) electric ranges of the various designs

Table 11: 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

Table 12: Simulation results for Prius PHEVs using various lithium-ion batteries

		60 kg Battery			
		Varta (Ovonic)	LFP (A123)	NCM (Gaia)	LTO (Altairnano)
		Ni-MH	Li-Ion	Li-Ion	Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	15	50	77	31
Motor peak power[b]	kW	**13**	**42**	**65**	**26**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	3.21	4.05	4.32	3.15
Available Energy[c]	kWh	**2.57**	**3.24**	**3.46**	**2.52**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**15**	**19**	**20**	**15**
# of Cells	#	**16**	**67**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	171	225	175	157
CD range	miles	15	14	20	16
CD gasoline use	mpg	98	3000	inf	425
CS gasoline use	mpg	44	44	43	43
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	149	126	97	93
CD range	miles	17	26	36	27
CD gasoline use	mpg	800	inf	inf	inf
CS gasoline use	mpg	67	73	69	71
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	178	155	120	114
CD range	miles	14	21	29	22
CD gasoline use	mpg	1500	inf	inf	inf
CS gasoline use	mpg	66	67	64	66

[a] Assuming packing factor = 0.75
[b] Assuming motor efficiency equals = 0.85
[c] Assuming DOD = 0.8

and their fuel economy in the CD mode are much different and the differences are highly dependent on the driving cycle. The CD ranges are larger for the batteries with the higher energy densities and the fuel economies in the CD mode are highest for the batteries that are capable of high peak power. High battery power capability permits the vehicle to operate in the all-electric mode (engine off) until the energy in the battery is depleted. The fuel economy in the charge sustaining (CS) mode is dependent on the driving cycle, but not significantly on the battery energy density and weight of the battery pack. The weight of the battery and its energy density has a large effect on CD operation as would be expected. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and

performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

Table 12 (continued): Simulation results for Prius PHEVs using various lithium-ion batteries

		120 kg Battery			
		Varta (Ovonic)	LFP (A123)	NCM (Gaia)	LTO (Altairnano)
		Ni-MH	Li-Ion	Li-Ion	Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	30	99	153	61
Motor peak power[b]	kW	**25**	**84**	**130**	**52**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	6.43	8.10	8.64	6.30
Available Energy[c]	kWh	**5.14**	**6.48**	**6.91**	**5.04**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**30**	**37**	**40**	**29**
# of Cells	#	**16**	**68**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	246	182	169	187
CD range	miles	21	36	41	27
CD gasoline use	mpg	329	inf	inf	inf
CS gasoline use	mpg	43	44	45	42
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	146	104	97	104
CD range	miles	35	62	71	48
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	69	71	71	72
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	171	127	118	126
CD range	miles	30	51	59	40
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	66	66	66	66

[a] Assuming packing factor = 0.75

[b] Assuming motor efficiency equals = 0.85

[c] Assuming DOD = 0.8

7 Summary and conclusions

It is well recognized that the key issue in the design of a plug-in hybrid-electric vehicle is the selection of the battery. The consensus view is the battery will be of the lithium-ion type, but which of the lithium-ion chemistries to use is still a major question. The selection will depend on a number of factors: useable energy density, useable power density, cycle and calendar life, safety (thermal stability), and cost. This paper is concerned with the testing and evaluation of various battery chemistries for use in PHEVs. Test data are presented for lithium-ion cells and modules utilizing nickel cobalt, iron phosphate, and lithium titanate oxide in the electrodes. The energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. The situation regarding the power capability (W/kg) of the different chemistries is not as clear because of the energy density/power capability trade-offs inherent in battery design. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it seems possible to design high power batteries (500-1000 W/kg at 90% efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life. The data indicate that high power iron phosphate cells can be designed without a significant sacrifice in energy density. When power densities greater than 2000 W/kg for lithium-ion batteries are claimed, it is for low efficiency pulses. For example, for an efficiency of 65%, the 15Ah EIG iron phosphate battery has a pulse power of 2330 W/kg rather than the 919 value for a 90% efficient pulse.

Simulations of Prius plug-in hybrids have been performed with **Advisor** utilizing lithium-ion batteries of the different chemistries. Simulations were made for battery packs weighing 60 kg and 120 kg. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

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