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The power capability of ultracapacitors and lithium batteries for electric and hybrid vehicle applications

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ABSTRACT

There is much confusion and uncertainty in the literature concerning the useable power capability of batteries and ultracapacitors (electrochemical capacitors) for various applications. Clarification of this confusion is one of the primary objectives of this paper. The three approaches most often applied to determine the power capability of devices are (1) matched impedance power, (2) the min/max method of the USABC, and (3) the pulse energy efficiency approach used at UC Davis. It has been found that widely different power capability for batteries and ultracapacitors can be inferred using these approaches even when the resistance and open-circuit voltage are accurately known. In general, the values obtained using the energy efficiency method for $EF = 90–95\%$ are much lower than the other two methods which yield values corresponding to efficiencies of 70–75%. For plug-in hybrid and battery electric vehicle applications, the maximum useable power density for a lithium-ion battery can be higher than that corresponding to 95% efficiency because the peak power of the driveline is used less frequently and consequently charge/discharge efficiently is less important. For these applications, the useable power density of the batteries can be closer to the useable power density of ultracapacitors. In all cases, it is essential that a careful and appropriate measurement is made of the resistance of the devices and the comparisons of the useable power capability be made in a way appropriate for the application for which the devices are to be used.

1. Introduction

There is much confusion and uncertainty in the literature concerning the useable power capability of batteries and ultracapacitors (electrochemical capacitors) and the comparison of their relative power capabilities. This is especially true when the application being considered involves battery electric or hybrid-electric vehicles. Part of this confusion results from the different ways in which batteries and ultracapacitors are used as energy storage devices in electric drivelines and the strategies used to control their charge and discharge. In almost all cases, ultracapacitors are used as pulse power devices in which the energy flows in and out of the device during the operation of the driveline and high roundtrip efficiency is a key consideration. Batteries can be used as either energy storage units with the state-of-charge being depleted over time (as in an EV or PHEV) or as pulse power devices maintained in a relatively narrow range of state-of-charge (as in a charge sustaining HEV). In the first case, the efficiency of the charge or discharge is not as important as in the second case and as a result, the maximum useable power of the battery is different for the two cases. These differences will be discussed in this paper along with how to determine from test data the power capabilities of the devices.

2. Definition and calculation of power capability

In discussing the power capability of batteries and ultracapacitors, it is necessary to specify the time of the charge or discharge and the conditions under which the energy transfer takes place. By this is meant, what fraction of the energy stored in the device is transferred and at what state-of-charge and/or voltage is the transfer process started and ended. The simplest process is the constant power discharge or charge of a device as is customarily done to determine the energy density (Wh kg^{-1} or Wh L^{-1}). This test is usually started at full charge and is terminated at a specified cut-off or final voltage. These voltages are device chemistry dependent. In this test, the useable energy is measured for different power densities (W kg^{-1}) and the power density at which the useable energy begins to decrease markedly (for example, has decreased by 20%) is determined. This power density is termed the $(W\,kg^{-1})_{const.,max}$. It can be easily determined from constant power testing of both batteries and ultracapacitors and there is little reason why the constant power capability of either batteries or ultracapacitors should be

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Table 1
Time-power steps for the PSFUDS test cycle.

Step no.	Time step duration (s)	Charge C/discharge D	P/P_{max}, P_{max} = 500 W/kg (base)
1	8	D	.20
2	12	D	.40
3	12	D	.10
4	50	C	.10
5	12	D	.20
6	12	D	1.0
7	8	D	.40
8	50	C	.30
9	12	D	.20
10	12	D	.40
11	18	D	.10
12	50	C	.20
13	8	D	.20
14	12	D	1.0
15	12	D	.10
16	50	C	.30
17	8	D	.20
18	12	D	1.0
19	38	C	.25
20	12	D	.40
21	12	D	.20
22	≥50	Charge to V_0	.30

unclear. An expression for the calculation of the effect of constant power density on the energy density of ultracapacitors is derived in Appendix A.

The definition and subsequent determination of pulse power capability is not as straightforward as that of constant power capability. This is because the power capability is highly dependent on the voltage range permitted during the pulse and the duration (s) of the pulse. In general, the power capability is higher if a larger voltage range is permitted and the duration of the pulse is shorter. The power capability of a battery is state-of-charge dependent (lower at low states-of-charge); for ultracapacitors, the voltage will change during charge/discharge even if the resistance of the device were zero and the power capability infinite. Hence the procedures utilized to test both batteries and ultracapacitors should clearly state the state-of-charge of the device and the voltage range and duration of the pulse. Further the power capabilities of devices should be compared only for equivalent voltage ranges, pulse times, and states-of-charge. In this paper, the maximum pulse power capability will be expressed in terms of $W\,kg^{-1}$ and $W\,L^{-1}$ for pulses of stated voltage ranges (efficiency) and time.

In general, there are two approaches to setting a limit to the power that can be taken from either a battery or an ultracapacitor. The first approach is to set a minimum voltage for a discharge pulse and a maximum voltage for a *charge* pulse that the device can experience during the pulse. This is the approach proposed by the United States Advanced Battery Consortium (USABC) in [1]. The initial voltage before the pulse is the open-circuit voltage at the stated state-of-charge of the device. The maximum power then occurs at the current for which

$$V_{ch,\max} - V_{oc} = I_{ch}R, \qquad P_{ch,\max} = I_{ch}V_{ch,\max}$$

$$V_{oc} - V_{disch,\min} = I_{disch}R, \qquad P_{disch,\max} = I_{disch}V_{disch,\min}$$

R, which is the resistance of the device, varies with state-of-charge and depends on the ionic conductivity of the electrolyte and the details of the ionic and electronic conductivity processes in the electrodes. R for the device is determined from pulse tests of the device. The equations shown are the simple expression of the ohmic voltage change due to the pulse current.

The second approach is concerned with the efficiency (EF) of the pulse or the fraction of the energy transferred from the device that is electrical energy rather than heat. In simplest terms using Ohm's law for a DC device,

$$P = VI, \qquad I = \frac{P}{V}, \qquad V = V_{oc} - IR$$

The efficiency is given by

$$EF = \frac{P}{P + I^2R} = \frac{1}{1 + IR/V} = \frac{V}{V_{oc}} \tag{1}$$

and the maximum power of the pulse becomes

$$P_{bat,\max} = \frac{EF(1 - EF)V_{oc}^2}{R} \tag{2}$$

The derivation of Eqs. (1) and (2) relating efficiency and maximum power to the voltage range of the pulse neglects the change in resistance during the pulse, but the equations show the direct relationship in principle between the power, open-circuit voltage, and resistance of the device. The efficiency at which the power capability is a maximum can be determined by differentiating Eq. (2) with respect to EF. One finds that the power is a maximum for $EF = 1/2$ resulting in a maximum power of

$$P_{\max,EF} = \frac{V_{oc}^2}{4R}$$

which is the well known match impedance power of the device.

A relationship similar to Eq. (2) is derived for an ultracapacitor in Appendix A.

$$P_{cap,\max} = 9/16(1 - EF)V_0^2/R$$

where V_0 is the rated voltage of the capacitor.

As will be seen later in the paper, the maximum useable power determined using the min/max voltage approach is much higher than that using the efficiency approach unless relatively low efficiencies (<80%) are acceptable for the application of interest.

Another aspect of determining the maximum useable pulse power is the time duration of the pulse. For vehicle applications, a time period of 10 s is usually the maximum period of interest. Shorter time periods are often applicable. In nearly all cases, the energy transferred during the pulse is small compared to the energy storage capacity of the device at more normal (average) power levels. Hence the change in state-of-charge (SOC) during the pulse is relatively small and the pulse power capability can be assigned to a specific SOC of the device. For both batteries andultracapacitors,

Table 2
Summary of the performance characteristics of ultracapacitor devices.

Device	*V* rated	*C* (F)	*R* (mOhm)	*RC* (s)	Wh kg^{-1} [a]	W kg^{-1} (95%)[b]	W kg^{-1} match. imped.	Wgt. (kg)	Vol. lit.
Maxwell[c]	2.7	2885	.375	1.08	4.2	994	8836	.55	.414
Maxwell	2.7	605	.90	.55	2.35	1139	9597	.20	.211
ApowerCap[d]	2.7	55	4	.22	5.5	5695	50,625	.009	–
Apowercap[d]	2.7	450	1.4	.58	5.89	2569	24,595	.057	.045
Ness	2.7	1800	.55	1.00	3.6	975	8674	.38	.277
Ness	2.7	3640	.30	1.10	4.2	928	8010	.65	.514
Ness (cyl.)	2.7	3160	.4	1.26	4.4	982	8728	.522	.38
Carbon Tech Non-acetonitrile	2.85	1600	1.0	1.6	5.8	1026	9106	.223	
Asahi Glass (propylene carbonate)	2.7	1375	2.5	3.4	4.9	390	3471	.210 (estimated)	.151
Panasonic (propylene carbonate)	2.5	1200	1.0	1.2	2.3	514	4596	.34	.245
EPCOS	2.7	3400	.45	1.5	4.3	760	6750	.60	.48
LS Cable	2.8	3200	.25	.80	3.7	1400	12,400	.63	.47
BatScap	2.7	2680	.20	.54	4.2	2050	18,225	.50	.572
Power Sys. (activated carbon, propylene carbonate)[d]	2.7	1350	1.5	2.0	4.9	650	5785	.21	.151
Power Sys. (graphitic carbon, propylene carbonate)[d]	3.3	1800	3.0	5.4	8.0	486	4320	.21	.15
	3.3	1500	1.7	2.5	6.0	776	6903	.23	.15
Fuji Heavy Industry-hybrid (AC/graphitic Carbon)[d]	3.8	1800	1.5	2.6	9.2	1025	10,375	.232	.143
JSR Micro (AC/graphitic carbon)[d]	3.8	1000	4	4	11.2	900	7987	.113	.073
		2000	1.9	3.8	12.1	1038	9223	.206	.132

[a] Energy density at 400 W kg^{-1} constant power, $Vrated - 1/2V_{rated}$.
[b] Power based on $P = 9/16 \times (1 - EF) \times V^2/R$, EF = efficiency of discharge.
[c] Except where noted, all the devices use acetonitrile as the electrolyte.
[d] All device except those with footnote d are packaged in metal containers, these devices are in laminated pouches.

the useable power capability varies with SOC. This variation is particularly important for batteries.

Another parameter of interest in considering the pulse power capability of a device is the roundtrip efficiency (η_{rtrp}) resulting from a sequence of charge and discharge pulses over an extended period of time. The roundtrip efficiency (η_{rtrp}) is simply the ratio of the energy transferred during discharge pulses to that transferred during charge pulses with the device at the same SOC at the start and end of the cycle or test. This efficiency is dependent on the detailed cycle, which is specified in terms of the power (W kg^{-1}) and time duration (s) of the pulses. In general, the roundtrip efficiency decreases as the power density of the pulses is increased. For many vehicle applications, a roundtrip efficiency of at least 90% is desired [1,2]. The USABC has defined pulse cycle test procedures for hybrid-electric vehicle applications [1,2]. Another pulse test cycle, the PSFUDS, which was first defined in [3] has been used extensively at UC Davis to test ultracapacitors and high power batteries. The test cycle, specified in terms of W kg^{-1} time steps, is given in Table 1. It can be utilized to test devices of all sizes and performance capabilities by adjusting the W kg^{-1} and time duration of the maximum power steps. Testing has been done using this cycle and maximum power steps of 500, 1000, and 1500 W kg^{-1}. The baseline cycle is one using 500 W kg^{-1}.

3. Experimental determination of the power capability

In the previous section, several approaches to defining and calculating the power capability of batteries and ultracapacitors have

Table 3
Test data for the Batscap 2700F ultracapacitor.

Current (A)	Time (s)	Capacitance (F)	Resistance (mOhm)
Constant current discharge (2.7–0 V)			
50	144.5	2685	–
100	72.4	2702	–
150	48.2	2698	–
200	35.8	2672	.18
300	24.2	2682	.20
400	17.6	2692	.21

Power (W)	W kg^{-1}	Time (s)	W-s	Wh kg^{-1}
Constant power discharge (2.7–1.35 V)				
100	200	76.4	7640	4.24
200	400	37.7	7540	4.19
300	600	24.3	7290	4.05
400	800	17.8	7120	3.96
500	1000	13.8	6900	3.83

Activated carbon electrodes, acetonitrile electrolyte. Mass of active materials – 500 g.

Table 4
Test data for the pouch packaged, APowerCap device 450F.

Current (A)	Time (s)	Capacitance (F)	Resistance (mOhm)
Constant current discharge data 2.7–0 V			
10	120.5	450	–
20	60.3	453	–
40	30	453	–
80	14.7	452	1.4
120	9.6	455	1.4
160	7.1	456	1.3

Power (W)	W kg^{-1} [a]	Time (s)	Wh	Wh kg^{-1}
Constant power discharges data 2.7–1.35 V				
12.5	219	95.5	.332	5.82
22	385	54.9	.336	5.89
41.5	728	28.8	.332	5.82
80.5	1412	14.6	.326	5.72
120	2105	9.1	.303	5.31

[a] Weight of device – 57 g as tested.

Table 5
Test data for the JSR 2000F cell.

Current (A)	Time (s)	*C* (F)	Resistance (mOhm)[a]
Constant current discharge 3.8–0 V			
30	102.2	2004	–
50	58.1	1950	–
80	34.1	1908	–
130	19.1	1835	2.0
200	11.1	1850	1.9
250	8.2	1694	1.84

Power (W)	W kg^{-1}	Time (s)	Wh	Wh kg^{-1} [b]	Wh L^{-1} [b]
Constant power discharges 3.8–2.2 V					
102	495	88.3	2.5	12.1	18.9
151	733	56	2.35	11.4	17.8
200	971	40	2.22	10.8	16.9
300	1456	24.6	2.05	10.0	15.7
400	1942	17	1.89	9.2	14.4
500	2427	12.5	1.74	8.5	13.3

Cell weight 206 g, 132 cm^3.
[a] Resistance is steady-state value from linear *V* vs. time discharge curve.
[b] Based on the weight and volume of the active cell materials.

been discussed. In this section, selected experimental data for ultracapacitors and lithium-ion batteries are presented from which the power density of those high power devices can be determined. For both technologies, the devices selected to discuss had the highest power capability of the devices tested at UC Davis.

3.1. Ultracapacitors

Ultracapacitors from a large number of manufacturers have been tested at UC Davis as reported in [4–6]. Most of the devices have been of the symmetric, activated carbon/carbon type, but a few have been non-symmetric devices using activated carbon in one electrode and graphitic carbon in the other electrode. All the devices were tested over ranges of constant current and constant power. Test procedures for ultracapacitors are discussed in detail in [7]. The charge/discharge conditions result in discharge times ranging from 5 to 60 s and power densities up near 2500 W kg^{-1}. Pulse tests are performed to determine the resistance of the devices. Pulse cycle tests are also run to determine the roundtrip efficiency for various peak powers (W kg^{-1}). A summary of the characteristics of the devices tested is given in Table 2. The energy density of the carbon/carbon devices are 3–5 Wh kg^{-1} and that of the non-symmetric carbon device 10–12 Wh kg^{-1}. The power density capability (W kg^{-1})$_{95\%}$ for *EF* = 95% varies significantly from about 700 to over 2500 W kg^{-1} depending on the design of the device.

Selected test data for several ultracapacitor devices are presented in Tables 3–5. These devices were selected because they exhibited particularly high power capability in both constant power and pulse power discharges without sacrifices in energy density. The power capabilities of these devices are summarized in Table 6. For constant power discharges at power densities of 1000–2000 W kg^{-1}, the energy density of the ultracapacitors is reduced by about 10% from the baseline value – a discharge at 200 W kg^{-1}. It is of interest to note that the pulse power capability at 95% efficiency is about equal to constant power capability for a 10% reduction in energy capacity. The roundtrip efficiencies of all the devices are high (94% and greater) even for peak power steps of 6 s at 1000 W kg^{-1}.

Table 6
Summary of the power capability of various ultracapacitors for constant and pulse power discharges.

Device/capacitance	*RC* (s)	Wh kg^{-1} [a]	(W kg^{-1})$_{95\%}$	(W kg^{-1})$_{const.pw}$ W kg^{-1}, %[b]	Roundtrip efficiency PSFUDS 500, 1000 W kg^{-1}
Batscap/2700F	.54	4.2	2050	1000, 90, 93	.98, .97
ApowerCap/450F	.63	5.8	2569	2105, 91, 89	.993, .985
Maxwell/2900F	1.1	4.3	981	900, 89, 89	.97, .94
Nesscap/3150F	1.3	4.5	982	1341, 90, 85	.97, .94
JSR/1900F	3.6	12	1037	971, 90, 89	.97, .94

[a] Useable energy density at 200 W kg^{-1} constant power.
[b] W kg^{-1} at constant power at which the energy is reduced to "%" of base energy density and predicted reduction using Eq. (A.7) at that constant power density.

Table 7
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^{-1}	W kg^{-1} 95% effic.[a]	Wgt. (kg)	Density (g cm^{-3})
Enerdel HEV	Graphite/Ni MnO_2	4.1–2.5	15	1.4	115	1044	.445	–
Enerdel EV/PHEV	Graphite/Ni MnO_2	4.1–2.5	15	2.7	127	568	.424	–
Kokam prismatic	Graphite/$NiCoMnO_2$	4.1–3.2	30	1.5	140	550	.787	2.4
Saft Cylind.	Graphite/NiCoAl	4.0–2.5	6.5	3.2	63	580	.35	2.1
GAIA Cylind.	Graphite/$NiCoMnO_2$	4.1–2.5	40	.48	96	885	1.53	3.22
A123 Cylind.	Graphite/Iron Phosph.	3.6–2.0	2.2	12	90	508	.07	2.2
Altairnano prismatic	LiTiO/$NiMnO_2$	2.8–1.5	11	2.2	70	350	.34	1.83
Altairnano prismatic	LiTiO/$NiMnO_2$	2.8–1.5	3.8	1.15	35	992	.26	1.91
Quallion Cylind.	Graphite/NiCo	4.2–2.7	1.8	60	144	252	.043	2.6
Quallion Cylind.	Graphite/NiCo	4.2–2.7	2.3	72	170	192	.047	2.8
EIG prismatic	Graphite/$NiCoMnO_2$	4.2–3.0	20	3.1	165	511	.41	–
EIG prismatic	Graphite/Iron Phosph.	3.65–2.0	15	2.5	113	407	.42	–
Panasonic EV prismatic	Ni Metal hydride	7.2–5.4	6.5	11.4	46	208	1.04	1.8

[a] Power density $P = \text{Eff.} \times (1 - \text{Eff.})V_{oc}^2/R$, 60% SOC.

Table 8
Test data for the Enerdel HEV High Power Cell.

Current (A)	Time (s)	Ah	nC	
Constant current discharges 4.1–2.5 V				
Charge at 15 A to 4.1 V and taper to 1 A				
20	2648	14.7	1.36	
40	1294	14.4	2.78	
60	844	14.1	4.26	
90	553	13.8	6.5	
120	409	13.6	8.8	
Power (W)	**Time (s)**	**Wh**	**Wh kg^{-1}**	**W kg^{-1}**
Constant power discharges 4.1–3.2 V				
32	5768	51.3	115	72
52	3522	50.9	114	117
92	1955	50.0	112	206
132	1336	49.0	110	297
182	945	47.8	107	409
222	762	47.0	106	499
Cell weight: 445 g				

SOC (%)	V_{oc}	Current initiation[a] resistance (mOhm)				Current interruption[b] resistance (mOhm)			
		90 A disch.	45 A charge	120 A disch.	60 A charge	90 A disch.	45 A charge	120 A disch.	60 A charge
Pulse resistance of the 15 Ah Enerdel HEV cell									
80	3.9	1.55	1.55	1.42	1.5	1.44	1.33	1.33	1.5
60	3.73	1.55	1.33	1.5	1.5	1.33	1.33	1.42	1.5
40	3.44	1.55	1.7	1.58	1.66	1.44	1.55	1.5	1.33
20	3.02	1.9	1.78	1.92	1.83	1.78	1.78	1.83	1.67

[a] Resistance calculated from the voltage at 2 s.
[b] Resistance calculated from the voltage at the end of a 5 s discharge pulse and the voltage 5 s after the current interruption.

Table 9
Test data for the Kokam cell.

Current (A)	Time (s)	Ah	nC	
Constant current discharges 4.1–3.2 V, charge at 31 A to 4.2 V and taper to 1.5 A				
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 31 A to 4.2 V and taper to 1.5 A				
Power (W)	**Time (s)**	**Wh**	**Wh kg^{-1}**	**W kg^{-1}**
Constant power discharges 4.1–3.2 V				
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				

SOC 60%	Current (A)	Resistance (mOhm)
V_{oc} = 3.75	150 A disch	1.53
	200 A disch	1.5
	310 A disch	1.45
	50 A charge	1.6
	100 A charge	1.5
	150 A charge	1.53

3.2. Lithium-ion batteries

A number of lithium-ion cells/modules of several chemistries have been tested at UC Davis [8–10]. A summary of the characteristics of the batteries tested is given in Table 7. Test data for selected batteries (cells) are given in Tables 8–11. The energy density and power capability of the batteries tested vary over a relatively large range depending on the chemistry and whether the batteries were designed for HEVs, PHEVs, or EVs. The test results shown in Table 7 indicate that there is a clear trade-off between energy density and power capability for lithium-ion batteries of the various chemistries. For example, the highest energy density MnO_2 battery has an energy density of 140 Wh kg^{-1} and a power capability at 95% efficiency of 550 W kg^{-1} while the battery of the same chemistry with the highest power capability (1044 W kg^{-1}) has an energy density of 115 Wh kg^{-1}. A similar trade-off between power and energy density is evident for the lithium titanate chemistry. The power capabilities of batteries with the high power capability

Table 10
Test data for the Altairnano 3.8 Ah lithium titanate oxide cell.

Current (A)	Ah	nC	
Constant current 2.8–2.0 V			
10	3.78	2.6	
20	3.81	5.3	
50	3.77	13.2	
100	3.66	26.3	
120	3.46	31.2	
Resistance: 1.1–1.2 mOhm from pulse tests			
Power (W)	W kg^{-1}	Wh	Wh kg^{-1}
Constant power 2.8–2.0 V			
20	77	8.64	33.2
40	154	8.99	34.5
60	230	9.10	34.9
90	345	9.16	35.2
120	460	9.04	34.7
150	576	8.78	33.7
Cell weight: 260.5 g			

Pulse power at 95% efficiency: R = 1.15 mOhm, V_0 = 2.5 V, P = 258 W 992 W kg^{-1}.

are shown in Table 12 for comparison with the power capability of ultracapacitors. The pulse power density (W kg^{-1})$_{95\%}$ was calculated at 60% SOC as that is the SOC at which the batteries operate in a HEV.

4. Comparisons of the power capability of ultracapacitors and batteries for vehicle applications

The power capability of lithium-ion batteries and ultracapacitors are summarized in Tables 6 and 12. For pulses with an efficiency of 95%, the pulse power capabilities of the ultracapacitors with the highest power capability are higher by a factor of 2–3 than the best of the lithium-ion batteries designed for use in HEVs. However, there are batteries with power capability comparable to those of some of the ultracapacitors. Hence it is not true that all ultracapacitors have higher power capability than high power lithium batteries.

The constant power capabilities of the batteries are also lower than that of the ultracapacitors. For a 10% reduction in energy density, the power density for the batteries is 400–600 W kg^{-1} compared to 1000–2000 W kg^{-1} for the ultracapacitors. The exception is the LiTiO battery which shows a very high power capability (see Table 10). Also shown in Table 12 is a battery time constant (3.6 Ah × mOhm/V_{oc}) calculated from the characteristics of the bat-

Table 11
Test data for the EIG 20 Ah $NiCoMnO_2$ lithium-ion battery.

Power (W)	W kg^{-1}	Time (s)	Wh	Wh kg^{-1}
Constant power discharges (4.1–3.0 V)				
62	151	4172	71.85	175
152	370	1586	67	163
202	492	1225	68.7	168
252	615	915	64.1	156
302	737	723	60.6	149
352	859	542	53.0	129
Weight .41 kg				
V_{oc}	I (A)	$V_{2\,s}$		R (mOhm)
Resistance from pulse tests (50% SOC)				
3.69	100 disch	3.38		3.1
3.69	50 ch	3.85		3.2
3.7	200 disch	3.1		3.0
3.7	100 ch	3.99		3.0

Table 12
Summary of the power capability characteristics of high power lithium-ion cells of various chemistries.

Device	Time constant 3.6 Ah (mOhm)/V_{ch} s	Wh kg^{-1} [a]	(W kg^{-1})$_{95\%}$ 60%SOC	(W kg^{-1})$_{const.pw}$, % Wh kg^{-1} [b]	Roundtrip efficiency PSFUDS 500 W kg^{-1}, 1000 W kg^{-1}
Kokam/NiMn 30 Ah	40.5	140	550	360, 90%; 612, 82%	.94, .90
Enerdel/NiMn 15 Ah	18.9	114	1044	499, 93%	.96, .93
EIG/NiCoMn 20 Ah	55.8	175	511	615, 90%; 860, 74%	.94, .885
EIG/FePhos. 15 Ah	37.5	117	407	476, 90%; 945, 84%	.91, .87
Altairnano LitTiO 3.8 Ah	5.6	35	877	576, 98%	.94, .896

[a] Energy density at 150 W kg^{-1} constant power.
[b] W kg^{-1} at constant power at which the energy is reduced to "%" of base energy density.

Table 13
Detailed comparisons of the power capabilities of selected ultracapacitors and lithium batteries.

Approach Pulse efficiency (%)	Maxwell 2885F W kg^{-1} R = .375 mOhm	Skeleton 1600F W kg^{-1} R = 1.3 mOhm	Apowercap 450F W kg^{-1} R = 1.4 mOhm	Kokam 31 Ah NiCo W kg^{-1} R = 1.5 mOhm	EIG 15 Ah iron Phosph. W kg^{-1} R = 2.5 mOhm
95	994	772	2569	551	458
90	1988	1542	5139	1044	866
80	3976	3084	10,277	1856	1540
70	5964	4626	15,415	2513	2021
USABC	4417	3427	11,419	2541	2264
Matched impedance	8836	6853	22,838	2879	2415

Table 14
Comparisons of the power capabilities of various devices for HEV and PHEVs using the different methods for calculation.

Lithium batteries 60% SOC	Matched impedance	USABC min/max	Efficient pulse *EF* = 95%	Efficient pulse *EF* = 80%
Device				
Kokam NCM 30 Ah	2893	2502	550	1848
Enerdel HEV NCM 15 Ah	5491	4750	1044	3507
Enerdel EV NCM 15 Ah	2988	2584	568	1908
EIG NCM 20 Ah	2688	2325	511	1721
EIG FePhosph. 15 Ah	2415	2035	458	1540
Altairnano LiTiO 11 Ah	2088	1750	350	1180
Altairnano LiTiO 3.8 Ah	5225	4385	992	3341
Ultracapacitors $V_0 = 3/4V_{rated}$				
Maxwell 2890F	8836	4413	994	
Nesscap 3100F	8730	4360	982	
Batscap 2700F	18,224	9102	2050	
ApowerCap 450F	22,838	11,406	2569	
LSCable 3200F	12,446	4609	1038	
JSR 2000F	9228	6216	1400	

teries. The battery time constant varies over a wide range from 6–55 s which compares to .5–3.6 s for the ultracapacitors. The LiTiO battery has the lowest time constant of the batteries by a wide margin. The relationship between the time constant and power capability of the battery is clearly dependent on the battery chemistry.

The roundtrip efficiencies of the batteries on the PSFUDS cycle with peak power steps of 500 and 1000 W kg^{-1} are also shown in Table 12. The battery tests were done at 60%SOC. The measured efficiencies are reasonably high, but significantly lower than those for the ultracapacitors for most of the devices.

There has been considerable discussion in the literature [11,12] comparing the power capability of lithium-ion batteries and ultracapacitors. The conclusions vary from statements that lithium batteries have power capability equal to that of ultracapacitors to statements that ultracapacitors have an order of magnitude higher power capability than lithium batteries. Detailed comparisons of the power capability of ultracapacitors and batteries are shown in Tables 13 and 14. As indicated in the tables, neither of the extreme statements is valid in general and that comparisons should be made between specific devices for specific applications. Comparisons are often made based on the matched impedance power of the two types of devices. These comparisons indicate that most ultracapacitors have a power capability (W kg^{-1}) of 3–6 times that of lithium batteries. However, for vehicle applications the matched impedance power is not appropriate and should not be the basis of comparison.

For HEV applications, a good basis of comparison is the W kg^{-1} at 95% efficiency at the SOC at which the devices will be used in the vehicle. On this basis, there are lithium batteries with the same power capability as some carbon/carbon ultracapacitors, but there are some ultracapacitors with power capability twice that of the highest power lithium batteries presently available for vehicle applications. In other words, it is not possible to make general statements that are applicable to all devices of either type. The issue is further complicated when one factors in that the density of the lithium batteries is about twice that of carbon/carbon ultracapacitors (2.2 g cm^{-3} for the batteries and 1.2 g cm^{-3} for the ultracapacitors). Hence on a volume basis W L^{-1} at 95% efficiency, the differences between the batteries and ultracapacitors are often quite small. Comparing Tables 6 and 12 for constant power discharges, the situation is not very different when one considers the relative power capabilities of batteries and ultracapacitors. Hence for HEVs, batteries alone and ultracapacitors alone can be an option with the decision being based on cycle life and cost in addition to relative power capability [13,14].

For plug-in hybrid and battery electric vehicle applications, the maximum useable power density from the lithium-ion battery can be higher than in an HEV because the peak power of the driveline is used less frequently and consequently charge/discharge efficiently is less important. For example, a pulse power efficiency of 80% is probably sufficient and most of the lithium batteries have a power capability of greater than 1000 W kg^{-1}, 2200 W L^{-1} for that efficiency. In addition, the battery is larger (heavier) in these vehicles and as a result, the power density requirement is less demanding. For PHEVs and EVs, the best application of ultracapacitors is likely to be in combination with batteries designed for high energy density, long cycle life, and low cost. In those cases, the ultracapacitors greatly reduce the peak currents and dynamic stress on the batteries and thus extend their cycle life. In addition, combining the batteries and ultracapacitors can permit the use of high energy density batteries with insufficient power capability to be used alone [15].

5. Summary and conclusions

There is much confusion and uncertainty in the literature concerning the useable power capability of batteries and ultracapacitors (electrochemical capacitors) and the comparison of their relative power capabilities. Clarification of this confusion is one of the primary objectives of this paper. This has been done by extensive testing of ultracapacitors and high power lithium-ion batteries using both steady power and pulsed discharge/charge test procedures. From these tests, the resistance of the devices, the effect of discharge time on energy capacity (Wh), and the roundtrip efficiency for charge/discharge cycles with different peak power density pulses were determined. From the resistances, the power capabilities of the devices were calculated for pulses of different efficiency at appropriate states-of-charge for the ultracapacitors and lithium batteries. From the tests and subsequent analysis of the data, the following conclusions can be stated:

1. Comparisons are often made based on the matched impedance power of the two types of devices. These comparisons indicate that most ultracapacitors have a power capability (W kg^{-1}) of 3–6 times that of lithium batteries. However, for vehicle applications the matched impedance power is not appropriate and should not be the basis of comparison.
2. For HEV applications, a good basis of comparison is the W kg^{-1} at 95% efficiency at the SOC at which the devices will be used in the vehicle. On this basis, there are lithium batteries with the same power capability as some carbon/carbon ultracapacitors, but there are some ultracapacitors with power capability twice that of the highest power lithium batteries presently available for vehicle applications. In other words, it is not possible to make general statements that are applicable to all devices

of either type. The issue is further complicated when one factors in that the density of the lithium batteries are about twice that of carbon/carbon ultracapacitors (2.2 g cm^{-3} for the batteries and 1.2 g cm^{-3} for the ultracapacitors). Hence on a volume basis W L^{-1} at 95% efficiency, the differences between the batteries and ultracapacitors are often quite small.

3. For plug-in hybrid and battery electric vehicle applications, the maximum useable power density from the lithium-ion battery can be higher than that corresponding to 95% efficiency because the peak power of the driveline is used less frequently and consequently charge/discharge efficiently is less important. For these applications, the useable power density of the batteries can be closer to the useable power density of ultracapacitors. For PHEVs and EVs, the best application of ultracapacitors is likely to be in combination with batteries designed for high energy density, long cycle life, and low cost.
4. For constant power discharges, the energy capacity of the lithium batteries decreases from the baseline at a low/moderate discharge rate about twice as fast as for ultracapacitors. For a 10% reduction, the power density is about 500 W kg^{-1} for the batteries and greater than 1000 W kg^{-1} for most of the ultracapacitors.

In all cases, it is essential that a careful and appropriate measurement is made of the resistance of the devices and the comparisons of the useable power capability be made in a way appropriate for the application for which the comparisons are being made.

Appendix A. Analysis of the discharge of ultracapacitors

A.1. Constant power discharges of ultracapacitors

A mathematical solution for the constant current discharge of a carbon/carbon double-layer capacitor is given in [7,16–18] including the starting transient of the current distribution in the electrode. The solution is based on solving the one-dimensional, unsteady partial differential equations for the ion transfer in the electrodes of the device. That solution has been used to interpret pulse current data to determine the resistance of the device [7]. In this appendix, a much simpler method has been used to analyze the constant power discharge as discussed in the following paragraphs.

If the capacitance C and resistance R of an ultracapacitor cell are assumed to be constant, an expression for the voltage for a constant power discharge can be derived. The governing equation for the discharge is

$$V_0 - V = IR + {}_V\int \frac{dq}{C}, \qquad dq = I\,dt \tag{A.1}$$

where V_0 is the voltage before the initiation of the discharge.

For discharge at constant power P, the current is given by

$$I = \frac{P}{V}$$

and Eq. (A.1) becomes

$$1 - \frac{V}{V_0} = [PR/V_0^2]/V/V_0 + [P/V_0^2]/C\left\{\int dt/V/V_0\right\} \tag{A.2}$$

Defining $z = V/V_0$, $K_1 = PR/V_0^2$, $K_2 = P/CV_0^2$, Eq. (A.2) becomes

$$1 - z = \frac{K_1}{z} + K_2\int \frac{dt}{z} \tag{A.3}$$

where $z_0' = 1 - (IR)_0/V_0 = 1 - PR/V_0^2 = 1 - K_1$ and $K_1/K_2 = RC$

Eq. (A.3) can be differentiated and then integrated in closed form to obtain

$$K_1[\ln z - \ln z_0'] - \frac{1}{2}(z^2 - z_0'^2) = K_2 t \tag{A.4}$$

Inputting the defined variables, Eq. (A.4) becomes

$$\frac{t}{RC} = [\ln V/V_0 - \ln(1-K_1)] - (1/2)/K_1[(V/V_0)^2 - (1-K_1)^2] \tag{A.5}$$

Eq. (A.5) can be rewritten as

$$t = 1/2\,CV_0^2/P[(1-K_1)^2 - (V/V_0)^2] + RC\ln[V/V_0/(1-K_1)] \tag{A.6}$$

where t is the time of the discharge. $K_1 = PR/V_0^2 = I_0R/V_0$ is an indicator of the efficiency EF of the discharge. $EF_0 = 1 - K_1$. The time t_0 for the discharge of an ideal capacitor having $R = 0$ is

$$t_0 = 3/8\;\; CV_0^2/P \;\; \text{for} \;\; V/V_0 = 1/2 \;\; \text{and} \;\; K_1 = 3/8\,RC/t_0$$

Eq. (A.6) can be written as

$$\frac{t}{t_0} = 4/3[(1 - (3/8RC/t_0))^2 - .25] + RC/t_0\;\ln[1/2/1 - 3/8\,RC/t_0] \tag{A.7}$$

The energy density of the constant power discharge is then

Wh kg^{-1} = tP/3600/weight of cell in kg

and

$$\text{Wh/kg}/(\text{Wh/kg})_0 = t/t_0 \tag{A.8}$$

Eq. (A.8) indicates that for constant power discharges the departure from ideal behavior depends on the parameter t_0/RC or the ratio of the ideal discharge time to the RC time constant of the device. A numerical evaluation of Eq. (A.7) indicates that for $t_0/RC = 9$, $t/t_0 = .82$ or about a 20% decrease in energy density from the ideal value. Writing power density in terms of t_0/RC and RC,

$$(\text{W kg}^{-1})_{\text{const.}} = 3600(\text{Wh kg}^{-1})_0/[(t_0/RC)(RC)] \tag{A.9}$$

For a device with an energy density of 5 Wh kg^{-1} and a time constant of 1 s, the constant power density for a 20% reduction in energy density is 2000 W kg^{-1}. For a device with a time constant of .75 s, the constant power density would be 2667 W kg^{-1}. Comparisons with constant power discharge test data indicate that Eq. (A.9) is in good agreement with the data for large devices from Maxwell and Nesscap and smaller devices from APowerCap.

A.2. Pulse power discharge of ultracapacitors

For the ultracapacitors, the efficiency of the pulse can be written as

$$EF = 1 - I^2R/P$$

If the current is approximated by $I = P/V_0$,

$$EF = 1 - PR/V_0^2, \qquad P = (1-EF)V_0^2/R$$

If the pulse is taken at $V_0 = 3/4V_R$, where V_R is the rated voltage of the ultracapacitor,

$$P = 9/16(1-EF)V_R^2/R \tag{A.10}$$

Eq. (A.10) is similar to Eq. (2) in Section 2 derived for batteries and depends on the rated voltage of the ultracapacitor and its resistance R. Since in most applications, the devices experience a wide range of voltage as they are charged and discharged, it seems reasonable to base their power capability on the intermediate voltage between V_R and $V_R/2$. Eq. (A.10) is used through out the paper to calculate the power capability of ultracapacitors.

A.3. Batteries

Unfortunately there does not seem to be a simple way of expressing the effect of discharge power onthe energy density of

lithium batteries. Without doubt, it will depend on the resistance of the battery and the manner in which the resistance and open-circuit voltage vary with state-of-charge.

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