Fast charging from the battery perspective

Andrew Burke
Institute of Transportation Studies
University of California-Davis

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What is meant by "fast charging"?

- Much faster than normally done - 1-3 hours or longer
- Fast enough to satisfy the needs of the battery/car user
- Charging time of less than 30 minutes often used
- CARB's definition is 10 minutes
- Fraction of energy returned to battery seems to be rather arbitrary - 50-70%?

Fast charging power requirements for PHEVs and EVs

nC	Charging time	PHEV battery 20Ah	7.2 kWh	EV battery 50Ah	18 kWh
		I_{DC} (A)	P_{DC} (kW)	I_{DC} (A)	P_{DC} (kW)
1/3	3 hr.	6.7	2.4	16.6	6.0
1	1 hr	20	7.2	50.0	18.0
2	.5 hr	40	14.4	100	36.0
3	20 min	60	21.6	150	54.0
4	15 min	80	28.8	200	72.0
5	12 min	100	36.0	250	90.0
6	10 min	120	43.2	300	108
7	8.6 min	140	50.4	350	126
8	7.5 min	160	57.6	400	144
12	5 min	240	86.4	600	216
20	3 min	400	144	1000	360

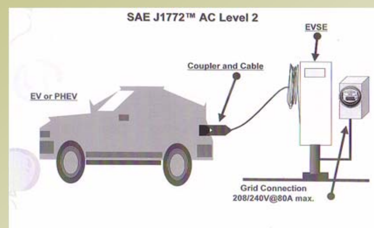
$I_{DC} = (Ah)_{cell} \times nC$, Vmax = 360V

$P_{DC} = I_{DC} \times 360/100$ kW

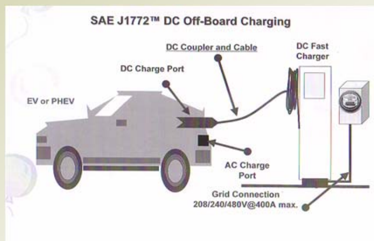
SAE Committee definition of electric vehicle charging standards

Charger characteristic	AC	DC
Level 1		
Input to vehicle	120V AC single phase	200-450V DC
Maximum current	16A	80A
Maximum power	1.9 kW	19.2 kW
Level 2		
Input to vehicle	240V AC single phase	200-450 DC
Maximum current	80A	200A
Maximum power	19.2 kW	90 kW
Level 3 ***Not defined yet***		
Input to vehicle		200-600V
Maximum current		400A
Maximum power		Up to 240 kW

Vehicle Charger Schematics



Level 2
AC to the vehicle
Onboard charger
<19 kW



Level 3 (real fast charge)
DC to the vehicle
Off-board charger
up to 240 kW

Important questions to consider from the battery perspective

- **How is the fast charge controlled? current, voltage, time, temperature, termination limits**
- **How often will the battery be fast charged?**
- **What changes in the design of the battery are needed to accommodate fast charging? Cooling system and the battery management unit (BMS)**
- **What will be the effect of fast charging on battery life?**
- **What is the effect of fast charging on battery safety in the case of lithium-ion batteries**

General approach to battery charging for all battery chemistries

- **Constant current to a clamp or max voltage and current taper at the clamp voltage**
- **Current depends on Ah rating of the cells in the battery**
- **Clamp voltage/cell depends on the battery chemistry and pack clamp voltage depends on number of cells in series**
- **Temperature limit for charge termination depends on battery chemistry**
- **Behavior near full charge depends on battery chemistry**

Key consideration is resistance heating during fast charge

- **Major heating due to the resistance of the battery I2R**
- **Chemistry contributes some heating particularly near the end of charge**

- **Resistance is dependent on Ah of cell** $Rx\ Ah = C_R$ **for fixed cell technology**
- $P_{heating} = I_{DC}^2\ C_R/Ah$
- ***$I_{DC} = (Ah)_{cell} \times (nC)$,***
- **nC is the charging rate, charging time = 1/nC hours**
- $P_{heating}/cell = I_{DC}^2\ C_R/Ah = C_R (Ah) (nC)^2$
- $P_{heating}$ = (number of cells) $C_R (Ah) (nC)^2$
- $E_{heating}/E_{stored} = P_{heating}/cell\ (1/nC)/(V_{cell}\ Ah) =$ ***$C_R (nC)/V_{cell}$***

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

Battery Developer/ Cell type	Electrode chemistry	Voltage range	Ah	Resist. mOhm	RxAh	Wh/kg	W/kg 90% effic.*
Enerdel HEV	Graphite/ Ni MnO2	4.1-2.5	15	1.4	.021	115	2010
Enerdel EV/PHEV	Graphite/ Ni MnO2	4.1-2.5	15	2.7	.041	127	1076
Kokam prismatic	Graphite/ NiCoMnO2	4.1-3.2	30	1.5	.045	140	1220
Saft Cylind.	Graphite/ NiCoAl	4.0-2.5	6.5	3.2	.021	63	1225
GAIA Cylind.	Graphite/ NiCoMnO2	4.1-2.5	40 7	.48 3.6	.019 .025	96 78	2063
A123 Cylind.	Graphite/Iron Phosph.	3.6-2.0	2.2	12	.026	90	1393
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	11 3.8	2.2 1.15	.024 .0044	70 35	940 2460
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	50	.7	.035	70	630
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	1.8	60	.108	144	577
EIG prismatic	Graphite/ NiCoMnO2	4.2-3.0	20	3.1	.062	165	1278
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	.0375	113	1100
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	.013	46	395
Hawker prismatic	Lead-acid	12-10.5	13	15	.033	29	176

* power density P= Eff.*(1-Eff.) Voc^2/R, $P_{match. imped.} = V^2/4R$

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

Battery6Developer/ Cell type	Electrode chemistry	Voltage range	Ah	Resist. mOhm	RxAh	Wh/kg	$E_{heating}/E_{store}$ nC=4
Enerdel HEV	Graphite/ Ni MnO2	4.1-2.5	15	1.4	.021	115	.022
Enerdel EV/PHEV	Graphite/ Ni MnO2	4.1-2.5	15	2.7	.041	127	.047
Kokam prismatic	Graphite/ NiCoMnO2	4.1-3.2	30	1.5	.045	140	.05
Saft Cylind.	Graphite/ NiCoAl	4.0-2.5	6.5	3.2	.021	63	.025
GAIA Cylind.	Graphite/ NiCoMnO2	4.1-2.5	40 7	.48 3.6	.019 .025	96 78	.022 .029
A123 Cylind.	Graphite/Iron Phosph.	3.6-2.0	2.2	12	.026	90	.032
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	11 3.8	2.2 1.15	.024 .0044	70 35	.04 .007
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	50	.7	.035	70	.058
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	1.8	60	.108	144	.12
EIG prismatic	Graphite/ NiCoMnO2	4.2-3.0	20	3.1	.062	165	.071
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	.0375	113	.045
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	.013	46	.045
Hawker prismatic	Lead-acid	12-10.5	13	15	.033	29	.066

* power density P= Eff.*(1-Eff.) Voc^2/R, $P_{match. imped.} = V^2/4R$

Summary of the charging characteristics of batteries of various chemistries

Battery chemistry	Ah	Clamp voltage	Charge current A	Time (min) to clamp/Ah	Time (min) to cut-off/Ah
NiCoMnO2	20	4.2	20	52/17.3	80/19.6
FePhosphate	15	3.65	15	60/15.2	64/15.4
LiTitanateOx	11	2.8	11	65/11.9	66/11.9
Lead-acid (12V)	38	14.7	25	81/33.9	11/40
			45	45/34	
			55	39/36	
			65	26/29	

Conclusions concerning fast charging of batteries of various chemistries

- All chemistries can be fast charged to clamp voltage if cooling is provided to maintain temperatures below specified values
- Temperature limits depend on the electrolyte characteristics - 40 deg C for aqueous electrolytes and 55-60 deg C for organic electrolytes in lithium batteries
- Chemistry near clamp voltage is key - gassing for aqueous electrolytes and final intercalation (diffusion into solid cathode particles) of Li+ ions
- Most problems with the chemistry can be avoided if only a fraction of the Ah/kWh is returned to the battery in the fast charge

Fast charging data for Lithium-ion cells

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

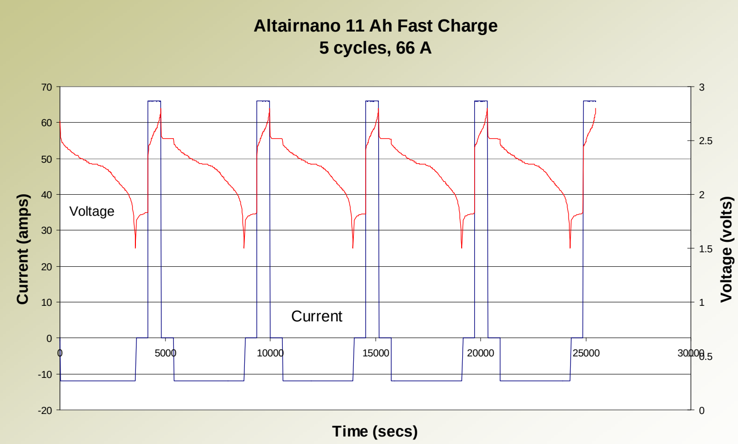
Charge Current (Amps)	Time to Cutoff (secs)	Taper Time (secs)		Charge (Amp-hrs)	Discharge (Amp-hrs)	Temp Rise During Cha Initial Temp (C)	Temp Change (C)
11	3920	81	11.9	12.0	12.00	22.5	0
22	1950	68.5	11.9	12.0	12.00	22	0.5
33	1300	57.7	11.9	12.0	12.00	22.5	1.5
44	970	59.2	11.8	12.0	12.01	23	2.5
55	760	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

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

Five cycle fast charge of the Altairnano 11 Ah cell



Fast charging tests of the 50Ah Lithium Titanate cells/modules

Batteries tested

- 50Ah Altairnano LTO cells 10
- 24V modules (10 cells per modules) 3

Instrumentation

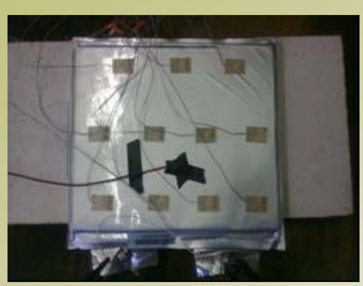
Cells

- voltage and current
- thermocouples attached to face (9)

Modules

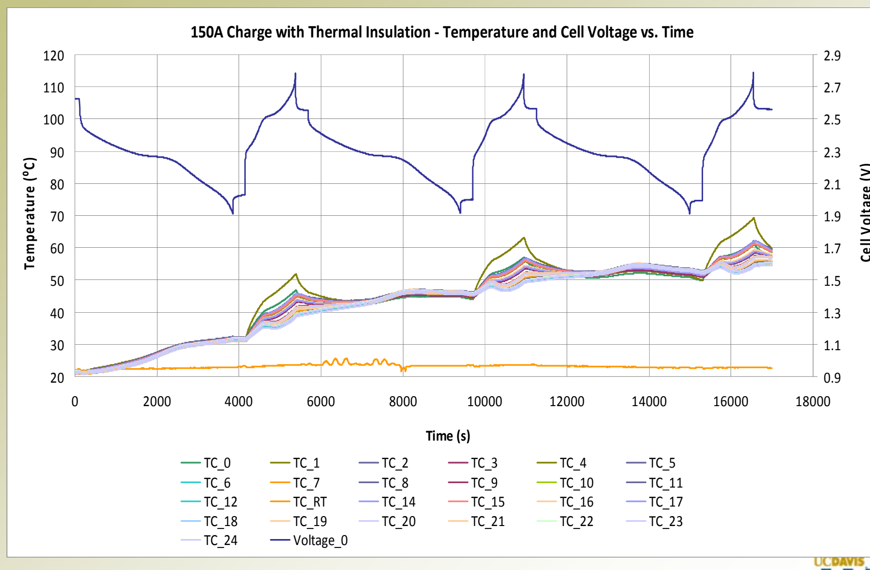
- cell voltages (10)
- interior temperatures (3)
- thermocouples on the cooling plate (9)

Laboratory set-up for testing the Altairnano batteries

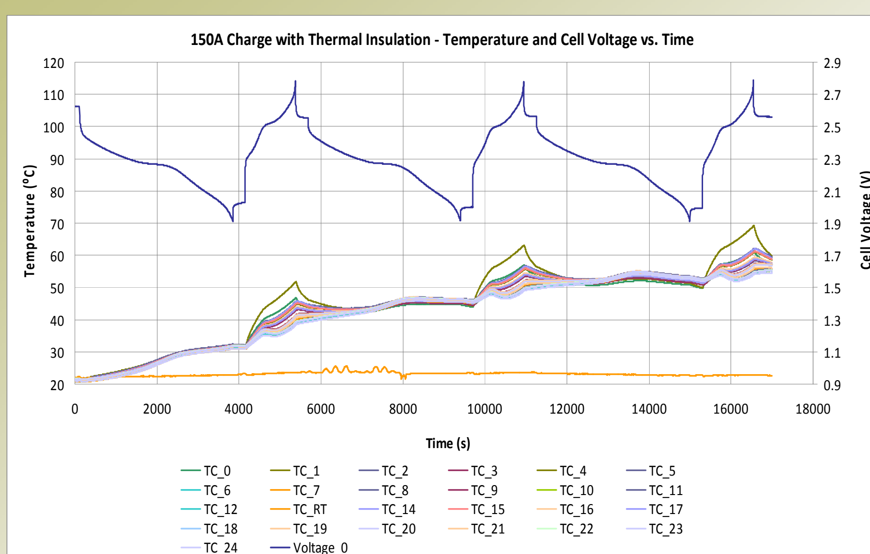


Single cell with thermo-couples and insulating blanket

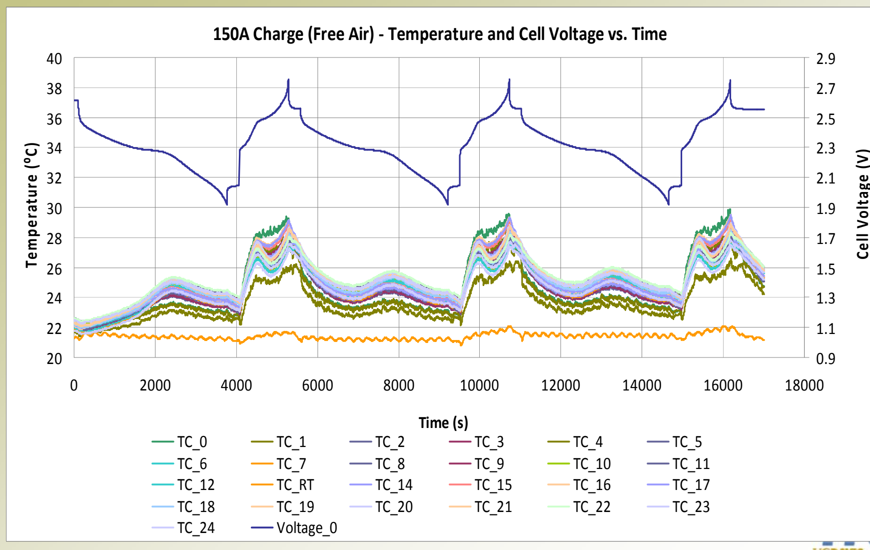
Cell 274 150A with thermal insulation



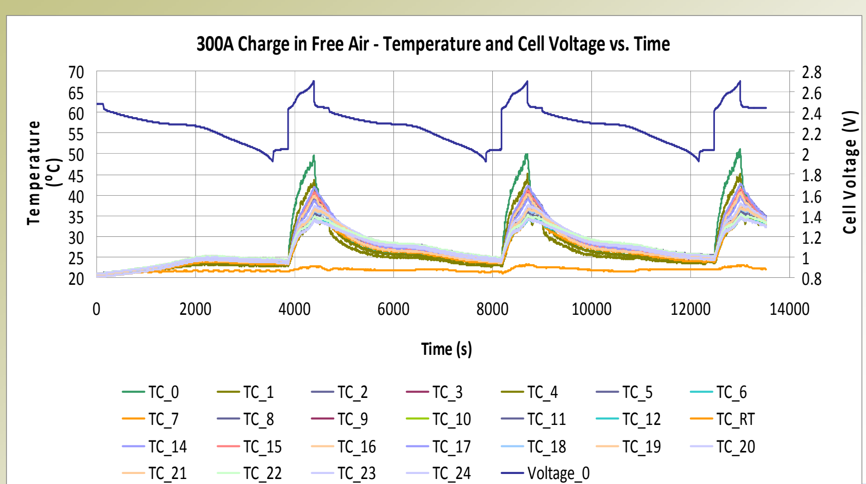
Cell 274 150A with thermal insulation

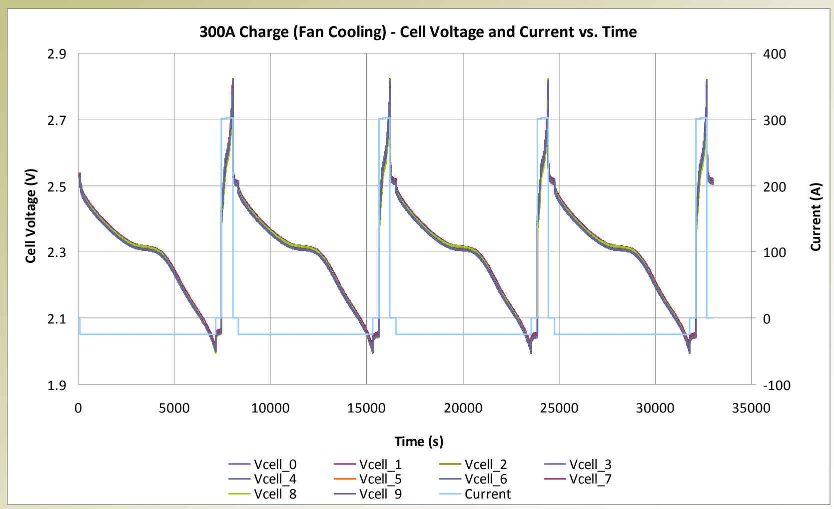


Cell 274 150A in Free Air

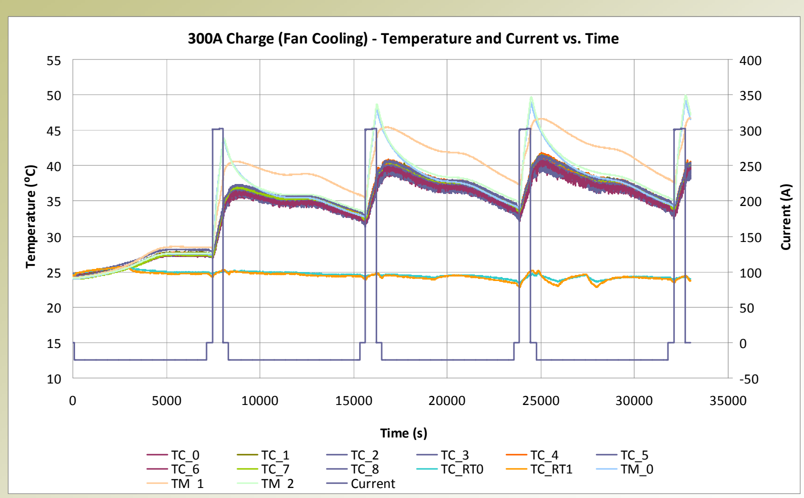


Cell 274 300A Charge in Free Air





Temperature distributions in module for fast charging-300A



Summary and conclusions

• At the present time, fast charging is not well defined either in terms of the charge time or fraction of energy returned to the battery by the fast charge

• All battery chemistries can be fast charged if proper cooling is provided and the clamp/maximum voltage limits are correctly regulated

• Some Lithium chemistries are well suited for “really” fast charging (less than 15 minutes) and all lithium batteries can be charged in 30-60 minutes without concern for battery life.

• In practice, fast charging will be more limited by the availability of high power fast chargers than the ability of the battery to accept the charge without damage.