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(RESEARCH ARTICLE)

Optimized model for rapid battery charging using constant current constant voltage protocol

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Abstract

This research, which aims to find the best constant current, constant voltage parameters for charging a battery in the quickest time possible, subjects battery cells to varied charging and discharge rates in order to determine their rate capabilities. Cycling the cells using constant current, constant voltage charge in 60 minutes and 90 minutes discharge for 400 cycles examines the effects of the charging current Charge Rate and the voltage limit for the constant voltage on the battery's discharge capacity. The results obtained showed that 1.3C-rate and 4.3V voltage limit produced the utmost discharge capacity and cycle life. During the cycling period, the cell temperature was under 39°C with a capacity loss after 400 cycles of 8%. A 3 percent capacity gain was seen after charging the batteries using the cccv methodology for 180 minutes and then discharging them for 120 minutes. This low capacity loss after 400 cycles suggests that an optimal charging model employing the cccv protocol is possible.

Keywords: Battery; Cells; Constant Current; Constant Voltage; C-Rate; Discharge Capacity

1. Introduction

The charging time is a major issue for all Lithium Ion Battery applications, particularly mobile electronics and electric mobility [1]. Rapid charging will undoubtedly benefit the future battery market. Every equipment or machine that runs on batteries has a usage time that is proportional to the amount of stored electrical energy within the battery's cells. [2,3]. The amount of stored electrical energy stored in the battery cells is the product of the energy density multiplied by the volume and mass of the entire battery system. There has been a notable increase in the energy density of industrial batteries in the last one decade, presently we have energy density of batteries at 260Wh/kg and 700Wh/I [4]. For battery powered electric vehicles (BEV) to fully gain acceptance, the charging time should be similar to the time required to refill the tank of an internal combustion engine vehicles which is typically about 10mins while ensuring a driving range of not less than 500km.

Rapid charging using Constant Current Constant Voltage (CCCV) protocol has been proposed to improve the charging time of batteries to at least 60mins for 100% gain in the state of charge. CCCV protocol is about applying a constant charging current (C-rate) up to an upper voltage limit (V_{lim}) and applying a constant voltage of V_{lim} till a current limit is achieved. The challenge faced when attempting to reduce the charging time of batteries to 60mins and below is active material degradation, Lithium metal plating at the anode and temperature rise [5,6,7]. In this work the CCCV protocol will be used to attempt reducing the charging time of LIBs while maintaining good safety and long cycle life. Rapid charging using CCCV protocol involves two distinctive phases, the CC phase with time t_{cc} and the CV phase with time t_{cv}. This gives the total charging time T_c as

$$T_c = t_{cc} + t_{cv} \qquad \text{(i)}$$

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1.1. Cell conditioning and rate capacity profiling

Two identical LIB batteries rated 3650mAh are employed in this study. All tests are carried out at room temperature (27±2°C). Charging and discharging was done repeatedly for five times using slow rate CCCV. A charge current of 740mA to V_{lim} of 4.4V was used for charging for 20mins while a discharge current of 740mA to 2.5V was used for discharging. At the end of the 5 cycles, a stabilized discharge capacity of 3600mAh was achieved. This discharge capacity is the battery cell's nominal capacity.

Before quick charging, rate capacity test is done to ascertain if the battery cells can withstand high discharge currents. The battery cells are subjected to CCCV protocol charging at C-rate of C/3 to 4.4V; after which it was also subjected to a discharge at increasing C-rates of C/5, C/2, C, 2C, 2.7C and 3.8C to 2.5V. The average voltage (E) and discharge capacity (Q^{dis}) were then ascertained. From the discharge data, the average voltage, energy density W_d and power density P_d are calculated as follows

$$E = \int_0^{Q^{dis}} \frac{E(q)dq}{Q^{dis}} \quad \text{(ii)}$$

$$W_d = \frac{Q^{dis} x \langle E \rangle}{m} \left({}^{Wh}/_{kg} \right) \quad \text{(iii)}$$

$$P_d = \frac{I_d x \langle E \rangle}{m} \left({}^{W}/_{kg} \right) \quad \text{(iv)}$$

Where $E(q)$ is the discharge profile

m is the cell's mass

I_d is the discharge current

2. CCCV protocol charging and cycle capacity

The battery cells are charged using the CCCV protocol for 60mins with varying charge rates and voltage limits. The corresponding t_{cc} and t_{cv} for each of the C-rate and V_{lim} were noted. Similarly, the charge gained during the CC (Q_{cv}^{ch}) steps were also calculated while the system temperature was continuously monitored through the whole process. The respective sets of C-rate and V_{lim} used are 1.2C/4.25V, 1.3C/4.3V and 1.4C/4.35V.

After charging the battery for 60mins, the cell is rested for a period of 30mins before discharging. The discharging is done within 90mins period at a 0.65C-rate. After the discharge process, another rest period of 30mins is observed before the next cycle commences. After 400 complete cycles, the C-rate and V_{lim} combination with the best discharge capacity and lowest capacity fade is identified.

3. Results and discussion

The various discharge data such as Power Density P_d, Energy Density W_d, Discharge Capacity Q^{dis} and Average Discharge Voltage E are shown in table 1.

Table 1 Cell Performance during Discharge at Different C-Rates

C-rate	C/5	C/2	C	2C	2.7C
<E> (V)	3.9	3.8	3.6	3.4	3.3
Q^{dis} (mAh)	3697	3681	3659	3567	3609
P_d (W/kg)	51.4	124.9	238.9	453.1	591.7
W_d (Wh/kg)	255.1	247.5	236.2	217.2	213.5

From the table, it is seen that the energy density was satisfying at all the discharge rates. It dropped from 260Wh/kg at C/5 rate to 219Wh/kg at 2.7C-rate which amounts to about 16% drop. On the other hand, the Power density increased from 52.4W/kg at C/5 rate to 593.2W/kg at 2.7C-rate. A low average cell polarization is also noticed as the difference between average discharge voltage E at 5C-rate and 2.7C-rate is only 13.2%. It was also noticed that the temperature raised above 55°C when discharged at 3.8C-rate after 180mins of charge. This situation forced the test to discontinue due to safety reasons. Fig 1 shows the voltage-time profiles during the charging using CCCV protocol at C/3-rate to V_{lim} 4.4V and during the discharge with different C-rates, while Fig 2. shows the voltage-capacity profile at different C-rate during discharge. Fig 3. is the Ragone plot from table 1.

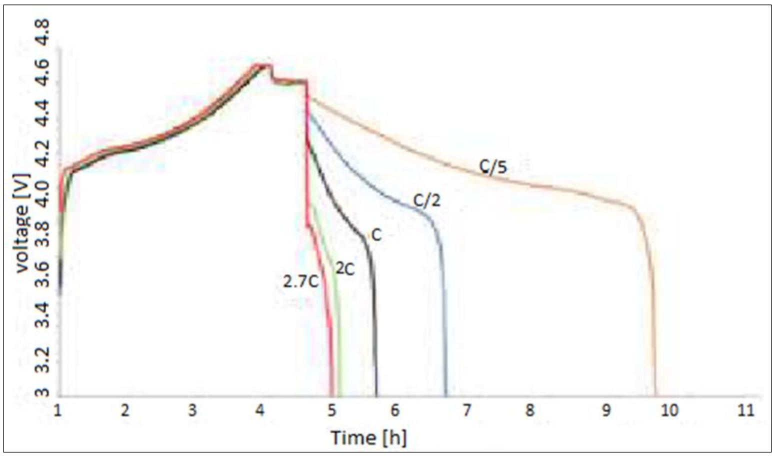

Figure 1 Voltage – Time Profile during CCCV Charge In 180min and Discharge at Different C-rates

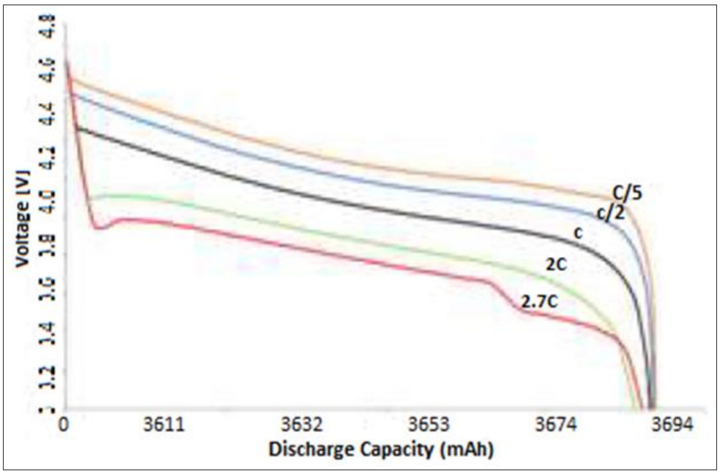

Figure 2 Voltage – Discharge Capacity Profile at Different C-rates

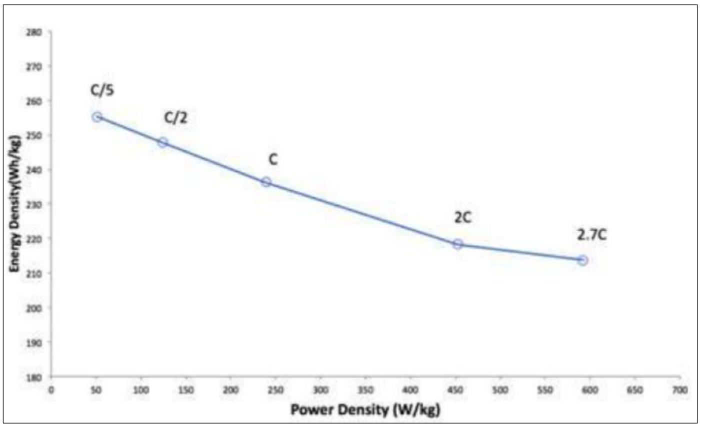

Figure 3 Ragone Plot Achieved at Different C-rates

The profile of CCCV charge and CC discharge is shown in Fig.4. It shows the current and voltage profile during 60mins charging using CCCV protocol with 30mins break followed by a 90mins discharge at C/1.5 rate and voltage limit 4.25V. Similarly the charge profile at 1.2C, 1.3C and 1.4C rates with voltage limits of 4.3V, 4.35V and 4.4V are shown in figures 5, 6 and 7 respectively with a total charging time t_{ch} of 60mins across board.

When the V_{lim} of 4.4V is used at any C-rate, a high cell polarization is seen which generates much heat and hastens electrode and electrolyte material degradation. Thus for long cycle life, V_{lim} values must be kept below 4.4V. The comprehensive CCCV charge and CC discharge data are shown in Table2 while Fig.8 shows a 3D plot of the effects of C-rate and V_{lim} on the discharge capacity. Maximum discharge capacity is reached at 4.35V for both 1.3C-rate and 1.4C-rate while it is 4.4V for 1.2C-rate.

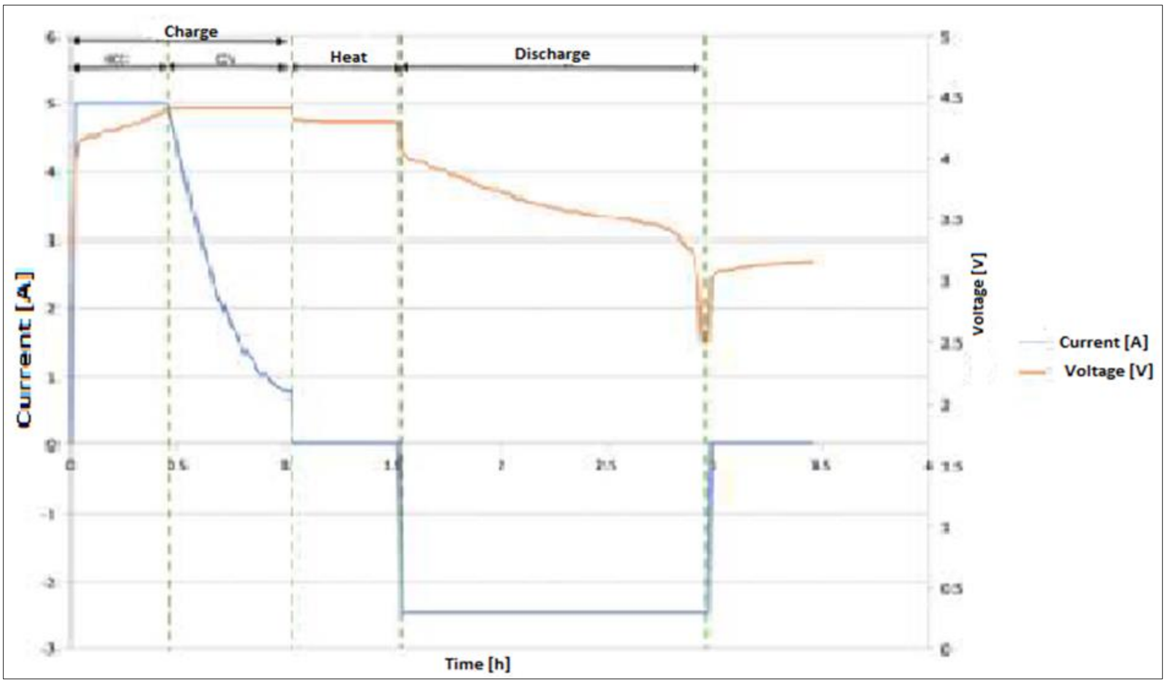

Figure 4 Current and Voltage Profiles during CCCV Charge in 60mins and Discharge in 90mins (with a rest period between Charge and Discharge)

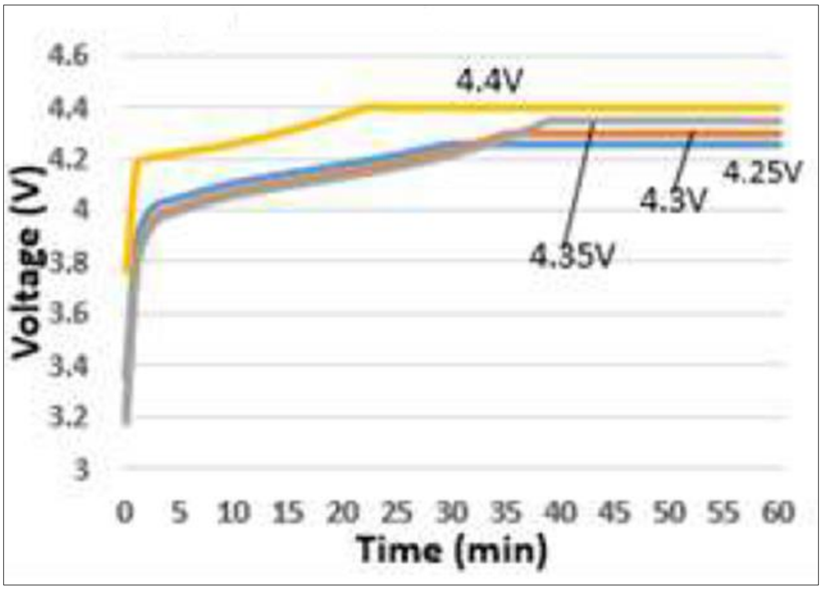

Figure 5 60mins CCCV Charge Profile with V_{lim} of 4.25V, 4.30V, 4.35V and 4.4V with C-rate of 1.2C

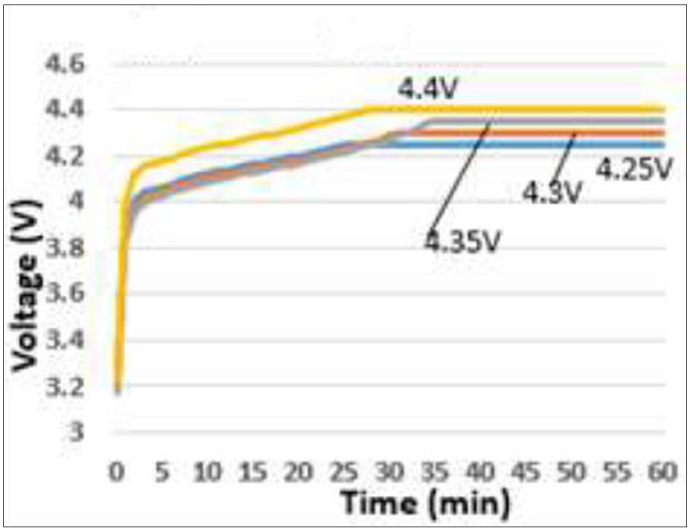

Figure 6 60mins CCCV Charge Profile with V_{lim} of 4.25V, 4.30V, 4.35V and 4.4V with C-rate of 1.3C

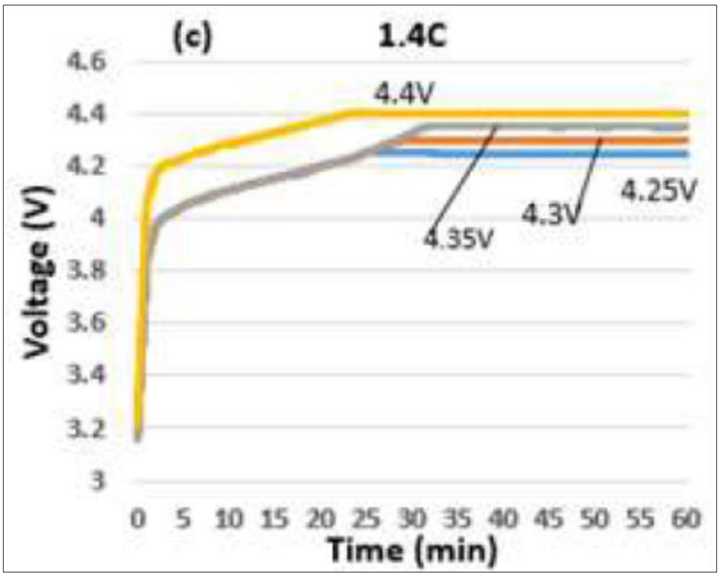

Figure 7 60mins CCCV Charge Profile with V_{lim} of 4.25V, 4.30V, 4.35V and 4.4V with C-rate of 1.4C

Table 2 Charge and Discharge Performance during 60mins CCCV Charge and 0.6 C-rate Discharge

C-Rate			1.2				1.3				1.4			
V_{lim} of CV (V)			**4.25**	**4.3**	**4.35**	**4.4**	**4.25**	**4.3**	**4.35**	**4.4**	**4.25**	**4.3**	**4.35**	**4.4**
Charge	CC	t_{cc} (min)	29	34	38	21	25	31	35	27	25	28	33	24
		Q_{cc}^{ch} (mAh)	2119	2471	2754	1549	1988	2372	2677	2136	2059	2388	2637	1975
		% of norminal	65.2	72.1	77.1	54.4	61.3	68.5	74.4	61.3	61.4	68.9	73.5	54.9
	CV	t_{cc} (min)	29	24	20	38	33	29	24	32	34	31	27	37
		Q_{cv}^{ch} (mAh)	1082	907	772	1248	1265	1048	898	1355	1257	1081	970	1551
		% of Q^{ch}	32.8	27.9	20.9	44.8	37.8	31.0	25.5	37.6	36.6	30.5	25.8	43.2
	Total	Q^{ch} (mAh)	3200	3379	3526	2799	3253	3420	3576	3491	3318	3471	3602	3524

		% of norminal	87.9	92.7	96.7	76.6	91.1	94.8	99.3	95.7	92.3	96.6	99.2	96.8
Discharge	Q^{dis} (mAh)		3214	3378	3522	3660	3251	3422	3571	3491	3314	3468	3601	3525
	% of norminal		86.8	92.4	95.3	101.2	88.6	93.7	98.0	94.7	90.1	93.9	99.0	96.1

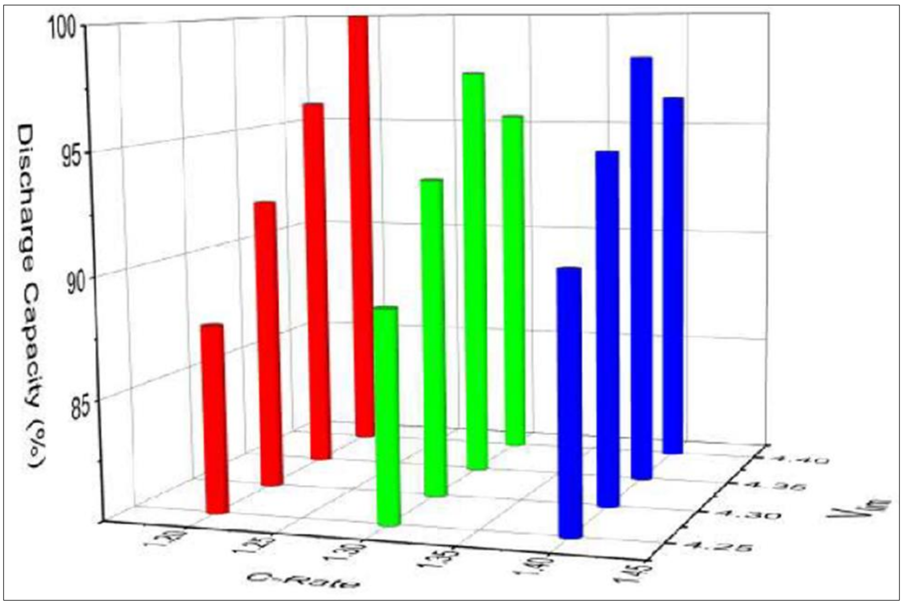

Figure 8 3D Plot of C-rate, V_{lim} and Discharge Capacity Percentage during 60mins CCCV Charging

The initial cycle life tests showed that when the V_{lim} was 4.4V, capacity fading was high during cycling when compared to a V_{lim} of 4.35V. This high fading capacity corresponds with other studies on performance degradation rate [1,8,9]. In line with this, 1.4C-rate and 4.35V V_{lim} was selected for long cycle test due to the good trade-off between lower cell's polarization and high capacity. Fig 9 shows the cycle capacity profile. It is seen that a drop of 7% in capacity occurred after 400 cycles with few slow rate CCCV cycles which had over 97% initial capacity received. Consequently, the optimized CCCV protocol charging condition for 60mins permits an irreversible capacity loss of less than 3% after 400 cycles. This implies that there was no significant electrode and electrolyte degradation within the 60mins charging using the CCCV protocol and 90mins discharging for the 400 cycles.

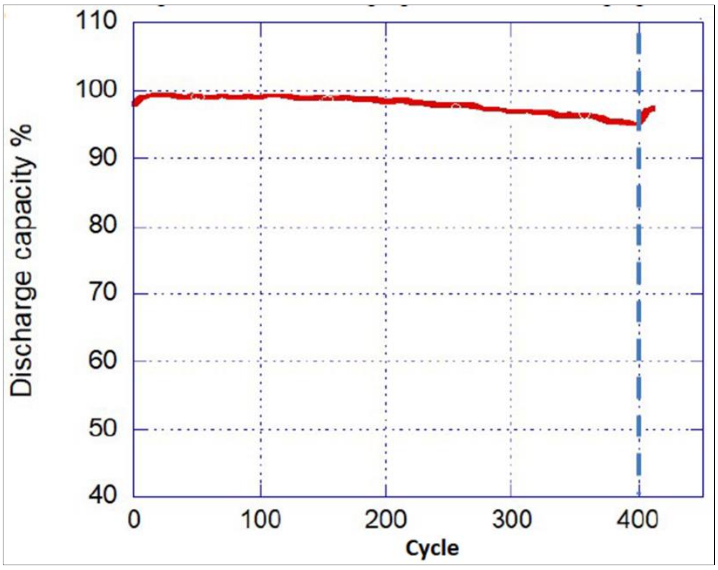

Figure 9 Discharge Capacity against Cycle Profile during CCCV Charge in 60mins for the first 400 Cycles

4. Conclusion

Using proper C-rate and voltage restrictions throughout the CC and CV phases, an optimal CCCV technique with a controlled charging period of 60 minutes was obtained. In this specific situation the cells employed are based on the graphite/NMC chemistry and the most acceptable C-rate and voltage limit combination was achieved at 1.4C-rate and 4.35V. After 400 cycles, 7% of the initial capacity was lost after 60mins CCCV charge at 0.6C discharge while 3% of initial capacity was lost after 300mins CCCV charge at same C-rate of 0.6C. The ability to fully charge an LIB cell in 60mins while maintaining a high cycle capacity of 400 cycles is a significant improvement in lowering the charging time from the usual PED and BEV manufacturer's recommended charging time of 90-120mins. It is worthy to note that the optimized C-rate and V_{lim} combinations for 60mins full charge of cells depends on the cell's chemistry and design. To implement a 60mins charge using the CCCV protocol, the best C-rate and V_{lim} combination should be adapted. The CCCV protocol conditions are very much specific to the cell's chemistry and design.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that the research serves no personal or organizational interest. The authors declare no conflict of interest.

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