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SOME INSIGHTS IN FAST CHARGE METHODS FOR NCA CELLS

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ABSTRACT

Low charge times are very desirable for battery electric vehicles. Lithium Nickel Cobalt Aluminum (NCA) chemistry is used in vehicles like the Tesla Model S for their energy density and also used in several consumer applications. Investigators used state of art NCA cells to conduct research into the tradeoffs between charge time, life and safety. Eight different charge profiles were compared. These included the standard CC-CV strategy and the state of the art Tesla Model S profile. Impact of temperature is also embedded in the selection of charge profiles. A non-dimensional charge metric is proposed as a composite of the impacts of charge time, effective charge stored, aging, overcharge sensitivity and lithium plating sensitivity. This metric is computed for all tested charge profiles and the best candidates are identified.

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1. INTRODUCTION

With the advent of high fuel efficiency and low emission standards, there is increasing demand for technologies that can deliver transportation solutions that meet these standards at fair costs. Current CAFÉ standards require vehicles to meet a target fuel economy of 54.5 mpg by 2025 and reduce CO2 emissions to 163 g/mile. One of the technology solutions that can achieve these goals is electrification of automotive powertrains. The key component for electrification in terms of cost and technology is the electrochemical energy storage system. Lithium-ion batteries have shown promise in satisfying energy and power densities needed for such electrification. Automotive manufacturers must ensure that a lithium-ion battery pack can provide the same durability as the rest of the powertrain with 8-10 year or 100,000-mile reliability while preserving the convenience of fast charging at charge stations. The task of minimizing charge time for lithium-ion batteries has intrigued researchers recently since the issue of range anxiety is being met by improved energy densities.

Fast charging increases battery internal temperature by accelerating side reactions and may result in lithium deposits on anode.

All of these effects reduce available active lithium ions which reduces the effective capacity of the battery. Hence, fast charging is known to reduce life of a battery if not designed appropriately. Thus, all battery types will usually require a lower charge current compared to its maximum possible discharge current. This is needed to preserve the life of the battery. Typically, manufacturer charge specification will recommend a low constant-current (CC) stage followed by a constant-voltage (CV) stage until a low threshold current is reached as shown in Figure 1 on the right axis.

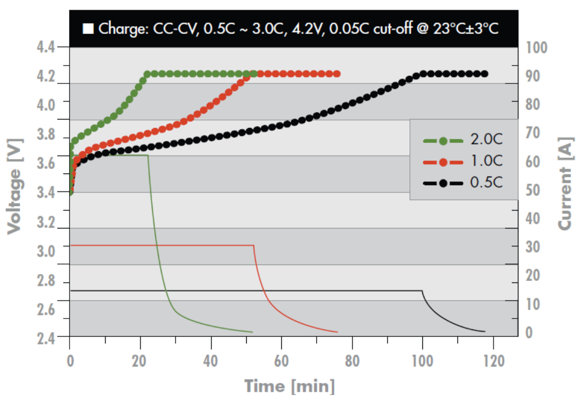

Figure 1 CC_CV Charge Protocol is most frequently Used - Courtesy: Dow Kokam/XALT

2. OBJECTIVE

Figure 2 Tesla 2013 Model S Cell

The primary objective of this paper is to examine the effect of fast charging on a commercially available battery pack, based on Tesla 18650 NCA cells (Figure 2), specifically in regard to:

- Battery safety margin
- Battery life

Work was conducted to:

- Develop a new charging metric
- Test multiple fast charging profiles (Table 1)

Cells were aged for 3-4 months by repeating the test profile charge current and using a nominal discharge current for typical driving. The rationale behind choosing the eight profiles is indicated in the comment's column. Lessons learned from these profiles were combined to create a formalized design of charge profile that can adapt with age. This work is out of scope of this paper and will be published in the future.

Table 1 Summary of Charge Profiles

Profile #	Charge Profile Label	Description	Comments
1	CC-CV	Use an optimum constant current until Vmax and switch to constant voltage mode	Current state of the art
2	V_{max} - based Constant Voltage Mode	Use constant voltage mode (CV) only with target voltage as Vmax	Most aggressive possible charge rate at the given temperature
3	Stepped Voltage-Controlled Charging	Real time pseudo-OCV profile is targeted with a voltage step above to drive charging	OCV curve is the inherent characteristic of cell at equilibrium at each SOC
4 (a)	Pulsed Current with period of 15 seconds - Controlled Charging at 25 °C and 45 °C	Pulsing charge current allows for reducing temperature and increasing charge acceptance	Reduction of polarization voltage could increase charge acceptance

4 (b)	Pulsed Current- with period of 60 seconds - Controlled Charging at 25 °C and 45 °C	Pulsing charge current allows for reducing temperature and increasing charge acceptance	Reduction of polarization voltage could increase charge acceptance
5	Piecewise Constant Current Charge Profile based on Charge Acceptance at 25 °C	Change current as a function of SOC based on minimum charge acceptance metric (dV/dQ)	Strategy maximizes current in each SOC domain with minimal increase in voltage there delaying onset of V_{max}
6	Tesla Model S Super Charger Profile	Consists of a constant current mode followed by a complex voltage track profile	This is the state of art in EV industry today.
7	1.5 C CC + CV	1.5 CC until V_{max} and CV mode	Tradeoff between fast aging at 2 C and Tesla Profile of 1.1 C
8	Piecewise Constant Current Charge Profile based on Charge Acceptance at 25 °C and 45 °C	Profile 5 with 0.2 C steps removed	Minimizing charge time with no thermal impact compared to Profile 5

3. CHARGE METRIC

A new charging metric was developed to relate the influence of charge time, charge quantity, variation in cell imbalance due to charging and temperature on the effectiveness of charging.

$$CM = \left(\frac{\Delta t_c\ actual}{\Delta t_c\ target}\right)\left(\frac{Rated\ Capacity}{Actual\ Capacity}\right)(OC\ Risk\ Factor)(LP\ Risk\ Factor)(Aging\ Factor)$$

where,
CM = charge metric
Δt_c,actual = actual charge time at BOL (Beginning of Life)
Δt_c,target = desired or reference charge time
Rated Capacity = cell’s rated capacity (3.1 Ah)
Actual Capacity = measured charge capacity at BOL
OC Risk Factor – Overcharge risk factor
LP Risk Factor – Lithium Plating risk factor
Aging Factor – Repeated fast charge based aging

The best profiles will have a very small numerical value for the combined charge metric. The first factor measures how quickly a profile can charge with respect the current state of art (target time). The second factor measures how much charge acceptance can be had compared to rated capacity. This factor is typically higher than unity as it is well known that charge acceptance decreases with increasing C-rate. The OC risk factor measures amount of SOC greater than 100% that the cell can tolerate before failure. This is typically lower for cells with more severe aging. It is also well known that when the probability of lithium plating increases with C-rate even at room temperature. Lithium plating (LP) risk factor measures the magnitude of plating observed as the C-rate is increased to reduce charge time. The aging factor is the normalized capacity fade observed during cycling. A low number indicates less aging. In essence the charge metric allows the selection of an optimal charge profile that can minimize charge time, maximize charge acceptance, minimize safety risk of overcharge and lithium plating and maximize durability (minimize aging).

The risk factor computation will be referenced in more detail in sections to follow.

3.1. Life Comparisons of Charge Profiles

All of the profiles in Table 1 were programmed into the power cyclers and cells aged with repeated charge and discharge cycles. The discharge cycle used was the manufacturer recommended standard cycle. This approach ensured that dominant factor in degradation was the charge profile. The results obtained are shown in Figure 3. Typically, automotive OEMs consider 80% capacity as end of useful life. Using this threshold, we can note that Profile 6 (Tesla Model S) has a useful charge life of 90 fast charge duty cycles. This means if a driver took his/her model S to the supercharger every day for 3 months and drove 250 miles every day the battery would reach end of life in an accelerated fashion. Also, we need to note this test was conducted at 25 °C which matches the average battery temperature at a supercharger during a typical spring or fall day. From a practical standpoint Tesla may have taken into consideration few other factors.

- Drivers will not go to the supercharger every day due to the inconvenience
- The 110 V / 240 V charging at home and parking periods may cause healing between supercharger visits

- Liquid cooling in contact with cells may cause slightly lower temperatures than ambient maintained in this work.
- A typical consumer keeps the vehicle parked for more time and typically drives 2-3 hours on average, resulting in long rest periods which are conducive to longer life.

An interesting feature to note is the difference in aging of profiles 4A, 4B, 6, 7 and 8 with temperature. As we predicted, the aging process is significantly reduced with an increase in temperature. This is an important finding that will help design and market novel thermal management strategies for battery pack design. We can also note that the industry standard CC-CV design is not necessarily the best for aging.

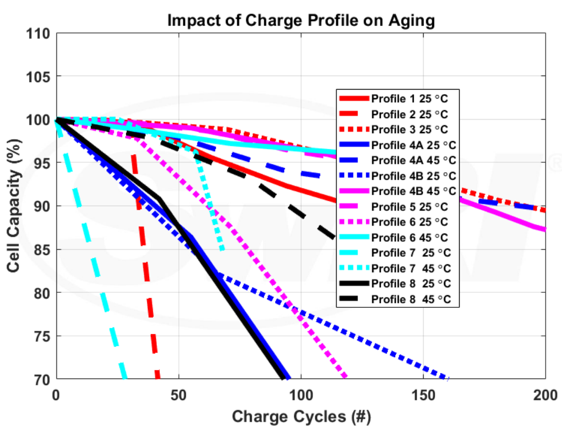

Figure 3 Degradation of capacity after multiple charge profile duty cycles

3.2. One Ah capacity Charge times vs Degradation

Comparison of 1 Ah charge times along with impact in aging is summarized in Table 2.

We can note that most of the profiles with shorter charge times have a severe impact on age except for 4A, 4B, 6 and 7 at 45 °C.

Table 2 Comparison Charge Times and degradation during Life Cycling

Charge Profile	Charge Time (min) to 1 Ah	Degradation*
1	30	Acceptable
2	20	Severe
3	50	Acceptable
4A – 25 °C	19	Severe
4A – 45 °C	20	Acceptable
4B – 25 °C	19	Severe
4B – 45 °C	19	Acceptable
5 – 25 °C	48	Acceptable
6 – 25 °C	20	High
6 – 45 °C	18.5	Acceptable
7 – 25 °C	13	Severe
7 – 45 °C	13	Acceptable
8 – 25 °C	15	Severe
8 – 45 °C	15	High

*** Quantitation to compute charge metric assumes Acceptable = 0.25, High = 0.5, Severe = 0.75, Failure = 1.0**

3.3. Lithium Plating of Charge Profiles

Lithium plating is a destructive phenomenon that occurs when a battery is charged at high currents at any temperature or at cold temperatures. At the high current rates or at low temperatures lithium ions are not accepted by the graphite anode and begin depositing on the surface of the anode. This plating reduces available lithium ion capacity and also results in dendritic growth that increases the risk of internal shorts through puncture of separators. Fast charge algorithms not managed appropriately result in high intensity Lithium plating. Based on work done by Gold Peak Industries [20] SwRI has developed a diagnostic procedure to measure the intensity of lithium plating. One sample of battery aged by each of the eight fast charge profiles was subjected to this diagnostic procedure. The results are shown in Figure 4. In conclusion, Lithium plating is also low for best aging candidates 4A, 4B, 6 and 7 at 45 °C. Quantification of severity of lithium plating is done similar to Table 2 Column 3.

3.4. Overcharge Tolerance of Charge Profiles

One battery sample for each profile was subjected SAE J2464 3C overcharge (OC) test and overcharge tolerance measured. The capacity (Ah) was measured at Beginning of Life (BOL), End of Life (EOL) and before Safety test. The amount of overcharge Ah was also measured to quantify tolerance of the battery to each accelerated fast charge profile. The results are summarized in Table 4. Out of all best aging and low Lithium plating profiles, overcharge tolerance is highest for Profile 7 at 45 °C.

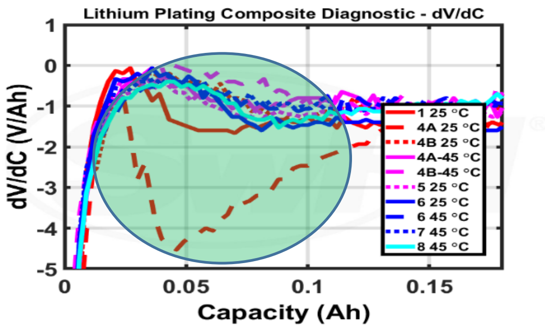

Figure 4 dV/dC of Discharge Capacity of Lithium Plating after Fast Charge Aging – Magnitude of the highlighted trough gives a Measurable Metric of Intensity of Plating

4. CONCLUSIONS

The work conducted examined the aging degradation, lithium plating, overcharge tolerance, and charge time for eight different charge profiles on a commercially available battery pack. A non-dimensional charge metric was developed to aid in creating a fast charge profile with minimal impact on battery degradation. This non-dimensional charge metric is based upon charge time, capacity, overcharge tolerance, lithium plating and number of charge cycles to EOL, with lower values of CM being better.

It was shown that a pure CV mode charging strategy can provide the theoretical maximum current for fast charging (Profile 2); however, charge time and aging factors were reduced further with more sophisticated charging profiles. A test and analysis method were used to identify the maximum current based on naturally occurring strong charge acceptance regions of SOC resulting in lower lithium plating and aging degradation, at the expense of increased charge time (Profile 5).

Of the eight profiles tested, the three best performing profiles were conducted at an elevated temperature of 45 °C (Profile 4A, 4B and 7 shown in Table 3). This opens up the possibility of implementing a thermal strategy to increase charge acceptance, decrease lithium plating, cell aging, and charge time.

Table 3 Profiles with Lowest (Best) Charge Metrics

Fast Charge Profile	BOL 1 Ah Charge Time/ Target Charge Time	BOL Rated/Actual Capacity	Aging Risk Factor	Lithium Plating Risk Factor	OC Risk Factor	Charge Metric (CM)
4A - 45 °C	1.0	0.65	0.25	0.25	0.72	0.03
4B - 45 °C	0.95	0.5	0.25	0.25	0.84	0.02
7 - 45 °C	0.65	0.97	0.25	0.25	0.69	0.03

Future work to be conducted includes developing an analytical formulation of the charge process in order to further optimize charge acceptance of the cell and minimize any cell degradation.

5. REFERENCES

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Table 4 Overcharge Tolerance of Batteries after Fast Charge based Aging

	Battery Capacity in Ah					
Fast Charge Profile	BOL	EOL	Before OC	OC before failure	% OC Tolerance	SAE J2464 Rating
1	2.946	2.520	2.538	0.840	28.513	7
2	2.984	1.088	1.081	0.371	12.433	2
3	3.010	2.654	2.749	0.839	27.874	7
4A 25 °C	2.965	1.365	1.757	0.445	15.008	2
4B 25 °C	2.964	1.696	2.060	0.528	17.814	7
4A 45 °C	2.960	2.478	2.569	0.838	28.311	2
4B 45 °C	2.983	1.364	1.600	0.466	15.622	2
5	2.843	2.756	2.689	0.726	25.536	3
6 25 °C	2.949	1.931	2.433	0.648	21.974	2
6 45 °C	3.009	2.877	2.874	0.059	1.961	3
7 25 °C	2.899	2.688	2.721	0.678	23.387	6
7 45 °C	2.958	2.730	2.624	0.919	31.068	7
8 25 °C	2.896	1.539	1.564	0.653	22.548	2
8 45 °C	2.995	2.055	2.153	0.730	24.374	2