Enabling fast charging – A battery technology gap assessment

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HIGHLIGHTS

- Key gaps in lithium-based battery technology are presented viz. extremely fast charging.
- At cell level, lithium plating on anode remains an issue.
- At cell level, stress-induced cracking of cathode material may be an issue.
- Safety at pack level must be explored.

ARTICLE INFO

ABSTRACT

The battery technology literature is reviewed, with an emphasis on key elements that limit extreme fast charging. Key gaps in existing elements of the technology are presented as well as developmental needs. Among these needs are advanced models and methods to detect and prevent lithium plating; new positive-electrode materials which are less prone to stress-induced failure; better electrode designs to accommodate very rapid diffusion in and out of the electrode; measure temperature distributions during fast charge to enable/validate models; and develop thermal management and pack designs to accommodate the higher operating voltage.

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1. Introduction

A lithium-ion cell usually consists of a metal oxide, such as LiCoO$_2$, as positive electrode; a mixture of organic carbonates containing a lithium-bearing salt as the electrolyte; and graphite as the negative electrode. During charging, lithium ions move from the positive electrode through the electrolyte and intercalate into the negative electrode; and, during discharge, they move in the reverse direction. The overall cell reaction is shown in Eq. (1) [1,2], with the charge reaction proceeding to the left and discharge, to the right:

$$Li_aC_6 + Li_bMO_c \leftrightarrow C_6 + Li_{a+b}MO_c, \tag{1}$$
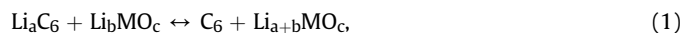
where $a \approx 1$, and M is a metal such as Mn, Co, Ni, etc.

During cell operation, the electrode particles become coated with products from the reaction between the electrode and the electrolyte. This coating is called the "solid-electrolyte interphase" (SEI). At the positive electrode, the SEI layer consists of electrolyte oxidation products, and, at the negative, electrolyte reduction products. Thus, the SEI layers are compositionally different, but both serve to passivate the electrode surface. At the positive electrode, the surface film can consist of Li$_2$CO$_3$ (from handling in air) and lithiated carboxylates, such as ROCO$_2$Li and alkylated metal oxides [1]. At the negative electrode, the number of possible components in the SEI increases. Lithiated alkoxides and carboxylates are formed by a free-radical reaction of the electrolyte

solvent with the negative electrode. In addition, LiF and lithiated oxyfluorophosphates are formed by the reduction and reaction of $LiPF_6$, a common salt used in the battery electrolyte [1,3,4].

Lithium-ion batteries are used in applications that need high energy or power densities. Thus, they are ideal for electric vehicles. Other battery technologies, such as Li/S and Li/O_2, in theory, can be used for the automotive application. But, as of this writing, these technologies are still immature and require much further development.

Typically, recharging lithium-ion batteries takes considerably longer than refueling of the internal-combustion-engine (ICE) car. Consumer acceptance of electric vehicles (EVs) will be facilitated by a recharge ("refueling") experience similar to that of an ICE-powered car, roughly 8–10 min. Additionally, recharging does not have to be from a completely discharged battery (empty) to a completely charged one (full). As with an ICE car, partial recharging is possible and should not adversely affect the battery.

The increased rate necessary for fast charging can adversely affect the performance, safety, and life of the battery, such as increased probability of lithium plating, increased rate(s) of side reaction(s), and increased battery temperature. This paper will focus on just the issues in battery technology. The heat rejection/management aspects will be discussed in a separate manuscript.

Available direct current fast chargers on the market are capable of charging light-duty EV battery packs at rates up to 120 kW, which is not sufficient to offer nearly the same refueling experience as gasoline consumers. For the purpose of this document, the next level of charging, extreme fast charging (XFC), is defined as recharging up to 80% of the battery capacity in 10 min or less. This definition has two caveats. It does not define the starting point of charging, which is consumer behavior driven and an unknown at this point; and it does not consider pack size, i.e., for a given available charging power, a smaller pack would charge faster than a bigger pack but not necessarily provide more driving range, assuming there is no current limitation.

Fig. 1(a) shows a theoretical plot of recharge time up to 70% capacity [state of charge (SOC) increased from 10% to 80%] and the corresponding charging rate as a function of charging power for three battery pack sizes with existing 400-V maximum charging voltage. The lower SOC limit, 10%, was assumed to avoid consumer range anxiety, and the higher one, 80%, was assumed to mitigate accelerated aging and safety concerns during XFC. It is obvious that the charging rate increases (or charging time decreases) with charging power regardless of the size of the pack. At a specific charging rate, increased pack size requires more time to charge due

to reduced effective C-rate. This indicates that chargers should be scaled based on the pack size to achieve the desired 70% recharge in 10 min. If pack size is large, e.g., 90 kWh, charging at the 400 kW rate is not sufficient to meet the recharge goal in 10 min. Bigger packs, however, will add much more driving range than the smaller packs for the same SOC increment.

Miles added per minute (mi min^{-1}) is another way of defining XFC. The U.S. Department of Energy (DOE) has set a fast charge goal (average) of 20 mi min^{-1} [5] or more. Fig. 1(b) shows XFC charging speed in terms of mi min^{-1} for EVs available in the market with XFC capability [6–10]. Also shown is an estimate of charging speed using a 400 kW XFC charger, assuming 300 Wh mi^{-1} energy consumption. While the charging speed of most of the EVs remains below 3 mi min^{-1}, Tesla can achieve up to 5.6 mi min^{-1} with its state-of-the-art 120 kW direct-current fast charger, which is the highest rate among all the EVs available in the market today.

The discussion that follows will be limited to what is in the battery pack, that is, cells, interconnects, and the battery management system. Everything outside the pack was considered part of the vehicle, charging station, or infrastructure. These items will be discussed in separate papers. The remaining sections of this paper are organized according to aspects of the technology.

2. Cell level

2.1. Lithium plating

Lithium ions (Li$^+$) are transported from the positive to the negative electrode during charge. These ions then reach the interface between the electrolyte and the negative electrode. Under normal operating conditions, lithium (Li$^+$ plus an electron from the external circuit) intercalates, as in the case of graphite, into the negative electrode material in stages, filling the space between the graphite layers (galleries) in a step-wise fashion [11–14]. However, intercalation is a diffusion-limited process, only a certain amount of lithium can enter the galleries per unit time at a given temperature. As the galleries fill, the rate at which more lithium can enter decreases. If lithium transport to the surface of the negative electrode is faster than it can intercalate, lithium metal can plate on the surface of the negative electrode.

Lithium plating can occur when the local potential at the negative electrode is below 0 V (vs. Li/Li$^+$) [15–17]. This can happen when the net cell voltage is about 4 V or greater in a capacity-balanced cell system (negative-to-positive ratio near 1.1). Lithium plating was reported to increase with increasing current density
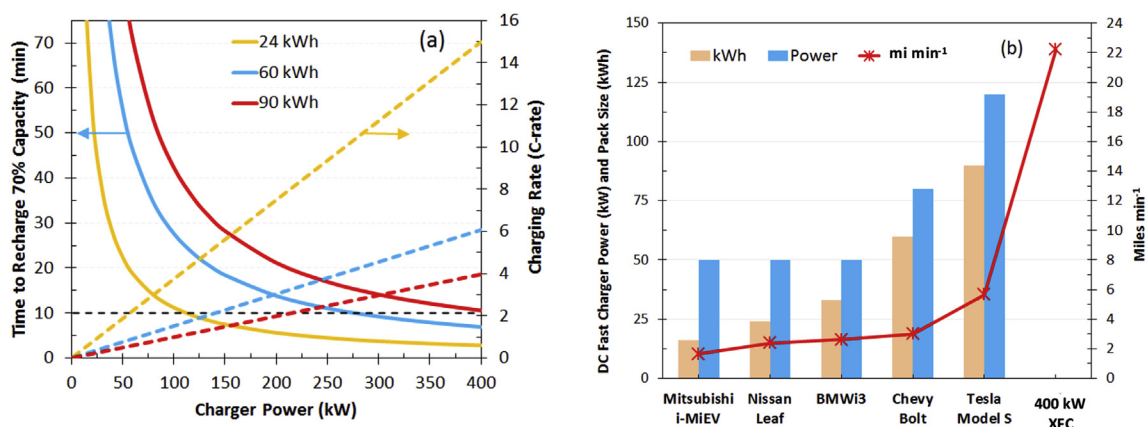

Fig. 1. (a) Time of charging and corresponding C-rate for different battery packs as a function of charger power. (b) Charging profiles for EVs with direct-current fast charging capabilities in the market [6–10].