EXTREME FAST CHARGING – A BATTERY TECHNOLOGY GAP ASSESSMENT

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PROJECT ID# ES305

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OVERVIEW

Timeline

- Project start date: October 2016
- Project end date: December 2016
- Percent complete: 100

Budget

- Total project funding: $300K (DOE)
- Funding received in 2016: $300K
- Funding for 2017: 0

Barriers

- Barriers addressed
  - Battery technology needs to enable extreme fast charging applications

Partners

- This was a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, and National Renewal Energy Laboratory
- The work was divided into four pillars: battery (PI: ANL), vehicle (NREL), infrastructure (INL), and economics (ANL)

*Discussed in other presentations

RELEVANCE / OBJECTIVES

- Overall objectives
  - Provide DOE with an assessment of battery technology needs that will enable extreme fast charging (≥350kW; XFC) of vehicle batteries
  - Identify the factors that technically limit XFC of an automotive lithium ion battery
  - Identify the factors that impact the cost of battery pack to enable XFC
  - Define the boundaries (scope) of the protocol for this DOE lab initiative (reference system being considered, where are the system boundaries, what constitutes extreme fast charge, what losses are observed, cost, who are the solution providers, ….)
  - Define the developmental needs to enable XFC of the system defined above.

APPROACH

The multi-lab team identified and addressed the following critical questions under the three objectives.

- Factors that technically limit XFC
  - How are the battery materials degrading while subjected to XFC?
    - Is lithium plating occurring, and, if so, at what rate does it occur?
    - What are the impacts to the electrodes?
    - Is there a particular electrode couple that is better suited for XFC?
    - How is the electrolyte degrading?
    - How fast can you charge?
  - What are the impacts of self-heating while subjected to high rate charging?
    - Is there a cell form-factor that performs better than others from a heat dissipation standpoint?
  - What are the impacts of XFC on the abuse response of the battery pack (safety)?
  - What are the impacts of XFC on cell balancing?
  - Are 400V systems adequate or would system voltage need to be increased?
- Cost factors
- What other cost implications will XFC bring to bear on the battery pack?
  - Will the battery cell design needed for XFC increase cell cost?
  - How much additional cost should be allocated to more robust thermal management?
  - Will new manufacturing techniques need to be employed?

MILESTONES

- Milestones
  - Provide a written report describing battery technology gaps (complete)
  - Identify developmental needs for the US DOE to consider, from cell to pack (complete)

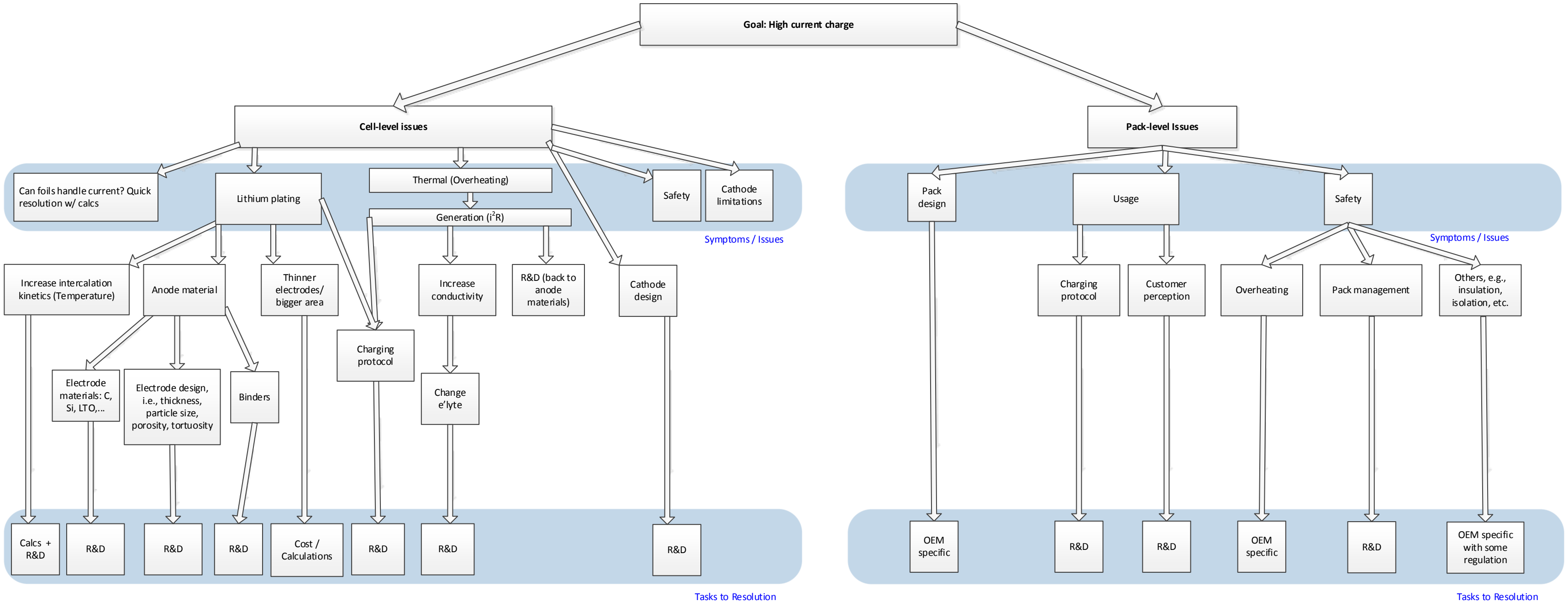
TECHNICAL ACCOMPLISHMENTS

INTRODUCTION

- Typically, recharging lithium-ion batteries takes much longer than the average, liquid-fueled-internal-combustion-engine (ICE) car owner is used to. 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 charging 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
- 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

TECHNICAL ACCOMPLISHMENTS

- From the critical questions, an issue tree for battery technology was developed



Goal: High current charge

Cell-level issues

Pack-level Issues

Can foils handle current? Quick resolution w/ calcs

Lithium plating

Thermal (Overheating)

Generation (i^2R)

Safety

Cathode limitations

Symptoms / Issues

Increase intercalation kinetics (Temperature)

Anode material

Thinner electrodes/ bigger area

Increase conductivity

R&D (back to anode materials)

Cathode design

Charging protocol

Change e'lyte

Electrode materials: C, Si, LTO,...

Electrode design, i.e., thickness, particle size, porosity, tortuosity

Binders

Calcs + R&D

R&D

R&D

R&D

Cost / Calculations

R&D

R&D

R&D

Tasks to Resolution

Pack design

Usage

Safety

Symptoms / Issues

Charging protocol

Customer perception

Overheating

Pack management

Others, e.g., insulation, isolation, etc.

OEM specific

R&D

R&D

OEM specific

R&D

OEM specific with some regulation

Tasks to Resolution

CELL LEVEL:
LITHIUM PLATING AT ANODE IS AN ISSUE

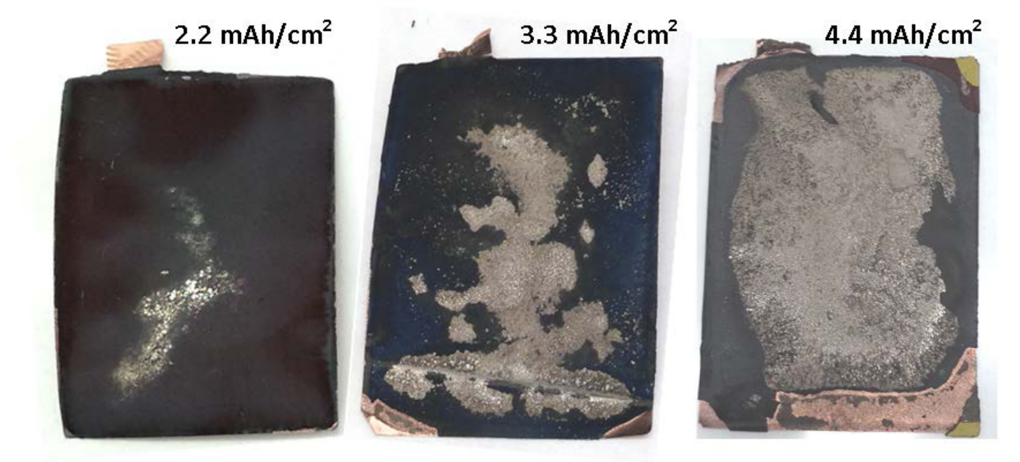
- Lithium plating can occur when the local potential at the anode is below 0 V (vs. Li/Li^+)
- This can happen when the net cell voltage is about 4 V or greater in a capacity-balanced cell system (negative-to-positive ratio near 1.1)
- Lithium plating was reported to increase with increasing current density and with decreasing temperatures. Plating can occur at charge rates as low as about C/6 at ~20°C
- There is a report that defects can cause lithium plating. Defects, "such as pore closure [in the separator], create local, high currents and overpotentials. If the overpotential exceeds the equilibrium potential in the negative electrode, plating can occur."[1]

[1] J. Cannarella and C. B. Arnold, *J. Electrochem. Soc.*, 162 (2015) A1365-A1373.

QUANTITY OF LITHIUM DEPOSITED ON ANODE SURFACE CAN DEPEND ON CAPACITY LOADING

Graphite issue

- Greater EV driving range needs energy-dense electrodes
- Increasing lithium deposition (metallic gray) on graphite electrodes as a function of capacity loading



- Lithium may or may not be removed during the following discharge subcycle
- *In-situ* methods to detect plating have appeared in the literature
- Stranded lithium may be a safety issue; abuse response after XFC is unknown

Image from K. Gallagher, S. Trask, C. Bauer, T. Woehrle, S. Lux, M. Tschech, P. Lamp, B. Polzin, S. Ha, B. Long, Q. Wu, W. Lu, D. Dees and A. Jansen, *J. Electrochem. Soc.*, 163 (2016), A138-A149.

OTHER ANODES, OTHER ISSUES

LTO, Si, Li

- LTO and related spinels seem to have the rapid Li diffusion kinetics needed to support LTO
  - Can be charged at the 10-C rate with and without graphite additives
  - Doping with La (lithium site in $Li_4Ti_5O_{12}$) or Sc (Ti site) improved charge rates to 20- to 40-C for 50 cycles
  - Sodium-bearing phases, $Na_2Li_{1.9}Ti_{5.9}M_{0.1}O_{14}$ (M=Al, Zr, V), have superior rate performance and cyclability than LTO (5.5-C)
  - Particle size and shape play important role in electrochemical performance
    - A nano-sized, Zn-bearing phase cycled for 200 cycles at 10-C rate
- **BUT**…the potential of fully-lithiated LTO is higher (1.5 V vs. Li/Li^+) than that of graphite (0.01V), limiting energy density
- Si and lithium metal may not be suitable for the XFC application
  - Si degrades physically and electrochemically
  - Lithium metal has dendrite growth issue

LTO-BASED BATTERIES ARE COMMERCIALLY AVAILABLE

- From the internet:

“The SCiB [super charge ion battery cell] charges in about half the time of a typical Li-ion battery, Toshiba says. An SCiB 20Ah cell charged with an 80-A current will reach 80% of capacity in 15 minutes and 95% in an additional 3 minutes. The SCiB generates little heat even during this fast recharging, eliminating the need for power to cool the battery module. Moreover, the full charge-discharge cycle for SCiB is 4,000 times, more than 2.5 times that of other Li-ion batteries. This long life could also contribute to the reuse of the battery.”

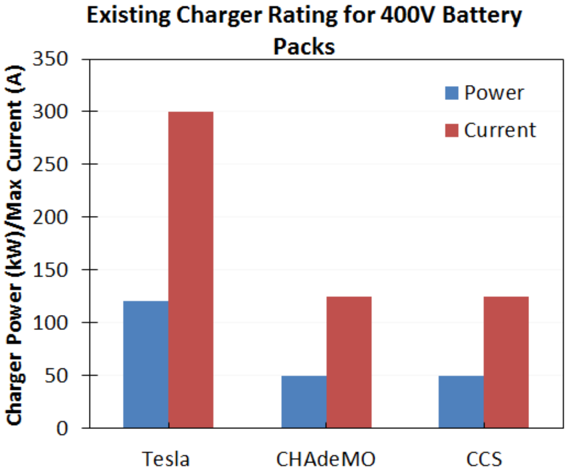
http://www.greencarcongress.com/2011/11/scib-20111117.html

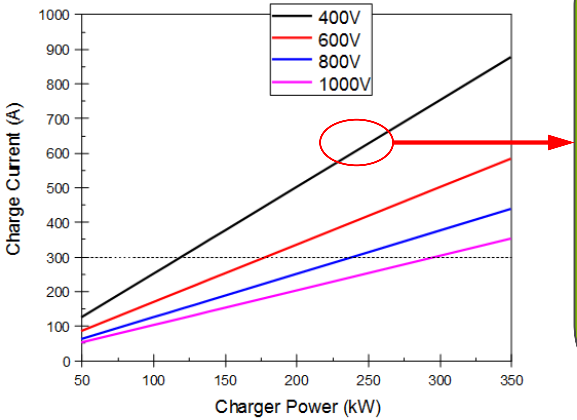
ISSUES ARE NOT LIMITED TO THE ANODE MATERIAL

- Cathode materials are susceptible to diffusion-induced stress, causing void formation, cracking and fragmentation of secondary particles
  - Associated with volume changes due to lithium diffusion in and out during cycling at high rates
  - Effects of diffusion-induced stress have been seen in most common cathode materials, such as LCO, LMO, LFP, NCM
  - XFC could exacerbate the problem
- Binders can affect cell performance and life; there is nothing in the open literature regarding the effect that XFC can have on the binder or vice versa, but binders are a source of impedance
  - May produce local heating (i^2R), which, in turn, may degrade adhesive properties of the binder
- Electrolyte composition can also impact cell performance and life, but there is no information available regarding XFC
- Charging protocol: Some automakers have indicated that XFC using a constant-current, constant-voltage protocol degrades the performance, life and safety of cells in the battery pack of their EV, primarily due to lithium plating in the negative electrode

PACK LEVEL:
HIGH VOLTAGE PACK DESIGN AND SAFETY

- Most of the current EV battery packs are rated at 400V with a maximum current rating of 300 A.





Going beyond 120 kW charger would require to accommodate:

- Higher current than 300 A, which will generate high heat (i^2R)
- Robust battery thermal management system (BTMS)
- Advanced battery management systems (BMS)
- Additional safety measures
- Higher pack weight and cost

A high voltage pack will lower the maximum charging current, but require additional design and safety modifications.

http://www.chademo.com http://www.charinev.org/about-us/mission
http://www.motortrend.com/news/tesla-supercharger-an-in-depth-look/
http://teslapedia.org/model-s/tesla-drivoer/understanding-charging-rates/

MORE ON HIGH VOLTAGE PACK DESIGN AND SAFETY

Higher Pack Voltage

Benefits

- Lower max charging current- thinner bus bar and low I^2R heat generation.
- Fewer cells in parallel and more cells in series- better control, management and fault detection
- Using smaller and less bulky power transistors
- Using smaller gauge wire in the motor winding
- Using smaller controllers
- Potentially reduce pack weight

Challenges

- Electrical safety such as arc flash mitigation, robust isolation and insulation with reliable all time monitoring
- Increased cell count in the series string-requires more sensors for monitoring and robust BMS
- Safe and efficient stranded energy extraction protocol
- Could be expensive

Finding the most appropriate pack voltage, which will allow the selection of ancillary hardware components for minimum weight and cost penalty (if any), is a key technological challenge and needs an R&D resolution.

THERMAL MANAGEMENT IMPROVEMENT

Cooling of the battery pack during XFC is an absolute necessity to avoid performance , life, and safety concerns.

Depends on

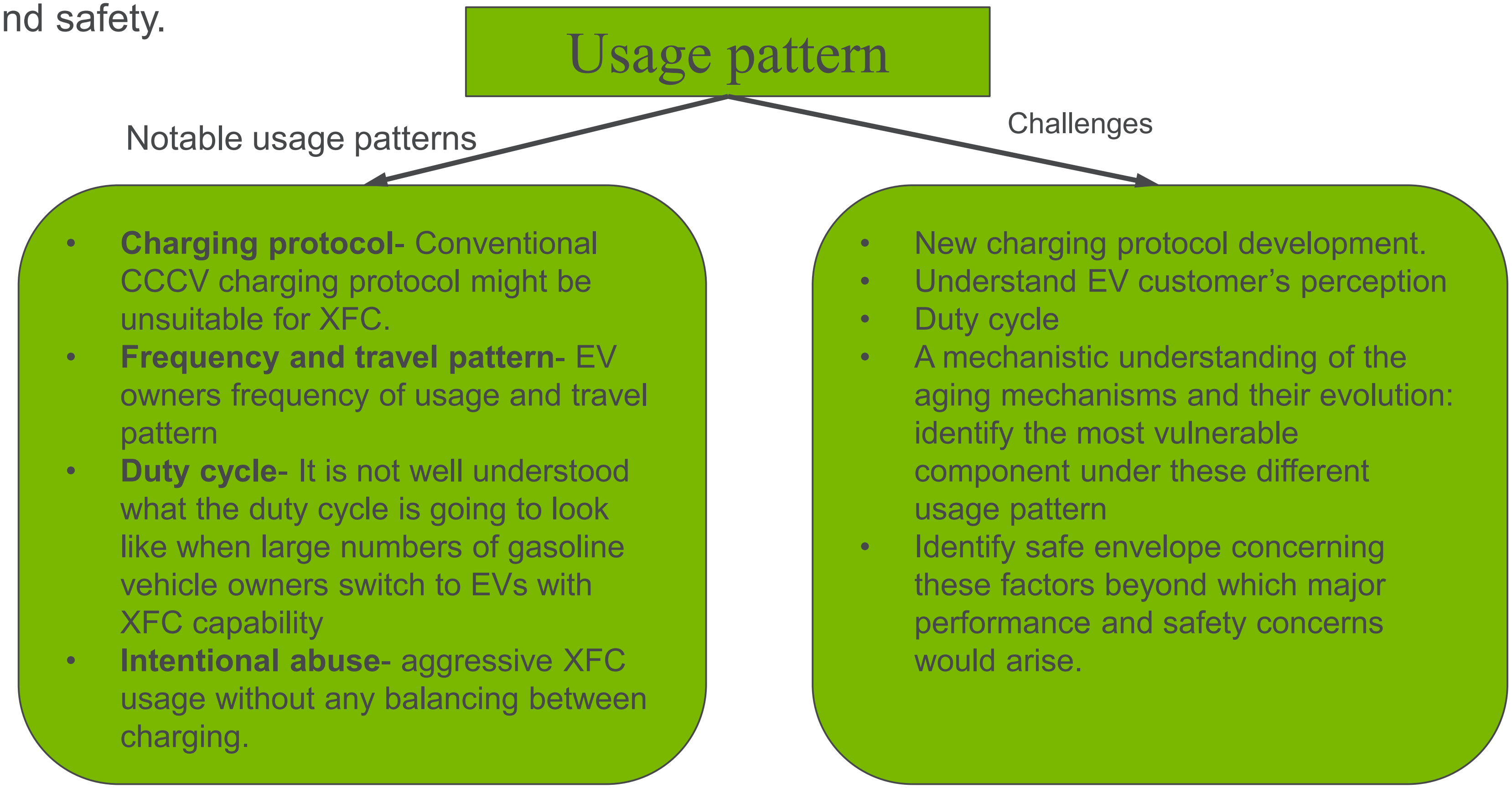
- Pack size
- Battery chemistry and design
- Max allowable temperature during XFC.

Challenges

- Pack design modification to facilitate better heat transfer from cell to cooling media
- Finding the most suitable method of heat rejection outside the pack
- Maintain minimum temperature gradient within the pack and individual cells
- Maintain minimum footprint

EFFECT OF XFC ON PACK LIFE

The usage pattern needs to be considered during the design process of battery cells and packs capable of XFC, since it is expected that the pattern will affect cell/pack performance, life and safety.



Usage pattern

Notable usage patterns

- **Charging protocol-** Conventional CCCV charging protocol might be unsuitable for XFC.
- **Frequency and travel pattern-** EV owners frequency of usage and travel pattern
- **Duty cycle-** It is not well understood what the duty cycle is going to look like when large numbers of gasoline vehicle owners switch to EVs with XFC capability
- **Intentional abuse-** aggressive XFC usage without any balancing between charging.

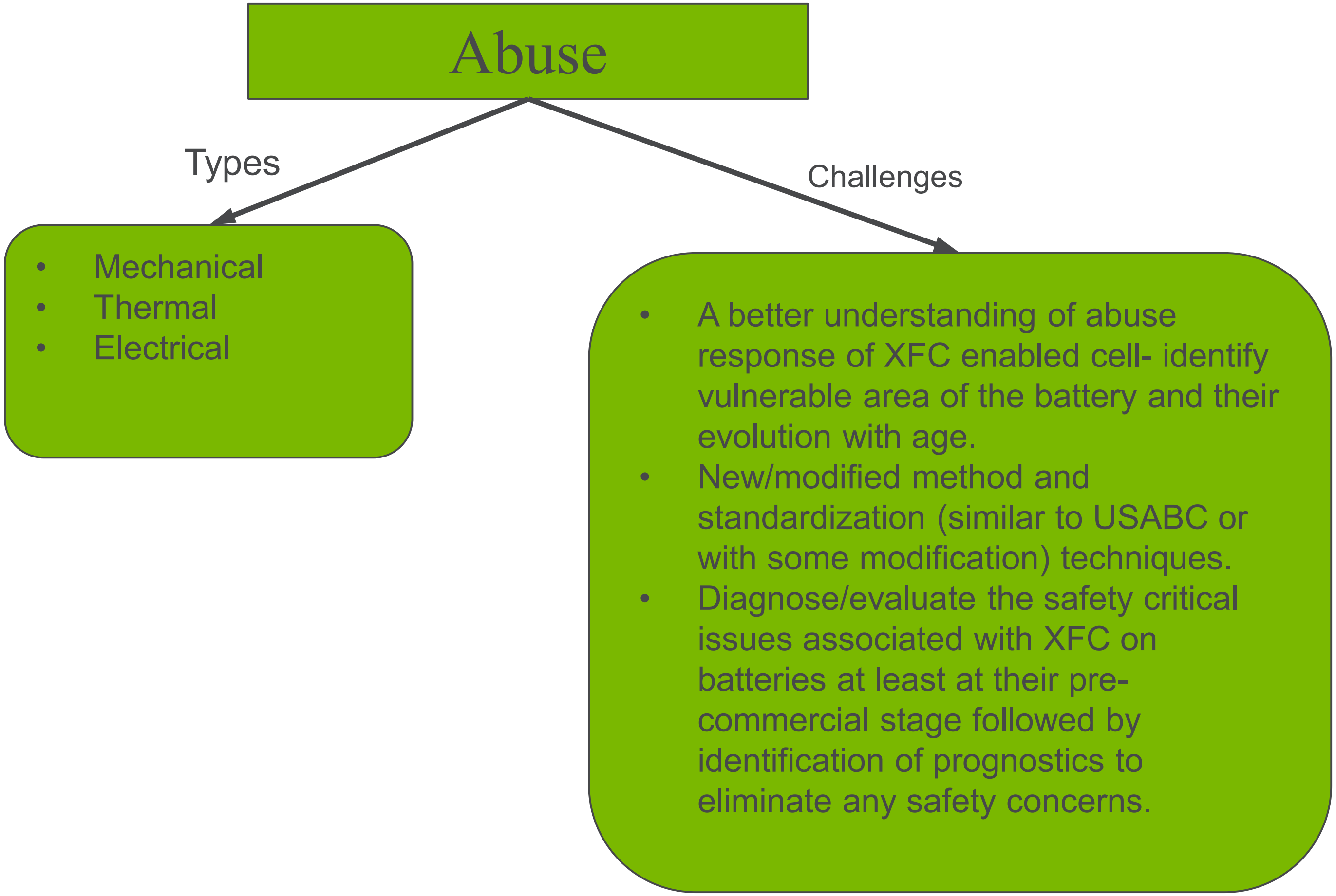
Challenges

- New charging protocol development.
- Understand EV customer’s perception
- Duty cycle
- A mechanistic understanding of the aging mechanisms and their evolution: identify the most vulnerable component under these different usage pattern
- Identify safe envelope concerning these factors beyond which major performance and safety concerns would arise.

The effect of some of these usage factors (charging protocol, frequency of XFC, etc.) can be tested in labs (similar to USABC activity or with some modifications) for R&D resolution. Others (travel pattern, customer perception, etc.) would need extensive relevant field data collection and analysis

ABUSE RESPONSE OF XFC ENABLED BATTERY

Abuse (mechanical, thermal, and electrical) response of battery due to XFC may change significantly which would raise some safety concerns and requires R&D resolution



Abuse

Types

- Mechanical
- Thermal
- Electrical

Challenges

- A better understanding of abuse response of XFC enabled cell- identify vulnerable area of the battery and their evolution with age.
- New/modified method and standardization (similar to USABC or with some modification) techniques.
- Diagnose/evaluate the safety critical issues associated with XFC on batteries at least at their pre-commercial stage followed by identification of prognostics to eliminate any safety concerns.

ADVANCED BATTERY MANAGEMENT SYSTEM (BMS)

Advanced BMS

Requirements

- More sensitive and robust BMS design to handle more cells in series
- More advanced diagnostics and safety features to monitor and identify any impending short circuit
- More robust balancing algorithms

SUMMARY

Developmental needs

- Models
  - Advanced models will be needed to incorporate effects/constraints of XFC
- Cell level
  - New anode and cathode materials which can tolerate stresses of XFC without lithium plating or degrading
  - Electrode designs for faster diffusion
  - Studies of impact of XFC on materials
  - Understand/prevent lithium plating
- Pack level
  - Improved thermal management
  - Impact of higher voltage(s) on electrical safety
  - Study effect of XFC on pack life and how usage impacts life/performance
  - Improved charging protocols
  - Impact of XFC on abuse response
  - Advanced battery management systems
- Findings will be published in a special issue of J. Power Sources

THE TEAM

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QUESTIONS?

www.anl.gov