

A non-aqueous NaPF₆-based electrolyte degradation study: formation and mitigation of HF

Pete Barnes, Kassiopeia Smith, Eric J Dufek, Chris Jones, Paige Skinner, Erik Storch, Quinn White, Changjian Deng, Devan Karsann, Miu Lun Lau, Joseph Dumais, Hui Xiong, Riley Parrish

January 2020



The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

A non-aqueous NaPF6-based electrolyte degradation study: formation and mitigation of HF

Pete Barnes, Kassiopeia Smith, Eric J Dufek, Chris Jones, Paige Skinner, Erik Storch, Quinn White, Changjian Deng, Devan Karsann, Miu Lun Lau, Joseph Dumais, Hui Xiong, Riley Parrish

January 2020

**Idaho National Laboratory
Idaho Falls, Idaho 83415**

<http://www.inl.gov>

**Prepared for the
U.S. Department of Energy
Office of Nuclear Energy, Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517, DE-AC07-05ID14517**

A non-aqueous sodium hexafluorophosphate-based electrolyte degradation study: formation and mitigation of hydrofluoric acid

Pete Barnes ^a, Kassiopeia Smith ^a, Riley Parrish ^a, Chris Jones ^a, Paige Skinner ^a, Erik Storch ^a, Quinn White ^a, Changjian Deng ^a, Devan Karsann ^a, Miu Lun Lau ^a, Joseph J. Dumais ^b, Eric J. Dufek ^{c,*}, and Hui Xiong^{a,*}

^a Micron School of Material Science and Engineering, Boise State University, 1910 University Drive, Boise, Idaho 83725, United States

^b Department of Chemistry and Biochemistry, Boise State University, 1910 University Drive, Boise, Idaho 83725, United States

^cEnergy Storage and Advanced Vehicles, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415, United States

* Corresponding author

E-mail: clairexiong@boisestate.edu, Phone: 1-208-426-5671, Fax: 1- 208-426-4466 (H. Xiong)
eric.dufek@inl.gov, Phone: 208-526-2132 (E., Dufek)

Abstract:

Fundamental characterization of battery electrolyte is vital for rechargeable batteries. This work reports the chemical stability of sodium hexafluorophosphate (NaPF₆)-based non-aqueous electrolytes containing different solvent mixtures (e.g., cyclic and acyclic carbonates) in the presence of water for Na-ion batteries. A degradation study is conducted using NaPF₆-based electrolytes, highlighting two electrolyte additives, 2,2,2-trifluoroethoxy-2,2,2-ethoxy phosphazene (FM2) and fluoroethylene carbonate (FEC), on degradation and cell performance of Na-ion batteries. Hydrolysis of NaPF₆ in acidic condition is particularly prone to form hydrofluoric acid (HF), and can be observed in electrolytes made with battery grade carbonate solvents (<20 ppm of water). Degradation mechanisms of NaPF₆-based electrolytes are studied using liquid nuclear magnetic resonance (NMR). Noticeable degradation takes place in high purity electrolytes with the presence of moisture to form HF and organophosphates in timeframes below the current shelf-life of the Na electrolytes. FEC is not efficient to protect the electrodes from being exposed to HF. On the other hand, FM2 is revealed as a “scavenger” of HF, which helps stabilize the shelf life of electrolytes that might contain or become exposed to water. Our study underscores the importance to understanding the degradation of electrolyte and improving stability toward better shelf life for sodium ion batteries.

Highlights:

- NaPF₆-based non-aqueous electrolytes are highly susceptible to the formation of HF in the presence of water.
- NMR results reveal an autocatalytic hydrolysis pathway of hexafluorophosphate to form HF in the electrolytes.
- FM2 can serve as an HF scavenger in electrolytes to improve their chemical stability and the cycling performance of full-cell sodium ion batteries.
- HF mitigation is closely related to the chemical stability of the NaPF₆-based non-aqueous electrolytes.
- HF formation can be observed in battery grade electrolytes which contain <20 ppm H₂O.

Keywords: Sodium-ion battery; NaPF₆ salt; Electrolyte; Degradation; mitigation of HF; HF scavenger

1. Introduction:

Lithium-ion batteries (LIBs) are at the forefront of current energy storage technologies offering high energy, power densities, and design flexibility that outperform various technologies [1]. However, availability and cost are current challenges [1-3]. As demand continues to grow, industry faces the depletion of raw material reserves for lithium and cobalt [3]. The challenges introduce a complex interplay of availability, production, recycling, geographical/political constraints, environmental impacts, and cost.[4] These possible issues are now a debate on whether the future energy demands can be met solely by lithium-based chemistry or if other alternatives need to be utilized. One of the most appealing options is to substitute lithium with sodium in key applications to enable a sustainable outlook due to sodium's high abundance and low cost.

There are a number of challenges associated with developing a long cycle life sodium-ion battery (SIB). An aspect that has not been fully investigated for SIBs is the electrolyte degradation and the effect of the degradation byproducts on battery performance. As learned from the development of LIB, the electrolyte plays a pivotal role to enable long cycle life and performance [5-7]. The advancement in LIBs using graphitic materials was enabled once electrolytes which formed an effective solid electrolyte interphase (SEI) were recognized [7-11]. Currently, the most commonly used electrolytes for SIB research mimic those from the lithium system. The most stable and widely used non-aqueous electrolyte for LIB is a mixture of aprotic cyclic and small alkyl branched carbonates (e.g., ethylene carbonate (EC); diethyl carbonate (DEC); ethyl methyl carbonate (EMC)) and lithium hexafluorophosphate (LiPF₆) salt [12]. Sodium hexafluorophosphate (NaPF₆) is the salt used in the Na systems which historically was expected to provide analogous chemistry to the Li system [13, 14]. Nevertheless, electrolytes that perform well for Li-ion batteries may not be suitable for SIBs. Differences exist between sodium and lithium electrolytes, which include thermodynamic (e.g., solvation and desolvation), kinetics (e.g., ion mobility) and interfacial properties [13, 15-17]. It is unknown if electrolytes containing NaPF₆ salt will degrade in the same manner and behave similar to the lithium analog.

The studies of lithium-based chemistry have uncovered important physiochemical properties of electrolytes that play a key role in improving battery performance [5, 18]. A great example of this effort is

LiPF₆-based electrolytes that have been extensively characterized through physical properties, degradation, and contribution to the SEI formation [12, 18-21]. Detailed analyses of LiPF₆-based electrolyte degradation have revealed that trace amount of HF can be formed due to the presence of water [22-24]. It has also been noted that water can be electrochemically reduced during the initial cycling to form a uniform and dense LiF-rich SEI layer on the surface of the electrode [25]. Degradation studies of LiPF₆-based electrolytes and their aging processes reveal that water and other protic impurities have a detrimental effect on electrolyte stability [26-33]. Additionally, the selection and optimization of binders, additives, and salts have made a dramatic effect on the electrochemical properties and performance of LIBs. The advancement of SIBs which can achieve high cycle and calendar life requires similar knowledge of stability and physicochemical properties [34, 35]. In SIBs, NaPF₆ is a salt that offers promise. It has high solubility that leads to a large number of charge carriers to be present in solution [36]. In addition, the salt is relatively stable under reductive and oxidative conditions [36]. To the best of our knowledge, no research has been done to elucidate the degradation mechanisms of NaPF₆-based electrolytes.

Herein, we report for the first time a degradation study of NaPF₆-based electrolytes as well as the effect of two electrolyte additives: 2,2,2-trifluoroethoxy-2,2,2-ethoxy phosphazene (FM2) and fluoroethylene carbonate (FEC) on degradation and cell performance. The water content in both battery grade (BG) and standard grade (SG) solvents is evaluated, which shows higher amount of water in all SG solvents compared to BG solvents. Degradation mechanisms of NaPF₆-based electrolytes are studied using liquid state nuclear magnetic resonance (NMR). The effect of additive is assessed in full-cell SIBs. Noticeable degradation takes place in high purity electrolytes with the presence of water to form HF and organophosphates in time frames well below the currently needed shelf-life of the sodium electrolytes. The fluorinated additive, FEC, is unable to protect the electrodes from the detrimental exposure of HF. On the other hand, FM2 is a “scavenger” of HF, which helps stabilize the shelf life of electrolytes that might contain or become exposed to water. This study underscores the importance to understand the degradation of electrolyte to improve its stability toward better shelf life for SIBs.

2. Experimental:

2.1. Water Content of Carbonates

Standard grade (SG) solvents of propylene carbonate (PC, Sigma Aldrich, anhydrous, 99%), ethylene carbonate (EC, Sigma Aldrich, anhydrous, 99%), dimethyl carbonate (DMC, Sigma Aldrich, anhydrous, 99%), diethyl carbonate (DEC, Sigma Aldrich, anhydrous, 99%), and ethyl methyl carbonate (EMC, Sigma Aldrich, 99%) were tested for water content. In addition, battery grade (BG) solvents of PC (BASF, anhydrous, 99.98%), EC (BASF, anhydrous, 99.98%), DMC (BASF, anhydrous, 99.99%), DEC (BASF, anhydrous, 99.99%), and EMC (BASF, 99.4%) were obtained for water content studies. Determination of the water content was completed on a V20S Compact Volumetric KF Titrator (Mettler Toledo) by coulometric Karl Fisher titration.

2.2. Electrolyte preparation:

All tested electrolytes consist of either 1.2 M or 1.0 M sodium hexafluorophosphate (NaPF_6 , Alfa Aesar) salt in pure or binary solvent mixtures (1:1 volume) of PC (BASF, anhydrous, 99.98%), EC (BASF, anhydrous, 99.98%), DMC (BASF, anhydrous, 99.99%), DEC (BASF, anhydrous, 99.99%), and EMC (BASF, 99.4%). In incremental amounts, water or aqueous 48-50% HF solution were added in the electrolyte solutions to be tested for degradation. Fluorinated cyclic phosphazene trimer (FM2) was prepared in house using previously published synthetic routes [37]. Fluorinated ethylene carbonate was obtained through Sigma Aldrich. Parallel sets of samples of each mixture were maintained at two different temperatures, room temperature (RT) and 52°C as controlled by an environmental chamber (ESPEC).

2.3. NMR sample preparation:

All electrolyte solutions were prepared in an argon filled glovebox and transferred into a polytetrafluoroethylene sleeve for storage to prevent HF, present in the evaluated samples, from etching the glass. All PTFE tubes were cleaned before use by rinsing with DI water and acetone followed by drying in an oven at 70°C overnight. These tubes (obtained from New Era Enterprise) were sealed in the glovebox with PTFE caps. In the case of addition of water/HF mixture the tubes were sealed, removed from the glovebox, quickly unsealed, impurity added, and resealed. The sample cell (Fig. S1) contained a

5 by 155 mm glass tube with a screw cap bulb for reference solvent storage. The desired electrolyte is contained within a 4 x 143 mm PTFE tube sealed with a cap. This liner fits within the glass caustic cell. External to the PTFE sleeve, the remaining void within the NMR tube is filled with a reference solvent of deuterated chloroform containing 99.8% atom D, 1% v/v% (SiMe4). Data processing was completed with the software TopSpin 4.0.6 (Bruker).

2.4. NMR Measurements:

NMR measurements were performed employing a Bruker AVANCE III spectrometer 300 MHz NMR operating at 300.130 MHz with a broadband probe (5 mm PA BBO probe, 300 MHz, Bruker). The ¹H and ¹³C NMR signals were referenced to TMS signal 0.0 ppm, while the ¹⁹F and ³¹P signals were referenced with respect to the signals of PF₆ at 72.7 ppm (¹⁹F) and 146.1 ppm (³¹P). Chemical shift data and coupling are given for compounds in electrolyte mixtures containing 1 M NaPF₆.

- Propylene carbonate (PC): ¹H NMR (300 MHz, Neat) δ 5.03 (hex, J = 6.50 Hz, 1H), 4.70 (d, J = 8.07 Hz, 1H), 4.17 (t, J 7.85 Hz, 1H), 1.53 (d, J = 6.48 Hz, 3H). ¹³C NMR (75 MHz, Neat): δ 156.5, 74.6, 71.3, 18.9.
- Ethylene carbonate (EC): ¹H NMR (300 MHz, Neat) δ 4.80 (s, J = 1.82 Hz, 4H). ¹³C NMR (75 MHz, Neat): δ 157.4, 66.1.
- Ethyl-Methyl carbonate (EMC): ¹H NMR (300 MHz, Neat) δ 4.38 (q, J = 7.10 Hz, 2H), 3.98 (s, 3H), 0.82 (t, J = 7.11 Hz, 3H). ¹³C NMR (75 MHz, Neat): δ 156.3, 64.7, 54.9, 14.1.
- Dimethyl carbonate (DMC): ¹H NMR (300 MHz, Neat) δ 3.98 (s, 6H). ¹³C NMR (75 MHz, Neat): δ 157.2, 55.1
- Diethyl carbonate (DEC): ¹H NMR (300 MHz, Neat) δ 4.37 (q, J = 7.20 Hz, 2H), 1.47 (t, J = 7.20, 3H). ¹³C NMR (75 MHz, Neat): δ 156.0, 64.1, 14.1.
- Sodium hexafluorophosphate (NaPF₆): ¹⁹F NMR (282 MHz, Neat): δ -71.7 (d, J = 712 Hz, 6F). ³¹P NMR (121 MHz, Neat): 146.1 282 MHz, (sep, J = 712 Hz, 1P)
- 2,2,2-trifluoroethoxy-2,2,2-ethoxy phosphazene (FM2). ¹H NMR (300 MHz, Neat): δ 4.25 (m, 6H), 4.05 (m, 6H) 1.33 (m, 9H).

2.5. Electrochemistry

$\text{NaNi}_{0.4}\text{Fe}_{0.2}\text{Mn}_{0.4}\text{O}_2$ (NFM) was prepared by a solid state reaction of coprecipitated precursor $\text{Ni}_{1/2}\text{Mn}_{1/2}(\text{OH})_2$, Fe_2O_3 , and Na_2CO_3 [38]. Stoichiometric amounts of chemicals were ground for 1 h and then pressed into pellets which were then heated at 800 °C for 24 h in a Vulcan 3-550. Commercial hard carbon (HC), (Carbotron P, Kureha Battery Materials Japan Co. Ltd.) was obtained as a gift from Pacific Northwest National Lab and used directly for anode electrode preparation.

A typical coin cell fabrication for the cathodes includes preparing a slurry of 80 wt% active material, 10 wt% C65, and 10 wt% polyvinylidene fluoride (PVDF) in N-methyl-2-pyrrolidone (NMP). This slurry was then laminated onto aluminum foil. Similarly, the anode material was prepared in a slurry of 90 wt% active material, 5 wt% C65, 5 wt% PVDF in NMP, and laminated onto copper foil. After drying at 100°C for about 4 h, electrode disks (15 mm) were punched and allowed to further dry under vacuum at 120°C for at least 18 h. The mass loading of active materials for NFM was between 4.26 to 4.71 mg cm⁻² and anode was 2.49 to 3.21 mg cm⁻². Both cathode and anode were pre-cycled in a Na half-cell before assembled into full-cell coin cells (CR2032). Half-cells were assembled in an Ar-filled glovebox (Mbraun) with an O₂ concentration less than 0.5 ppm. These electrodes were used as the working electrode and placed opposite that of Na metal disks (15 mm). A separator (Celgard 2325) was placed between the two electrodes. An electrolyte of 1 M NaPF₆ in either EC:PC or EC:DEC was freshly mixed the day before use. The NFM electrodes were cycled 5 full cycles from 4 to 2 V, after being charged to 4 V. The HC electrodes were cycled 5 full cycles from 2 to 0.01 V. Subsequently, full cells were assembled using the pre-cycled HC anode and NFM cathode, with a capacity-based negative:positive (N:P) ratio of at least 1.1:1. Various aged electrolytes with or without additive and water were utilized in full cell testing.

3. Results and Discussion:

3.1. Water content in carbonate solvents (standard grade vs. battery grade)

All BG solvents exhibit water content below 20 ppm (*Table 1*), with many containing less than 10 ppm (the lower detection limit of the KF titration method). The water level dramatically increases for SG solvents from lowest concentration being contained with DMC of 24.6 ppm to EMC of up to 530.8 ppm. In

the case of SG carbonate solvents from general chemical suppliers, it is shown that the water content is in general higher compared to BG solvents. Battery grade solvents are needed to promote high performance by limiting electrolyte degradation. The use of SG solvents increases the amount of water available to participate in electrolyte degradation. This is especially important to SIB research as

Table 1: Comparison of water content in SG and BG carbonate solvents.

Solvent	SG H ₂ O (ppm)	BG H ₂ O (ppm)
Ethylene Carbonate (EC)	-	-
Propylene Carbonate (PC)	61.8	<10
Diethyl Carbonate (DEC)	47.2	11.2
Ethylmethyl Carbonate (EMC)	530.8	<10
Dimethyl Carbonate (DMC)	24.6	<10

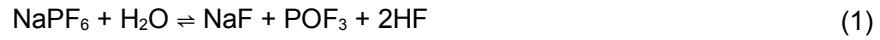
commercially available Na electrolytes are scarce and the few that are available are cost prohibitive presenting barriers to many laboratories. Thus, most research labs blend their own electrolytes. The grade of solvents used is particularly important to limiting the water content in the electrolytes. For the sake of controlling the water content in the electrolytes, we used BG solvents for all electrolytes tested for the remaining degradation studies.

3.2. Degradation of electrolytes in the presence of water

Electrolytes containing PF₆⁻ salt are known to degrade in the presence of water through a process of hydrolysis to form HF and fluorophosphates.[19, 39, 40] In this work, the degradation products in BG electrolytes are monitored by NMR. After aging at 52°C for 31 days (Fig. 1), a distinct increase in HF and phosphorus-containing salt byproducts is observed for the sample with 0.2% v/v water content.

HF is generated through hydrolysis of the hexafluorophosphate as indicated by the singlet at -183.9 ppm in Fig. 1a and 1c. The presence of HF is a key concern since the rate for degradation in acidic environment is significantly enhanced [41]. The increased concentration of H⁺, as noted by the increased concentration of HF can in turn facilitate an autocatalytic process which accelerates the rate of

degradation. This catalytic process that is supported by the data in Fig. 1, is proposed through the following pathways which mirror observations in Li salts [19, 23]:



For the aged BG electrolyte, only trace amounts of HF and two organophosphate ions, monofluorophosphate (PO_3F^{2-}) and difluorophosphate (PO_2F_2^-), are present (Fig. 1a,b). These two organophosphate ions have been noted as major products in the hydrolysis of PF_6^- , and are observed as two doublets in the ^{19}F NMR [19]. The corresponding ^{31}P spectrum exhibits a splitting pattern of a doublet (PO_3F^{2-}) and a triplet (PO_2F_2^-), corroborating with the results from ^{19}F NMR. To confirm the location and coupling constants of PO_2F_2^- , the corresponding difluorophosphoric acid was obtained and measured in a carbonate solvent. The chemical shift and splitting pattern matched with a deviation of 0.06 ppm and 17.4 Hz. The 0.2% water containing aged electrolyte shows a dramatic increase in HF as well as four byproducts due to NaPF_6 degradation (Fig. 1c,d). These include a large amount of both PO_2F_2^- and PO_3F^{2-} . The additional byproducts are possibly related to solubilized PF_5 or POF_3 gas which was observed to

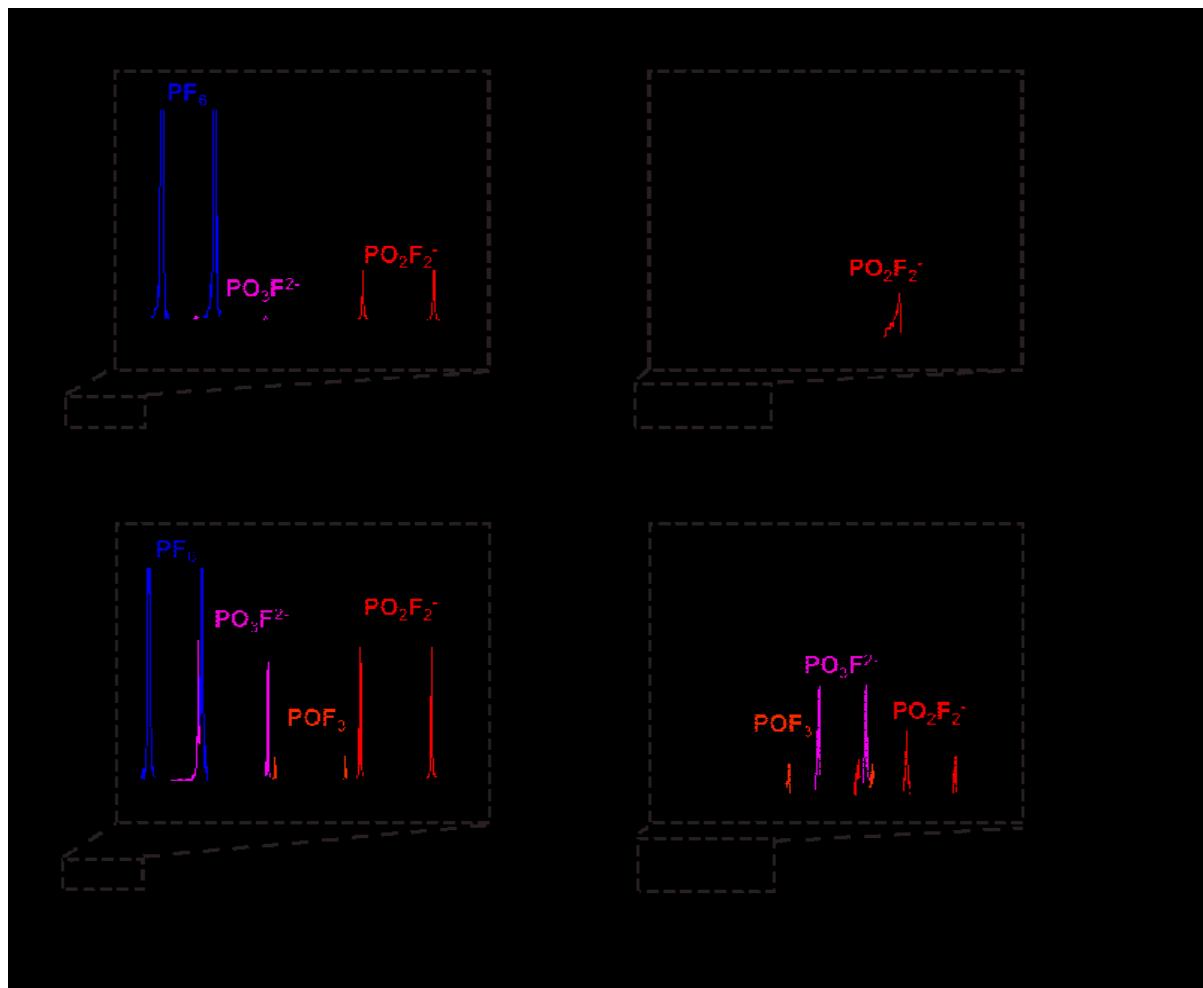


Figure 1: ^{19}F and ^{31}P NMR spectra of thermally aged 1.2 M NaPF_6 in 3:7 EC:EMC (w/w) electrolyte for 31 days at 52°C, BG electrolyte (a-b) and electrolyte with 0.2 % (v/v) H_2O (c-d). Insets: Zoomed in spectra.

form in the NMR tubes (Supporting Information, Fig. S1). The fourth degradation product is the insoluble precipitate, NaF as determined by energy-dispersive X-ray spectroscopy (Supporting Information, Fig. S2). As NaF precipitates it promotes further hydrolysis. Electrolytes at room temperature with the same concentration of water took several months to show observable hydrolysis products (Supporting Information, Fig. S3). The concentration of the phosphates and HF are considerably lower (40-100 times smaller) than electrolytes held at higher temperature. This is in stark contrast to the lithium battery system where PF_6^- has been shown to degrade much faster even at room temperature [19]. To accelerate degradation, temperatures were held at 52°C for the remaining NMR-based hexafluorophosphate degradation studies.

As expected, as the water content increases so does the concentrations of the HF and the fluorinated phosphates (Fig. 2). Increasing the water content from 0.2% to 1.25% (v/v), led to a shift in the major component of the electrolyte from PF_6^- to a mixture of degraded fluorophosphates and HF. While this level of water content is not observed in commercial electrolytes, it does suggest that the extent of degradation in an electrolyte is determined by the initial amount of water. While the abundance of the PF_6^- is held

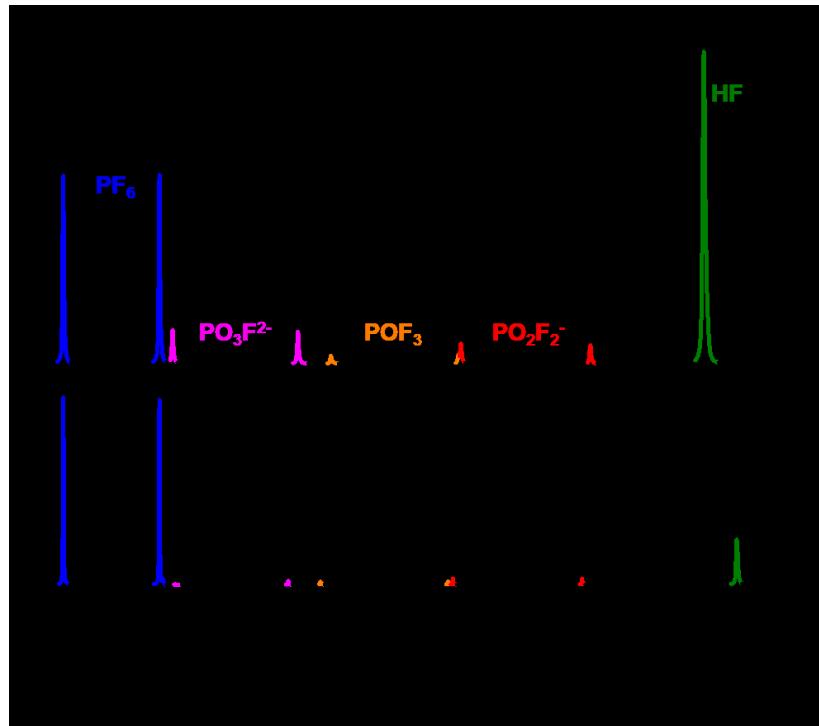


Figure 2: ^{19}F NMR spectra of aged 1 M NaPF_6 in 1:1 EC:PC (v/v) electrolyte containing 0.2% (v/v) of water and 1.25% water (v/v) with degradation products of HF, PO_2F_2^- , POF_3 (likely), and PO_3F^{2-} .

constant as shown in Fig. 2, the concentration of HF increases by 500%. In addition, the formation of PO_2F_2^- and $\text{PO}_3\text{F}_2^{2-}$ shows a two-fold and three-fold increase, respectively.

To better understand more realistic battery electrolyte conditions, smaller additions of water (10 – 100 ppm) are studied (Fig. 3). HF is present in every sample. After aging the electrolyte with 100 ppm added water, the HF concentration nearly doubles of that found in the pristine BG electrolyte. The concentration of fluorophosphates, PO_2F_2^- and $\text{PO}_3\text{F}_2^{2-}$, only increases by a fourth compared to the pristine electrolyte. It is interesting to note the formation of these degradation byproducts in the pristine electrolyte. The pristine electrolyte of 1 M NaPF_6 in EC:PC shows water content well below the commercial standard (<20 ppm). Such result reinforces the effect that trace water can have on the

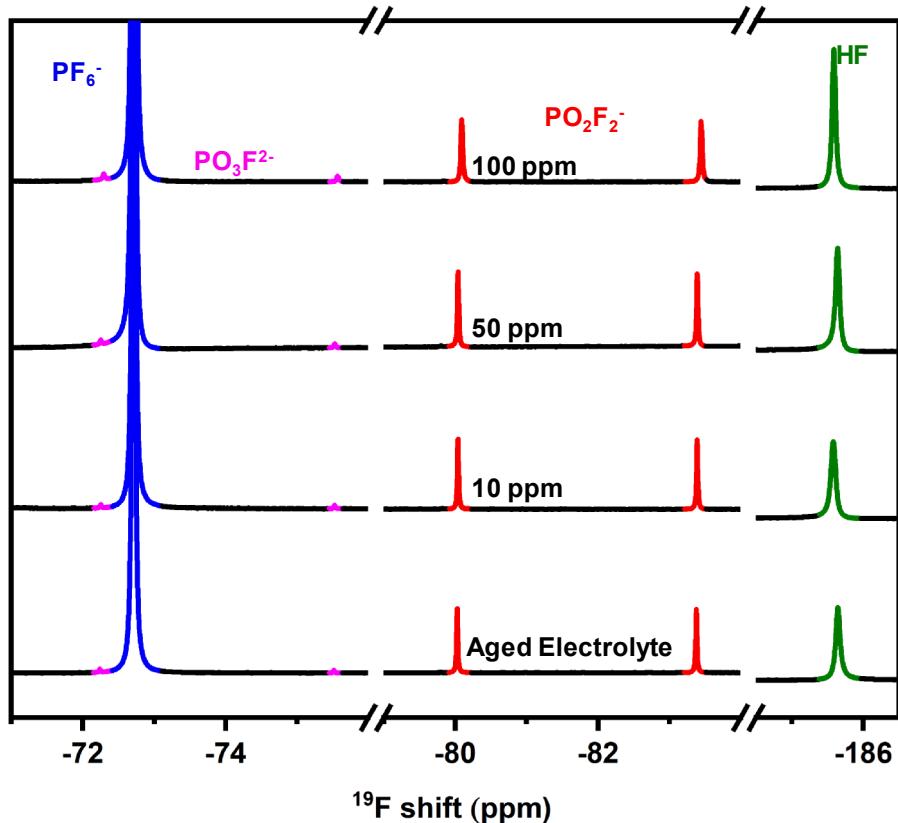


Figure 3: ^{19}F NMR spectra of increasing water concentration from aged (31 days at 52°C) BG to 100 ppm of added water electrolytes containing 1 M NaPF_6 1:1 EC:PC. degradation of NaPF_6 -based electrolytes given enough thermal energy or time.

3.3. Carbonate solvents degradation in the presence of HF

Carbonate solvent stability study is performed via ^1H NMR on five electrolyte mixtures in the presence of HF (Fig. 4). Aging the electrolytes includes the addition of a 1:1 (v/v) HF:H₂O (final concentrations of 0.125 % (v/v) HF and 0.125% (v/v) H₂O). The ^1H NMR spectra were obtained after 4 weeks (or 28 days). From these results, cyclic EC is the most vulnerable form of the five tested carbonates. As demonstrated by the appearance of 1,2-ethanediol (4.05 ppm) in solvent mixtures containing EC. The most plausible formation for this alcohol is through acid catalyzed hydrolysis, which leads to decarboxylation of the cyclic EC [42-44]. The formation of 1,2-ethanediol is the only observable degradation product over the 28 day period at room temperature in the blended carbonate of EC:DEC. Decarboxylation of DEC would have led

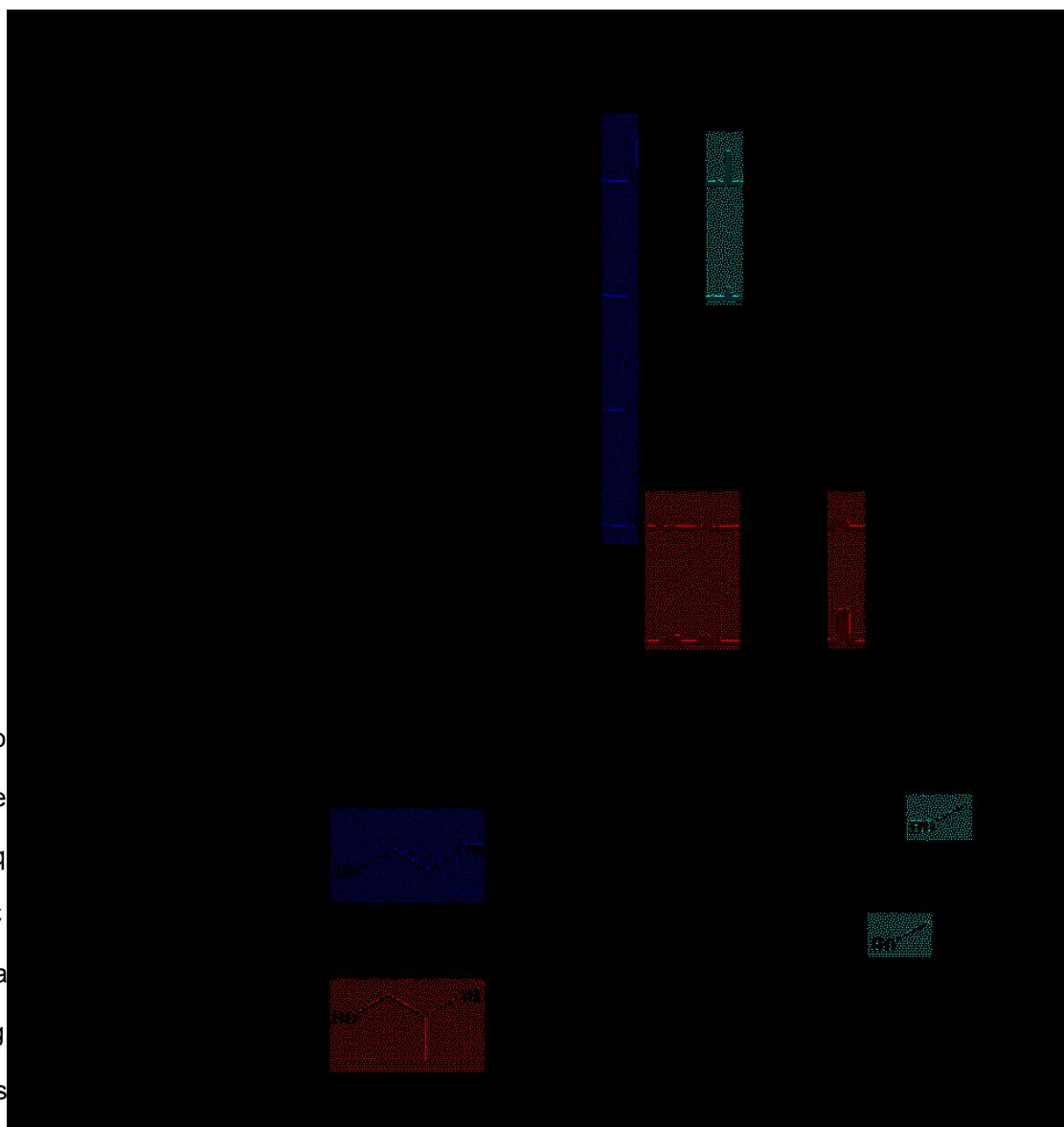


Figure 4: Stability of carbonates in NaPF₆ electrolytes via ^1H NMR. Highlighted area: EC degradation product 1,2-ethanediol (blue), PC degradation product 1,2-propanediol (red) and EMC/DMC degradation product methanol (cyan).

containing electrolyte in which methanol is the only observable degradation product. EMC contains both ethyl and methyl moieties, though the more favorable intermediate would promote the hydrolysis reaction at the shorter alkyl branch. When the electrolyte contains EC:PC, 1,2-ethanediol becomes the major degradation product. In addition, the electrolyte contains a small amount of 1,2-propanediol. The corresponding alcohol of PC. Based on these observations, it suggests that both the steric hindrance and the ability to act as an electron donating group of the -CH₃ moiety makes PC less susceptible to chemical breakdown. Based on the near equimolar ratios of solvent molecules it is clear from the results that EC is the most susceptible to proton attack. A possible explanation for this heightened susceptibility is the intramolecular stress of the five-membered ring of the cyclic carbonates, such as EC and PC. However, the steric hindrance assumed from the methyl moiety of PC improves its stability. The linear carbonates also exhibit a decreasing rate of degradation as the aliphatic chain lengths increased, DMC > EMC > DEC.

3.4. Full cell degradation performance

The degradation seen in the NMR data for the carbonate electrolytes poises the question of how degradation impacts overall cell cycling performance. To better understand the role of electrolyte degradation cycling performance of NaNi_{0.4}Fe_{0.2}Mn_{0.4}O₂ (NFM)/hard carbon (HC) full cells in the presence of degraded electrolytes with and without additives that contain 0 ppm and 100 ppm added water is shown in Fig. 5. In addition to standard and water-containing electrolyte, the role of two different additives (FM2 and FEC) is investigated. The first additive is a promising phosphazene derivative, which has proven beneficial to battery electrolytes by increasing the thermal and electrochemical stability [37]. This work also investigates FEC, a popular additive that is linked to the production of a more resilient SEI layer [46, 47]. Improved resilience may lead to less impact from impurities such as HF[48]. These two additives act through one of the two methods: either mitigation of electrolyte degradation or through the production of a more resilient SEI.

Aged pristine electrolyte (black) is identical in performance of aged 5% FM2 containing electrolyte (red) (Fig. 5). In comparison, the full cell with electrolyte that contain 5% FEC (blue) exhibits a ~ 20 mAh/g capacity drop. When 100 ppm water is added with no electrolyte additives the cell (purple) retains only 14 ± 2 mAh/g after 100 cycles. This is expected as the NMR results indicate large quantities of both HF and salt degradation products with water addition. When FM2 is added (green) the initial capacity is improved to nearly 44 ± 3 mAh/g. This result indicates that mitigating the degradation of the salt in the electrolyte can prevent the battery from complete failure. For the FEC added electrolyte with 100 ppm water (cyan), the capacity is similar to the additive-free electrolyte. Insignificant HF mitigation has taken place leading to poor cycling performance. FEC has been established as a promising additive to improve hard carbon electrode performance via the formation of a more resilient SEI layer [20, 47, 49, 50]. However, HF has been proposed as a detrimental component in electrolytes related to the dissolution of transition metals in cathode materials [51]. The dissolved transition metals can then deposit on the surface of the anode, which leads to poor cycle life performance [52-54]. From our results, it is suggested that in order to extend the shelf life of Na ion batteries it might be necessary to mitigate both the chemical stability of the

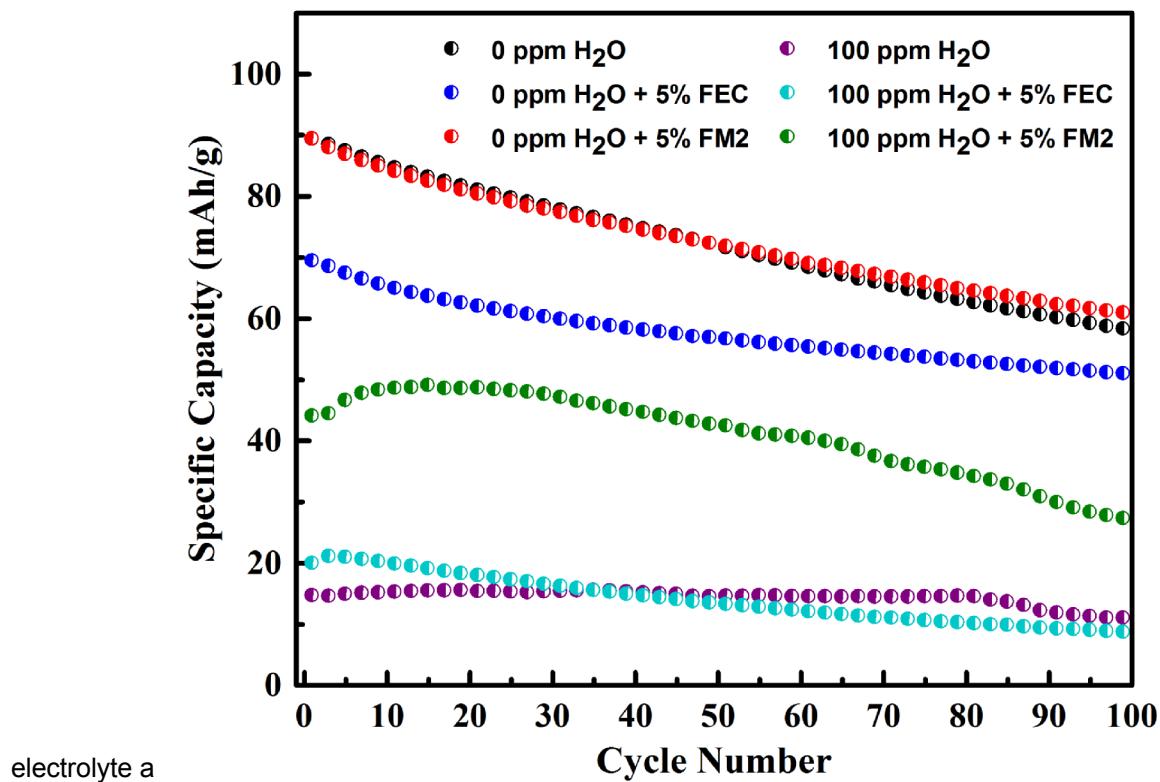


Figure 5: Cycle life performance of 1:1 EC-PC aged electrolytes with and without additives and

water.

3.5. Effect of additive in degradation

As indicated in the cycling data the use of FEC and FM2 present two distinctly different performance levels in full cells. To discern the role that both play in electrolyte degradation FM2 and FEC are evaluated during the degradation process (Fig. 6).

The ^1H and ^{19}F NMR results of 1 M NaPF_6 in EC:PC (1:1) with 100 ppm added water (Fig. 6a and b) indicate that FM2 acts as a “scavenger” and inhibits the formation of HF. This phosphazene additive has been used in other studies to stabilize LiPF_6 -based electrolytes at high temperatures [37]. In the absence of HF the degradation of PF_6^- salts is dramatically reduced. The ^{31}P NMR result (Fig. 6c) suggests FM2 degradation accompanies the F^- formation. This in turn removes or scavenges F^- from the catalytic pathway of PF_6^- salt hydrolysis. Intrinsically, FM2 has mitigated the complete formation of HF. We believe that this result stems from the structure of the phosphazene additive, which has a cyclic ring with resonating π bonds between P and N. This structure leaves P susceptible to nucleophilic attacks from free ions in solution such as F^- or from H_2O . For comparison, the more commonly used FEC additive exhibits only a small effect in mitigating the degradation products. Through ^{19}F and ^{31}P NMR characterization, even with up to 10% FEC, HF concentration remains high (Supporting Information, Fig. S4).

Combining the NMR and cycle life data using elevated water content suggest that degradation of the electrolyte may be a key contributor to shortened cycle life for SIBs. While it is not anticipated that future SIBs will contain the high levels of water used here, the degradation at elevated temperatures, even for

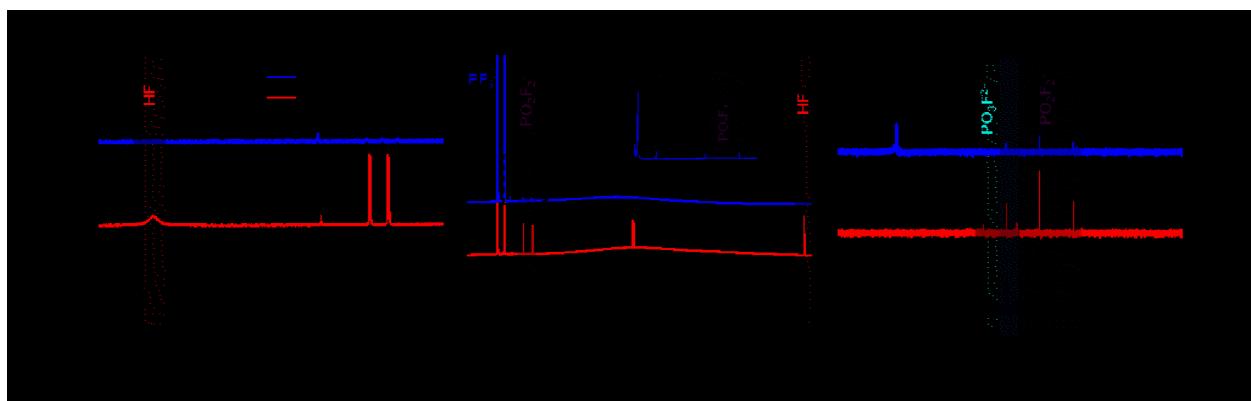


Figure 6: (a) ^1H (b) ^{19}F (c) ^{31}P NMR spectra of 1 M NaPF_6 in EC:PC 1:1 with 100 ppm added water aged over a 31 day period at 52°C, with no additive (black), 2% v/v FEC additive (red), 2% v/v FM2 (blue).

4. Conclusion

Water has a dynamic, significant role in the stability of NaPF_6 -based non-aqueous electrolytes for sodium ion batteries. These electrolytes are highly susceptible to the formation of HF in the presence of water. Most remarkably, HF formation can be observed in BG electrolytes which contain <20 ppm H_2O . The NMR results demonstrate an autocatalytic hydrolysis pathway of hexafluorophosphate to form HF in the electrolyte. Byproducts of the salt degradation, PO_3F_2^- and PO_2F_2^- , are also confirmed with NMR. It is acknowledged that these species may play a dramatic role in the stability of the electrolyte. The most vulnerable carbonate solvent is shown to be cyclic EC. In comparison, PC clearly shows a slower rate of degradation. The rate of decarboxylation of the acyclic carbonate species depends on the length of the aliphatic chain (i.e., DMC > EMC > DEC). Electrolytes with and without added water are tested in full-cell batteries of NFM cathode and hard carbon anode with FM2 and FEC. The full cell with aged electrolyte with no added water and containing FM2 shows comparable performance to aged pristine electrolyte without added water at 91 ± 0.5 mAh/g. In comparison the full cell with FEC demonstrates a dramatic decrease in initial capacity. When water is added (100 ppm), the capacity drastically decreases to 14 ± 2 mAh/g, similar to the additive-free electrolyte. Remarkably, when FM2 is present in the aged electrolyte with added water the full cell has an initial capacity of $\sim 44 \pm 3$ mAh/g and an overall capacity retention of 62% at 100 cycles. This verifies that the byproducts of the salt degradation are detrimental to the performance of a sodium ion battery. This study links HF mitigation and the chemical stability of the NaPF_6 -based non-aqueous electrolytes. In the research and development of sodium ion battery technologies, electrolytes should be closely monitored for degradation. Similarly, additives such as FM2 should be considered to increase the stability of the electrolyte. Stabilizing the electrolyte and mitigating the degradation of the electrolyte could promote the shelf life and performance sodium ion batteries.

Author Contributions

HX, PB, and ED conceived and designed all experiments. KS and RP conducted the physiochemical properties characterization. PB, DK, CJ, CD, ES, PS, ML and QW fabricated electrodes for the full cell. PB, JD, and DK conducted all electrolyte degradation monitoring via NMR. ML prepared solid work digital

diagrams. PB conducted all electrochemical measurements. PB conducted electron dispersion spectroscopy. PB, HX, and ED wrote the manuscript.

Acknowledgement

This work was supported by the National Science Foundation [Grant No. DMR-1454984]; Visiting Faculty Program of the Department of Energy. The authors acknowledge Dr. X. Li from Pacific Northwest National Lab for generous supply of the commercial hard carbon samples and helpful discussion. ES acknowledges the Project SEED Scholarship from the American Chemical Society for summer research. Funding for ED was provided from INL Laboratory Directed Research and Development funds. This manuscript has been authored by Battelle Energy Alliance, LLC under Contract No. AC07-05ID14517 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

5. References

- [1] N. Nitta, F. Wu, J. Lee, G. Yushin, Li-ion battery materials: present and future, *Mater. Today*, 18 (2015) 252-264. 10.1016/j.mattod.2014.10.040.
- [2] J. Tarascon, M. Armand, Issues and challenges facing rechargeable lithium batteries, *Nature*, 414 (2001) 359-367. 10.1038/35104644.
- [3] E.A. Olivetti, G. Ceder, G.G. Gaustad, X.K. Fu, Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, *Joule*, 1 (2017) 229-243. 10.1016/j.joule.2017.08.019.
- [4] H. Vikstrom, S. Davidsson, M. Hook, Lithium availability and future production outlooks, *Applied Energy*, 110 (2013) 252-266. 10.1016/j.apenergy.2013.04.005.
- [5] D. Aurbach, Y. Gofer, The Behavior of Lithium Electrodes in Mixtures of Alkyl Carbonates and Ethers, *J. Electrochem. Soc.*, 138 (1991) 3529-3536. Doi 10.1149/1.2085454.
- [6] E. Goren, O.C. Youngman, D. Aurbach, The Application of Insitu Ftir Spectroscopy to the Study of Surface-Films Formed on Lithium and Noble-Metals at Low Potentials in Li Battery Electrolytes, *J. Electrochem. Soc.*, 138 (1991) L6-L9. Doi 10.1149/1.2085828.
- [7] M. Winter, B. Barnett, K. Xu, Before Li Ion Batteries, *Chem. Rev.*, 118 (2018) 11433-11456. 10.1021/acs.chemrev.8b00422.
- [8] M. Winter, The Solid Electrolyte Interphase - The Most Important and the Least Understood Solid Electrolyte in Rechargeable Li Batteries, *Z. Phys. Chem.*, 223 (2009) 1395-1406. 10.1524/zpch.2009.6086.
- [9] D. Aurbach, A. Zaban, Impedance Spectroscopy of Lithium Electrodes .1. General Behavior in Propylene Carbonate Solutions and the Correlation to Surface-Chemistry and Cycling Efficiency, *J. Electroanal. Chem.*, 348 (1993) 155-179. Doi 10.1016/0022-0728(93)80129-6.
- [10] P. Verma, P. Maire, P. Novak, A review of the features and analyses of the solid electrolyte interphase in Li-ion batteries, *Electrochim. Acta*, 55 (2010) 6332-6341. 10.1016/j.electacta.2010.05.072.
- [11] E. Peled, The Electrochemical-Behavior of Alkali and Alkaline-Earth Metals in Non-Aqueous Battery Systems - the Solid Electrolyte Interphase Model, *J. Electrochem. Soc.*, 126 (1979) 2047-2051. Doi 10.1149/1.2128859.
- [12] K. Xu, Electrolytes and Interphases in Li-Ion Batteries and Beyond, *Chem. Rev.*, 114 (2014) 11503-11618. 10.1021/cr500003w.
- [13] A. Ponrouch, E. Marchante, M. Courty, J.M. Tarascon, M.R. Palacin, In search of an optimized electrolyte for Na-ion batteries, *Energ. Environ. Sci.*, 5 (2012) 8572-8583. 10.1039/c2ee22258b.
- [14] H.L. Pan, Y.S. Hu, L.Q. Chen, Room-temperature stationary sodium-ion batteries for large-scale electric energy storage, *Energ. Environ. Sci.*, 6 (2013) 2338-2360. 10.1039/c3ee40847g.

[15] M. Shakourian-Fard, G. Kamath, K. Smith, H. Xiong, S.K.R.S. Sankaranarayanan, Trends in Na-Ion Solvation with Alkyl-Carbonate Electrolytes for Sodium-Ion Batteries: Insights from First-Principles Calculations, *J. Phys. Chem. C*, 119 (2015) 22747-22759. 10.1021/acs.jpcc.5b04706.

[16] G. Kamath, R.W. Cutler, S.A. Deshmukh, M. Shakourian-Fard, R. Parrish, J. Huether, D.P. Butt, H. Xiong, S.K.R.S. Sankaranarayanan, In Silico Based Rank-Order Determination and Experiments on Nonaqueous Electrolytes for Sodium Ion Battery Applications, *J. Phys. Chem. C*, 118 (2014) 13406-13416. 10.1021/jp502319p.

[17] D. Buchholz, A. Moretti, R. Kloepsch, S. Nowak, V. Siozios, M. Winter, S. Passerini, Toward Na-ion Batteries-Synthesis and Characterization of a Novel High Capacity Na Ion Intercalation Material, *Chem. Mater.*, 25 (2013) 142-148. 10.1021/cm3029615.

[18] K. Xu, Nonaqueous liquid electrolytes for lithium-based rechargeable batteries, *Chem. Rev.*, 104 (2004) 4303-4417. 10.1021/cr030203g.

[19] A.V. Plakhotnyk, L. Ernst, R. Schmutzler, Hydrolysis in the system LiPF₆-propylene carbonate-dimethyl carbonate-H₂O, *J. Fluorine Chem.*, 126 (2005) 27-31. 10.1016/j.jfluchem.2004.09.027.

[20] E. Markevich, G. Salitra, K. Fridman, R. Sharabi, G. Gershinsky, A. Garsuch, G. Semrau, M. Schmidt, D. Aurbach, Fluoroethylene Carbonate as an Important Component in Electrolyte Solutions for High-Voltage Lithium Batteries: Role of Surface Chemistry on the Cathode, *Langmuir*, 30 (2014) 7414-7424. 10.1021/la501368y.

[21] S. Zhang, A review on electrolyte additives for lithium-ion batteries, *J. Power Sources*, 162 (2006) 1379-1394. 10.1016/j.jpowsour.2006.07.074.

[22] S.F. Lux, J. Chevalier, I.T. Lucas, R. Kostecki, HF Formation in LiPF₆-Based Organic Carbonate Electrolytes, *ECS Electrochem. Lett.*, 2 (2013) A121-A123. 10.1149/2.005312eel.

[23] S.F. Lux, I.T. Lucas, E. Pollak, S. Passerini, M. Winter, R. Kostecki, The mechanism of HF formation in LiPF₆ based organic carbonate electrolytes, *Electrochem. Commun.*, 14 (2012) 47-50. 10.1016/j.elecom.2011.10.026.

[24] V. Kraft, W. Weber, M. Grutzke, M. Winter, S. Nowak, Study of decomposition products by gas chromatography-mass spectrometry and ion chromatography-electrospray ionization-mass spectrometry in thermally decomposed lithium hexafluorophosphate-based lithium ion battery electrolytes, *RSC Adv.*, 5 (2015) 80150-80157. 10.1039/c5ra16679a.

[25] J.F. Qian, W. Xu, P. Bhattacharya, M. Engelhard, W.A. Henderson, Y.H. Zhang, J.G. Zhang, Dendrite-free Li deposition using trace-amounts of water as an electrolyte additive, *Nano Energy*, 15 (2015) 135-144. 10.1016/j.nanoen.2015.04.009.

[26] P. Handel, G. Fauler, K. Kapper, M. Schmuck, C. Stangl, R. Fischer, F. Uhlig, S. Koller, Thermal aging of electrolytes used in lithium-ion batteries - An investigation of the impact of protic impurities and different housing materials, *J. Power Sources*, 267 (2014) 255-259. 10.1016/j.jpowsour.2014.05.080.

[27] T. Kawamura, A. Kimura, M. Egashira, S. Okada, J.I. Yamaki, Thermal stability of alkyl carbonate mixed-solvent electrolytes for lithium ion cells, *J. Power Sources*, 104 (2002) 260-264. Doi 10.1016/S0378-7753(01)00960-0.

[28] D. Aurbach, Y. Eineli, B. Markovsky, A. Zaban, S. Luski, Y. Carmeli, H. Yamin, The Study of Electrolyte-Solutions Based on Ethylene and Diethyl Carbonates for Rechargeable Li Batteries .2. Graphite-Electrodes, *J. Electrochem. Soc.*, 142 (1995) 2882-2890. Doi 10.1149/1.2048659.

[29] D. Aurbach, A. Zaban, A. Schechter, Y. Eineli, E. Zinigrad, B. Markovsky, The Study of Electrolyte-Solutions Based on Ethylene and Diethyl Carbonates for Rechargeable Li Batteries .1. Li Metal Anodes, *J. Electrochem. Soc.*, 142 (1995) 2873-2882. Doi 10.1149/1.2048658.

[30] U. Heider, R. Oesten, M. Jungnitz, Challenge in manufacturing electrolyte solutions for lithium and lithium ion batteries quality control and minimizing contamination level, *J. Power Sources*, 81 (1999) 119-122. Doi 10.1016/S0378-7753(99)00142-1.

[31] S.E. Sloop, J.K. Pugh, S. Wang, J.B. Kerr, K. Kinoshita, Chemical reactivity of PF5 and LiPF6 in ethylene carbonate/dimethyl carbonate solutions, *Electrochem. Solid St.*, 4 (2001) A42-A44. Doi 10.1149/1.1353158.

[32] N. Ohmi, T. Nakajima, Y. Ohzawa, M. Koh, A. Yamauchi, M. Kagawa, H. Aoyama, Effect of organo-fluorine compounds on the thermal stability and electrochemical properties of electrolyte solutions for lithium ion batteries, *J. Power Sources*, 221 (2013) 6-13. 10.1016/j.jpowsour.2012.07.121.

[33] G.G. Botte, R.E. White, Z.M. Zhang, Thermal stability of LiPF6-EC : EMC electrolyte for lithium ion batteries, *J. Power Sources*, 97-8 (2001) 570-575. Doi 10.1016/S0378-7753(01)00746-7.

[34] E.M. Erickson, E. Markevich, G. Salitra, D. Sharon, D. Hirshberg, E. de la Llave, I. Shterenberg, A. Rozenman, A. Frimer, D. Aurbach, Review-Development of Advanced Rechargeable Batteries: A Continuous Challenge in the Choice of Suitable Electrolyte Solutions, *J. Electrochem. Soc.*, 162 (2015) A2424-A2438. 10.1149/2.0051514jes.

[35] K. Kubota, S. Komaba, Review-Practical Issues and Future Perspective for Na-Ion Batteries, *J. Electrochem. Soc.*, 162 (2015) A2538-A2550. 10.1149/2.0151514jes.

[36] A. Ponnouch, D. Monti, A. Boschin, B. Steen, P. Johansson, M. Palacin, Non-aqueous electrolytes for sodium-ion batteries, *J. Mater. Chem. A*, 3 (2015) 22-42. 10.1039/c4ta04428b.

[37] H.W. Rollins, M.K. Harrup, E.J. Dufek, D.K. Jamison, S.V. Sazhin, K.L. Gering, D.L. Daubaras, Fluorinated phosphazene co-solvents for improved thermal and safety performance in lithium-ion battery electrolytes, *J. Power Sources*, 263 (2014) 66-74. 10.1016/j.jpowsour.2014.04.015.

[38] N. Yabuuchi, M. Yano, H. Yoshida, S. Kuze, S. Komaba, Synthesis and Electrode Performance of O3-Type NaFeO2-NaNi1/2Mn1/2O2 Solid Solution for Rechargeable Sodium Batteries, *J. Electrochem. Soc.*, 160 (2013) A3131-A3137. 10.1149/2.018305jes.

[39] L. Terborg, S. Weber, F. Blaske, S. Passerini, M. Winter, U. Karst, S. Nowak, Investigation of thermal aging and hydrolysis mechanisms in commercial lithium ion battery electrolyte, *J. Power Sources*, 242 (2013) 832-837. 10.1016/j.jpowsour.2013.05.125.

[40] S. Wiemers-Meyer, M. Winter, S. Nowak, Mechanistic insights into lithium ion battery electrolyte degradation - a quantitative NMR study, *Phys. Chem. Chem. Phys.*, 18 (2016) 26595-26601. 10.1039/c6cp05276b.

[41] A.E. Gebala, M.M. Jones, The Acid Catalyzed Hydrolysis of Hexafluorophosphate, *J. Inorg. Nucl.*

Chem., 31 (1969) 771-776. Doi 10.1016/0022-1902(69)80024-2.

[42] L. Vogdanis, W. Heitz, Carbon-Dioxide as a Monomer .3. The Polymerization of Ethylene Carbonate, *Makromolekulare Chemie-Rapid Communications*, 7 (1986) 543-547.

[43] S.E. Sloop, J.B. Kerr, K. Kinoshita, The role of Li-ion battery electrolyte reactivity in performance decline and self-discharge, *J. Power Sources*, 119 (2003) 330-337. 10.1016/S0378-7753(03)00149-6.

[44] M. Metzger, B. Strehle, S. Solchenbach, H.A. Gasteiger, Hydrolysis of Ethylene Carbonate with Water and Hydroxide under Battery Operating Conditions, *J. Electrochem. Soc.*, 163 (2016) A1219-A1225. 10.1149/2.0411607jes.

[45] A.S. Gordon, W.P. Norris, A Study of Pyrolysis of Methyl Ethyl and Diethyl Carbonates in Gas Phase, *J. Phys. Chem-US*, 69 (1965) 3013-3017. Doi 10.1021/J100893a032.

[46] Y. Lee, J. Lee, H. Kim, K. Kang, N.S. Choi, Highly stable linear carbonate-containing electrolytes with fluoroethylene carbonate for high-performance cathodes in sodium-ion batteries, *J. Power Sources*, 320 (2016) 49-58. 10.1016/j.jpowsour.2016.04.070.

[47] M. Nie, J. Demeaux, B. Young, D. Heskett, Y. Chen, A. Bose, J. Woicik, B. Lucht, Effect of Vinylene Carbonate and Fluoroethylene Carbonate on SEI Formation on Graphitic Anodes in Li-Ion Batteries, *J. Electrochem. Soc.*, 162 (2015) A7008-A7014. 10.1149/2.0021513jes.

[48] S.S. Zhang, A review on electrolyte additives for lithium-ion batteries, *J. Power Sources*, 162 (2006) 1379-1394. 10.1016/j.jpowsour.2006.07.074.

[49] I.A. Shkrob, J.F. Wishart, D.P. Abraham, What Makes Fluoroethylene Carbonate Different?, *J Phys Chem C*, 119 (2015) 14954-14964. 10.1021/acs.jpcc.5b03591.

[50] F.A. Soto, P.F. Yan, M.H. Engelhard, A. Marzouk, C.M. Wang, G.L. Xu, Z.H. Chen, K. Amine, J. Liu, V.L. Sprenkle, F. El-Mellouhi, P.B. Balbuena, X.L. Li, Tuning the Solid Electrolyte Interphase for Selective Li- and Na-Ion Storage in Hard Carbon, *Adv Mater*, 29 (2017) 1606860. 10.1002/adma.201606860.

[51] S. Nowak, M. Winter, The Role of Cations on the Performance of Lithium Ion Batteries: A Quantitative Analytical Approach, *Acc. Chem Res*, 51 (2018) 265-272. 10.1021/acs.accounts.7b00523.

[52] J.L. Tebbe, A.M. Holder, C.B. Musgrave, Mechanisms of LiCoO₂ Cathode Degradation by Reaction with HF and Protection by Thin Oxide Coatings, *ACS Appl. Mater. Interfaces*, 7 (2015) 24265-24278. 10.1021/acsami.5b07887.

[53] T. Nordh, R. Younesi, M. Hahlin, R.F. Duarte, C. Tengstedt, D. Brandell, K. Edstrom, Manganese in the SEI Layer of Li₄Ti₅O₁₂ Studied by Combined NEXAFS and HAXPES Techniques, *J. Phys. Chem. C*, 120 (2016) 3206-3213. 10.1021/acs.jpcc.5b11756.

[54] S. Nowak, M. Winter, Elemental analysis of lithium ion batteries, *J. Anal. At. Spectrom.*, 32 (2017) 1833-1847. 10.1039/c7ja00073a.