The Use of Li-ion Batteries for a 50-Year Space Flight

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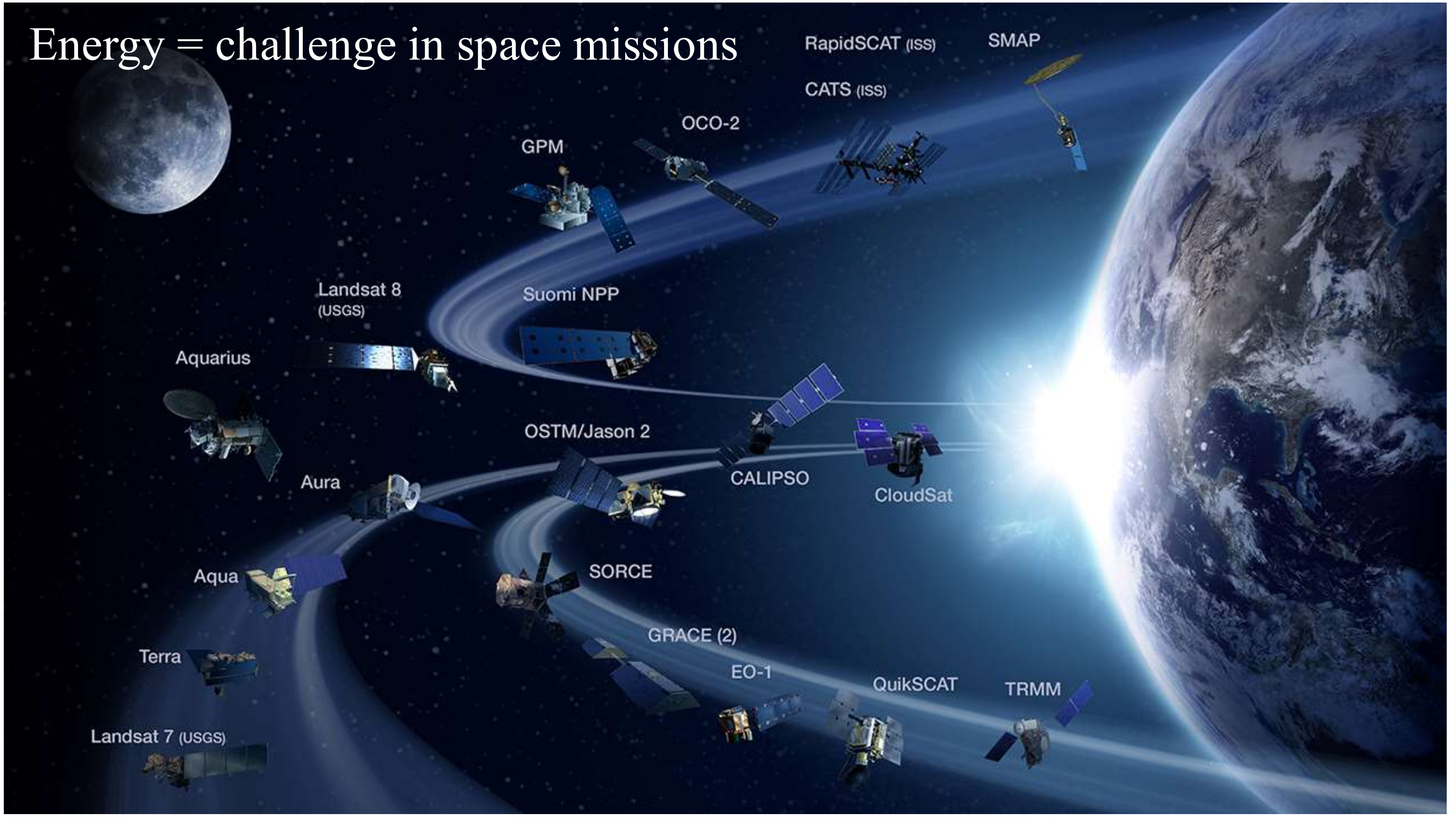
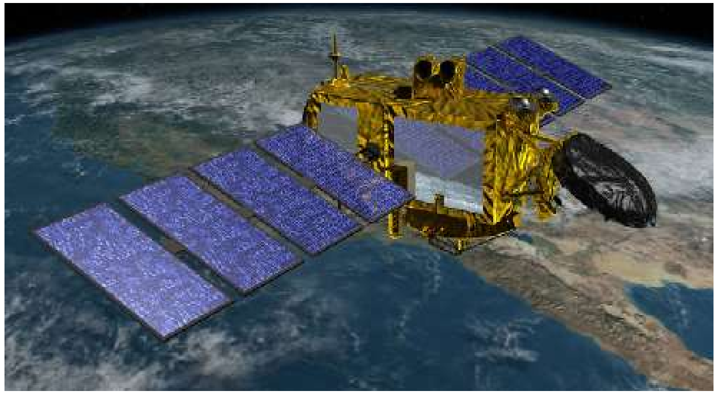
Introduction



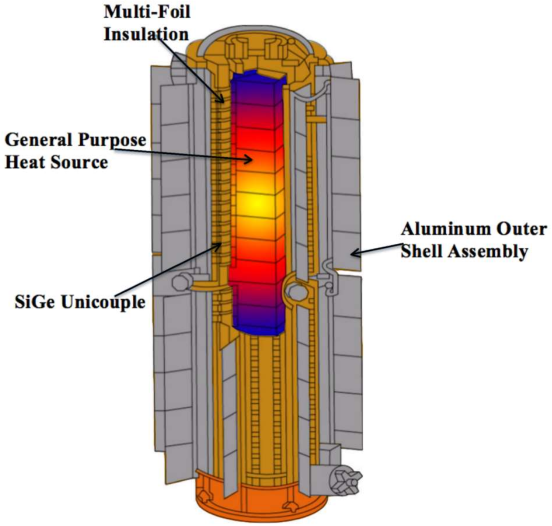
Artwork from NASA depicting NASA Earth Science Division Operating Missions. Public Domain

Current Solutions to Power Satellites

- Historically, space satellites have depended on various combinations of solar arrays, radioisotope thermoelectric generators (RTGs), and batteries for power.



National Oceanic and Atmospheric Administration (NOAA) Satellites. Credit: NOAA



RTG Scheme. Credit: Parker Beatty @Wikipedia. CC BY-SA 4.0

Nickel-Hydrogen batteries for the Hubble telescope. Credit: NASA

Pros & Cons of Current Solutions

- Solar cells are a mature technology but would not be adequate for powering deep space missions since solar flux decreases as the spacecraft goes further away from the Sun.

- RTGs are also reliable since they have experienced no known life/failure issues in space missions until now and present a slow power capacity decay, making them part of the solution for deep space missions. However, they have specific electrical powers from 25 to 35 W/kg, which is a limited value to energize high-power equipment.

- Several rechargeable battery types of various chemistries have been used in space missions and satellites until now: Nickel-Hydrogen, Nickel-Cadmium, Lithium-ion. The observed averaged-life for these types of batteries to date is around 16, 19, and 8 years, respectively. These figures are far away from the 50-year horizon envisioned for deep space missions.

Goal of the Work

Energy requirements for long missions in deep space will compulsorily imply the use of secondary batteries for high power applications upon arrival to its destination, while these batteries will have undergone a long trip under storage mode. A minimal amount of capacity fade is thus desired and required → Li-ion technology.

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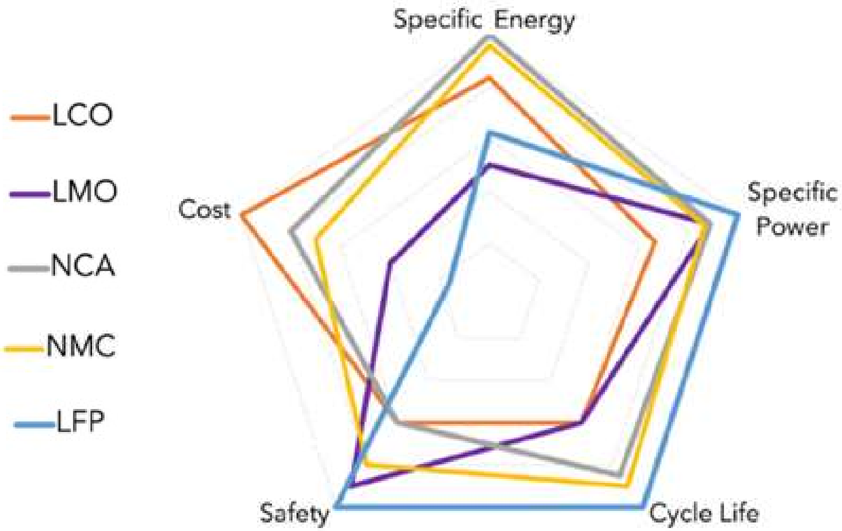
Objective: Estimate the capacity fade of Li-ion batteries during a 50-year trip in stand-by operation at low temperatures (around 0 ºC) and provide some insights on the optimal conditions to minimize their aging.

Lithium-ion Battery Types

- The Li-ion chemistries commercially available today combine graphite or Li_2TiO_3 (LTO), as anode, and transition metal oxides such as $LiCoO_2$ (LCO), $LiNiMnCoO_2$ (NCM), $LiNiCoAlO_2$ (NCA), $LiMn_2O_4$ (LMO), or $LiFePO_4$ (LFP), as cathodes.



Source: Walvekar, Harsha, et al. "Implications of the Electric Vehicle Manufacturers' Decision to Mass Adopt Lithium-Iron Phosphate Batteries." IEEE Access (2022).

- All these batteries present degradation mechanisms mainly associated with the loss of active Li^+ ions in the organic liquid electrolyte. These are basically identified with: formation of passivation layers, electrolyte decomposition, and lithium plating.

Lithium-ion Calendar Aging Mechanisms

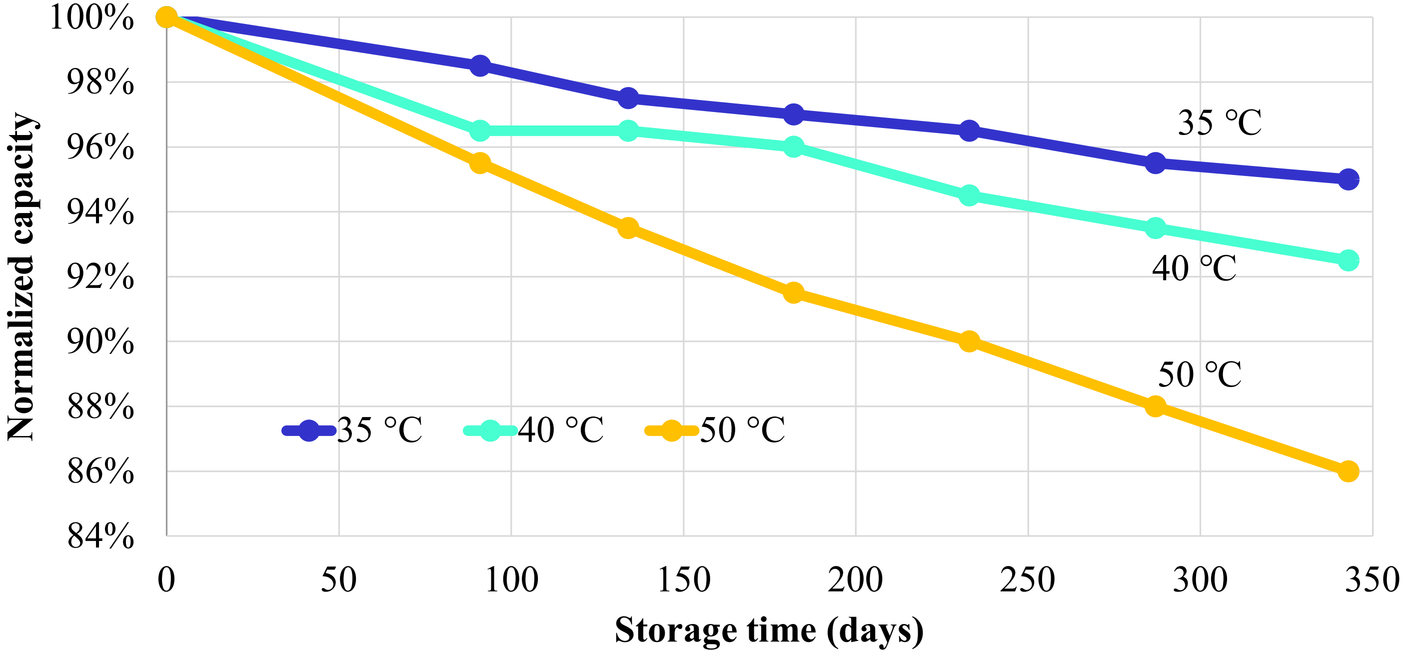
- According to the literature, in contrast to cycle aging where mechanical strain in the electrode active materials or lithium plating can cause severe degradation, the main causes for calendar aging are parasitic reactions between electrolyte and electrodes. They can be classified into three categories:
  - anode reactions (electrolyte reduction leads to Solid Electrolyte Interface (SEI) growth),
  - cathode reactions (including electrolyte oxidation and transition metal dissolution), and
  - coupled reactions (e.g. transition metals dissolved from the cathode affect SEI growth at the anode).
- SEI growth is assumed to be the dominant aging mechanism and causes irreversible decrease in capacity due to loss of lithium inventory.
- **Both the evolution of passivation layers and the transition-metal dissolution are promoted by higher temperatures and a high state-of-charge (SOC)**.

Operation in Satellites Vs. Calendar Aging

- Batteries will have to be kept at a low SOC level during the journey (reducing the SEI formation and the overhang effect).
- Battery temperatures must be kept above -10 ºC (preventing the electrolyte from freezing) and even require some warmup before recharging. This implies that the batteries will have to be protected against low space temperatures using part of the RTG energy in that goal.
- Recharging processes will have to be avoided as far as possible and low charging C-rates should be always applied (what is compatible with the RTG power supply capabilities). Together with the low SOC, this will allow controlling the anode potential to avoid it from falling below that of the lithium metal at any time, hence preventing lithium plating.
- The aging analysis can focus on the SEI formation and increase. Not many literature and data are available due to the difficulty to test cells resting at low temperatures without modifying the aging with the test checkup.

Li-ion Battery Previous Degradation Datasets (I)

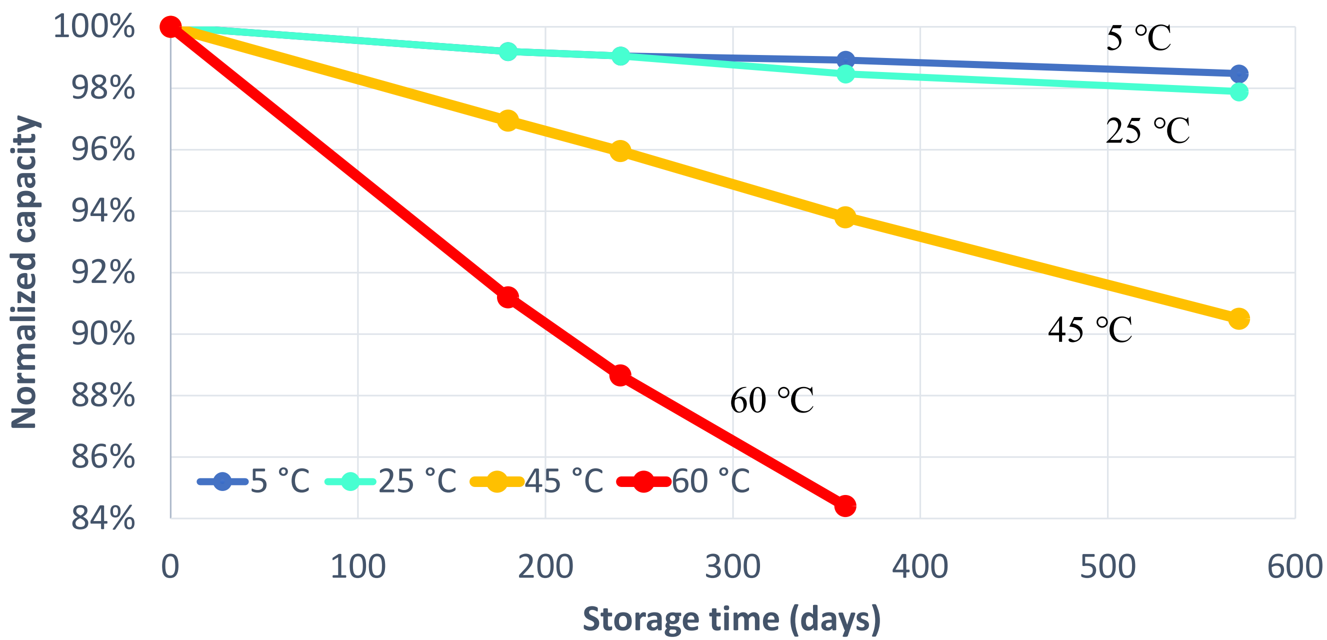
- This study mainly uses three datasets published in previous works that analyze the calendar aging of different types of Li-ion cells under various resting conditions:
  - (A) A study conducted by Ecker et al., where **cylindrical** 18650 format **NMC**/graphite cells were stored at the temperatures of 35, 40, and 50 °C and **50%** SOC for hardly one year.



M. Ecker, N. Nieto, S. Käbitz, J. Schmalstieg, H. Blanke, A. Warnecke and D. Uwe Sauer, "Calendar and cycle life study of Li(NiMnCo)O2-based 18650 lithium-ion batteries," *Journal of Power Sources*, pp. 839-851, 2014.

Li-ion Battery Previous Degradation Datasets (II)

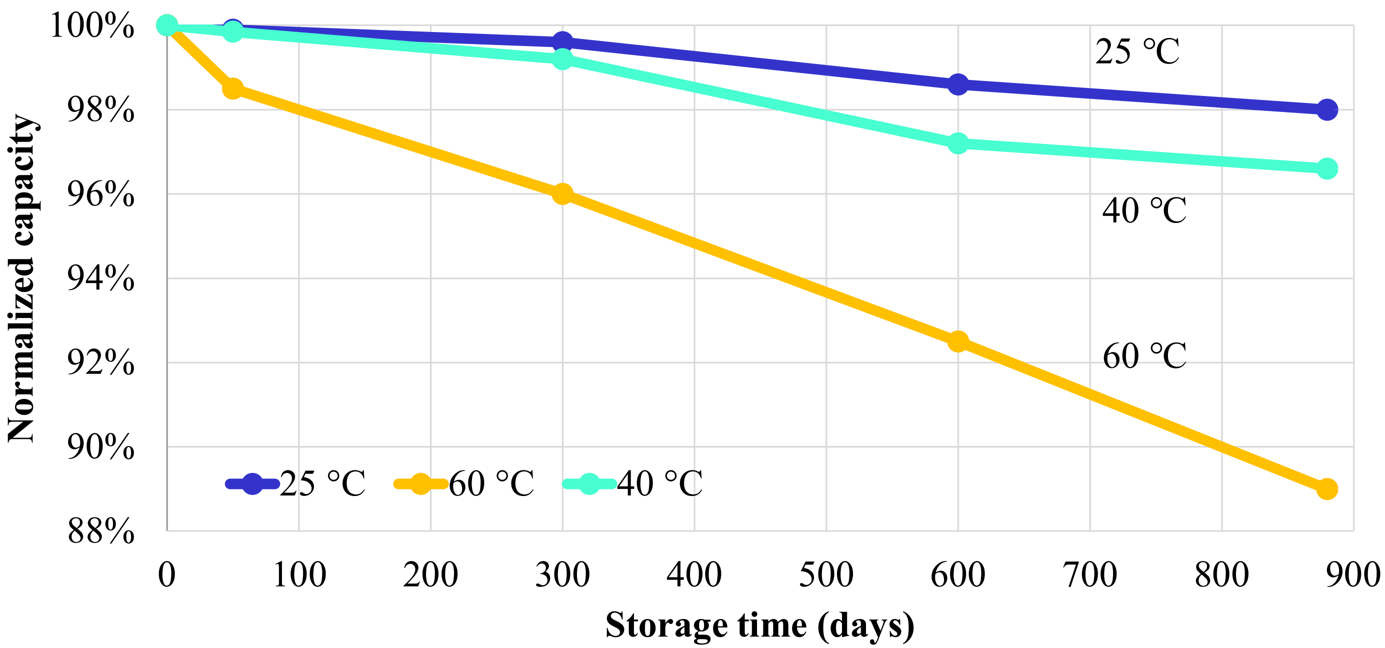
- This study mainly uses three datasets published in previous works that analyze the calendar aging of different types of cells under various resting conditions:
  - (B) A study conducted by Matadi et al., where the **NMC**/graphite **pouch** cells' capacity fade was measured at storage temperatures of 5, 25, 45, and 60 °C and **100%** SOC.



B. P. Matadi, S. Geniès, A. Delaille, T. Waldmann, M. Kasper, M. Wohlfahrt-Mehrens, F. Aguesse, E. Bekaert, I. Jiménez-Gordon, L. Daniel, X. Fleury, M. Bardet, J.-F. Martin and Bulte, "Effects of Biphenyl Polymerization on Lithium Deposition in Commercial Graphite/NMC Lithium-Ion Pouch-Cells during Calendar Aging at High Temperature," *Journal of The Electrochemical Society,* vol. 164, no. 6, pp. A1089-A1097, 2017.

Li-ion Battery Previous Degradation Datasets (III)

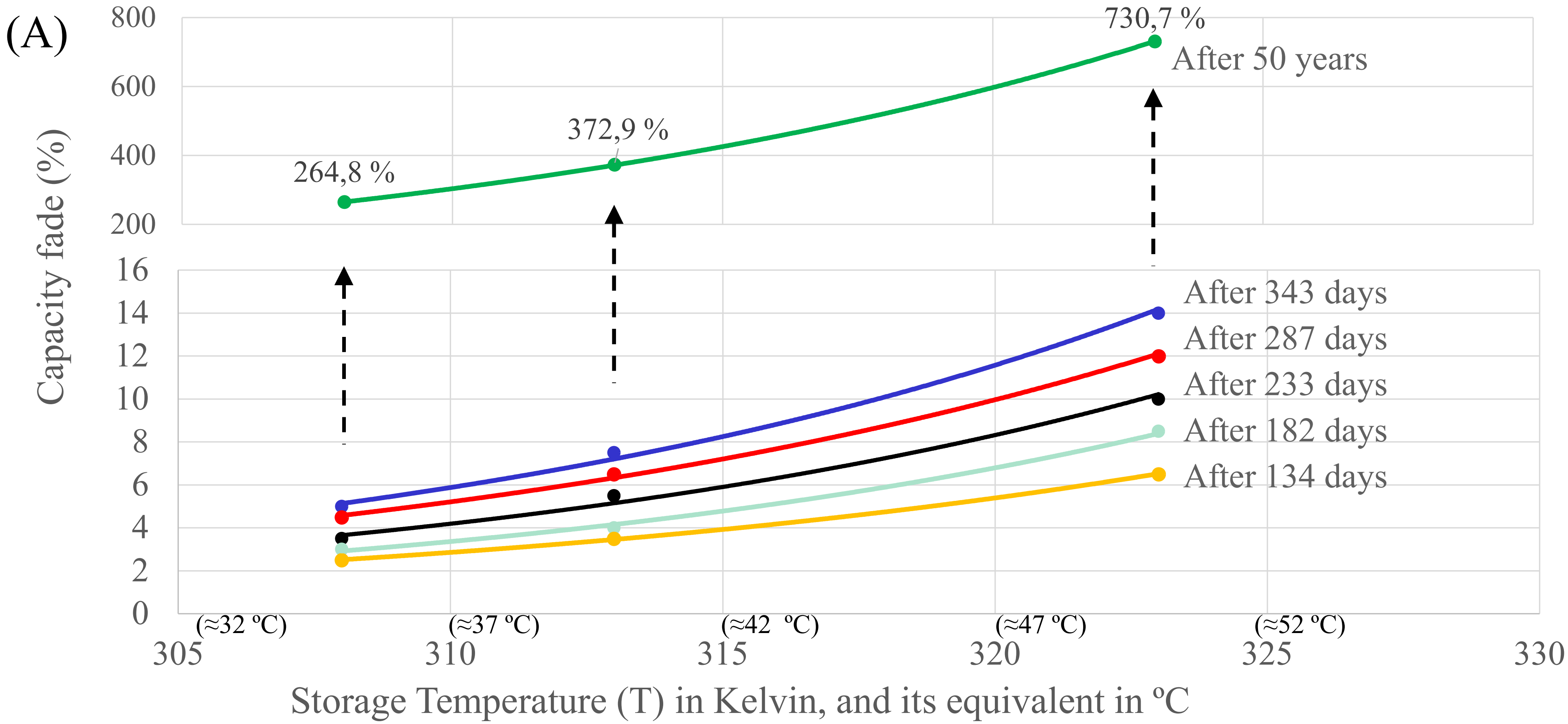
- This study mainly uses three datasets published in previous works that analyze the calendar aging of different types of cells under various resting conditions:
  - (C) A study conducted by Naumann et al. where **LFP**/graphite cells were stored at the temperatures of 25, 40, and 60 °C and **50%** SOC for about 29 months.



M. Naumann, M. Schimpe, P. Keil, H. C. Hesse and A. Jossen, "Analysis and modeling of calendar aging of a commercial LiFePO4/graphite cell," *Journal of Energy Storage,* vol. 17, pp. 153-169, 2018.

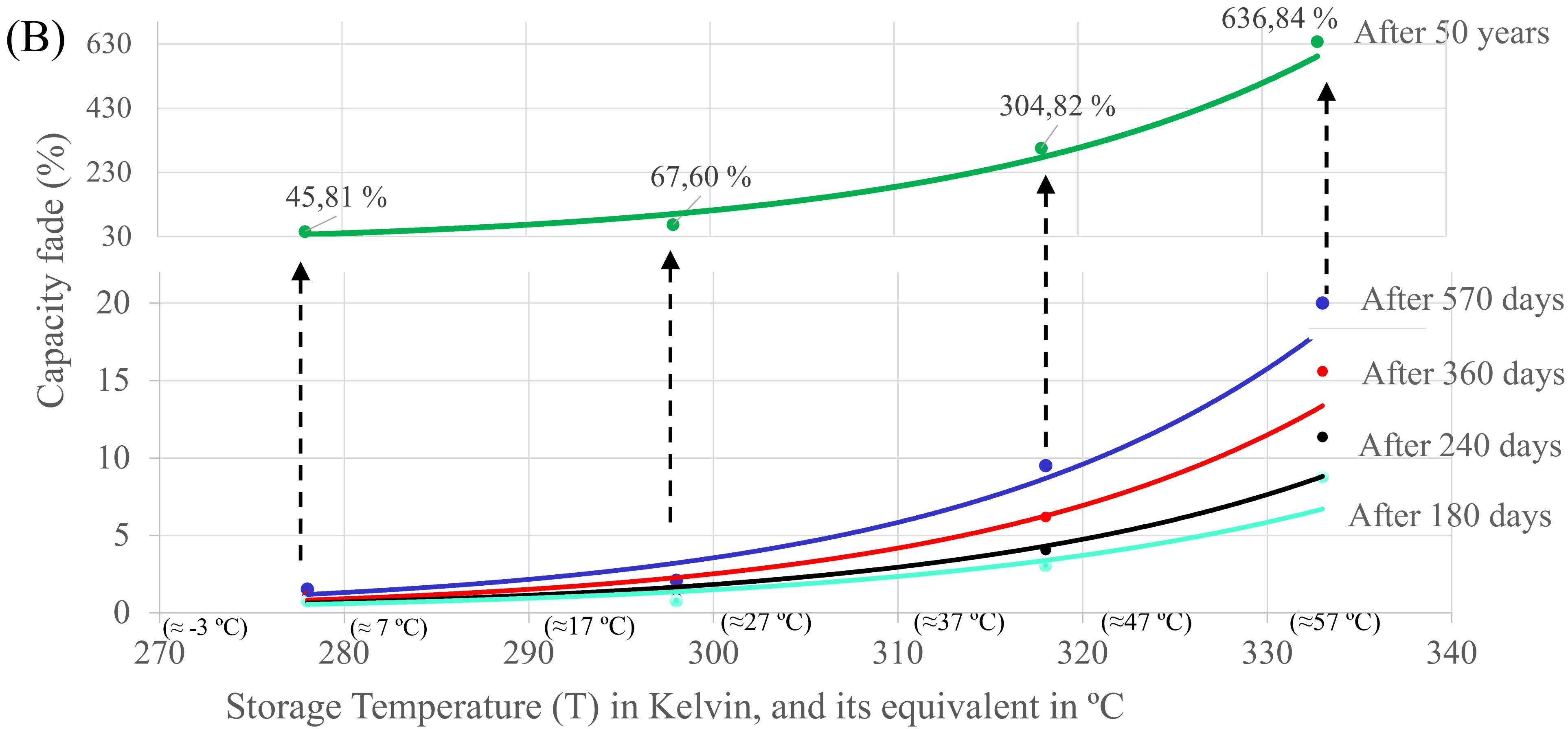
Capacity Fade Evolutions with T (I)

Degradation Rate for NMC cylindrical cells at 50% SOC



Capacity Fade Evolutions with T (II)

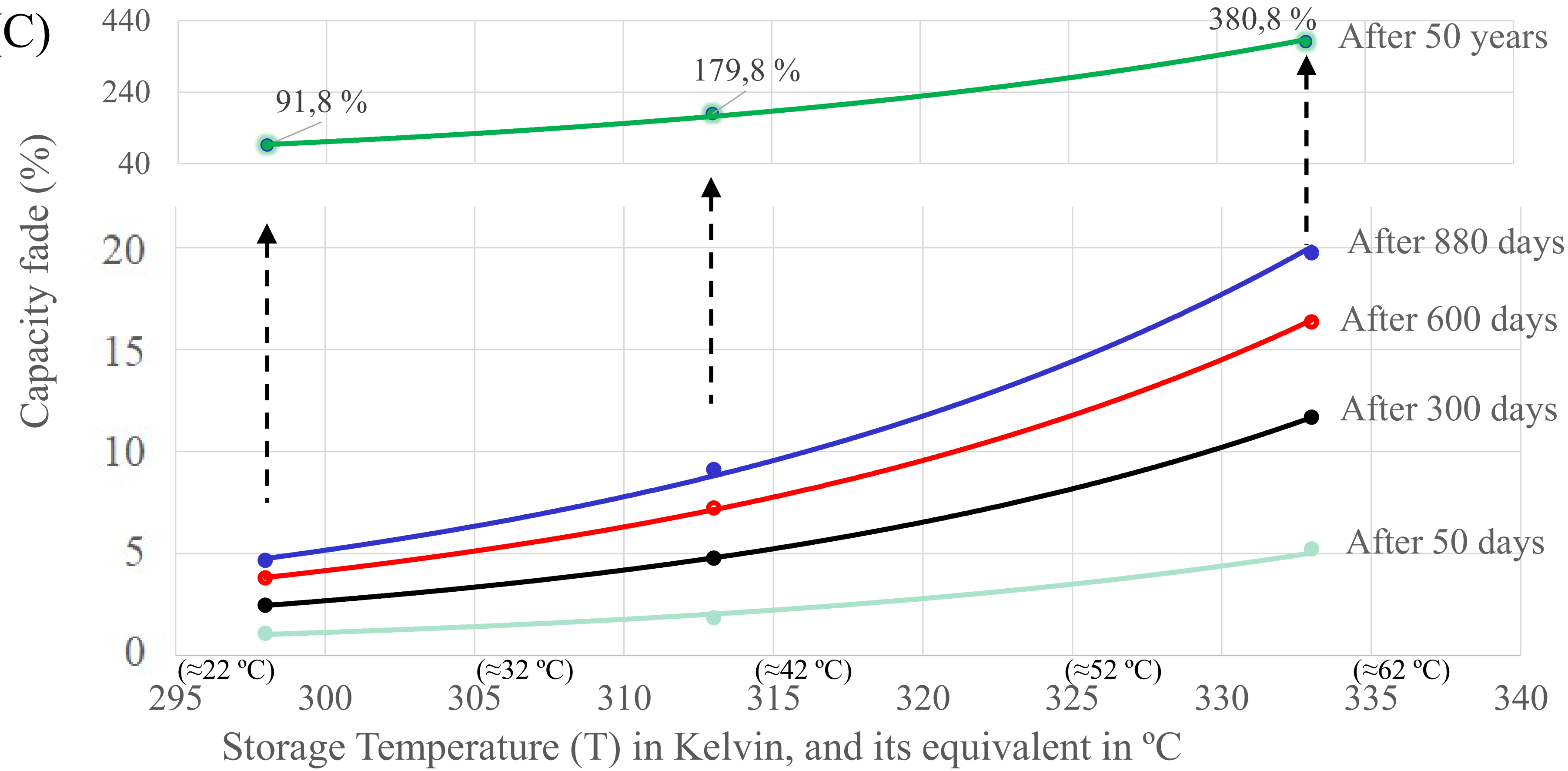
Degradation Rate for NMC pouch cells at 100% SOC



Capacity Fade Evolutions with T (III)

Degradation Rate for LFP at 50% SOC

(C)



Capacity Fade Model for Temperature

- Since we want to extrapolate the results from the previous models (developed at high temperatures) in order to identify the capacity fade they would suffer at 0 ºC for 50 years, we implemented the following model that provides the evolution of the capacity fade with temperature at each of the check up times:

$$Capacity\ fade\ (time) = A \times e^{B \cdot T}$$

where A and B are empirical constants and T is the storage temperature.

- This model is fitted with Matlab® to each of the explored datasets.

Estimations on CF Evolutions with T

- We can then estimate the capacity fade (at 0 °C) at the time-intervals when the characterization was conducted and extrapolate the value after 50 years since the relation of degradation Vs time at the different temperatures experiences a linear relation.

- For instance, we obtain for the first dataset (NMC cylindrical cells at 50% SOC):

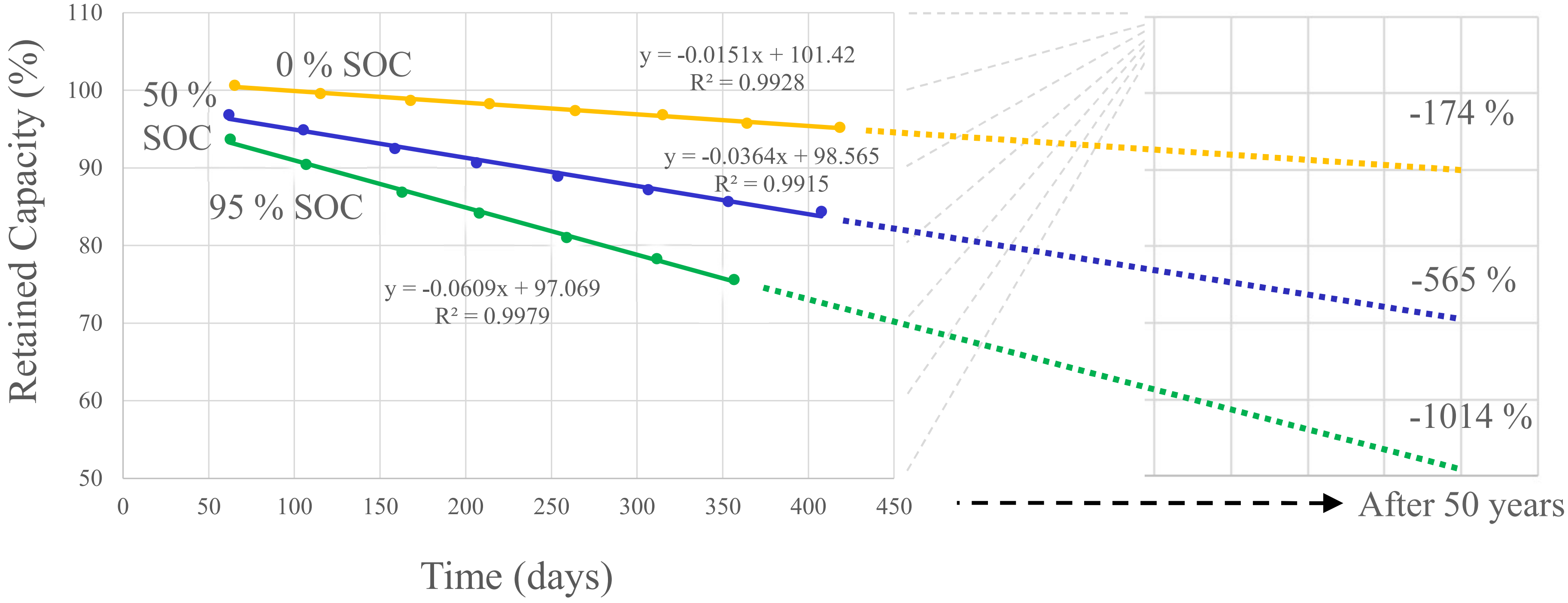
Days/Temp	50 °C	40 °C	35 °C	0 °C (model estimated)
134	6.5 %	3.5 %	2.5 %	0.26 %
182	8.5 %	4.0 %	3.0 %	0.22 %
233	10.0 %	5.5 %	3.5 %	0.26 %
287	12.0 %	6.5 %	4.5 %	0.48 %
343	14.0 %	7.5 %	5.0 %	0.44 %
18250 (50 years)	730.7 %	372.9 %	264.8 %	**20.69 %**

$$Capacity\ fade\ (time) = A \times e^{B \cdot T}$$

- For the NMC at 100 % SOC and the LFP at 50 % we get: **29.95** %, and **31.68** %.

Capacity Fade Model Evolutions with SOC (I)

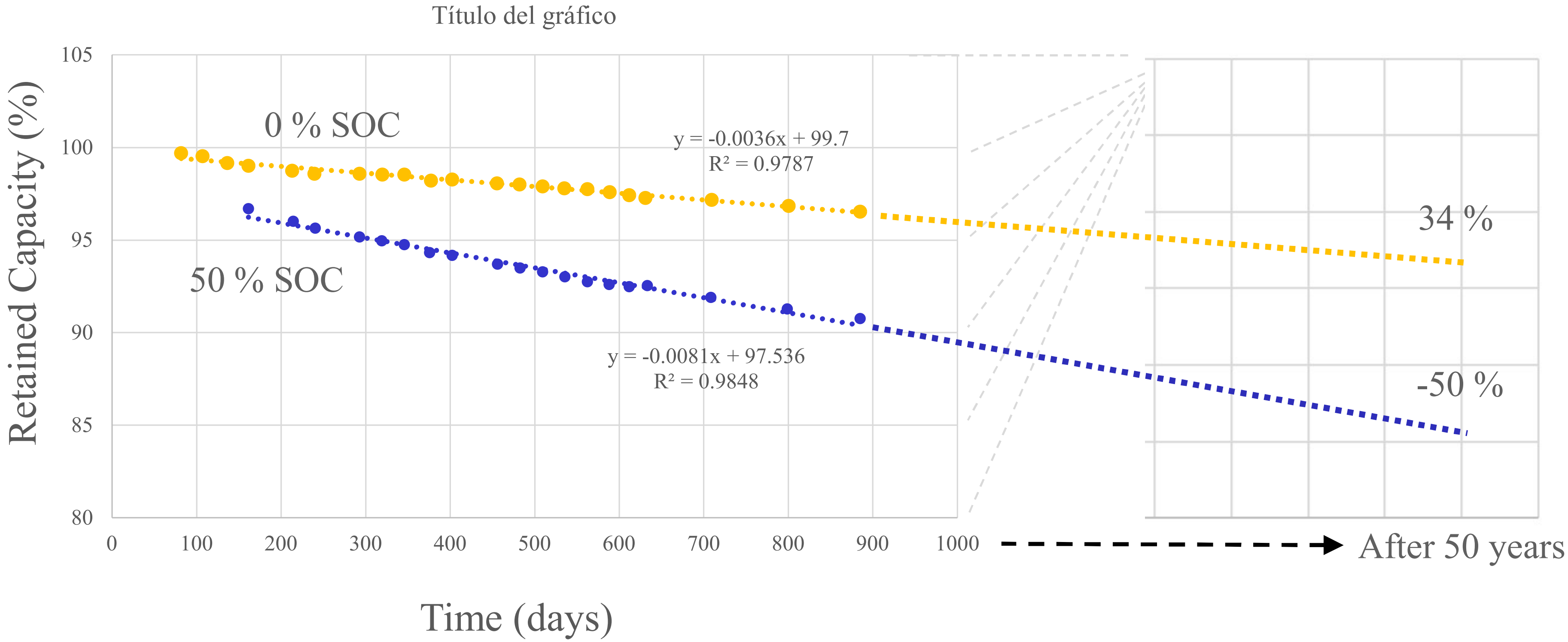
- Another extrapolation is used to determine the capacity loss at 0% SOC.
- The aging relation among SOC values at 50 ºC is taken as reference for NMC cells.



M. Ecker, et alter, "Calendar and cycle life study of Li(NiMnCo)O2-based 18650 lithium-ion batteries," *Journal of Power Sources,* pp. 839-851, 2014.

Capacity Fade Model Evolutions with SOC (II)

- Another extrapolation is used to determine the capacity loss at 0% SOC.
- The aging relation among SOC values at 40 ºC is taken as reference for LFP cells.



Naumann, M., Schimpe, M., Keil, P., Hesse, H. C., & Jossen, A. (2018). Analysis and modeling of calendar aging of a commercial LiFePO4/graphite cell.

Resulting Capacity Fade After 50 Years

- Therefore, the calculated aging ratios among different SOC values after 50 years are:
  - 0.41 between NMC cells stored at 0% and cells at 50% SOC
  - 0.24 between NMC cells stored at 0% and cells at 100% SOC
  - 0.44 between LFP cells stored at 0% and cells at 50% SOC
- Taking these ratios into account and combining them with the calendar aging results obtained as a function of the temperature for the different types of commercial Li-ion cells, we can conclude that the expected remained capacity for this cells **after a 50-year space trip at 0ºC and 0% SOC** would be:

Type of cell	NMC cylindrical	NMC pouch	LFP cylindrical
Capacity fade	**8.5**	**7.2**	**13.9**

Conclusions

- Results are encouraging and confirm Li-ion batteries as a potential solution to be combined with RTGs in a 50-year space mission.
- Extrapolations from the tests performed at higher temperatures and SOCs allow concluding that NMC and LFP commercial cells would likely lose no more than 15% capacity in 50 years if stored at 0% state-of-charge and 0 °C.
- NMC cells seem to respond better than their LFP counterparts under these conditions.
- Further research analyzing other datasets and also some experimental aging characterization at temperatures below 0ºC will have to be undergone to validate the calculated results.

Acknowledgements

- The authors gratefully acknowledge support received from the Center for Advanced Life Cycle Engineering (CALCE), University of Maryland.

- The authors also acknowledge support received from the University Jaume I and the Generalitat Valenciana for this work under grants UJI-B2021-35 and CIBEST/2021/54, respectively.

Thank you!! Any questions?

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