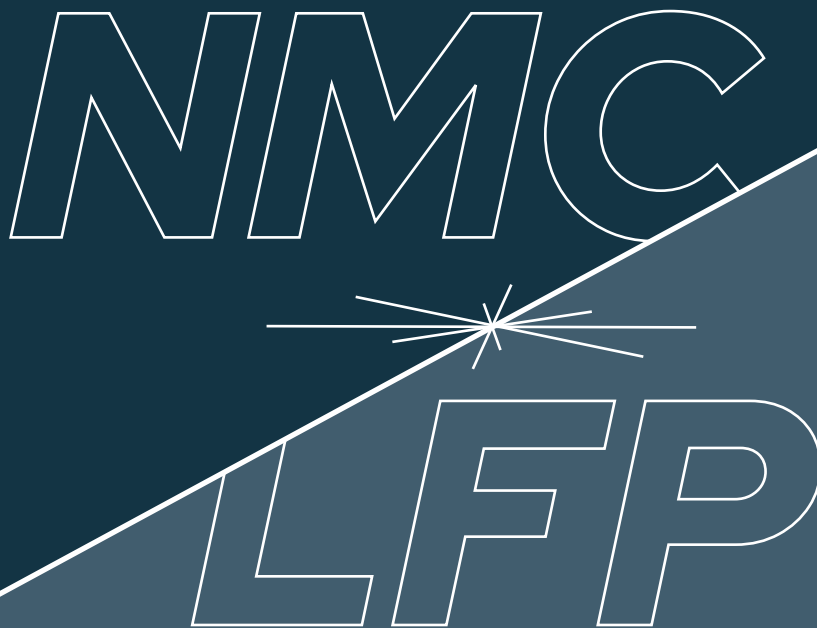


NMC VERSUS LFP BATTERY SAFETY

How the complete system architecture
determines the safety of a battery



1. INTRODUCTION

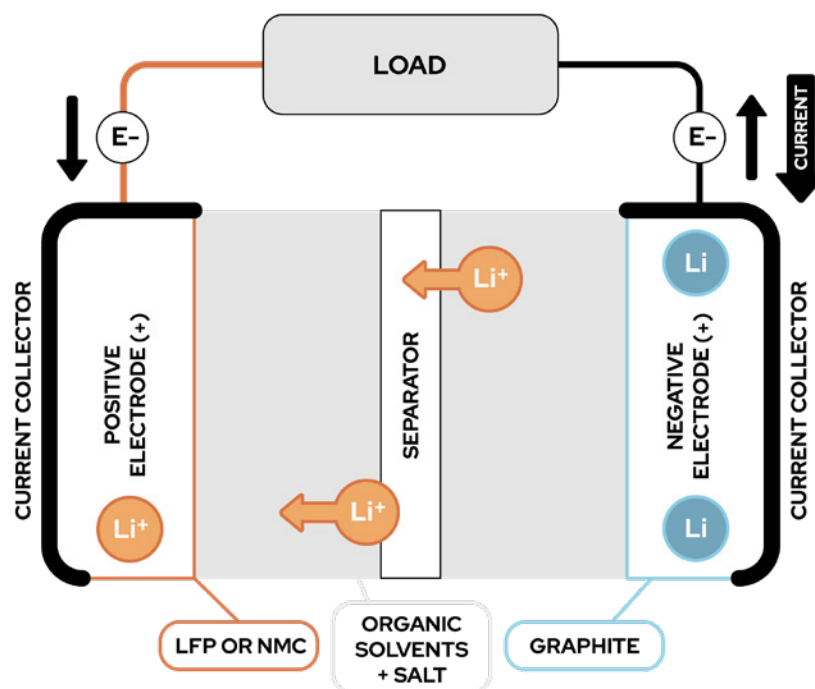
NMC – Lithium Nickel Manganese Cobalt Oxide – and LFP – Lithium Iron Phosphate – are popular lithium-ion battery chemistries. These chemistries differ in their performance characteristics and behave differently during a catastrophic thermal event. This paper dives into the facts of the safety behavior of the different chemistries and aims to give a balanced view.

2. THE CELL

A state-of-the-art lithium-ion battery is often very complex, with a design involving several electronic control units, advanced hardware and software, and an elaborate design. At the core of the battery is the cell. The cell is where the electrochemical reactions that provide electricity take place. The cell is complex as well, containing many components, as shown in Figure 1.

For the present discussion, the relevant components are:

1. The positive electrode: Both LFP and NMC are materials that are used in the positive electrode.
2. The negative electrode: In most lithium-ion batteries, the negative electrode consists of graphite.
3. The electrolyte: A liquid medium between the electrodes. It consists of organic solvents and lithium salts.



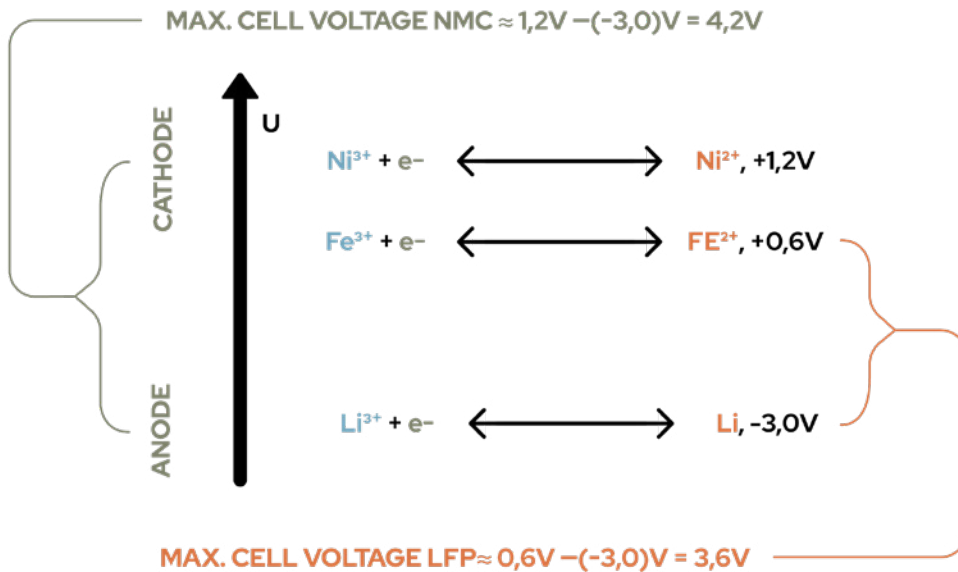
"Figure 1" A lithium-ion cell in principle

Summary: When comparing NMC and LFP cells, we are comparing positive electrode materials. Everything else in the cell is the same.

3. MATERIAL PROPERTIES

Voltage

The differences between LFP and NMC are rooted in their chemical properties. Electrochemical reactivity can be ordered in an electrochemical voltage series. An example is shown in Figure 2 for the cell reactions involving LFP and NMC. For NMC, one of the reactions that generate electricity is the one between nickel and lithium. As shown in the picture, this material combination gives a maximum cell voltage of 4,2V. For LFP, the reaction of interest is the one between iron and lithium. This material combination only gives a maximum cell voltage of 3,6V.

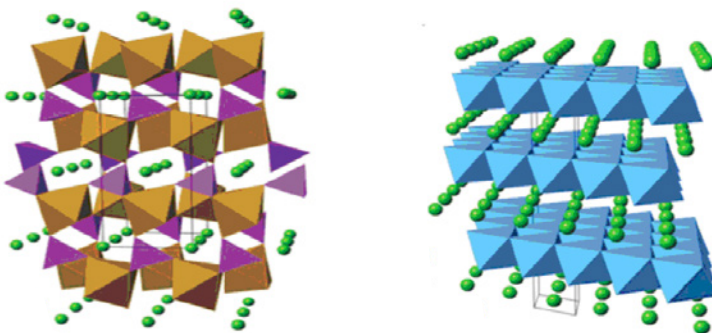


“Figure 2” Standard electrode potentials of battery reactions.

NOTE: These are standard tabulated values and will vary depending on the exact composition of the cell.

Capacity

On cell level, capacity can be translated to the density of lithium in the electrode materials. Figure 3 shows the structures of NMC and LFP. The layered structure of NMC can hold more lithium per unit of mass than the open structure of LFP. The open structure of LFP allows for better discharge power than the more compact structure of NMC, as the ions can move more freely in and out of the structure. As energy equals capacity times power, there are two material factors contributing to NMC having higher energy than LFP. Especially power is also strongly influenced by material granularity and cell design – there are NMC cells with very good power density.



“Figure 3” The crystalline structures of NMC and LFP. Lithium ions are shown as green points.

Summary: Many of the typical properties of NMC and LFP can be traced back to fundamental chemical characteristics.

4. PERFORMANCE

NMC and LFP batteries perform differently. A few properties are listed in Table 1. Much of the performance can be explained by the material properties in Chapter 3. A few notes:

- Charge power is not listed in Table 1. The reason is that this property is mainly linked to the negative electrode, which is the same for both chemistries.
- In general, power depends very much on the cell design and the details of the cell materials.
- LFP can cycle for more cycles than NMC. But we need to consider the fact that for LFP, there is less energy per cycle. If cycle life is calculated as total energy throughput, the difference between the materials is much smaller.

Property	NMC	LFP
Specific energy	High	Low
Discharge power	Moderate	High
Low-temperature discharge power	Moderate	Low
Cycle life	Moderate	High

"Table 1" Some properties of NMC and LFP

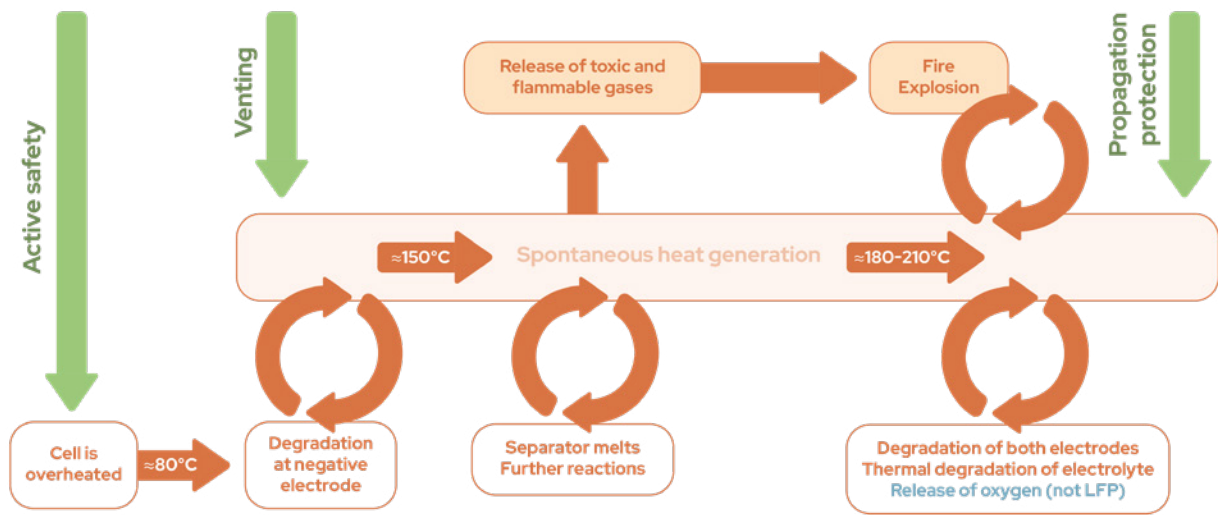
Summary: LFP and NMC differ in terms of energy and power. There is also a difference in cycle life, but this difference is not very large when you compare energy throughput instead of cycles.

5. THERMAL RUNAWAY

The thermal runaway process

Thermal runaway means a rapid increase in cell temperature that eventually leads to fire and emission of toxic gases. The thermal runaway process starts with the overheating of a cell. Chemical reactions release heat, which further fuels the detrimental reactions, and triggers new heat-generating reactions. Once the thermal runaway has started, it is very difficult to interrupt it.

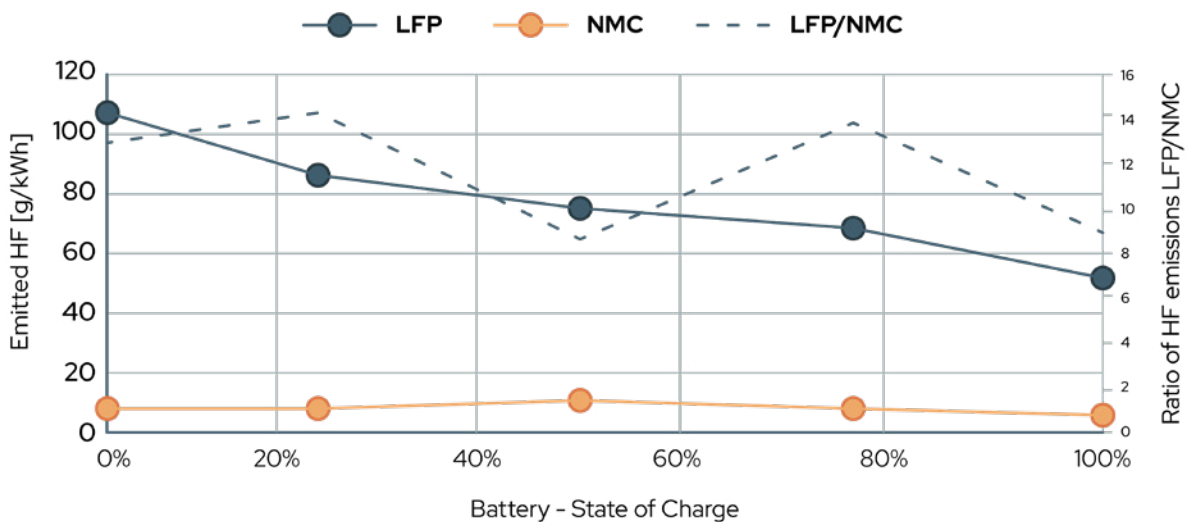
A schematic picture of the thermal runaway process is shown in Figure 4. The initiation takes place at the negative electrode and is thus unrelated to whether it is an NMC or an LFP cell. The final stage differs between the chemistries: Here, NMC releases oxygen, and LFP does not. The release of oxygen leads to an earlier onset of this stage for NMC, and to higher temperatures due to more energy being released momentarily. But LFP sees all other parts of the thermal runaway. The flammable electrolyte is identical for both chemistries and, in total, the same amount of energy will be released in case of fire.



"Figure 4" Schematic picture of the thermal runaway process. The red arrows indicate the system protection.

Emission of toxic gases

All cells have a vent that releases hot gases to the environment when the pressure inside the cell becomes high. The venting cools down the cell and may stop or slow down the thermal runaway process. The gases contain the extremely toxic substance hydrogen fluoride – HF. LFP releases about ten times more HF per battery energy unit than NMC (Figure 5). As the thermal runaway of LFP is less intense, the detection probability is lower. That the process is less violent does not mean that it is less dangerous, and an LFP battery may emit lots of harmful HF that goes unnoticed.



"Figure 5" Emission of HF per kWh for NMC and LFP. Data is from Bugryniec et al., Journal of Energy Storage 87 (2024). The article is a meta study, collecting results from several studies.

Causes and mitigation

The thermal runaway always starts with the over-heating of a cell. The over-heating can be caused by misuse during operation or by non-functional factors e.g. in the environment or faults in cell production.

The battery system has both active and passive safety. The active safety functions serve to prevent the thermal runaway from being initiated while the battery is in operation. Since the thermal runaway process starts at the negative electrode, these mechanisms are identical for LFP and NMC. Passive safety addresses hazards not directly related to the usage of the battery. It mitigates the impact of external short-circuiting, mechanical damage and external fire. Thermal runaway causes and their mitigation strategies are listed in Table 2.

Overheating cause	Mitigating strategy
Over-temperature	Active safety
Under-temperature	Active safety
Over-voltage	Active safety
Under-voltage	Active safety
Over-current	Active safety
Mechanical damage	Passive safety
External short-circuiting	Passive safety
Internal short-circuiting	Passive safety
External fire	Passive safety

"Table 2" Causes of thermal runaway and their mitigation

The passive safety also serves to prevent propagation, i.e. the spreading of the thermal runaway between cells. There are vents on cell-, module- and pack level to release gases and cool down in the earlier stages of thermal runaway. In the later stages, there are adequate cell-to-cell distances, fire-proof materials and mechanical protection. As well as for active safety, the strategy for passive safety is identical between cell chemistries, but the details may vary depending on the safety behavior. The red arrows in Figure 4 indicate when the system acts to protect against thermal runaway.

Key take-away from Chapter 5: Both LFP and NMC undergo thermal runaway, but with different characteristics. The process is more intense for NMC, but more hydrogen fluoride is emitted for LFP. The mitigation strategies are identical for the two chemistries.

6. CONCLUDING REMARKS

LFP and NMC lithium-ion batteries exhibit distinct performance and safety profiles, shaped by their positive electrode materials. NMC offers higher specific energy, while LFP excels in discharge power. These differences mean that each chemistry is suited for specific application needs.

Both LFP and NMC cells are susceptible to thermal runaway, though their responses diverge. NMC cells tend to release more energy at the onset of the last stage of the thermal runaway, leading to a more intense process at this stage. LFP cells tend to emit much more of the toxic hydrogen fluoride gas.

The safety of lithium-ion batteries depends on robust system-level mechanisms, including both active and passive safety features. The overall safety strategy is consistent between NMC and LFP, regardless of chemistry, and system design shall never compromise safety for cost.

Ultimately, battery safety is determined by the complete system architecture, not the cell chemistry alone.

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